Northeast Fisheries Science Center Reference Document 24-04

The Summer Flounder Chronicles IV: four decades of population dynamics, 1976-2022

February 2024

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US DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
Woods Hole, Massachusetts

February 2024

Northeast Fisheries Science Center (NEFSC) Reference Documents

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Information Quality Act Compliance: In accordance with section 515 of Public Law 106-554, the NEFSC completed both technical and policy reviews for this report. These pre-dissemination reviews are on file at the NEFSC Editorial Office.

This document may be cited as:

Terceiro M. 2024. The Summer Flounder Chronicles IV: four decades of population dynamics, 1976-2022. US Dept Commer Northeast Fish Sci Cent Ref Doc. 24-04; 137 p.

TABLE OF CONTENTS

ABSTRACT

The summer flounder or fluke (*Paralichthys dentatus*) supports the most biologically and economically important commercial and recreational flatfish fisheries of the U.S. Atlantic coast, ranging from Massachusetts to North Carolina. Three previous papers recounted how fishing mortality had stabilized by 2017 at its lowest level in over 40 years, with stock biomass near its highest since the comprehensive stock assessments began in the mid-1970s. This sequence of stock decline to near collapse and subsequent successful rebuilding had a significant effect on the observed and estimated biological characteristics of the population. It is widely expressed that northwest Atlantic Ocean temperatures have rapidly increased over this same period and likely have a range of impacts on marine populations (Pershing et al. 2019). In this work, the assessment results and biological and environmental information associated with the stock are updated through 2022, and some exploratory analyses are conducted to quantify significant drivers of summer flounder population dynamics, all with the goal of providing useful information and direction for future stock assessments.

INTRODUCTION

Summer flounder (*Paralichthys dentatus*) support important commercial and recreational fisheries along the U.S. Atlantic coast from Massachusetts to North Carolina. Summer flounder are the most important commercial flatfish species in the southern New England and Mid-Atlantic regions in terms of landed weight and ex-vessel value. Summer flounder have historically also been highly sought by sport fishermen, especially in New York and New Jersey waters, and summer flounder is currently the most frequent recreationally-caught flatfish species (Terceiro 2016). Summer flounder is also currently the largest flatfish stock in terms of biomass of the U.S Atlantic coast (NEFSC 2023). The joint Atlantic States Marine Fisheries Commission (ASMFC)/Mid-Atlantic Fishery Management Council (MAFMC) Fisheries Management Plan (FMP) for summer flounder (MAFMC 1988) defined the Plan's management unit as occurring from the southern border of North Carolina to the U.S.-Canada border. This designation closely follows the definition of Wilk et al. (1980) of a unit summer flounder stock extending from Cape Hatteras, NC, north to the U.S.-Canada border, and this definition has been used in all recent benchmark stock assessments (NEFSC 2008a, 2013).

Three previous papers chronicled the sequence of stock assessments, the development of the FMP and its Amendments, and the various scientific and political controversies and lawsuits that constituted the history of summer flounder fishery from 1975-2000 (Terceiro 2001), 2001-2010 (Terceiro 2011), and 2011-2016 (Terceiro 2018). This paper focuses on the changes in the biological characteristics and rates that have occurred over the corresponding 47-year period from 1976-2022. First, recent stock assessment (2018-2023) estimates of time series trends of abundance and mortality are summarized to provide context and data inputs for the work that follows. Second, the long-term changes and/or trends in the biological characteristics of the stock are described in detail. Third, relevant environmental and climate factors are compiled and their relationship to some aspects of the population dynamics are investigated. Finally, some analyses are conducted that relate biological characteristics of the stock to fishery and environmental metrics.

STOCK ASSESSMENTS FOR 2018-2023

Introduction

As summarized in Terceiro (2001, 2011, and 2018), the stock assessments conducted during the 1970s through the mid-2010s described how the stock had been overfished and severely depleted, reaching a nadir in abundance during the late 1980s and early 1990s. The management regime enacted in the 1990s reversed this trend, and under decreased fishing mortality, the stock began to rebuild toward the management biomass target after 2000, reaching that target in 2011 (Terceiro 2018). In its review of the 2013 SAW 57 benchmark assessment, the MAFMC Scientific and Statistical Committee (SSC) stated "…the Summer Flounder assessment has multiple sources of data, which are largely internally consistent, and it does a thorough job of exploring the impacts of sources of uncertainty on the estimated model fits. As a result, the SSC believes that the Summer Flounder stock assessment is considerably more accurate than other assessments of Mid-Atlantic stocks and, therefore, considers use of the default Coefficient of Variation (CV) = 100% not appropriate. Accordingly, the SSC determined that it should use a CV = 60%" (2013 memorandum from John Boreman to Richard M. Robins, Jr.). This change effectively allowed the SSC to reduce the standard buffer between the Overfishing Limit (OFL) and the Allowable Biological Catch (ABC). The SSC then applied the P-star 40 risk policy and control rule using an OFL CV = 60% in specifying a 2014 ABC of 9,950 metric tons (mt; 21.9 million lb) and a 2015 ABC of 10,329 mt (22.8 million lb). The 2014 ABC represented only a 1% decrease from the 2014 placeholder ABC previously established from the 2012 assessment.

The subsequent assessment update in 2015 (Terceiro 2015) found that the stock was not overfished but that overfishing was occurring in 2014, with an increasing trend in fishing mortality (F) on the fully selected age 4 fish, a decreasing trend in spawning stock biomass (SSB), a new concern that the recruitment for the most recent 5 years (2010-2014) had been average to below average, and an emerging retrospective pattern (Terceiro 2015). These factors eventually resulted in a 2016 ABC (7,375 mt = 16.3 million lb) that represented a 29% reduction from the 2015 ABC (10,329 mt = 22.8 million lb) and an 11% reduction from the 2015 catch (8,285 mt = 18.3 million lb; Terceiro 2015). The SSC accompanied its catch advice with a recommendation for an expedited benchmark assessment to "…seek to improve model performance and reduce the retrospective bias present in the current assessment update" (2015 memorandum from John Boreman to Richard M. Robins, Jr.).

The next assessment update in 2016 (Terceiro 2016) found that the stock was not overfished but that overfishing was occurring in 2015. Consistent with the 2015 update, the 2016 update estimated an increasing trend in F on the fully selected age 4 fish, a decreasing trend in SSB, continuing concern that the recruitment for the most recent 6 years (2010-2015) had now been below average, and a now consistent retrospective pattern of underestimating F and overestimating SSB in the last several terminal years. The historical assessment retrospective likewise indicated the emergence of a gradual upward adjustment of recent F estimates and downward adjustment of recent SSB estimates since the 2011 assessment. Tracking of recent assessment estimates and projections of F and SSB indicated that the aforementioned retrospective patterns in concert with the below average recruitment of the 2010-2015 year classes had resulted in projected Fs being exceeded and projected SSBs not being attained, even though fishery catches had been about equal to the projected ABCs. The SSC recommended an ABC for 2017 of 5,125 mt (= 11.3 million lb) and an ABC for 2018 of 5,999 mt (= 13.2 million lb; 2016 memorandum from John Boreman to Richard M. Robins, Jr.). This new ABC for 2017 was 29% less than the original 2017 ABC specified in 2015 and 31% less than the expected 2016 catch. The SSC's newly recommended 2017 ABC brought mostly negative reactions from external scientists, fishermen, politicians, and the media during the final months of 2016. Despite demands from many quarters for a stay of catch reductions and an immediate benchmark assessment, the National Marine Fisheries Service (NMFS) Greater Atlantic Regional Office (GARFO) and the U.S. Department of Commerce (DOC) accepted the MAFMC rationale for reducing the 2017 OFL to the recommended ABC buffer and implemented those ABCs for 2017 and 2018 (Fisheries of the Northeastern…2016). The recent low productivity of the stock, as evidenced by the 2016 update estimation of 6 consecutive (2010-2015) below-average year classes, remained a concern, and scientists and managers were in general uneasy about the biomass trend of the stock. The ABCs set for 2017-2018 were the lowest since quota management was implemented in 1993, and a new benchmark assessment of summer flounder was scheduled for late 2018.

The 2018 SAW 66 Benchmark Assessment

Important issues

Entering the meetings to prepare the 2018 SAW 66 benchmark assessment (NEFSC 2019), the most important issues and controversies for summer flounder included: 1) debate over the nature and causes of the observed changes in the spatial distribution of summer flounder and potential impacts for science and management, 2) scientific and political debate over the necessity of including sex structure in the summer flounder assessment, and 3) the re-emergence of retrospective error in the assessment modeling results affecting the evaluation of stock status and the reliability of catch forecasts (Terceiro 2018).

In response to issue 1 (spatial distribution), catch data from both recreational and commercial fisheries vessel trip reports (VTRs) as well as observer reports were summarized to determine spatial trends in catch and effort within the fishery in recent decades. The assessment concluded that a northerly trend of offshore commercial catches had developed since 2000 with the largest catches now south of Rhode Island and catches of summer flounder at its southern extent reduced after 2005. The fishery observer data showed a much larger presence of large summer flounder catches on Georges Bank after 2005. Recreational fishing catch distribution from party and charter boats was found to be relatively unchanged throughout the 1990s and 2000s. Research survey data indicated apparent changes in the spatial distribution of summer flounder over the past few decades, with generally increased abundance northward and expansion eastward. Spatial expansion was also more apparent in the years of greater abundance since about 2000. A Vector Auto-regressive Spatio-Temporal (VAST) model was used to investigate whether the stock had shifted and the extent to which an observed shift could be explained by changes in abundance, size structure, environmental variables, and fishing. Data from the Northeast Fisheries Science Center (NEFSC) and Northeast Area Monitoring and Assessment Program (NEAMAP) spring and fall surveys were used in the VAST model. The VAST model work indicated that summer flounder shifted northeast over time. The distribution shift did not appear to be driven by an increase in the abundance of older, larger fish which tend to inhabit more northeastern waters, with the shift northward evident even in small fish. Indeed, recruits appeared to be shifting northward at a faster rate than spawners, suggesting they were not merely tracking the expansion of spawners northward. Instead, they appeared to be reacting to some other driver. The northward shift of recruits also suggests that the driver was unlikely to be fishing as recruits are relatively lightly exploited by the fishery. However, neither total biomass nor environmental covariates explained the distribution shift. Instead, the distribution shift was attributed to unexplained sources (NEFSC 2019).

In response to issue 2 (sex-structured assessment models), several new modeling approaches were developed. For the existing age structured assessment program (ASAP) model, the existing combined sex model was compared with results from independent models structured by sex by incorporating NEFSC and NEMAP sex-ratio and mean weight by sex information in the construction of fishery and survey catches by sex. A Stock Synthesis (SS) model was developed that mimicked a sex-structured Virtual Population Analysis. The features included flexible initial numbers at age, time varying sex and age-specific selectivity, freely estimated recruitment, and the use of weight-at-age data. The assessment concluded the SS model would need to go through a systematic model building and diagnostic approach before further consideration. A Sex-Age-Length (SAL) was constructed in Template Model Builder (TMB) to address sex-specific differences in growth and mortality that can result in differences in size specific selectivity by fishery. Preliminary analyses were conducted using simulated data. The model was intended to be applied to the actual SAL based data derived from available data sources and configured using the NEFSC survey data and 4 fleet configurations. A state-space, sex-specific, age-structured assessment model was configured in various ways for consideration. This approach used a basic statistical catch at age model core but with certain parameters shared by the 2 sexes. The differences in numbers at age for males and females (sex states) were informed by observations of the proportion at age in the NEFSC surveys. Size effects on selectivity were modeled using empirical estimates of size at age by sex. Ultimately, there was no statistical evidence found for differences in selectivity at age by sex, and size-based selectivity did not outperform age-based selectivity. The assessment concluded that there were not strong differences in the results of the different models (i.e., trends in SSB, F, recruitment [R]) between those that incorporated additional sex-specific complexity and those that did not; therefore, significant gains from the additional sex-specific information were not demonstrated and did not warrant selection of a less developed sex structured model that required additional parameters and assumptions (NEFSC 2019).

In response to issue 3 (retrospective error), an internal retrospective analysis for the 2018 SAW 66 final ASAP model run was conducted to examine the stability of the model estimates as data were removed from the end of the model time series (terminal year = 2017). Seven retrospective runs (peels) were made for terminal years back to 2010. Over the terminal 7 years, the annual retrospective change in F averaged -4% (underestimated by 4%), the annual retrospective change in SSB averaged +2% (overestimated by 2%), and the annual retrospective change in R (true age 0, model age 1) averaged +2% (overestimated by 2%). These were substantial reductions in retrospective error compared to the previous benchmark and 2 prior update assessments. A historical retrospective analyses comparing the final 2018 SAW 66 model F and SSB estimates with those from the previous 25 assessments dating back to 1990 indicated that general trends of F and SSB had been consistent since the 1990s assessments. The use of the new calibrated estimates of recreational landings and discards in the 2018 SAW 66 assessment increased the 1982-2017 total catch by an average of almost 30%. While the magnitude of F was not strongly affected, the increased catch has resulted in increased estimates of SSB compared to the historical assessments and reduced the internal retrospective pattern (NEFCS 2019).

Model estimates of stock size and fishing mortality and stock status

Based on the 2018 SAW 66 final model, the summer flounder stock was judged to be not overfished and that overfishing had not occurred in 2017 relative to the newly estimated FMSY proxy (F35%) reference points. The F in 2017 was estimated to be 0.334, 25% below the new FMSY proxy = F35% = 0.448. SSB in 2017 was estimated to be 44,552 mt (98 million lb), about 78% of the new SSBMSY proxy = SSBMSY35% = 57,159 mt (126 million lb). Arithmetic average R from 1982-2017 was estimated to be 53 million fish. R was estimated to have been below average since 2011, ranging from 29 to 52 million and averaging 38 million fish. The relative survival of summer flounder recruits, expressed as the recruitment production per unit of spawning stock biomass (R/SSB), was higher in the 1980s and early 1990s than in the years since 1996. The SAW 66 Review Panel and the MAFMC SSC both concluded that the use of multiple data sets for key biological parameters such as R, analyses of alternative models and model configurations, and sensitivity analyses of key assumptions all contributed to the quality of the 2018 SAW 66 assessment (NEFSC 2019; 2019 memorandum from John Boreman to Michael Luisi).

Projected OFL/ABC for 2019-2021

The SSC was asked by the MAFMC to recommend 2 alternative ABCs based on the 2018 SAW 66 assessment: ABCs for 2019-2021 fishing years derived by the typical approach resulting in ABCs varying each year, and a constant ABC for all 3 fishing years derived by averaging the three ABCs resulting from the typical approach. The constant ABC alternative was proposed to help stabilize management changes, whether catches were increasing or decreasing over the projected years, if the P-star 40 risk policy could still be met. The SSC recommended the use of the most recent 7-year series of R (2011-2017) from the 2018 SAW 66 ASAP model results for OFL/ABC projections, judging that near-term future conditions were more likely to reflect recent R patterns than those in the entire 36-year assessment model time series. The SSC continued to use the 60% OFL CV, concluding that the latest benchmark assessment did not result in major changes to the quality of the data and model that the SSC has previously determined met those criteria. The SSC recommended and NMFS accepted a fixed catch scenario for the 2020-2021 ABCs (Fisheries of the Northeastern…2019, 2020) averaging 11,354 mt (25.031 million lb).

The 2021 Management Track Assessment

Important issues

In 2020, the Northeast Region Coordinating Council (NRCC; the cooperative body responsible for managing the U.S. Northeast stock assessment process) instituted an enhanced stock assessment process. The new process laid out 2 tracks of assessment work: a Management Track that includes the more routine assessments that provides catch advice but with more flexibility to make improvements than in the past, and a Research Track that allows comprehensive research and development of improved assessments on a stock-by-stock or topical basis. The process provides clear opportunities for input and engagement from stakeholders and research partners, and the process also provides a longer-term planning horizon to carry out research to improve assessments on both tracks. A key aspect of the new process is the NRCC's development and negotiation of long-term Management Track cycles for each stock (i.e., how often each stock is assessed and in what years) as well as a 5-year Research Track schedule. With the most recent benchmark (i.e., Research Track) assessment having occurred just 2 years before, summer flounder was put on a 2-year management track assessment (MTA) cycle, with the first to occur in 2021.

Between 2018 and 2020, the NEFSC and GARFO were working to integrate their data reporting, compilation, and estimation systems for the commercial landings and discards, so that there would be a single system for use in quota monitoring and stock assessment. This integrated system would ultimately be known as the Catch Accounting and Monitoring System (CAMS), to be used for commercial catch for the years 2020 and later, but it would not become available for general use until 2022. As a result, because the commercial catch estimates for 2020 were still under development, the 2021 MTA would include total catch only through 2019 rather than 2020 as in normal practice.

Model estimates of stock size and fishing mortality and stock status

Based on the 2021 MTA final model, the summer flounder stock was judged to be not overfished and that overfishing had not occurred in 2019 relative to the newly updated FMSY proxy (F35%) reference points. The F in 2019 was estimated to be 0.340, 19% below the new FMSY proxy = F35% = 0.422. SSB in 2019 was estimated to be 47,397 mt (104 million lb), about 86% of the new SSBMSY proxy = SSBMSY35% = 55,217 mt (122 million lb). Arithmetic average

R at age 0 from 1982-2019 was estimated to be 53 million fish. R was estimated to have been below average between 2011 and 2017, ranging from 31 to 45 million and averaging 36 million fish. The 2018 year class was estimated at 61 million fish, however, above average and the largest since 2009, while the 2019 year class was below average at 49 million fish. The assessment model retrospective error was considered to be minor (adjustment for the retrospective errors in F and SBB fell within the 90% confidence intervals of the terminal year estimates), with no adjustments needed for stock status determination or projections. The R/SSB was higher in the 1980s and early 1990s than in the years since 1996, as the stock had varied near SSBMSY (NEFSC 2022).

Projected OFL/ABC for 2022-2023

Projections using the results of the 2021 MTA model (data through 2019) were made to estimate the OFL/ABC catches for 2022-2023. The projections assumed that the 2020 and 2021 ABCs of 11,354 mt and 12,297 mt (adjusted upward from the initial 2018 SAW 66 projections due to changes in the MAMFC OFL to ABC buffer policy that accepted more risk than previously) were caught. Given the continuing pattern of below-average R to the stock, the projections sampled from the estimated R for the most recent 9 years (2011-2019; average R = 40 million fish). The SSC continued to use the 60% OFL CV, concluding that the 2021 MTA did not result in major changes to the quality of the data and model that the SSC had previously determined met those criteria. The SSC recommended and NMFS accepted (Fisheries of the Northeastern…2021, 2023) a fixed catch scenario for the 2022-2023 ABCs averaging 15,021 mt (33.116 million lb), a 32% increase over the 2020-2021 ABC of 11,354 mt (25.031 million lb). The increase was due to improved stock status since 2017 relative to SSBMSY, expectations of an above average 2018 year class entering the exploitable stock biomass, and the new MAFMC management policy that allowed more risk as the stock neared SSBMSY.

The 2023 Management Track Assessment

Important issues

The most important issue for the 2023 MTA (NEFSC 2023) was the inclusion of the CAMS commercial landings and discards estimates for 2020-2022, as there was initial concern that some discontinuity might be evident between the old NEFSC catch series and the new CAMS series. However, no such issue was detected, and the new catch estimates were incorporated into the assessment model without any diagnostic problems. A second issue was the continued declining trends in growth rates and changes in the sex-ratio at age, and recognition that these trends would likely change the realized productivity of the stock and in turn affect estimates of the biological reference points. It was recognized that changes in growth, maturity, and R may be environmentally mediated, but the mechanisms remained unknown.

Model estimates of stock size and fishing mortality and stock status

Based on the 2023 MTA final model, the summer flounder stock was judged to be not overfished but that overfishing had occurred in 2022 relative to the newly updated FMSY proxy (F35%) reference points (NEFSC 2023). The F in 2022 was estimated to be 0.464, 3% above the new FMSY proxy = F35% = 0.451. SSB in 2022 was estimated to be 40,994 mt (90 million lb), about 83% of the new SSBMSY proxy = SSBMSY35% = 49,561 mt (109 million lb). Arithmetic average R from 1982-2022 was estimated to be 51 million fish. R was estimated to have been below average between 2011 and 2017, ranging from 27 to 39 million and averaging 34 million fish. R was found to have improved since 2017 but was still below the time series average, ranging from 36 to 43 million and averaging 40 million fish during 2018-2022 (Figures 1 and 2).

The model estimates of F and SSB in 2022 adjusted for internal retrospective error were within the model estimate 90% confidence intervals and so no adjustment of these terminal year estimates was made for stock status determination or projections. However, the retrospective error for R was relatively large (overestimated by about 28%), and the size of the 2018 year class initially estimated in the 2021 MTA at 61 million fish was reduced to 43 million, a reduction of 28% and below the long-term average. The R/SSB was higher in the 1980s and early 1990s than in the years since 1996, as the stock has varied near SSBMSY (Figure 3). The historical retrospective analysis (comparison between assessments) indicated that the general trends in SSB, R, and F were consistent over the history of the assessment (Figure 4).

Projected OFL/ABC for 2024-2025

Projections using the results of the 2023 MTA model (data through 2022) were made to estimate the OFL/ABC catches for 2024-2025. The projections assumed that the final 2023 ABC of 15,023 mt was caught. Given a continuing recent pattern of below average R the 2018 SAW 66 and MAFMC SSC had used the most recent 7 below-average R in projections, and the SSC used the most recent 9 R in 2021 MTA projections. In light of the now decade-long pattern of below-average R, the SSC used most recent 12 R (2011-2022) in the 2023 MTA projections. The SSC continued to use the 60% OFL CV, concluding that 2023 MTA did not result in major changes to the quality of the data and model that the SSC has previously determined met those criteria. The SSC and MAFMC recommended (MAFMC 2023) a fixed catch scenario for the 2024-2025 ABCs averaging 8,761 mt (19.315 million lb), a 42% decrease from the 2023 ABC of 15,023 mt (33.120 million lb). The 2023 MTA and SSC peer reviews noted there were a number of reasons for the decrease in the ABC, including a) the continued decreasing trend in mean weights leading to a less productive stock (i.e., lower biomass and catch for the same number of fish); b) the continued small but persistent retrospective error that lead to a compounding over years of overestimation of SSB and underestimation of F; and more immediately, c) the substantial retrospective overestimation of the 2018 year class, which had a large effect on the projections for 2024-2025 as that cohort passed into and through the exploitable stock biomass (NEFSC 2023).

BIOLOGICAL DATA

Aging Research History

Historical studies of summer flounder age and growth include those of Poole (1961), Eldridge (1962), Powell (1974), Smith and Daiber (1977), Henderson (1979), and Shepherd (1980). A summer flounder aging workshop held in 1980 (Smith et al. 1981) noted that these early studies provided differing interpretations of the growth zones on summer flounder scales and otoliths. After a comparative study by fisheries biologists from along the Atlantic coast, the workshop concluded that both structures followed the generalized temperate waters pattern of rapid growth during early summer through early winter. Scales were identified as the better structure for aging, being preferred over otoliths due to the possibility of poor otolith calcification and/or resorption. Spawning was noted to occur to from early September in the north through the following March in the south. For uniformity, January 1 was considered the birthday, with fish not considered 1 year old until passing their first summer, to eliminate the possibility of fall spawned fish being classified as age 1 the following January. The 1980 workshop effectively set the first coast-wide conventions for aging summer flounder and importantly concluded that the minimum observed mean length of age 1 fish should be at about 17-18 cm and of age 2 fish at about 28-29 cm (Smith et al. 1981).

A second summer flounder aging workshop was held in 1990 (Almeida et al. 1992) in response to continuing confusion among summer flounder biologists over the proper interpretation of the conventions established by the 1980 workshop (Smith et al. 1981). Several issues were addressed, including the differences in processing, interpretation of scale and otolith marks, the age classification of the first distinct annulus measured from the focus, and consideration of new studies completed since the 1980 workshop. The 1990 workshop agreed to accept the summer flounder aging criteria provided in Dery (1988), and in particular noted that first annulus formation for a given cohort could occur after 18-21 months of growth for fish spawned in the north in the fall, and after 10-16 months of growth for fish spawned in the south early the subsequent spring. The latter conclusion was based on a review of the work of Szedlmayer and Able (1992), which validated the first-year growth assumption and interpretation of the first annulus. The 1990 workshop most importantly concluded that there was consistency in aging techniques and interpretation and that first-year growth for summer flounder was extremely rapid. The workshop noted the potential for fish born early in the calendar year and inhabiting estuarine areas of the mid-Atlantic to reach 30 cm by their first winter and be classified as age 0, in support of the Poole (1961) and Szedlmayer and Able (1992) conclusions (Almeida et al. 1992).

Work performed in preparation for the Stock Assessment Workshop 22 stock assessment (SAW 22; NEFSC 1996) indicated a major expansion in the size range of 1-year-old summer flounder collected during the 1995 and 1996 NEFSC winter bottom trawl surveys. The work also brought to light developing differences between ages determined by NEFSC and North Carolina Division of Marine Fisheries (NCDMF) fishery biology staffs. Age structure (scale) exchanges were performed prior to the SAW 22 assessment to explore these differences. The results of the first 2 exchanges were reported at SAW 22 (NEFSC 1996) and indicated low levels of agreement between age readers at the NEFSC and NCDMF (31% and 46%). During 1996, research was conducted to determine inter-annular distances and to back-calculate mean length at age from scale samples collected on all NEFSC bottom trawl surveys (winter, spring, and fall) for comparison with NCDMF commercial winter trawl fishery samples. While mean length at age remained relatively constant from year to year, inter-annular distances increased sharply in the samples from the 1995-1996 winter surveys and increased to a lesser degree in samples from other 1995-1996 surveys. As a result, further exchanges were suspended pending the resolution of an apparent NEFSC aging problem.

Age samples from the winter 1997 bottom trawl survey, aged utilizing both scales and otoliths by only by 1 reader, subsequently indicated a similar pattern as the previous 2 winter surveys (i.e., several large age 1 individuals) and some disagreement between scale and otolith ages obtained from the same fish. Because of these problems, a team of 5 experienced NEFSC readers was formed to re-examine the scales aged from the winter survey. After examining several hundred scales, the team determined that re-aging all samples from 1995-1997 would be appropriate, including all winter, spring, and fall samples from the NEFSC and Massachusetts Division of Marine Fisheries (MADMF) bottom trawl surveys and all samples from the commercial fishery. The age determination criteria remained the same as those developed at the 1990 workshop (Almeida et al. 1992) and described in the aging manual utilized by NEFSC staff (Dery 1988). Only those fish for which a 100% agreement of all team members was attained were included in the revised database. The data from the re-aged database were used in analyses in the SAW 25 assessment (NEFSC 1997).

A third summer flounder aging workshop was held at the NEFSC in 1999 to continue the exchange of age structures and review of aging protocols for summer flounder (Bolz et al. 2000). Participants at this workshop concluded that the majority of aging disagreements in recent NEFSC-NCDMF exchanges had arisen from inconsistency among readers in the interpretation of marginal scale increments due to highly variable timing of annulus formation and in the interpretation of first-year growth patterns and classification of the first annulus. The workshop recommended regular sample exchanges between NEFSC and NCDMF, and further analyses of first-year growth. Subsequently, Sipe and Chittenden (2001) concluded that sectioned otoliths were the best structure for aging summer flounder over the age range from 0 to 10 years. Beginning in 2001, both scales and otoliths began to be routinely collected in all NEFSC trawl surveys for fish larger than 60 cm.

An exchange of NEFSC and NCDMF aging structures for summer flounder occurred again in 2006, after the SAW Southern Demersal Working Group (SDWG) listed the age sample exchange as a high research priority. This exchange examined samples from fish aged 1 to 9 (23-76 cm total length) and determined that the consistency of aging between NCDMF and the NEFSC was at an acceptable level. Between 2006 and 2011, overall summer flounder aging precision, based on sample-size weighted intra- and inter-reader aging agreement, averaged 86% with an overall CV of 3%. The degree of precision was very similar for structures sampled from surveys and the commercial fisheries. Figures 5 and 6 show the intra-ager age bias and percent agreement for the 2011 NEFSC trawl survey age samples, and Figures 7-9 show the intra-ager age bias and percent agreement for the 2011 NEFSC commercial fishery age samples.

NEFSC commercial fishery and survey samples began to transition from scales only to scales and otoliths (to allow comparison and possible calibration) beginning in 2009. A fourth summer flounder aging workshop was held at the Virginia Institute of Marine Science (VIMS) in 2014 to continue the exchange of age structures and review of aging protocols for summer flounder. When the NEFSC compared scale and otoliths ages from 619 samples collected from 2009-2013, there was good agreement for all age classes up to 12 years of age (Figure 10). However, there was a minor systematic bias detected with otoliths having slightly higher ages on average. Participants at the 2014 workshop concluded that sectioned otoliths were the desired hard-part to use for summer flounder aging.

In 2017, ASMFC sponsored another aging workshop. For sectioned otoliths, the agreement between aging laboratories was found to be above 80% with low variation and no systematic bias (ASMFC 2017). Both NEFSC survey and commercial samples were completely transitioned to otoliths beginning in 2015 with the 2015 spring trawl survey and quarter 1 commercial samples. Figures 11 and 12 show the intra-ager age bias and percent agreement for the 2016 NEFSC trawl survey and commercial fishery quarter 1 age samples, which are typical of results for about the past decade.

Growth

Trends in NEFSC survey mean length and weight at age: 1976-2022

The NEFSC winter, spring, and fall bottom trawl survey sample data were examined for trends in mean length and weight by sex and age. Age collections for the spring and fall series begin in 1976; the winter survey was conducted between 1992 and 2007. Data are generally presented here for age 0 through age 12; samples for ages 8 and older are more sporadic and variable, although they are more numerous and consistent since 2001.

The winter and spring series indicate no strong trend in the mean lengths of ages 1-2 for sexes combined. For ages 3 and older, there is an increasing trend in mean length from 1976 to about 1990, and then there is a decreasing trend until the mid- to late 1990s. Beginning in about 2000, there are generally decreasing trends in mean length for ages 3 and older (Figures 13 and 14). There is no obvious trend in the fall series for ages 0-1, but there are relatively strong decreasing trends in mean length for combined sexes for ages 2 and older from the mid-1990s until about 2010. Since then, ages 2-4 showed an increasing trend for a few years before again decreasing, while ages 5 and older generally show a decreasing trend (Figure 15).

Individual fish weight collection on NEFSC trawl surveys began in spring 1992. In general, the patterns in mean weight reflect those in mean length, with a decreasing trend in mean weight evident for ages 3 and older since about 2000 (Figures 16-18). As with mean length, there is no obvious trend in the fall series for ages 0-1, but there are relatively strong decreasing trends in mean length for combined sexes for ages 2 and older from the mid-1990s until about 2010. Since then, ages 2-4 showed an increasing trend for a few years before again decreasing, while ages 5 and older generally show a decreasing trend (Figure 18). Trends in the mean weights at age in the total, combined sexes fishery catch (landings plus discards) exhibit a comparable pattern, with strongest declining trends since the 1990s for ages 3 and older (Figure 19).

Trends in mean length at age by sex for all 3 seasonal survey series follow comparable patterns. There are no trends in the mean lengths for ages 0-1, with a generally declining trend since the 1990s for ages 2 and older (Figures 20-22).

When the mean length data for the 3 seasonal survey series are examined by sex and cohort (year class), the slope of the mean as the cohort ages over time generally decreases from the 1970s and 1980s until near the end of the series in the 2020s. For many of years in the 1990s, and near the end of the series when cohort life spans are short, inference of the relative growth rates can be uncertain, but the trends in slopes by cohort generally indicate decreasing growth rates over the time series, and especially since about 2000 (Figures 23-27).

von Bertalanffy Parameters

Early estimates of summer flounder age and growth were limited in spatial and temporal scope, and include those of Poole (1961), Eldridge (1962), Smith and Daiber (1977), and Henderson (1979). Smith and Daiber (1977) used data from 319 fish sampled from Delaware Bay between 1966 and 1968 to estimate the von Bertalanffy asymptotic length parameter, Linf, for males of 62 cm and for females of 88 cm, although their observed maximum ages were only age 7 for males and age 8 for females. Henderson (1979) estimated Linf for sexes combined to be 92 cm and the von Bertalanffy growth rate parameter (k) to be 0.21 based on fish sampled from the commercial fishery in 1976 with a maximum age of 10.

Fogarty (1981) used data from the NEFSC spring and fall trawl surveys for 1,889 scale samples obtained between 1976 and 1979 to estimate von Bertalanffy growth parameters. Fogarty concluded that female summer flounder attained a significantly larger asymptotic size than males but that there was not a significant difference in the growth rate coefficient k. Fogarty (1981) estimated that the parameters for males were Linf = 72.7 cm, k = 0.18, with maximum age of 7; the parameters for females were Linf = 90.6 cm, k = 0.16, with maximum age of 10.

Pentilla et al. (1989) provided information on mean lengths at age for both sexes of summer flounder sampled during NEFSC trawl surveys between 1975 and 1988; the summer flounder ages have since been corrected to be 1 year younger (Almeida et al. 1992; 1997 personal communication from JM Burnett III to author; Bolz et al. 2000). The data from Pentilla et al. (1989) provide parameters for males of Linf = 72.7 cm, k = 0.18, with maximum age of 11; parameters for females of Linf = 90.7 cm, k = 0.16, with maximum age of 11; and parameters for sexes combined of Linf = 81.6, k = 0.17, with maximum age of 11.

In the current work, the NEFSC trawl survey data for 1976-2022 were used to estimate growth parameters for males, females, and sexes combined for the full time series and for 7 multi-year (generally 5 year) bins. The full time series data provide parameters for males (n = 21,962) of Linf = 55.1 cm, k = 0.26, with maximum length of 70 cm (age 8) and age of 16 (length 55, 60 cm); parameters for females (n = 22,773) of Linf = 79.4 cm, k = 0.18, with maximum length of 82 cm (age 11) and age of 15 (length 66, 72 cm); and parameters for sexes combined (n = 44,620, including small fish of undetermined sex) of Linf = 74.2, k = 0.18, with maximum age of 16 (Table 1; Figure 28). One caveat to these survey data results is that they do not include some larger and older fish of both sexes that have been sampled from the commercial catch since 2000, including maximum ages of 18 and 20 for males (at 50 and 57 cm) and 19 for females (at 73 and 79 cm).

The 8 multi-year bins were for the years 1976-1981, 1982-1987, 1988-1993, 1994-1999, 2000-2005, 2006-2011, 2012-2016, and 2017-2022. Von Bertalanffy parameters were estimated for males, females, and sexes combined. For the bins with more limited age ranges, the asymptote of the von Bertalanffy function is not well defined, and so the Linf estimates tend to be unrealistically high and the k estimates tend to be low. In some cases, the model did not converge to provide realistic model parameter estimates, although the predicted lengths over the observed age range were still realistic. The multi-year bin growth curves are tightly clustered through age 5 for females, with some divergence at older ages (in part due to the lack of older ages as noted above), with the most recent bin (2017-2022) indicating smaller predicted lengths at age than in previous years. The growth curves are more variable for males, and therefore for sexes combined, again with the most recent 2017-2022 curve indicating smaller predicted lengths for older males and for all ages when sexes are combined (Figures 29 and 30).

Length-weight parameters

The length-weight parameters used to convert commercial and recreational fishery landings and discards sampled lengths (cm) to weight (kg) are taken from the work of Lux and Porter (1966; L&P), which used individual fish lengths and weights from 2,051 fish collected between 1956 and 1962 to compute the parameters by calendar quarters. Wigley et al. (2003; Wigley) updated the length-weight parameters used in audits of the NEFSC trawl survey data, using individual length and weight information from 9,373 fish for 1992-1999.

In the current work, individual length and weight information from 37,129 fish for 1992-2022 sampled in the NEFSC trawl surveys were used to estimate length-weight parameters for comparison with the earlier studies to judge whether changing from the historical Lux and Porter (1966) parameters would be justified in assessments. Parameters were estimated for the entire 1992-2022 time series, for multi-year blocks (1992-1995, 1996-2000, 2001-2005, 2006-2010, 2011-2015, and 2016-2022), and by survey seasonal time series (winter 1992-2007, spring 1992-2022, and fall 1992-2022).

A comparison among these alternative compilations indicates very little difference in the estimated length-weight relationships from Lux and Porter (1966), Wigley et al. (2003), and the current examination for the NEFSC trawl survey data. The curves are virtually identical through a total length of 62 cm (the combined surveys mean length of age 7 fish; age 7 and older fish compose the assessment plus group), a threshold below which over 95% of the fishery catch has occurred (see the SVs Age 7 xl vertical line in Figures 31 and 32). Above 62 cm, the quarterly length-weight curves of Lux and Porter (1996) bracket the Wigley et al. (2003) and survey multi-year bin curves in the expected way, with first quarter, pre-spawning fish larger in weight at length than fourth quarter, post-spawning fish (Figure 31). In a comparison with survey seasonal curves, the curves are again nearly identical through 62 cm. Above 62 cm, the quarterly length-weight curves of Lux and Porter (1996) align with the survey seasonal curves in the expected way, with the seasonal winter (post-spawning) and spring (pre-spawning) curves close to the Lux and Porter first quarter curve, with the fall survey (September; nearest to peak spawning) curve closest to the Lux and Porter third quarter curve (Figure 32).

K condition factor

Fulton's condition factor, K, is a measure of the relationship between fish length and weight that attempts to quantify the condition of an individual or group of fish. Nash et al. (2006) note that it was Heincke (1908) who first used K as a measure of condition, building on the cubic law of growth in weight first introduced by Fulton in 1904 (K = x*weight / length**3, where x is a constant to scale K near 1). Nash et al. (2006) further point out that it was Ricker (1957) who first attributed the factor K to Fulton and coined the name Fulton's condition factor. The NEFSC winter, spring, and fall trawl survey sample data were examined for trends in condition factor by season and sex. Individual fish weight collection began on NEFSC surveys in spring 1992; the winter survey was conducted between 1992 and 2007. There are no long-term trends in condition factor by season or sex (Figures 33-35).

Sex Ratio

Sex ratio in NEFSC survey raw sample data

The NEFSC winter, spring, and fall trawl survey raw sample data (not the stratified indices by sex and age, although they generally show similar patterns; see the Sex ratio in NEFSC stratified mean indices section) were examined for trends in sex ratio by season and age, expressed as the proportion of females at age. The spring and fall series have sufficient data for the compilation beginning in 1976; the winter survey was conducted from 1992-2007. In the winter survey, the proportion of females showed no trend for age 1, and the mean proportion was 49%. For ages 2 and 3, the proportion has decreased from about 0.7-0.8 in the early 1990s to 0.4-0.6 in the mid-2000s. For ages 4-6, the proportion has decreased from about 0.8-1.0 in the early 1990s to about 0.7 in the mid-2000s. For ages 7 and older that compose the plus group, the proportion has ranged from 0.8 to 1.0 over the series (Figure 36).

In the spring survey, the proportion of females showed no trend for age 1, and the time series mean proportion was 0.4; the recent mean for 2018-2022 was 0.5. For ages 2 and 3, the proportion has decreased from about 0.6-1.0 in the early 1990s to about 0.4-0.5 since 2000; the recent means for 2018-2022 were about 0.4. For ages 4 and 5, the proportion has decreased from a range of 0.8 to 1.0 in the early 1990s to about 0.5 in the mid-2000s; the recent means for 2018-2021 were about 0.6. For ages 6-8, the proportion ranged from 0.5 to 1.0 with no trend for most of the series, but has most recently decreased to near 0.5; the recent means for 2018-2022 were about 0.4-0.6. For older ages 9-15, the ratio is highly variable, but since 2010 has often been 0.5 or lower (Figure 37).

In the fall survey, the proportion of females shows no trend for age 0, and the mean proportion was 0.4. For age 1, the proportion has decreased from about 0.5-0.6 in the 1980s to 0.4-0.5 by the 2010s; the mean for 2018-2022 was about 0.3. For age 2, the proportion has decreased from about 0.5-0.6 in the 1980s to 0.4-0.5 by the 2010s; the mean for 2018-2022 was about 0.4. The proportions at ages 3 and 4 have strongly decreased from about 0.9 through the late 1990s to about 0.5 by the 2010s; the means for 2018-2022 were 0.4 and 0.6. For ages 5-8 and older, the proportions have most recently decreased to about 0.7; the means for 2018-2022 were 0.6, 0.7, 0.7, and 0.7 (Figure 38).

For all NEFSC trawl surveys sample data combined, the proportion of females shows no trend for age 0, and the time series mean proportion was 0.4. For age 1, the proportion females has been below the mean of 0.4 since 2012. For age 2, the proportion has decreased from about 0.5-0.6 in the 1980s to 0.4-0.5 by the 2010s and has been below the mean of 0.5 since 2006. The proportions at ages 3 and 4 strongly decreased from about 0.8-0.9 through the late 1990s to about 0.5 by the 2010s and has been about 0.4 since 2012. For ages 5-8 and older, the proportions have most recently decreased to about 0.5 or lower. The proportion of females for all ages in the stock has most recently been in the range of 0.4-0.5 (Figure 39).

Sex ratio in NEFSC stratified mean indices

NEFSC stratified mean abundance indices (numbers per tow) were calculated for the winter (1992-2007), spring and fall (1976-2022) series. In the most recent benchmark stock assessment (2018 SAW 66; NEFSC 2019), the FSV *Albatross IV* (hereafter Albatross) part of the series (sampling from 1976-2008) and the FSV *HB Bigelow* (hereafter Bigelow) part (sampling from 2009-2022) were split into separate time series. The male and female indices generally follow similar trends over time (Figures 40 and 41).

As in the raw sample data, the sex ratio in the NEFSC stratified indices has changed over the last decade, with generally decreasing proportions of females at ages 2 and older. In the winter indices, the proportion of females showed no trend for age 1, and the mean proportion was 46%. For ages 2, 3, and 4, the proportion has decreased from about 0.6-0.8 in the early 1990s to about 0.4-0.5 by 2007. For ages 5 and 6, the proportion has decreased from about 0.8-1.0 in the early 1990s to about 0.6-0.7 by 2007. For ages 7 and older that compose the plus group, the proportion has ranged from 0.8 to 1.0 over the series (Figure 40).

In the spring indices over the Albatross and Bigelow series, the proportion of females has an increasing trend for age 1 from about 0.3 to 0.5, and the mean proportion was 40%. For ages 2, 3, and 4, the proportion has decreased from about 0.6-0.7 in the late 1970s to about 0.3-0.5 since 2000. For ages 5 and older, the indices during the 1980s and 1990s are generally very small values (often < 0.001 fish per tow, and so round to 0 and appear as missing in the figures) and the proportion of females over the series is variable without a strong trend. Most recently, the proportion of females at ages 5 and older has generally decreased to less than 0.5 (Figures 41, 42, 44, and 45).

In the fall indices over the Albatross and Bigelow series, the proportion of females shows no trend for age 0, and the mean proportion was 0.3. For ages 1-3, the proportion has decreased from about 0.5-0.6 in the 1980s to 0.4-0.5 since about 2016. The proportions at ages 4-7 have strongly decreased from about 0.8 through the late 1990s to 0.6 or less since 2016; proportions at age 8 are highly variable (Figures 41, 43, 44, and 46).

Maturity

Morse (1981) examined the reproductive characteristics of summer flounder using a special collection sampled during the 1974-1979 NEFSC trawl surveys (2,910 total fish). Morse (1981) estimated that the length at 50% maturity (L50%) was 24.7 cm for males and 32.2 cm for females. O'Brien et al. (1993) used NEFSC fall trawl survey data for 1985-1989 (875 total fish) and estimated L50% to be 24.9 cm for males and 28.0 cm for females.

The maturity schedule at age for summer flounder used in the 1990 SAW 11 and subsequent stock assessments through 1999 was developed by the 1990 SAW 11 SDWG using NEFSC fall survey maturity data for 1982-1989 (1999 personal communication from G. Shepherd to author; NEFSC 1990; Terceiro 1999). The 1990 SAW 11 work indicated that the median length at maturity (50^{th} percentile, L_{50}) was 25.7 cm for male summer flounder, 27.6 cm for female summer flounder, and 25.9 cm for the sexes combined. Under the aging convention used in the 1990 SAW 11 and subsequent assessments (Smith et al. 1981, Almeida et al. 1992, Szedlmayer and Able 1992, and Bolz et al. 2000), the median age of maturity (50^{th} percentile, A_{50}) for summer flounder was determined to be age 0.1 years for males and 0.5 years females (i.e., fish about 13-17 months old, based on the actual spawning month and the January 1 aging convention relative to fall sampling). Combined estimated (logistic regression) maturities indicated that at peak spawning time in the autumn (November 1), 38% of age 0 fish are mature, 72% of age 1 fish are mature, 90% of age 2 fish are mature, 97% of age 3 fish are mature, 99% of age 4 fish are mature, and 100% of age 5 and older fish (age 5+) are mature. The maturities for combined sexes age 3 and older (age 3+) were rounded to 100% in the 1990 SAW 11 and subsequent assessments through 1999.

The NEFSC maturity schedules are based on simple gross morphological examination of the gonads, and it was suggested in the early 1990s that they may not have accurately reflected (i.e., overestimated) the true spawning potential of the summer flounder stock, especially for age-0 and age-1 fish. It was also noted, however, that SSB estimates based on age-2 and older fish showed the same long term trends in SSB as estimates which included age 0 and 1 fish in the spawning stock. A research recommendation that the true spawning contribution of young summer flounder to the SSB be investigated was included in research recommendations from summer flounder stock assessments beginning in 1993 (NEFSC 1993).

Research conducted at the University of Rhode Island (URI) by Drs. Jennifer Specker and Rebecca Rand Merson (hereafter referred to collectively as the "URI 1999" study) attempted to address the issue of the true contribution of young summer flounder to the spawning stock. The URI 1999 study examined the histological and biochemical characteristics of female summer flounder oocytes to determine if age-0 and age-1 female summer flounder produce viable eggs and to develop an improved guide for classifying the maturity of summer flounder collected in NEFSC surveys (Specker et al. 1999; Merson et al. 2000). The URI 1999 study examined 333 female summer flounder (321 aged fish) sampled during the NEFSC winter 1997 survey (February 1997) and 227 female summer flounder (210 aged fish) sampled during the NEFSC fall 1997 survey (September 1997) using radio-immunoassays to quantify the biochemical cell components characteristic of mature fish. In light of the completion of the URI 1999 study to address the long-standing research recommendation, the maturity data for summer flounder for 1982-1998 were examined in the 2000 SAW 31 assessment (NEFSC 2000) to determine if changes in the maturity schedule were warranted.

The NEFSC 1982-1998 and URI 1999 maturity determinations disagreed for 13% of the 531 aged fish, with most (10%) of the disagreement due to NEFSC mature fish classified as immature by the URI 1999 histological and biochemical criteria. The URI 1999 criteria indicated that 15% of the age-0 fish were mature, 82% of the age-1 fish were mature, 97% of the age-2 fish were mature, and 100% of the age 3 and older fish were mature. When the proportions of fish mature at length and age were estimated by logistic regression, median length at maturity (50^{th} percentile, L_{50}) was estimated to be 34.7 cm for females, with the following proportions mature at age: age-0: 30%, age-1: 68%, age-2: 92%, age-3: 98%, and age-4: 100%. Median age of maturity

(50^{th} percentile, A_{50}) was estimated to be about 0.5 years. Based on this new information, the 2000 SAW 31 (NEFSC 2000) re-considered the summer flounder maturity schedule for the assessment but ultimately retained the maturity schedule for sexes combined as in the 1990 SAW 11 and subsequent assessments (rounded to 0.38, 0.72, 0.90, 1.00, 1.00, and 1.00 as in the 1997 SAW 25 and 1999 assessment analyses). In the 2005 SAW 41 work (NEFSC 2005), the maturity schedule was updated and broadened to include data from 1992-2004, covering the year range for individually measured and weighed fish sampled in NEFSC research surveys.

The 2008 SAW 47 SDWG (NEFSC 2008a) examined the proportions mature at age from 1982-1991 as well as the new NEFSC sampling protocol, using individual fish information on length and age at maturity from 1992-2007. Using NEFSC fall survey maturity data from 1992-2007 and logistic regression, the median length at maturity (50^{th} percentile, L_{50}) was estimated at 27.0 cm for males, 30.3 cm for females, and 27.6 cm for sexes combined. The median age of maturity (50^{th} percentile, A_{50}) was determined to be 0.1 years for males, 0.4 years for females, and 0.2 years for sexes combined. These findings were consistent with the findings of the 1990 SAW 11, the URI 1999 study, the 2000 SAW 31, and the 2005 SAW 41. An examination of the proportions of mature age-0 and age-1 fish did not indicate any trend which would warrant modification of the maturity schedule, and so the 2008 SAW 47 concluded that it was appropriate to again retain the maturity schedule from the 2005 SAW 41 assessment (NEFSC 2008a). The 2005 SAW 41 combined sex maturity schedule was also retained in the subsequent 2009-2012 updated assessments (Terceiro 2012).

In work for the 2013 SAW 57 benchmark assessment (NEFSC 2013), David McElroy and other members of the NEFSC Fishery Biology Investigation produced a working paper detailing their examination of the sources of variability in summer flounder female maturity rates: whether they are dependent on method, year, or both, and if so, to what magnitude. They compared at-sea and histological maturity assignments made during recent NEFSC resource surveys, and compared female maturity schedules derived from ovarian histology to those from the earlier studies noted above. McElroy studied 266 female summer flounder sampled from September through November over the course of 5 years, 2008-2012, as part of the NEFSC fall bottom trawl survey. They also studied female summer flounder sampled as part of the Enhanced Biological Sampling of Fish (EBSF) project supported by the NEFSC Northeast Cooperative Research Program (NEFSC-NCRP). A total of 935 mature females were collected either in monthly sampling from December 2009 to May 2011 or in targeted sampling during the primary spawning season from September to November (2011 and 2012), as well as in March and April when spawning has also been reported (2012 and 2013 only). Catches were sampled from commercial vessels participating in the NEFSC–NCRP's Study Fleet or other NEFSC-NCRP research studies while fishing in southern New England waters (NMFS statistical areas 537, 539, and 611). These commercial fishery sampled data were used to aid in the interpretation of gonad histology; specifically, to identify the pattern and progression of oocyte maturation (reproductive seasonality).

McElroy concluded that "… at-sea assignments have a high rate of agreement with microscopic classifications (89%). During this season, the majority of mature females were developing or even actively spawning; regenerating (spent) fish were rare. The largest of immature fish were difficult to classify correctly using macroscopic criteria, as some of these fish were preparing to spawn next year, for the first time; these fish were incorrectly classified at sea as resting, similar misclassifications have also been noted for winter flounder (McBride et al. 2013). An earlier study on summer flounder (NEFSC 2000) using gonad histology reported a similar misclassification rate between at-sea and histological assignments (13% vs. 11% in the current study). The non-matching maturity assignments were concentrated at the ages where the process of maturation was active (age 1 and age 2). Maturity in female summer flounder is rapid with 99% maturity achieved by age 4, using either histology or macroscopic methods. Most of the errors were for immature fish identified as resting at sea. Removing the resting fish from the dataset improved the rate of agreement (95%) between at-sea and histological classifications, and it resulted in overlapping confidence intervals (CIs) for the maturity ogives between the classification methods. This may be one way to reduce observational error in the at-sea maturity ogives. Otherwise, macroscopic classification remains an effective and cost efficient method for tracking female summer flounder maturity." They also concluded, "The temporal trend using histology indicated that recently the declines in proportion mature at age for age 1 and age 2 fish were even greater than were evident in the macroscopic data, which are the ages with the most misclassifications."

McElroy found that most of the macroscopic classification errors were for immature females misclassified as resting (T) mature in the age 0-2 range, which were actually IFM fish—first time maturing females that likely would not effectively spawn until the next year. It is not clear that the same misclassification problem occurs for T males, as the maturity stage is less ambiguous in them. The new maturity analysis removed the T females from the NEFSC Fall survey 1982-2012 data. This action removed 1,866 T females from the initial 11,073 fish (of both sexes), or 17% of the initial sample. This change, when maturities at ages are calculated for sexes combined, resulted in about an average decrease (unweighted average of annual maturities over the 1982-2012 series) in maturity of 4% for age 0, 2% for age 1, and no change for ages 2 and older. The McElroy approach was adopted in compiling the maturities used in the 2013 benchmark assessment (NEFSC 2013) and subsequent assessments.

Since the 2008 SAW 47 assessment, the NEFSC's general approach to the estimation of maturity schedules has advanced, mainly from work conducted for Northeast groundfish assessments in 2008 and subsequent years (NEFSC 2008b, 2012). The new approach involves the evaluation of both observed and logistic regression estimated maturity schedules to look for periodicity and/or trends. Sometimes the number of samples taken for a given year, season, or sex is not sufficient for estimation, or the observed and estimated maturity shows high inter-annual variability due to small sample sizes, and so different year-bin combinations (annual, discrete multi-year blocks, multi-year moving windows, and time series) are examined. For the 2023 MTA (NEFSC 2023), the NEFSC fall trawl survey 1982-2022 maturity data analysis was updated. The current data set consists of 8,218 males from age 0 to 16 and 6,411 females from age 0 to 15, for a total of 14,629 fish. The time series value of L50% was estimated to be 26.2 cm for males, 30.0 cm for females, and 27.1 cm for sexes combined (both). The A50% was 0.15 years for males, 0.47 for females, and 0.26 years for sexes combined (i.e., fish about 13-17 months old, based on the actual spawning month and the January 1 aging convention relative to fall sampling). The current L50% and A50% estimates are comparable to those in previous assessments. In keeping with the approach from the previous benchmark assessments (NEFSC 2008a, 2013, and 2019), a sexes combined, 3-year moving window ogive was compiled from the NEFSC 1982-2022 fall survey data for the 2023 MTA. The 3-year moving window approach provides well-estimated proportions mature at age that transition smoothly over the course of the time series, while still reflecting any shorter-term trends. The sexes combined, 3-year moving window estimates are presented in Figure 47. The 1982-2022 mean maturities at age (unweighted, simple arithmetic average of annual values at age) are 28% at age 0, 84% at age 1, 98% at age 2, and 100% at ages 3 and older. The most recent 5-year (2018-2022) mean values are 16% at age 0, 69% at age 1, 97% at age 2, and 100%

at ages 3 and older. Maturities at ages 0, 1, and 2 in the recent 5-year period are 43%, 18%, and 1% lower than the time series means.

Instantaneous Natural Mortality Rate (M)

The instantaneous natural mortality rate (M) for summer flounder was assumed to be 0.2 in early summer flounder assessments (SAW 20; NEFSC 1996). In the SAW 20 work, estimates of M were derived using methods described by a) Pauly (1980) using growth parameters derived from NCDMF age-length data and a mean annual bottom temperature (17.5ºC) from NC coastal waters; b) Hoenig (1983) using a maximum age for summer flounder of 15 years; and c) consideration of age structure expected in unexploited populations (3/M rule; Anthony 1982). The 1996 SAW 20 (NEFSC 1996) concluded that M = 0.2 was a reasonable value given the mean (0.23) and range (0.15-0.28) obtained from the various analyses, and this value for M was used in all subsequent assessments until 2008. For the 2008 SAW 47 assessment (NEFSC 2008a), longevity- and life history-based estimators of M were reviewed. Sex and age-specific estimates of M were calculated from 1976-2007 summer flounder age and growth data from the NEFSC trawl surveys. A summary of the methods and conclusions from that work is provided here.

Longevity based estimators of M are sensitive to critical underlying assumptions which include the value of p, or the small proportion of the population surviving to a given maximum age, and the maximum observed age under no or low exploitation conditions. Using a maximum age of 15 years for summer flounder, and the methods of Hoenig (1983) and Hewitt and Hoenig (2005), longevity-based estimates of M for combined sexes ranged from 0.20 to 0.36 depending on whether a p=1.5% or p=5% was assumed. Other life history-based approaches were used, including those from Pauly (1980), Jensen (1996), Gunderson and Dygert (1988), and Gunderson (1997), with resulting estimates ranging from 0.20 to 0.45. Age-specific and size variable estimates of M, based on the work of Peterson and Wroblewski (1984), Chen and Watanabe (1989), Lorenzen (1996), and Lorenzen (2000), ranged from 0.19 to 0.90, with the highest values associated with age 0-1 fish (fish at smaller lengths).

While the 2008 SAW 47 work provided a wide range of methods and M estimates to be considered, each estimate involved a suite of underlying assumptions which were debated. In addition, the modeling frameworks of virtual population analysis (VPA), age structured assessment program (ASAP) statistical catch-at-age analysis, and stock synthesis (SS) statistical catch-at-age analysis used in the SAW 47 assessment allowed for log-likelihood profiling of M to determine which M estimate provides the best model fits. Based on an exercise using the base cases, the M that minimized the log-likelihood was 0.35, 0.20, and 0.25 under the models VPA, ASAP, and SS, respectively. The estimate of M that resulted in the lowest residual or likelihood was found to be sensitive to model selection and configuration, as the data input configurations were very similar across the 3 models.

The SAW 47 considered the different methods of estimating M and after lengthy discussion assumed an M of 0.20 for females and 0.30 for males, based mainly on recently observed maximum ages in the NEFSC survey data of 14 years (at 76 cm, in NEFSC Winter Survey 2005) for females and 12 years (at 63 cm, in NEFSC Spring Survey 2007) for males, and the expectation that larger and older fish are likely if F was maintained at low rates in the future. A combined sex M-schedule at age was developed by assuming these initial M rates by sex, an initial proportion of females at age 0 of 40% derived from the NEFSC Fall survey indices by age and sex, and population abundance decline over time at the sex-specific M rates. The final abundance weighted combined sex M-schedule at age ranged from 0.26 at age 0 to 0.24 at age 7 and older, with a mean of 0.25 (NEFSC 2008a). This M-schedule was retained in the subsequent 2009-2023 updated and benchmark assessments (NEFSC 2013, 2019, 2022, 2023; Terceiro 2012, 2015, 2016).

For the 2023 MTA (NEFSC 2023), NEFSC survey and fishery catch longevity (i.e., maximum size and age) were again reviewed, indicating maximum ages of 18 and 20 for males (at 50 and 57 cm) and 19 for females (at 73 and 79 cm). The increasing abundance of older males and older fish of both sexes indicates that the assumption of M should be revisited in future stock assessments.

Summary

This examination of the biological data for summer flounder from the NEFSC survey and fishery catch data in general indicates:

a) there is evidence that the aging of the hard structures is consistent and unbiased;
b) there are trends over the nearly 50-year time series, and especially since the early 2000s, of decreases in mean length and mean weight at age for both sexes and by cohorts, with some reversal of that trend in the most recent 5 years (2018-2022);
c) the length-weight relationships have been stable over the time series;
d) the weight-based condition factors have been stable over the time series;
e) the relative proportion of females at larger sizes and older ages (larger than 60 cm and older than age 5) has decreased since the early 2000s, which has changed the sex ratio at larger sizes and older ages and decreased the combined sexes mean lengths and weights as more smaller and lighter male fish account for an increasingly larger proportion of the larger and older fish;
f) the maturity of combined sexes age 0, 1, and 2 fish had decreased since the early 2000s, but a fairly strong reversal of the that trend has occurred in the most recent 5 years;
g) the maximum size and age of both sexes has increased since the early 2000s, with latest estimates for maximum ages of 18 and 20 for males (at 50 and 57 cm) and 19 for females (at 73 and 79 cm) and
h) the increasing abundance of older males and older fish of both sexes indicates that the assumption of M should be revisited in future stock assessments.

ENVIRONMENTAL DATA

Introduction

The 2018 SAW 66 benchmark stock assessment of summer flounder documented the northward and eastward shifts in the geographical distribution of the stock coincident with decreases in fishing mortality and increases in abundance since about 2000 (Terceiro 2019). Physical environmental factors such as water depth, physical habitat, light, dissolved oxygen, water temperature, and salinity are known to affect the distribution of marine fish. For summer flounder, Packer et al. (1999) synthesized a broad array of historical scientific studies describing the most important physical environmental factors impacting the life history and distribution of summer flounder in U.S Northeast regional waters, most prominently dissolved oxygen, light, salinity, and water temperature. Szedlmayer et al. (1992) demonstrated that abnormally cold winter estuarine water temperature could result in the temperature-induced mortality of young-of-the-year summer flounder, therefore possibly influencing the magnitude of recruitment of age 0 fish to the stock. It is widely expressed that northwest Atlantic Ocean temperatures have rapidly increased over this same period and are likely to have a range of impacts on marine populations (Pershing et al. 2019). In general, however, the drivers of the perceived shifts in summer flounder distribution and abundance have proven difficult to identify quantitatively and have not been strongly attributed to trends in temperature or climate (e.g., O'Leary et al. 2019, Perretti and Thorson 2019). Several studies on the Southern New England stock of yellowtail flounder (*Limanda ferruginea*), however, have been more successful in linking metrics of recruitment to the intensity and duration of the Middle Atlantic Bight cold pool index and the Gulf Stream position indices. Studies exploring several of these environmental drivers are summarized below.

Gabriel (1992) noted that the Middle Atlantic Bight cold pool was the southernmost habitat for number of cold-water species in the Northwest Atlantic. Taylor et al. (1957) and Sissenwine (1974) linked declines in yellowtail flounder stock size to environmental factors such as air and ocean temperature, and Sullivan et al. (2000, 2005) hypothesized that southern New England yellowtail flounder recruitment was higher when the cold pool was colder and more persistent. Miller et al. (2016) included indices of the temperature of the cold pool as covariates in a state-space age-structured assessment model for the Southern New England/Mid-Atlantic Bight (SNEMA) stock of yellowtail flounder (*Limanda ferruginea*) to evaluate the cold pool effect on the stock's recruitment. Miller et al. (2016) found that both the cold pool and SSB were important predictors of recruitment and led to annual variation in estimated biomass and yield reference point. Miller et al. (2016) and Xu et al. (2018) explored the influence on both the cold pool index and the Gulf Stream Index (GSI) on SNEMA yellowtail flounder recruitment dynamics.

Brodziak and O'Brien (2005) examined relationships between environmental indices and summer flounder Recruit-Spawner Anomalies (RSAs) and found the North Atlantic Oscillation (NAO) winter index forward lagged by 2 years was a significant predictor of summer flounder RSA, with positive NAO anomalies (wet and mild winters) correlating with positive RSAs. The 2008 SAW 47 assessment (NEFSC 2008a) built on the work of Brodziak and O'Brien (2005) to further explore the relationship between recruitment as estimated in the stock assessment and temperature data and climate indices. A Generalized Additive Model (GAM) model indicated a positive predictive relationship between the NAO winter climate index and the RSA, consistent with simple correlation analysis results.

Nye et al. (2009) found that the maximum latitude of occurrence of summer flounder had shifted northward (mainly during the 1970s) consistent with environmental warming as indexed by some climatic indices, but no statistically significant drivers for this shift could be identified.

Bell et al. (2014) reconstructed a 40-year time series of coastal water temperature for the major spawning and nursery areas to examine changes in the thermally available habitat for summer flounder. Bell et al. (2014) found that summer flounder abundance was negatively correlated with fishing mortality but exhibited no link with temperature. They also found that while summer flounder productivity as measured by recruitment had varied without a trend, a reduction in fishing mortality over the past 2 decades had led to rebuilding of the summer flounder stock and an expansion of its age structure.

Bell at al. (2015) examined the distribution of summer flounder sampled with the NEFSC trawl surveys to determine if the along-shelf center of biomass had changed over time and if the changes were attributed to changes in temperature or fishing pressure through changes in abundance and length structure. Summer flounder exhibited a significant poleward shift in distribution, and a GAM indicated that the change in the distribution was largely attributed to a decrease in fishing pressure and an expansion of the length-age structure rather than a change in ocean temperature. Bell at al. (2015) concluded that while changes in ocean temperatures will have major impacts on the distribution of marine taxa, the effects of fishing can be of equivalent magnitude and on a more immediate time scale.

O'Leary et al. (2019) explored the influences of the GSI on summer flounder abundance through M and stock-recruitment relationships in a series of age-structured hierarchical Bayesian models. The model diagnostics indicated the best estimates of abundance resulted from a climate-dependent M model that included log-quadratic responses to the GSI. However, the estimates of M from this model were very high (up to 4 times for fully recruited ages) compared to that used in the summer flounder stock assessments.

Perretti and Thorson (2019) used a VAST model with survey and fishery data to investigate whether the stock had shifted and the extent to which distributional shifts could be attributed to changes in stock abundance, size structure, environmental variables (local and regional bottom temperature and depth), or fishing mortality. They found that the summer flounder distribution had shifted north and east in both the spring and fall. The shift was observed for both recruits (age 0 fish) and spawners (age 1 and older fish), with recruits shifting northward faster than spawners, suggesting that increased spawner abundance might not be driving the shift in recruits. Perretti and Thorson (2019) found that only a small portion of the variability in summer flounder distribution could be attributed to changes in abundance, fishing, or environmental covariates.

Morley et al. (2020) conducted 21st century projections for shifts in suitable habitat for seven economically important marine species including summer flounder, using Generalized Linear Models (GLMs), GAMs, and Boosted Regression Trees (BRT). Species occurrence and biomass data were taken from long-term surveys that encompassed most of the continental shelf area of the United States and Canada and was coupled with sea surface temperature (SST), sea bottom temperature, sea floor rugosity (spatial variation in depth), and bottom sediment grain size. The GLM and GAM delta-biomass niche models for summer flounder performed poorly when predicting regional scale abundance ($R^2 <= 0.01$), but the BRT models for summer flounder were strongly related to observed values ($R^2 = 0.73$). For summer flounder, habitat suitability was shown to decrease south of Cape Hatteras, NC, from the initial time period of 2007-2020 to the projected 2081-2100 time period. Habitat suitability was shown to increase on Georges Bank, on the Scotian Shelf, and in the Gulf of Maine between these periods.

Summary of NEFSC Trawl Survey Temperature and Salinity Data

For this work, some of the environmental data routinely collected by the NEFSC spring and fall bottom trawl surveys were summarized for the summer flounder standard strata sets to further explore the correspondence between these data and the distribution of summer flounder. The data were bottom water temperature in degrees Celsius (^oC), bottom water salinity in parts per thousand (ppt), and surface water temperature in degrees Celsius (^oC). Valid water temperature data on a per tow basis are generally available for the entire 1968-2022 time series for the summer flounder survey strata (Great South Channel to Cape Hatteras) in both spring and fall with the exception of fall 2008, for which large numbers of observations are missing. Bottom water salinities are generally available for 1996/1997 and later years, except for 2008.

First, the cumulative distributions of the summer flounder survey catches (expcatchnum) and the temperature and salinity data were compiled for the spring (offshore strata 1-12, 61-76) and fall (offshore strata 1-2, 5-6, 9-10, 61, 65, 69, 73) long-time series (1968-2022) strata sets. For this simple compilation, the cumulative totals are not weighted by stratum area. In the spring survey strata, over the full 1968-2022 time series, summer flounder were in general caught at stations (tow sites) that had a warmer bottom temperature (Figure 48; median [50^{th} percentile] catch at 9.2°C, median tows at 7.4°C), higher bottom salinity (Figure 49; median [50^{th} percentile] catch at 34.4 ppt, median tows at 33.7 ppt), and warmer surface temperature (Figure 50; median [50th percentile] catch at 7.2°C, median tows at 6.6°C) compared to the average environment of the strata set. In the fall survey strata, summer flounder were in general caught at stations (tow sites) that had a warmer bottom temperature (Figure 51; median [50^{th} percentile] catch at 15.9°C, median tows at 12.6°C), lower bottom salinity (Figure 52; median [50^{th} percentile] catch at 32.5 ppt, median tows at 32.9 ppt), and about the same surface temperature (Figure 53; median [50th percentile] catch at 18.7°C, median tows at 18.8°C) compared to the average environment of the strata set.

In a second compilation, the annual stratified mean values of the temperature and salinity data for positive summer flounder catch tows (expcatchnum > 0) were compared with the annual stratified mean values of the environmental factors for all tows to investigate trends over time. Figure 54 shows the the mean bottom temperature on NEFSC spring survey tows with positive summer flounder catches (FLK_bottemp) was generally warmer than the mean bottom temperature of all tows (All_bottemp) from 1968 through the 1980s. Since 1990, the mean temperatures are more similar. The solid blue trend line shows that the mean bottom water temperature of all tows in the spring strata set has increased over time by about 0.7°C, while the mean bottom temperature of positive summer flounder catch tows has decreased by about 0.5°C as the stock has shifted to the north and east (NEFSC 2018). Figure 55 shows the pattern for NEFSC fall survey tows, with the bottom temperature on tows with positive summer flounder catches generally warmer than the mean bottom temperature of all tows over the entire series. The solid red trend line shows that the mean bottom water temperatures of all tows in the fall strata set has increased by about 1.25°C, while the mean bottom temperature of positive summer flounder tows increased by about 0.5°C.

Figure 56 shows that the mean bottom salinity on NEFSC spring survey tows with positive summer flounder catches (FLK_botsalin) was generally higher than the mean salinity of all tows (All_botsalin) since 1997. The solid blue trend line shows that the mean bottom salinity of all tows and positive summer flounder tows in the spring strata set have increased by about 0.25 ppt. Figure 57 shows the pattern for NEFSC fall survey tows, with the bottom salinity on tows with positive summer flounder catches generally lower than the mean salinity of all tows since 1997. The solid red trend line shows that the mean salinity of all tows in the fall strata set has no trend, while the mean salinty of positive summer flounder tows has decreased by about 0.75 ppt.

Figure 58 shows that the mean surface temperature on NEFSC spring survey tows with positive summer flounder catches (FLK_surftemp) was generally warmer than the mean surface temperature of all tows (All_suftemp) from 1968 until about 2000. Since then, the mean surface temperature of positive summer flounder catch tows has been lower than the mean of all tows. The solid blue trend line shows that the mean surface water temperature of all tows in the spring strata set has increased by about 1.5°C, while the mean temperature of tows with summer flounder catch has remained unchanged. Figure 59 shows the pattern for NEFSC fall survey tows, with the surface temperature on tows with positive summer flounder catches generally cooler than the mean surface temperature of all tows over the entire series. The solid red trend line shows that the mean surface water temperature of all tows in the fall strata set has increased by about 5°C, while the mean surface temperature of tows with summer flounder catch has increased by about 3°C.

These comparisons indicate that the measures of environmental factors associated with or weighted by summer flounder catch have changed less or in the opposite direction (spring mean bottom temperature, fall mean salinity) than those for all bottom trawl survey tows. This result may indicated a buffered or delayed response of the population to those enviromental factors or the stronger influence of other factors such as changes in population demographics or mortality rates on the geographical distribution of the population.

The well-known adage “correlation does not imply causation” does not also imply that one should not investigate if significant correlation between 2 variables exists as the first step in attempting to determine if such causation does exist (i.e., data snooping). In that spirit, a correlation analysis between the NEFSC temperatures and salinity was conducted. To facilate comparison, annual values for each series were expressed as simple residuals or anomalies from the time series mean. In the subsequent climate indices and recruitment modeling sections, correlation analyses were also done as that first exploratory step in the same fashion.

A simple Pearson correlation analysis compared trends of the seasonal temperature and salinty averages for all tows over the 55-year time series (Table 2; $rcrit_{0.05} \sim 0.27$). Of the 15 potential correlations for the 12 factors, 10 (67%) were significant at alpha = 0.05. The significant correlations were between the fall bottom temperature and bottom salinity (r = 0.70), the spring bottom temperature and surface temperature (r = 0.54), spring bottom salinity and fall bottom salinity (r = 0.53), spring bottom temperature and fall bottom temperature (r = 0.45), spring surface temperature and fall surface temperature (r = 0.36), spring surface temperature and spring bottom salinity (r = 0.35), and fall surface temperature and fall bottom salinty (r = 0.28); these correlations are all generally intuitive. Less intuitive are the correlations (i.e., related by covariance) between the spring surface temperature and fall bottom salinity (r = 0.55), spring bottom temperature and fall bottom salinity (r = 0.45), and spring surface temperature and fall bottom temperature (r = 0.42).

North Atlantic Climate Indices

Many of the papers noted in the Introduction of this section use climate indices in addition to or as proxies for temperature and salinity as factors that potentially drive trends in population distribution, recruitment, and stock biomass. This section focuses on the climate indices that have been previously shown to have some statistical relationship to fish abundance or fishery production in the North Atlantic, either in general or for summer flounder in particular.

Atlantic Multidecadal Oscillation (AMO)

The Atlantic Multidecadal Oscillation (AMO) is a metric of climate variability occurring in the North Atlantic Ocean with an estimated period of 60-80 years. The AMO index is based upon the average anomalies of SST in the North Atlantic basin, typically over the latitude range of 0-80N. The observed large-scale multidecadal fluctuations in the Atlantic SST has been referred to as the AMO (Kerr 2000) to emphasize its multidecadal character and distinguish it from the interannual variability associated with the atmospheric NAO (Enfield et al. 2001). Positive AMO indices correspond with positive SST anomalies over most of the North Atlantic, generally with stronger anomalies in the subpolar region and weaker anomalies in the tropics. Warm AMO phases occurred during the middle of the 20th century and the recent decades since 1995, and cold phases occurred during the early 20th century and between 1964 and 1995. The SST-based definition of the AMO index often leads to the incomplete understanding of the AMO only in terms of North Atlantic SST anomalies. In contrast, the AMO actually reflects coherent multivariate low-frequency variability observed in the Atlantic, including correlated variations in the subpolar North Atlantic heat content, salt content, and ocean-driven surface turbulent heat fluxes, as well as anti-correlated variations in the tropical North Atlantic subsurface temperature (Trenberth at al 2021). Shackell et al. (2012) investigated common biological responses of plankton and fish to metrics of climate and fishing across 7 Northwest Atlantic ecosystems and found the common patterns and drivers were fishing indices and the AMO. The AMO indices used in this work are the National Oceanographic and Atmospheric Administration (NOAA) Climate Prediction Center AMO smoothed version and were taken from the NOAA Physical Sciences Laboratry Climate Indices website (Climate indices…2023).

North Atlantic Oscillation (NAO)

The NAO (Barnston and Livezey 1987) consists of a north-south dipole of anomalies, with one center located over Greenland and the other center of opposite sign spanning the central latitudes of the North Atlantic between 35N and 40N. The positive phase of the NAO reflects below-normal sea heights and pressure across the high latitudes of the North Atlantic and above-normal sea heights and pressure over the central North Atlantic, the eastern United States, and western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport (Hurrell 1995). Strong positive phases of the NAO tend to be associated with above-average temperatures in the eastern United States and across northern Europe and below-average temperatures in Greenland and oftentimes across southern Europe and the Middle East. They are also associated with above-average precipitation over northern Europe and Scandinavia in winter, and below-average precipitation over southern and central Europe. Opposite patterns of temperature and precipitation anomalies are typically observed during strong negative phases of the NAO. The NAO exhibits considerable interseasonal and interannual variability, and prolonged periods (several months) of both positive and negative phases of the pattern are common. The wintertime NAO also exhibits significant multidecadal variability (Hurrell 1995; Chelliah and Bell 2005). The NAO indices used in this work are the NOAA Climate Prediction Center version and were taken from the NOAA Physical Sciences Laboratry Climate Indices website (Climate indices…2023).

Gulf Stream Index (GSI)

Lucey and Nye (2010) indicated that fish and invertebrate assemblages on the U.S. Northeast shelf respond to changes in water mass properties as indicated by the Gulf Stream path, even when taking into account the impacts of fishing. Saba et al. (2015) also suggest that the Gulf Stream position is associated with phytoplankton biomass on the shelfbreak, slope, and specific coastal regions of the Mid-Atlantic Bight. Observations and modeling studies in the Northwest Atlantic point to an inverse relationship between the Atlantic Meridional Overturning Circulation (AMOC) and the position of the Gulf Stream, suggesting that a weaker AMOC relates to a more northerly position of the Gulf Stream (Joyce and Zhang 2010; Zhang et al. 2011), with a northerly shift in the Gulf Stream then associated with warmer bottom temperatures on the shelf (Saba et al. 2016; Zhang and Vallis 2007).

Chen et al. (2021) recently summarized how the fisheries ecosystem on the U.S. Northeast continental shelf structure and function has experienced significant recent changes as a result of climate-scale changes in the physical environment, with shifts in marine species distribution, growth, and recruitment being directly linked to changes (mainly increases) in ocean temperature, associated oxygen decline, and subsequent increases in physiological stress on fish and benthic invertebrates (Brennan et al. 2016). Chen et al. (2021) further note that variability in bottom temperature on the shelf is strongly influenced by local oceanic processes including bottom circulation and intrusions of warm and saline slope waters. Besides these advective processes, bottom water temperatures on the U.S. Northeast shelf are also influenced by cross-shelf exchange processes associated with Gulf Stream warm-core rings and meanders, changes in the AMOC, and the NAO. Chen at al. (2021) developed a hierarchy of statistical models for the prediction of seasonal U.S. Northeast shelf bottom temperature with the goal of meeting the scientific needs of fisheries stock assessments and management. One product of the Chen et al. (2021) work is an index based on the subsurface temperature at 200 m depth (T200; following Joyce et al. 2009), reflecting the position variability of the Gulf Stream North Wall that was also used in O'Leary et al. (2019). The Gulf Steam Index (GSI) used in this work was taken from Chen et al. (2021) as updated by the senior author (2023 personal communication from Zhoumin Chen to author). As O'Leary et al. (2019) succinctly noted, "A positive GSI is associated with higher shelf temperatures at depth and therefore less stratified water, a stronger current system, and less cross-shelf warm core eddies, and thus serves as a proxy for both the bottom temperature and oceanographic conditions. Spring mean stratified bottom temperatures in southern New England, the center of distribution for summer flounder, increase when the Gulf Stream shifts from a southerly position (GSI ≈ –1) to a more northerly position (GSI ≈ 2)."

Cold Pool Index (CPI)

The cold pool is the common name for the distinctive band of cold bottom water typically located over the mid-to-outer U.S. continental shelf, often extending from the southern part of Georges Bank to Cape Hatteras, NC. It annually develops in the spring as temperatures increase and the water column stratifies, persists though the summer, and dissipates in the fall as temperatures decrease and the water column overturns and mixes. The cold pool was first described by Bigelow (1933), who thought it was remnant winter-cooled shelf water that was not replenished from other upstream cold water sources. Later studies (e.g., Colton et al. 1968, Davis 1979) showed the coldest summer cold pool water was located in the New York Bight between Cape May, NJ, and Montauk Point, NY. Houghton et al. (1979) concluded that the cold pool in the New York Bight north of Hudson Canyon persists during the summer due to its relative isolation due to the bathymetry of the region rather than by renewal from upstream sources of cold water such as the Gulf of Maine, northern Georges Bank, or the continental slope. The Cold Pool Index (CPI) used in this work was taken from DuPontavice et al. (2022) as updated by the senior author (2023 personal communication from Hubert DuPontavice to author). The DuPontavice CPI uses bottom temperature estimates from a regional ocean model and a global ocean data assimilated hindcast, and was tailored to provide a metric that better characterizes cold pool interannual variations that are associated with the historical and contemporary variability of the SNEMA bight yellowtail flounder recruitment.

Summary of Trends in Climate Indices

The 1976-2022 time series trends of the climate indices (the AMO, 3 compilations of the NAO, the GSI, and the CPI) are presented in Figures 60-62. Although earlier data are available, these series were started in 1976 to align with the start of the NEFSC length-age data for the analyses that follow. The vertical axes of these plots have been set to the same scales to present a consistent range of anomaly to facilitate comparison. The AMO index has the smallest range and smallest linear slope (Figure 60), while the ranges and slopes of the GSI and CPI indices are the largest (Figure 61). The NAO indices are intermediate for these characteristics, with the mean and fall indices exhibing slightly negative slopes and the winter exhibiting a positive slope (Figure 60). Viewed in aggregate, the climate indices indicate a positive trend in anomalies over the time series of 1976-2022 (Figure 62).

A simple Pearson correlation analysis compared trends of the NEFSC bottom trawl survey averaged annual temperatures, salinities, and climate indices for 1976-2022 (Table 3; n=47 $rcrit_{0.05}$ ~ 0.28). To facilate comparison among the various metrics, annual values for each series of temperature, salinity, and climate were expressed as anomalies from the time series mean (some of the time series provided by others were already provided as anomalies). Of the 36 potential correlations for the 9 metrics, 19 (53%) were significant at alpha = 0.05. The temperature and salinity correlations were qualitatively the same as in Table 2, albeit with slightly different values due to annual averaging and the longer time series in Table 2. Both the GSI and CPI have significant correlations with all the NEFSC temperature and salinity anomalies. For the climate indices alone, the significant correlations were between the AMO and NAO mean and fall, the AMO and the CPI, among the 3 NAO indices, the NAO winter and the GSI, the NAO winter and the CPI, and the GSI and the CPI; the CPI had the most significant correlations with the other climate indices.

MODELS RELATING BIOLOGICAL PARAMETERS, ENVIRONMENTAL DATA, AND FISHING MORTALITY

Introduction

Ricker (1975) noted that, "For fishes having moderate to long life spans, even a little fishing can cause a marked change in age structure." And as Gulland (1977) succinctly summarized for this basic theory of fish population dynamics: "As size of a fish is closely related to mortality, the greater the mortality the fewer old and large fish." Trippel (1995), Stokes and Law (2000), and Sinclair et al. (2002a, b), among others, all noted that varying intensities of size-selective fishing mortality in highly exploited fish populations can influence the observed size and age structure (and therefore sex-ratio, rates of growth and maturity, and fitness) of those populations, over both short and evolutionary time scales. Stokes and Law (2000) in particular noted, "… 1) there is likely to be genetic variation for traits selected by fishing, 2) selection differentials due to fishing are substantial in major exploited stocks, and 3) large phenotypic changes are taking place in fish stocks, although the causes of these changes are hard to determine unambiguously." Sinclair et al. (2002b) noted that effects of size-selective fishing mortality, density-dependent growth, and occupied temperature regime all affected the observed growth increment and therefore the mean length at age for Gulf of St. Lawrence cod (*Gadus morhua*).

More recently, O'Leary et al. (2020) modeled population-level size variability from NEFSC trawl survey summer flounder mean length at age data from 1992-2015 using an autoregressive state-space modeling approach with annual fishing and oceanographic covariates, finding that summer flounder length at age varies annually and suggesting that productivity can vary annually due to variable sizes. O'Leary et al. (2020) found that the location and depth of the observed fish, the rate of fishery exploitation, and the position of the Gulf Stream appeared to influence the magnitude of length at age variation, whereby lengths at age were above the mean length (i.e., positive anomalies) at greater depth, northern latitudes, and during periods characterized by a northerly Gulf Stream position or higher fishing exploitation. O'Leary et al. (2020) stated that, "The identification of both exploitation effects and the Gulf Stream position as indicators to estimate post-recruit summer flounder length at age variation, whether causative or predictive, is an important tool for managers and stock assessment scientists to track length at age and reduce uncertainty of one component of the productivity calculation for summer flounder. The consistently reduced unexplained variance for all random effects structures that included an oceanographic condition indicator (e.g., temperature, productivity, salinity, currents) suggests that basin-wide climate conditions in the Northwest Atlantic should be explored further for a causative relationship on summer flounder length at age."

For summer flounder, as noted in the Stock Assessments section, the theories of Ricker (1975), Gulland (1977), and others have manifested as the truncation of the length and age structure for combined sexes under high F during the 1980s and 1990s, and an expansion of length and age structure under lower F since about 2000 (Terceiro 2018, 2019; NEFSC 2023). F averaged greater than 1.0 (a percentage exploitation rate of about 60%) between 1982 and 1996 but has decreased to less than 0.5 (a percentage exploitation rate of about 30%) since 2001. A shift in the age of full recruitment (selectivity by the total fishery equals 1.0) from age 2 in the 1980s to age 4 since the mid-2000s has also occurred, further decreasing the impact of F on the stock (NEFSC 2023).

Gulland (1977) also stated: "Therefore, any increase in the total mortality should (with due reserve concerning possible differences in the original strength of the year-classes present) be reflected in a decrease in the average size of the fish in the stock." As Ricker (1975) noted, this is a result of Rosa Lee's phenomenon wherein for a given mortality rate on a given cohort, often a larger fraction of the larger fish die. Therefore, the recent decreases in total mortality for summer flounder driven by F (assuming small variation in M) might be expected to result in increases in aggregate mean lengths and aggregate mean weights for summer flounder. This does appear to be the case for summer flounder, as observed in the trends for the survey aggregate mean length and fishery aggregate mean weight (Figures 63-65; indicated in the figures as MALL, FALL, CALL).

However, the response of the summer flounder stock's biological parameters when considered by age and sex is more nuanced and counter to this second part of Gulland's (1977) summarization of the mortality to size relationship in a fish population. As noted earlier in the Biological Data section, the NEFSC survey and total fishery catch data show trends of decreasing mean length and weight at age in all seasons and for both sexes (Figures 13-27), a trend in von Bertalanffy parameters that indicates apparent slower growth (smaller predicted length at age; Figures 29 and 30), a decreasing proportion of females at larger sizes and older ages (and obviously therefore an increasing proportion of males; Figures 36-46), and a subtle trend of delayed maturity for sexes combined (as used in the assessment; Figure 47) since about 2000. Perhaps due at least in part to the interaction of changing F and sexually dimorphic growth, the decrease in F over the past 2 decades apparently has been sufficient to allow slower growing fish by age class of both sexes to survive older ages over that time frame, thus decreasing the mean lengths and weights at age and sex, particularly for the age 3 and older fish most strongly impacted by F.

The trends in these biological parameters for summer flounder are also coincident (mainly since about 2000) with trends in temperature and salinity sampled by the NEFSC trawl surveys and several indices of northwest Atlantic Ocean climatic conditions. A simple quantitative approach is developed here that builds on the ideas and work of Stokes and Law (2000), Sinclair et al. (2002a, b), and O'Leary et al. (2020) to further explore the potential environmental drivers of the biological dynamics of summer flounder over the last 40-plus years. Building on the concepts and results of those previous studies, correlation analyses and GAMs were conducted to quantify the statistically significant drivers with the goal of informing future stock assessments and research models.

Biological correlation analyses

Again keeping in mind the adage "correlation does not imply causation," a correlation analysis of some of these biological parameters (maturity was excluded because the trend is mainly limited to age 1 fish, with a recent reversal) with the NEFSC averaged annual temperatures and salinities, the climate indices, and F (Figure 1; NEFSC 2023) was conducted as the first step in attempting to determine if evidence for such causation might exist. To reduce the dimensions of the analysis and keep all variables on an annual basis, annual means of the seasonal biological parameters, NEFSC temperatures, and salinites were computed and used in the correlations and modeling work.

NEFSC trawl survey sampled mean lengths

Correlations were calculated of the NEFSC trawl survey sampled mean lengths at age by sexes and for all lengths-ages in aggregate by sex, with the temperatures, salinity, climate indices, and F. Significant correlations at age (shown in blue in Tables 4 and 5) vary together and are of similar magnitude, confirming the visual perception conveyed by the mean length plots (e.g., Figures 20-27, 63, and 64). As just noted, however, the aggregate mean lengths for all fish trend in the opposite direction and so are negatively correlated with the individual ages. These patterns generally agree wth O'Leary et al.'s (2020) conclusion that "…the deviation in summer flounder size anomalies are driven by an annual process and that the annual size deviation is constant across ages." Correlations of mean length at age by sex with the environmental factors (significant correlations shown in green in Tables 4 and 5) revealed patterns that were generally intuitive given trends in the parameters and factors. For both sexes, mean lengths at age 3 and older were generally highly variable from the late 1970s until the early 2000s, after which most have decreasing trends (Figures 63 and 64).

These trends result in frequent significant negative correlations for males at age with environmental factors that have been trending in a positive direction (increasing slope over time) such as the surface and bottom temperatures, and a significant positive correlation between the aggreagte mean length of all males and the surface temperature and bottom salinity (Table 4). Correlations with the climate indices have similar patterns; since all have generally increasing trends (Figures 60-62), there are significant negative correlations with male mean length at age and positive correlations with the mean length of all males. Correlations with F (decreasing trend over the time series, relatively stable since about 2000; Figure 1) are positive for the male mean length at age and negative for the mean length of all males. The patterns for females are generally similar, as the mean lengths at age generally decreased while the aggregate mean length of all females generally increased from the 1980s into the early 2000s (Table 5; Figure 63). For the temperatures and salinty, the surface temperature had the most significant correlations with the mean lengths for males and females. For the climate indices and F, the GSI had the most significant correlations with the mean lengths for males and F had the most for females.

NEFSC total fishery mean weights

Correlations were calculated of the NEFSC estimated total fishery mean weights (for sexes combined) used in the stock assessment with the temperatures, salinity, climate indices, and F. The total fishery mean weights (for sexes combined) are the biological parameters most closely related to the total stock biomass and SSB estimated in the assessment model (NEFSC 2023). As with the survey mean lengths, the trends in the estimated fishery catch mean weights suggest the decrease in F over the past 2 decades has apparently been sufficient to allow slower growing fish of both sexes to survive to older ages over that time frame, thus lowering the mean weights at age (particularly of age 3 and older, nearly to fully recruited fish). With observations of more larger, older fish of both sexes in the stock since about 2000, the aggregate mean weight of all fish combined increased from the mid-1990s into the mid-2000s, but has since stabilized (Figure 65).

Significant correlations at age (shown in blue in Table 6) vary together and are of similar magnitude, confirming the visual perception conveyed by the mean weight plot (Figure 65). Correlations of mean weight at age with the environmental factors (significant correlations shown in green in Table 6) revealed patterns that were, as with the survey mean lengths, generally intuitive given the coincident trends. For the temperatures and salinty, the bottom salinty had the most signifiant correlations with the mean weights. For the climate indices and F, F had the most significant correlations with the mean weights.

NEFSC trawl survey sampled proportion female (sex ratio)

Correlations were calculated of the NEFSC trawl survey sampled proportion female at age by sexes and for all lengths-ages in aggregate, with the temperatures, salinity, climate indices, and F. Figure 66 shows that most of the changes in sex ratio as indicated by a decrease in proportion female have occurred for fully mature ages 3 and older since about 2000. The change in aggregate proportion female is less pronounced than for the individual ages. While the negative slopes of these trends are evident, the pattern is highly variable from year to year.

Significant correlations at age (shown in blue in Table 7) vary together and are of similar magnitude, confirming the visual perception conveyed by the proportion female plot (Figure 66). Correlations of proportion female at age with the environmental factors (significant correlations shown in green in Table 7) revealed patterns that were, as with the survey mean lengths and weights, generally intuitive given the coincident trends. The proportion female data are generally more variable than the mean length and weight data. Also notable is that lack of significant correlations for the proportion females in aggregate (across all lengths-ages), likley due to the subtle decreasing trend. For the temperatures and salinty, the bottom salinty had the most significant correlations with the proportion female. For the climate indices and F, F had the most significant correlations with the proportion female.

Biological Generalized Additive Models (GAMs)

The time series plots and correlation analyses show that there are many statistically significant coincident trends between several biological parameters, a variety of environmental factors, and F on the summer flounder stock. A GAM approach was undertaken in an attempt to further quantitatively identify significant drivers of the trends in aggregate mean length (MALL, FALL), aggregate mean weight (CALL), and aggregate sex ratio expressed as proportion female (profall). These biological parameters are specified as the dependent response variables in the model, while the environmental factors and F are the independent predictive variables. The GAM approach is a nonparametric regression technique that relaxes error distribution assumptions in modeling the relationships between the predictive and dependent variables. The GAMs fit by SAS PROC GAM combine an additivity assumption that enables relatively many nonparametric relationships to be explored simultaneously with the distributional flexibility of generalized linear models (McCullagh and Nelder 1989; Hastie and Tibshirani 1990; Wood 2017; SAS 2020).

In an initial step to confirm the correlation analyses, GAM models for the 4 biological parameters were first fit using singular models for each of the 9 environmental factors (bottom temperature, surface temperature, bottom salinity, AMO, NAO Mean, NAO Winter, NAO Fall, GSI, and CPI) and F, for the assessment time series of 1982-2022. Because the large scale climate indices are thought to integrate temperature, circulation patterns, and other oceanographic conditions potentially over multi-year scales (Brodziak and O'Brien 2005; O'Leary 2019), 1 and 2 year forward-lagged time series of the climate indices (e.g., NAO Winter plus 1 and 2 years) were also modeled, for a total of 22 single factor models for each of the dependent biological parameters. These singular models were fit using smoothing splines with 3 degrees of freedom and the standard back-fitting algorithm (SAS 2020). Where needed, a constant positive integer (1, 2, or 3) was added to the variable values to allow the model to function properly (SAS 2020). The independent predictive variables with the 3 highest probabilities of significant parametric coefficient (Pr > t) and smoothing spline (Pr > ChiSq) were carried on to the next stage to select the best model for this exploratory exercise. Although the correlation analyses indicated the potential for significant covariance and therefore interaction terms, only main effect terms were explored in this exercise.

NEFSC trawl survey sampled mean lengths

For the male aggregate mean length model, the top 3 most significant single factor models were for the AMO plus 1 index (AMO_1), the NAO Winter plus 1 index (NAOWin_1), and F, all with Pr > ChiSq of less than 0.001. Figures 67 and 68 show the 3 factor model scatter plot of data and the smoothing spline results. In the 3 factor model, the F parameter in the GAM regression model component (not shown) and the smoothing parameter (Figure 68) were not significant at the 0.100 level. Therefore, F was dropped from the next step, a 2 factor model with AMO_1 and NAOWin_1. Figures 69 and 70 show the 2 factor model scatter plot of data and the smoothing spline results. In the 2 factor model, both the AMO_1 and NOAWin_1 parameters were significant at the 0.100 level, indicating the best predictive model for the male aggregate mean length. The scatter plots suggest some relationship between these significant factors in line with the correlation analyses (Table 4 for MALL). For example, the AMO and F plots show discernable positive and negative relationships, respectively. The smoothing component plots for both predictors (Figure 70) show complex responses that are hard to interpret mechanistically (e.g., there is not a definitive linear or simple curvilinear relationship indicating that a higher value predictive variable value relates definitively to a higher or lower value in the response variable).

For the female aggregate mean length model, only 2 models had significant single factors, the AMO plus 1 index (AMO_1) and F, both with Pr > ChiSq of less than 0.050. Figures 71 and 72 show the 2 factor model scatter plot of data and the smoothing spline results for this best predictive model. The scatter plots suggest some relationship between these significant factors in line with the correlation analyses (Table 5 for FALL). As with the male model, the smoothing component plots for both predictors (Figure 72) show complex responses that are hard to interpret mechanistically.

NEFSC total fishery mean weights

For the aggregate mean weight model, the top 3 most significant single factor models were for F, the AMO plus 1 index (AMO_1), and surface temperature, all with Pr > ChiSq of less than 0.001. Figures 73 and 74 show the 3 factor model scatter plot of data and the smoothing spline results. In the 3 factor model, all parameters were significant at the 0.100 level, indicating the best predictive model. The smoothing component plots for the predictors (Figure 74) show complex responses that are hard to interpret mechanistically.

NEFSC trawl survey sampled proportion female (sex ratio)

For the aggregate proportion female model, the top 3 most significant single factor models were for the GSI_2 index, the AMO_2 index, and F, all with Pr > ChiSq of less than 0.100. Figures 75 and 76 show the 3 factor model scatter plot of data and the smoothing spline results. In the 3 factor model, only the GSI_2 parameter was significant at the 0.10 level. Figures 77 and 78 show the 1 factor model scatter plot of data and the smoothing spline results for the best predictive model. The smoothing component plot for the predictor (Figure 78) shows a complex response that is hard to interpret mechanistically.

Summary

The scatter plots and correlation analyses indicate there are quantifiable relationships between the biological parameters and some of the environmental factors. The GAM results relating biological parameters and environmental factors are hard to interpret because of the nature of the time series trends, wherein roughly the first half of the biological response variable time series are highly variable with no trend, while the second half generally have a strong trend. This may be why the best model smoothers have multiple strong peaks and troughs indicating complex responses that suggest quadratic or higher order behaviors that are hard to explain mechanistically. Across the 4 biological parameter models, F was initially identified as a significant driver in all 4 models, followed by the AMO_1 in 3 models, and the AMO_2, GSI_2, and ST in 1 each. As with most of the previous analyses presented in the literature, the effects identified as drivers are suggestive but not definitive, and so the specific, underlying mechanisms for the environmental effects remain unclear. For F, as discussed earlier, there is stronger empirical evidence available for the underlying mechanism. Future modeling efforts in this vein should include F as one of the primary drivers considered.

MODELS RELATING RECRUITMENT METRICS AND ENVIRONMENTAL DATA

Introduction

The most recent stock assessment for summer flounder (NEFSC 2023) indicated that R has varied annually by a factor of about 8 over the past 41 years (Figure 2). A recent concern for the stock has been decreased R accompanied by relatively low but stable R/SSB over the past decade (2011-2022; NEFSC 2019, 2023). There is ongoing interest among scientists, managers, and fishermen in exploring the relationship between summer flounder R success and environmental factors. Such factors might include the influence of physical parameters such as water temperature, salinity, and climatic factors such as the position of the Atlantic Gulf Stream (GSI index), the position and intensity of the Mid-Atlantic Bight Cold Pool (CPI index), and other Atlantic basin-scale climatic drivers such as the Atlantic Multidecadal Oscillation (AMO index) and the North Atlantic Oscillation (NAO index).

Evidence from several historic studies suggests that low water temperatures could negatively impact summer flounder R. Summer flounder spawning occurs during an annual offshore migration from coastal areas to the continental shelf from August through December, and is generally considered to peak around November 1 (O'Brien et al. 1993). Summer flounder eggs have been collected as early as September in the northern Mid-Atlantic Bight and as late as January off Cape Hatteras, NC, with peak egg concentrations in October and November (Smith 1973; Able et al. 1990). Summer flounder eggs in the wild are tolerant to a wide range of temperatures between about 9°C and 22°C, with most occurring in temperatures of about 13-17°C (Smith 1973). Summer flounder larvae have been collected over an even wider range of temperatures (0-23°C; Smith 1973). Laboratory studies suggest that summer flounder eggs and larvae are tolerant to relatively high temperatures (Johns and Howell 1980; Johns et al. 1981) but that both eggs and larvae are susceptible to shock exposure to low temperatures of about 0°C (Hoss et al. 1974).

Summer flounder larvae undergo metamorphosis during the late autumn and early winter months as they enter the estuarine zone along the mid-Atlantic coast (Able et al. 1990). Szedlmayer et al. (1992) investigated the first year growth and effects of water temperature on survival for summer flounder juveniles migrating into New Jersey estuaries in the winter of 1988-1989 and found that the survival of metamorphosing larvae decreased drastically when water temperatures dropped below 2°C. Malloy and Targett (1991) conducted laboratory experiments on juvenile summer flounder and found 100% survival above 3°C, suggesting that the juveniles were able to survive most winter water temperatures encountered in the Mid-Atlantic Bight. However, Malloy and Targett (1994) found 42% mortality of juveniles at 2°C and concluded that mortality in the wild from acute exposure to low water temperatures probably occurred during one 2 to 4 week period each winter, and that summer flounder recruitment success in the north/central Mid-Atlantic Bight may be lower in years with late winter cold periods due to increased exposure to lethal temperatures.

Over the past 2 decades, persistent significant relationships have been found between environmental factors and R success for a variety of fish species around the world. Daskalov (1999) used correlation analysis and a GAM approach (Hastie and Tibshirani 1990) to document significant relationships between the R success of Black Sea anchovy (*Engraulis encrasicolus*), 3 predator stocks, and environmental factors including SST, wind speed, wind stress, mixing, atmospheric pressure, and river run-off. Williams and Quinn (2000) used correlation analysis to identify significant environmental factors affecting Pacific herring (*Clupea pallasii*) R success. Beentjes and Renwick (2001) used correlation analysis to identify a significant relationship between New Zealand red cod (*Pseudophycis bachus*) R success and SST. Chen and Ware (1999), Chen at al. (2000), Chen (2001), and Dreyfus-Leon and Chen (2007) used neural network, fuzzy logic, and genetic algorithm models to explore the relationships between environmental factors and R success of Pacific herring (*Clupea pallasi*) stocks.

Megrey et al. (2005) examined the utility of linear and non-linear regression, GAMs, and Artificial Neural Network (ANN) models in identifying relationships between R and the environment for both simulated and real Norwegian herring (*Clupea harengus*) stock-recruit data. Brodziak and O'Brien (2005) used randomization methods and the GAM approach to evaluate the response of New England groundfish recruit-spawner ratios to environmental variables such as the NAO index, water temperature, wind stress, and shelf water volume anomalies. Bell et al. (2014) reconstructed a 40-year time series of coastal water temperature for the major spawning and nursery areas to examine changes in the thermally available habitat for summer flounder. Bell et al. (2014) found that summer flounder abundance was negatively correlated with F but exhibited no link with temperature. They also found that while summer flounder productivity as measured by R had varied without a trend, a reduction in fishing mortality over the past 2 decades had led to rebuilding of the summer flounder stock and an expansion of its age structure. O'Leary et al. (2019)

explored the influences of the position of the GSI on summer flounder abundance through M and stock-recruitment relationships in a series of age-structured hierarchical Bayesian models. The model diagnostics indicated the best estimates of abundance resulted from a climate-dependent M model that included log-quadratic responses to the GSI.

This section explores the relationships between metrics of summer flounder R success and the physical environmental factors reviewed here by applying some of the approaches of Brodziak and O'Brien (2005) and Megrey et al. (2005), in effect updating the analyses conducted in the 2008 SAW 47 assessment (NEFSC 2008a). Specifically, Brodziak and O'Brien (2005) examined relationships between environmental indices and summer flounder R success, finding that the NAO winter index forward lagged by 2 years was a significant predictor of summer flounder R/SSB anomalies, with positive NAO anomalies (wet and mild winters) correlating with positive R/SSB anomalies. Megrey et al. (2005) used GAMs in identifying relationships between R and the environment, considering the absolute estimates of R as another measure of R success which may or may not be subject to strong influence of the magnitude of SSB. The work in the 2008 SAW 47 assessment (NEFSC 2008a) found the best model relating R/SSB to environmental data included only the NAO Winter climate index, indicating a positive and fairly strong predictive relationship, in line with the results of correlation analysis. The 2008 SAW 47 work (NEFSC 2008a) found the best model relating absolute R to environmental data included relatively weak relationships the bottom temperature lagged forward 2 years, the NAO Winter index, and the NAO Fall index lagged forward 1 year.

Haltuch et al. (2019) conducted a review of studies describing and hypothesizing the impact of climate change and environmental processes on vital rates of fish stocks, noting that previous research had indicated that including environmental drivers of R in forecasting has proven to be of limited value and that the potential for spurious relationships was sufficient to advise against inclusion. Haltuch et al. (2019) advised that species with more complex early life histories and longer pre-recruit survival windows would benefit from future research to improve mechanistic understanding of abiotic-biotic interactions. Brooks (2024) noted the challenges of incorporating environmental drivers into fisheries assessment modeling, including questions about how many different covariates and model formulations to consider, how to make judgments of best fit, and how to avoid post-hoc justification for model selections. Brooks (2024) advised that skepticism of spurious results does not make one a climate denier but rather a careful and dispassionate analyst, and that while work to identify drivers will likely continue, one should be mindful of the potential for environmental "hitchhikers" in the quest to identify drivers.

Recruitment correlation analysis

Notwithstanding the concerns of Haltuch et al. (2019) and Brooks (2024), and such caveats as "correlation does not imply causation" and "do not use assessment results as data" (Brooks and Deroba 2015), a correlation analysis between the absolute R and the R/SSB ratio estimates from the 2023 stock assessment (NEFSC 2023; Figures 79 and 80), and using the same environmental data used in the biological data models, was conducted as the first step in attempting to determine if such causation does exist. Figure 81 presents those assessment estimates as the anomalies used in the following analyses and models, with decreasing trends over the time series for both R metrics.

The correlation bewteen R and R/SSB is significant (shown in blue in Table 8), as would be expected given the common linear decreasing trends. Correlation analysis of the R metrics with the environmental factors (significant correlations shown in green in Table 8) revealed significant correlations with the AMO index, the NAO Mean index, and bottom salinity.

Recruitment Generalized Additive Models (GAMs)

The time series plots and correlation analyses show that there are a few significant coincident trends between summer flounder R and R/SSB and the environmental factors. A GAM approach (SAS 2020) was used in an attempt to further quantitatively identify significant drivers of the trends in R and R/SSB. The recruitment metrics are specified as the dependent response variables in the model, while the environmental data are the independent predictive variables.

In an initial step to confirm the correlation analyses, GAM models for the R metrics were first fit using singular models for each of the 9 types of environmental data (bottom temperature, surface temperature, bottom salinity, AMO, NAO Mean, NAO Winter, NAO Fall, GSI, and CPI) for the assessment time series of 1982-2022 (1983-2022 for R/SSB due to the manner in which the R to SSB pairs are compiled for the fall/winter spawning summer flounder [e.g.. the fall 1982 SSB produces the recruits estimated in 1983 at age 0]). Because the large scale climate indices are thought to integrate temperature, circulation patterns, and other oceanographic conditions potentially over multi-year scales (Brodziak and O'Brien 2005; O'Leary 2019), 1 and 2 year forward-lagged time series of the climate indices (e.g., NAO Winter plus 1 and 2 years) were also modeled, for a total of 21 single factor models for each R metric. These singular models were fit using smoothing splines with 3 degrees of freedom and the standard back-fitting algorithm (SAS 2020). Where needed, a constant positive integer (1, 2, or 3) was added to the variable values to allow the model to function properly (SAS 2020). The independent predictive variables with the 3 highest probabilities of significant parametric coefficient (Pr > t) and smoothing spline (Pr > ChiSq) were carried on to the next stage to select the best model for this exploratory exercise. Although the correlation analyses indicated the potential for significant covariance and therefore interaction terms, only main effect terms were explored in this exercise.

Absolute Recruitment (R) at age 0

For the R model (RAnom), the top 3 most significant single factor models were for the CPI index, the GSI plus 1 index (GSI_1), and the NAO Fall index (NAOFall), all with Pr > ChiSq of less than 0.001. Figures 82 and 83 show the 3 factor model scatter plot of data and the smoothing spline results. In the 3 factor model, none of the factors were significant at the 0.100 level. Therefore, NAOFall was dropped from the next step, a 2 factor model with CPI and GSI_1. In the 2 factor model, only CPI was significant, with Pr > ChiSq = 0.080. Therefore, the 1 factor model with CPI was indicated as the best predictive model for the R metric. Figures 84 and 85 show the 1 factor model scatter plot of data and the smoothing spline results. Once again, the smoothing component plot (Figure 85) shows a complex response that is hard to interpret mechanistically (e.g., there is not a definitive linear or simple curvilinear relationship indicating that a higher value predictive variable value relates definitively to a higher or lower value in the response variable).

Recruits per Spawning Stock Biomass (R/SSB)

For the R/SSB model (RSAnom), the top 3 most significant single factor models were for the AMO plus 1 index (AMO_1), the NAO Winter plus 2 index (NAOWin_2), and the GSI Plus 1 index (GSI_1), all with Pr > ChiSq of less than 0.050. Figures 86 and 87 show the 3 factor model scatter plot of data and the smoothing spline results. In the 3 factor model, none of the factors were significant at the 0.100 level. Therefore, GSI_1 was dropped from the next step, a 2 factor model with AMO_1 and NAOWin_2. In the 2 factor model, only AMO_1 was significant, with Pr >

ChiSq = 0.010. Therefore, the 1 factor model with AMO_1 was indicated as the best predictive model for the R/SSB metric. Figures 88 and 89 show the 1 factor model scatter plot of data and the smoothing spline results. Once again, the smoothing component plot (Figure 89) shows a complex response that is hard to interpret mechanistically.

Summary

The scatter plots and correlation analyses indicate there are quantifiable relationships between the R metrics and some of the environmental factors. The GAM results are presumably hard to interpret because of the nature of the time series trends, wherein roughly the first two-thirds of the R response variable time series are highly variable with a generally decreasing trend, while the last third has been generally stable and not coincident with the generally increasing trends in the environmental factors. These characteristics of the time series may be why the best model smoothers have multiple strong peaks and troughs indicating complex responses with quadratic or higher order behaviors that are hard to explain mechanistically. Different climate indices were quantified as the best predictors for each R metric: the CPI for absolute R and the AMO lagged forward 1 year (AMO_1) for the R/SSB. These results are different than the climate indices identified as the best predictors of summer flounder R dynamics in similar analyses by Brodziak and O'Brien (2005) and NEFSC (2008a; different lags of the NAO index), and by O'Leary et al. (2019; the GSI), with the caveat that the time series of R metrics and climate indices have been temporally updated. Collectively, these studies indicate how little is understood about how summer flounder R success and the environmental factors are truly related, and the question of whether the factors are in fact causative drivers or simply predictive covariates remains unclear.

DISCUSSION

The 2023 Management Track Assessment indicated that F on the summer flounder stock decreased from greater than 1.0 (a percentage exploitation rate of about 60%) during the 1980s and 1990s to less than 0.5 (a percentage exploitation rate of about 30%) since 2001. A shift in the age of full selection (selectivity by the total fishery equals 1.0) from age 2 in the 1980s to age 4 since the mid-2000s has also occurred, further decreasing the impact of F on the stock. SSB increased from a nadir in 1989 to a peak in 2003, and has since decreased to just below the SSB target in 2022. The R dynamics of the stock have been a recent concern as absolute R has been below the time series average since 2011, accompanied by relatively low but stable R/SSB (NEFSC 2023).

The observed trends in mean length, mean weight, and sex ratio since about 2000 are coincident with trends in F and some environmental and climate factors. The empirical data for these biological parameters indicate the trends are likely due to the interaction of F and sexually dimorphic growth. Relevant work in the fisheries literature over the past 30 years suggests that environmental factors may also be drivers of the observed changes in summer flounder length and age structure and R. The statistical analysis and modeling results presented here identify some statistically significant drivers of the biological trends. The results are suggestive but not definitive, however, and so the specific underlying mechanisms for the environmentally driven effects remain unclear. For F, there is a stronger theoretical basis and empirical evidence for the underlying mechanisms. Future modeling efforts in this vein should include F as one of the primary drivers considered.

The statistical analysis and modeling results for R success presented here indicate an evolving perception of the most important environmental drivers, as they were found to be different from those identified in previous work. As with the biological parameter models, the results are suggestive but not definitive. It is unclear if these environmental factors are causative effects or simply predictive covariates, with large uncertainty about the underlying mechanisms (e.g., water temperature tolerance, match/mismatch with larval prey, or transport to favored environmental conditions). This data compilation and the associated exploratory analyses conducted to quantify the significant drivers of summer flounder population dynamics should provide useful information and direction for future stock assessments.

ACKNOWLEDGEMENTS

I thank Fred Serchuk for his always sharp humor, helpful writing tips, and insightful reviews of the first 3 summer flounder "Chronicles," and Gary Shepherd, Paul Rago, Russell Brown, Chris Legault, and multiple anonymous reviewers for their valuable critiques that helped improve some or all 4 papers.

TABLES AND FIGURES

Table 1. Data and results from growth rate studies for summer flounder (*Paralichthys dentatus*).

Study	N fish	Max age (M, F)	Linf (M, F, B)	k (M, F, B)
Smith & Daiber (1977)	319	7,8	62,88	n/a
Henderson (1979)	n/a	10	92	0.21
Fogarty (1981)	1,889	7,10	72.7, 90.6	0.18, 0.16
Pentilla et al. (1989)	n/a	11,11	72.7, 90.7, 81.6	0.18, 0.16, 0.17
Current work	45,569	16,15	55.1, 79.4, 74.2	0.26, 0.18, 0.18

Table 2. Pearson correlation analysis of the Northeast Fisheries Science Center (NEFSC) bottom trawl survey seasonal temperature and salinty averages for all tows over the 55-year time series, where available. Green highlighted cells indicate significant correlations (n=55 $rcrit_{0.05}$ ~ 0.27).

	Spr Bottemp	*Spr Surftemp*	*Spr Botsalin*	*Fall Bottemp*	*Fall Surftemp*	*Fall Botsalin*
Spr Bottemp	1.00					
Spr Surftemp	0.54	1.00				
Spr Botsalin	0.24	0.35	1.00			
Fall Bottemp	0.45	0.42	0.22	1.00		
Fall Surftemp	0.25	0.36	0.20	0.12	1.00	
Fall Botsalin	0.45	0.55	0.53	0.70	0.28	1.00

Table 3. Pearson correlation analysis of the Northeast Fisheries Science Center (NEFSC) bottom trawl survey averaged annual temperatures and salinities (BT = bottom temperature, ST = surface temperature, BS = bottom salinty) and selected Climate Indices for the U.S. Northeast shelf (Atlantic Multidecadal Oscillation [AMO]; North Atlantic Oscillation [NAO] compiled as annual Mean (Jan-Dec), Winter (Dec-Mar), and Fall (Sep-Nov) indices; Gulf Stream Index [GSI]; Cold Pool Index [CPI]) for 1976-2022. Green highlighted cells indicate significant correlations (n=47, $rcrit_{0.05}$ ~ 0.28).

	BT	*ST*	*BS*	*AMO*	*NAO Mean*	*NAO Win*	*NAO Fall*	*GSI*	*CPI*
BT	1.00								
ST	0.64	1.00							
BS	0.29	0.10	1.00						
AMO	0.13	0.28	0.04	1.00					
NAO Mean	-0.01	-0.11	0.26	-0.39	1.00				
NAO Winter	0.23	0.26	0.46	0.11	0.48	1.00			
NAO Fall	-0.23	-0.15	0.17	-0.29	0.58	0.06	1.00		
GSI	0.57	0.45	0.65	0.27	0.07	0.37	-0.03	1.00	
CPI	0.66	0.52	0.60	0.33	0.05	0.38	-0.05	0.70	1.00

Table 4. Pearson correlation analysis of the Northeast Fisheries Science Center (NEFSC) bottom trawl survey averaged annual sampled male summer flounder (*Paralichthys dentatus*) mean lengths at age (M0 = age 0 mean length, etc.) and for all lengths-ages (MALL) with temperatures and salinities (BT = bottom temperature, ST = surface temperature, BS = bottom salinty), selected Climate Indices for the U.S. Northeast shelf (Atlantic Multidecadal Oscillation [AMO]; North Atlantic Oscillation [NAO] compiled as annual Mean (Jan-Dec), Winter (Dec-Mar), and Fall (Sep-Nov) indices; Gulf Stream Index [GSI]; Cold Pool Index [CPI]) for 1976-2022, and the annual fishing mortality rate (F for age 4 and older, 1982-2022). Blue and green highlighted cells indicate significant correlations (n=47, $rcrit_{0.05}$ ~ 0.28).

Males	*M0*	*M1*	*M2*	*M3*	*M4*	*M5*	*M6*	*M7*	*MALL*
M0	1.00								
M1	0.17	1.00							
M2	0.23	0.60	1.00						
M3	0.28	0.54	0.78	1.00					
M4	0.18	0.38	0.58	0.80	1.00				
M5	0.46	0.45	0.54	0.76	0.71	1.00			
M6	0.50	0.33	0.42	0.54	0.71	0.79	1.00		
M7	0.51	0.20	0.17	0.33	0.56	0.76	0.75	1.00	
MALL	-0.36	-0.06	-0.12	-0.31	-0.47	-0.24	-0.03	-0.19	1.00
BT	-0.41	-0.06	-0.18	-0.33	-0.25	-0.45	-0.44	-0.22	0.26
ST	-0.36	-0.16	-0.23	-0.37	-0.59	-0.59	-0.47	-0.55	0.50
BS	-0.31	-0.17	-0.29	-0.20	-0.38	-0.13	-0.16	-0.17	0.30
AMO	-0.20	0.07	-0.05	-0.31	-0.53	-0.44	-0.47	-0.34	0.73
NAO Mean	-0.09	0.05	0.21	0.32	0.24	0.10	-0.13	-0.42	-0.28
NAO Winter	-0.13	0.13	0.11	0.09	-0.18	-0.29	-0.30	-0.42	-0.02
NAO Fall	-0.13	-0.19	0.02	0.17	0.09	0.25	0.06	-0.26	-0.08
GSI	-0.43	-0.23	-0.28	-0.36	-0.45	-0.69	-0.56	-0.53	0.28
CPI	-0.39	-0.06	-0.26	-0.32	-0.32	-0.50	-0.40	-0.45	0.37
F	0.47	0.18	0.33	0.40	0.51	0.36	0.34	0.11	-0.79

Table 5. Pearson correlation analysis of the Northeast Fisheries Science Center (NEFSC) bottom trawl survey averaged annual sampled female summer flounder (*Paralichthys dentatus*) mean lengths at age (M0 = age 0 mean length, etc.) and for all lengths-ages (MALL) with temperatures and salinities (BT = bottom temperature, ST = surface temperature, BS = bottom salinty), selected Climate Indices for the U.S. Northeast shelf (Atlantic Multidecadal Oscillation [AMO]; North Atlantic Oscillation [NAO] compiled as annual Mean (Jan-Dec), Winter (Dec-Mar), and Fall (Sep-Nov) indices; Gulf Stream Index [GSI]; Cold Pool Index [CPI]) for 1976-2022, and the annual fishing mortality rate (F for age 4 and older, 1982-2022). Blue and green highlighted cells indicate significant correlations (n=47, $rcrit_{0.05}$ ~ 0.28).

Females	*F0*	*F1*	*F2*	*F3*	*F4*	*F5*	*F6*	*F7*	*FALL*
F0	1.00								
F1	0.27	1.00							
F2	0.32	0.53	1.00						
F3	0.44	0.49	0.83	1.00					
F4	0.43	0.32	0.77	0.84	1.00				
F5	0.27	0.24	0.58	0.72	0.76	1.00			
F6	0.35	0.36	0.45	0.62	0.50	0.57	1.00		
F7	0.35	-0.03	0.44	0.61	0.72	0.69	0.03	1.00	
FALL	-0.48	-0.18	-0.19	-0.47	-0.41	-0.43	-0.22	-0.66	1.00
BT	-0.46	0.00	-0.14	-0.27	-0.24	-0.21	-0.07	-0.15	0.25
ST	-0.54	-0.06	-0.24	-0.35	-0.33	-0.48	-0.11	-0.24	0.54
BS	-0.18	-0.14	-0.27	-0.47	-0.43	-0.49	-0.16	-0.12	0.44
AMO	-0.41	0.03	-0.14	-0.39	-0.30	-0.42	-0.41	-0.48	0.60
NAO Mean	0.16	0.10	0.29	0.30	0.18	0.26	0.21	0.09	-0.16
NAO Winter	-0.13	0.11	0.13	0.17	0.15	-0.05	0.16	0.29	-0.05
NAO Fall	0.13	-0.05	0.09	0.02	-0.09	0.09	0.03	-0.14	0.09
GSI	-0.42	-0.11	-0.31	-0.34	-0.36	-0.33	-0.06	-0.33	0.34
CPI	-0.42	0.07	-0.28	-0.38	-0.42	-0.30	-0.23	-0.37	0.39
F	0.50	0.26	0.46	0.72	0.77	0.64	0.64	0.65	-0.78

Table 6. Pearson correlation analysis of the Northeast Fisheries Science Center NEFSC estimated total fishery catch summer flounder (*Paralichthys dentatus*) mean weights at age (C0 = age 0 mean weight, etc.) and for all weights-ages (CALL) with temperatures and salinities (BT = bottom temperature, ST = surface temperature, BS = bottom salinty), selected Climate Indices for the U.S. Northeast shelf (Atlantic Multidecadal Oscillation [AMO]; North Atlantic Oscillation [NAO] compiled as annual Mean (Jan-Dec), Winter (Dec-Mar), and Fall (Sep-Nov) indices; Gulf Stream Index [GSI]; Cold Pool Index [CPI]), and the annual fishing mortality rate (F for age 4 and older, 1982-2022). Blue and green highlighted cells indicate significant correlations (n=41, $rcrit_{0.05}$ ~ 0.30).

Fish xw	*C0*	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*CALL*
C0	1.00								
C1	0.58	1.00							
C2	0.31	0.75	1.00						
C3	0.49	0.54	0.45	1.00					
C4	0.53	0.57	0.36	0.91	1.00				
C5	0.53	0.57	0.37	0.73	0.89	1.00			
C6	0.49	0.51	0.39	0.74	0.83	0.92	1.00		
C7	0.51	0.40	0.29	0.72	0.77	0.73	0.71	1.00	
CALL	-0.53	-0.34	-0.16	-0.74	-0.77	-0.73	-0.74	-0.69	1.00
BT	-0.24	-0.22	-0.02	-0.30	-0.19	-0.16	-0.10	-0.24	0.06
ST	-0.10	-0.20	-0.07	-0.31	-0.25	-0.21	-0.15	-0.23	0.25
BS	-0.14	-0.06	0.25	-0.18	-0.41	-0.42	-0.28	-0.47	0.54
AMO	-0.44	-0.22	-0.11	-0.76	-0.74	-0.57	-0.59	-0.69	0.76
NAOMean	0.02	0.06	0.23	0.36	0.25	0.15	0.19	0.12	-0.26
NAOWinter	0.01	0.14	0.28	0.04	-0.11	-0.10	-0.02	-0.25	0.02
NAOFall	-0.17	-0.16	-0.01	0.18	0.11	-0.07	-0.03	-0.06	-0.01
GSI	-0.29	-0.23	-0.07	-0.33	-0.38	-0.47	-0.40	-0.43	0.34
CPI	-0.34	-0.26	-0.09	-0.43	-0.43	-0.46	-0.42	-0.43	0.32
F	0.50	0.39	0.10	0.62	0.72	0.71	0.77	0.57	-0.89

Table 7. Pearson correlation analysis of the Northeast Fisheries Science Center (NEFSC) bottom trawl survey averaged annual sampled proportion female (sex ratio) at age and in aggregate (prof0= proportion female at age 0, etc.) and for all lengths-ages (profall) with temperatures and salinities (BT = bottom temperature, ST = surface temperature, BS = bottom salinty), selected Climate Indices for the U.S. Northeast shelf (Atlantic Multidecadal Oscillation [AMO]; North Atlantic Oscillation [NAO] compiled as annual Mean (Jan-Dec), Winter (Dec-Mar), and Fall (Sep-Nov) indices; Gulf Stream Index [GSI]; Cold Pool Index [CPI]) for 1976-2022, and the annual fishing mortality rate (F for age 4 and older, 1982-2022). Blue and green highlighted cells indicate significant correlations (n=47, $rcrit_{0.05}$ ~ 0.28).

Prop Female	*prof0*	*prof1*	*prof2*	*prof3*	*prof4*	*prof5*	*prof6*	*prof7*	*profall*
prof0	1.00								
prof1	-0.06	1.00							
prof2	-0.14	0.21	1.00						
prof3	-0.20	0.21	0.73	1.00					
prof4	0.10	0.43	0.56	0.50	1.00				
prof5	0.00	0.11	0.57	0.56	0.48	1.00			
prof6	-0.35	0.28	0.64	0.73	0.52	0.62	1.00		
prof7	-0.15	0.25	0.18	0.47	0.25	0.34	0.52	1.00	
profall	0.15	0.57	0.28	0.08	0.43	0.17	0.19	0.19	1.00
BT	-0.20	0.12	-0.05	-0.20	-0.11	-0.09	-0.27	-0.14	0.02
ST	-0.54	0.04	-0.31	-0.27	-0.24	-0.17	-0.22	-0.19	-0.08
BS	0.19	-0.21	-0.50	-0.60	-0.36	-0.29	-0.37	-0.34	-0.27
AMO	0.22	-0.28	-0.67	-0.68	-0.39	-0.32	-0.65	-0.27	-0.04
NAOMean	0.04	-0.05	0.28	0.25	0.34	0.27	0.31	-0.01	0.05
NAOWinter	0.12	-0.11	0.04	0.00	0.21	0.18	-0.03	-0.26	-0.01
NAOFall	-0.10	-0.02	0.02	0.17	0.10	-0.18	0.19	-0.07	-0.16
GSI	0.04	-0.02	-0.32	-0.47	-0.16	-0.38	-0.47	-0.35	-0.11
CPI	-0.08	-0.09	-0.38	-0.45	-0.23	-0.31	-0.45	-0.23	-0.15
F	-0.21	0.17	0.76	0.83	0.45	0.61	0.71	0.33	-0.01

Table 8. Pearson correlation analysis of the summer flounder (*Paralichthys dentatus*) absolute Recruitment at age 0 (R Anom) and Recruit per Spawning Stock Biomass (R/SSB Anom) anomalies with temperatures and salinities (BT = bottom temperature, ST = surface temperature, BS = bottom salinty), and selected Climate Indices for the U.S. Northeast shelf (Atlantic Multidecadal Oscillation [AMO]; North Atlantic Oscillation [NAO] compiled as annual Mean (Jan-Dec), Winter (Dec-Mar), and Fall (Sep-Nov) indices; Gulf Stream Index [GSI]; Cold Pool Index [CPI]) for 1983-2022. Blue and green highlighted cells indicate significant correlations (n=40, $rcrit_{0.05}$ ~ 0.30).

	R Anom	*R/SSB Anom*
R Anom	1.00	
R/SSB Anom	0.47	1.00
BT	-0.03	0.03
ST	-0.12	-0.19
BS	-0.23	-0.52
AMO	-0.38	-0.66
NAOMean	-0.03	0.34
NAOWinter	-0.25	0.08
NAOFall	0.00	0.12
GSI	-0.20	-0.16
CPI	-0.29	-0.17

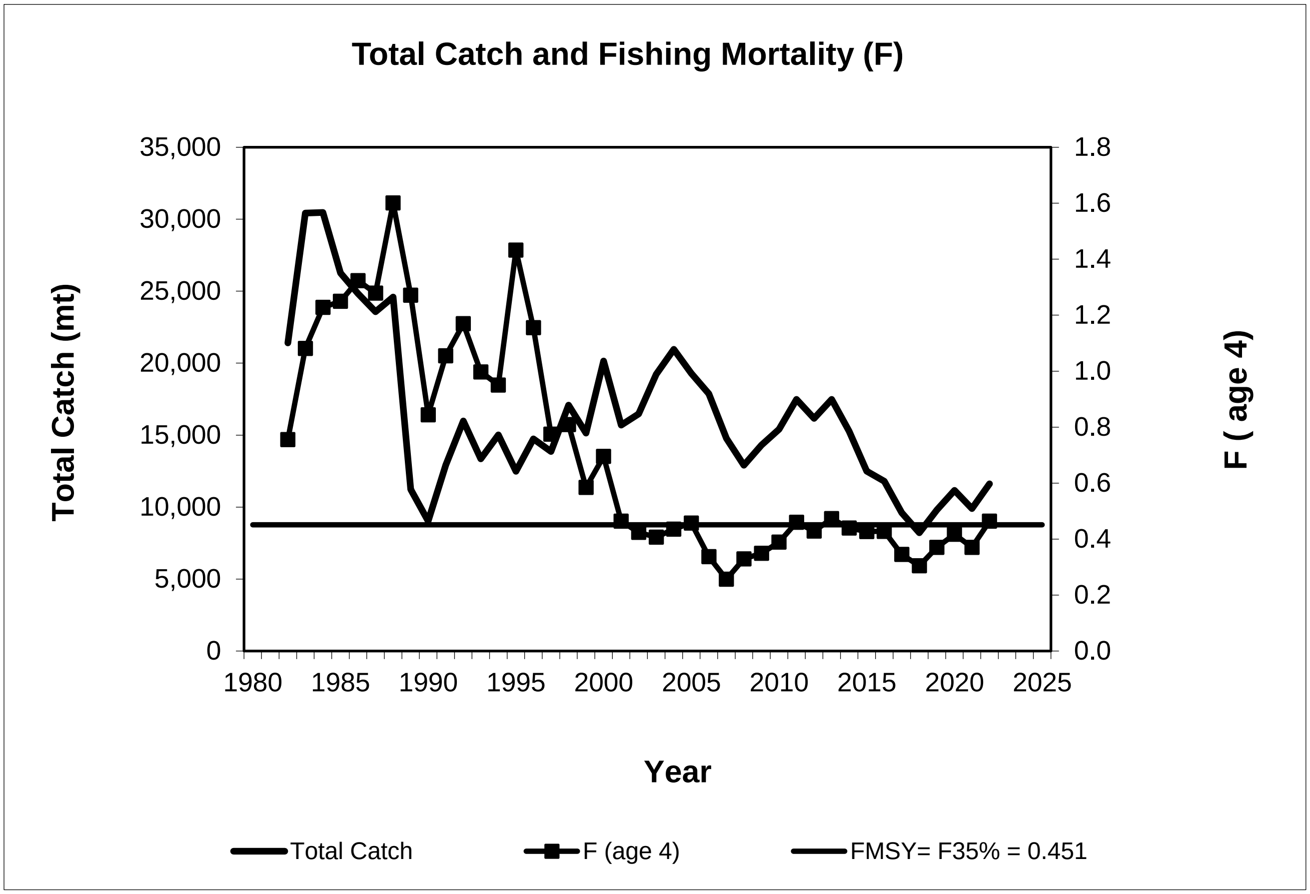


Figure 1. Total fishery catch (metric tons [mt]; solid line) and fully-selected fishing mortality (F, peak at age 4; squares) of summer flounder (*Paralichthys dentatus*) through 2022 (NEFSC 2023). The horizontal solid line is the updated threshold fishing mortality reference point proxy.

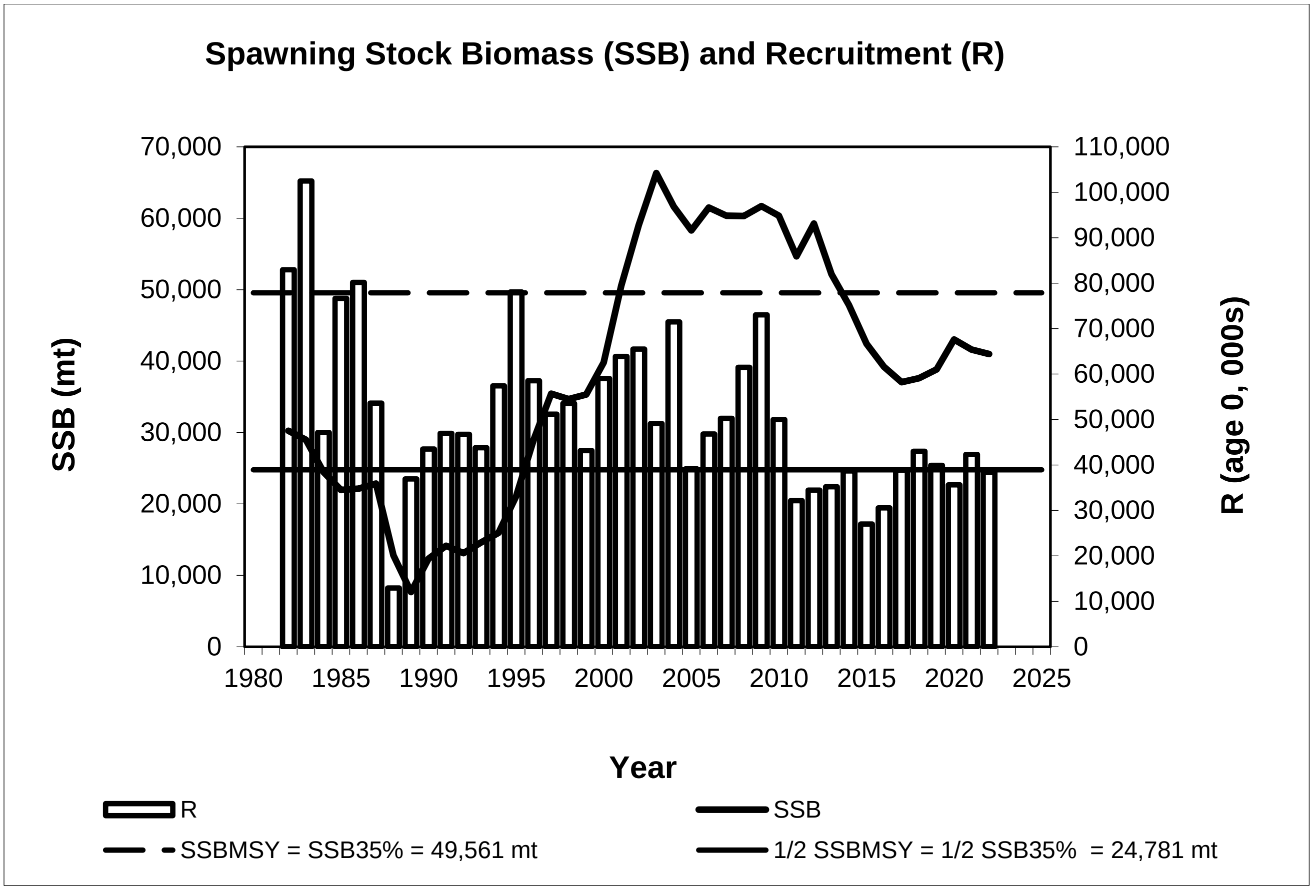


Figure 2. Summer flounder (*Paralichthys dentatus*) spawning stock biomass (SSB; solid line) and recruitment at age 0 (R; vertical bars) by calendar year through 2022. The horizontal dashed line is the updated target biomass reference point proxy. The horizontal solid line is the updated threshold biomass reference point proxy.

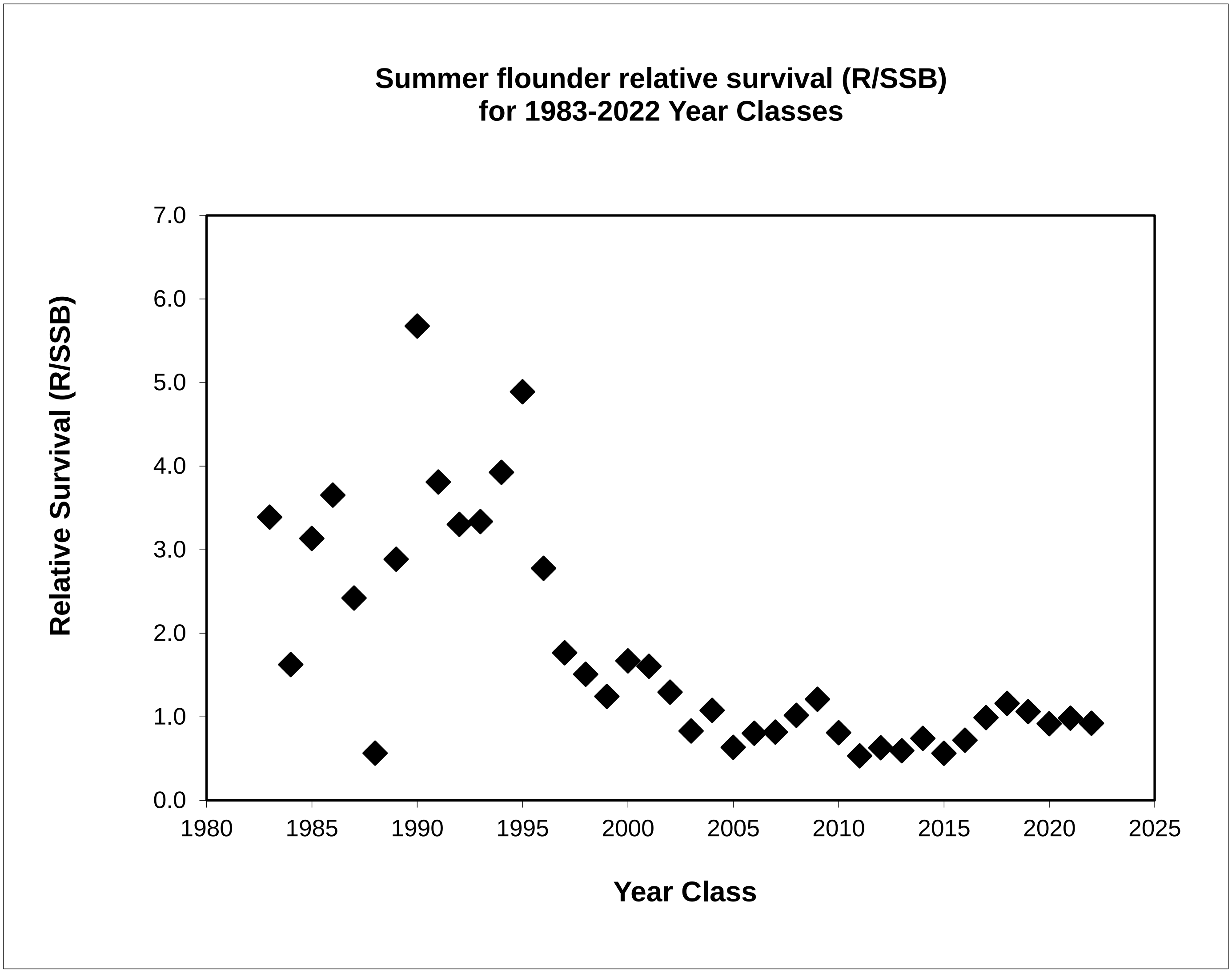


Figure 3. Recruits per spawning stock biomass plot (R/SSB) indicative of the relative survival of the summer flounder (*Paralichthys dentatus*) 1983-2022 year classes.

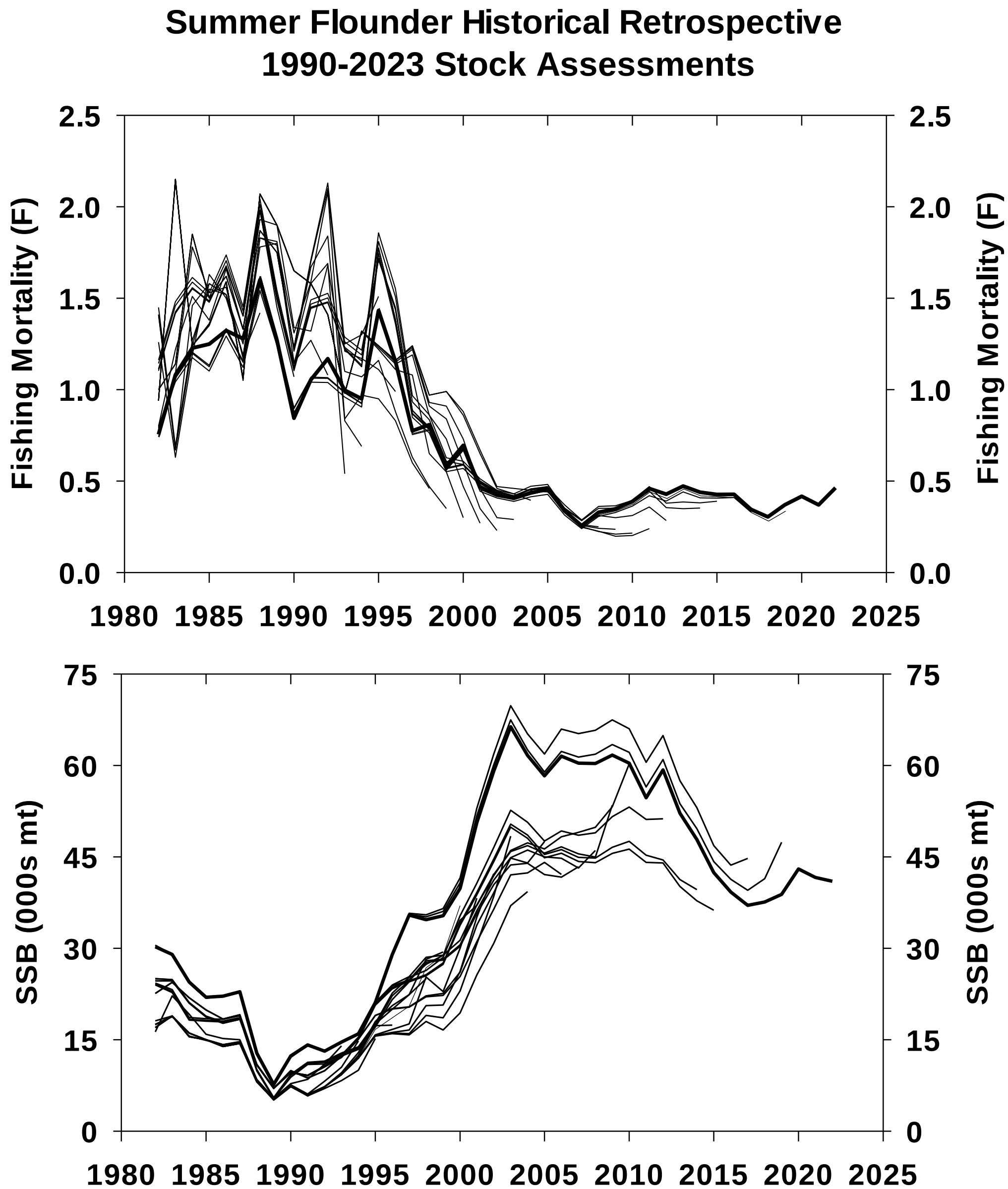


Figure 4. Historical retrospective error pattern in estimates of fully-recruited fishing mortality (F; top panel) and spawning stock biomass (SSB in 000s metric tons [mt]; bottom panel) from the 1990-2023 summer flounder (*Paralichthys dentatus*) stock assessments. The 1990-2007 assessments used single fleet virtual population analysis models and an average M = 0.20. The 2008-2023 assessments used multi-fleet statistical catch at age models and an average M = 0.25. The 2023 assessment results (NEFSC 2023) are the longest series in the thick lines.

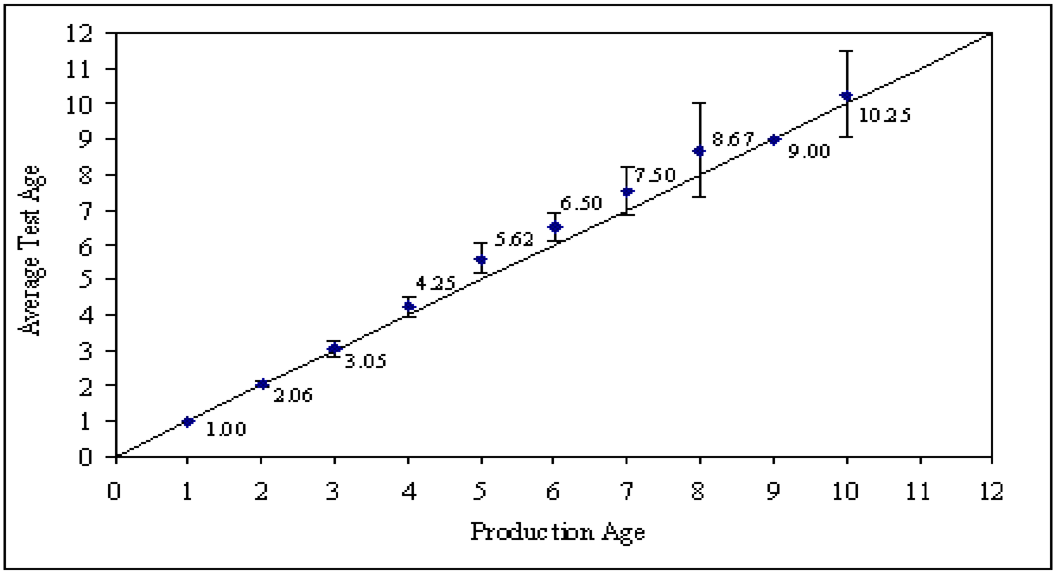


Figure 5. Age bias plot for Northeast Fisheries Science Center (NEFSC) 2011 summer flounder (*Paralichthys dentatus*) spring survey ages, 75% agreement.

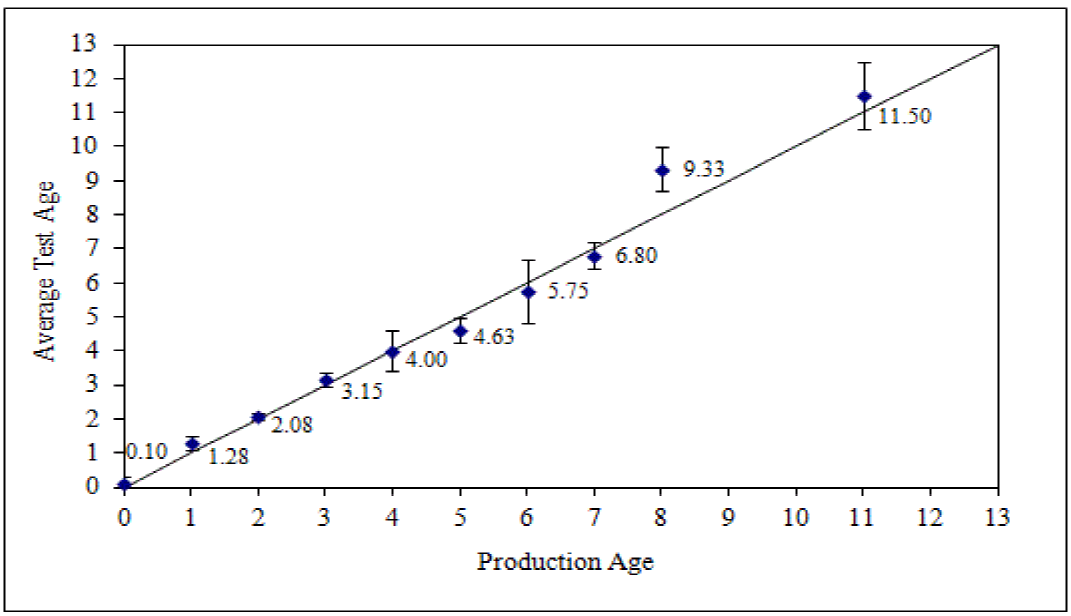


Figure 6. Age bias plot for Northeast Fisheries Science Center (NEFSC) 2011 summer flounder (*Paralichthys dentatus*) fall survey ages, 73% agreement.

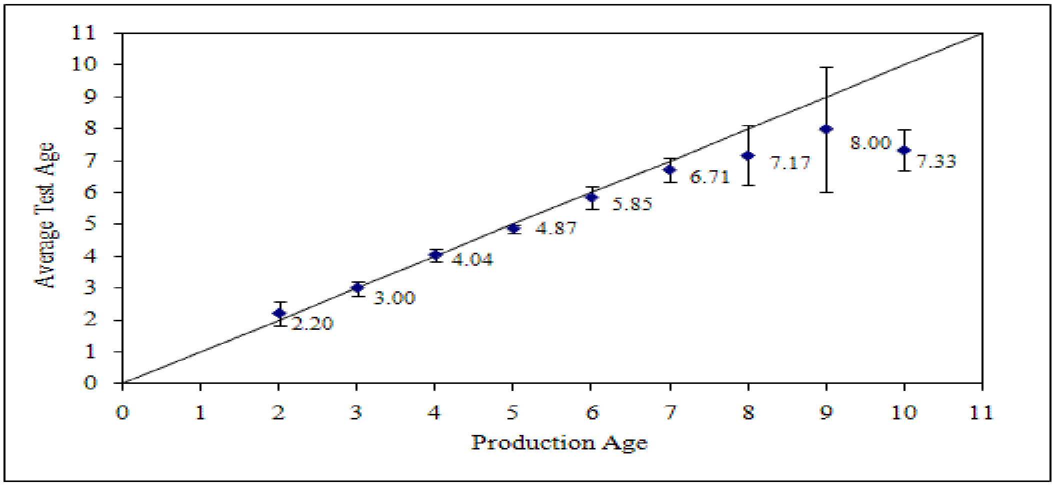


Figure 7. Age bias plot for Northeast Fisheries Science Center (NEFSC) 2011 summer flounder (*Paralichthys dentatus*) quarter 1 commercial ages, 69% agreement.

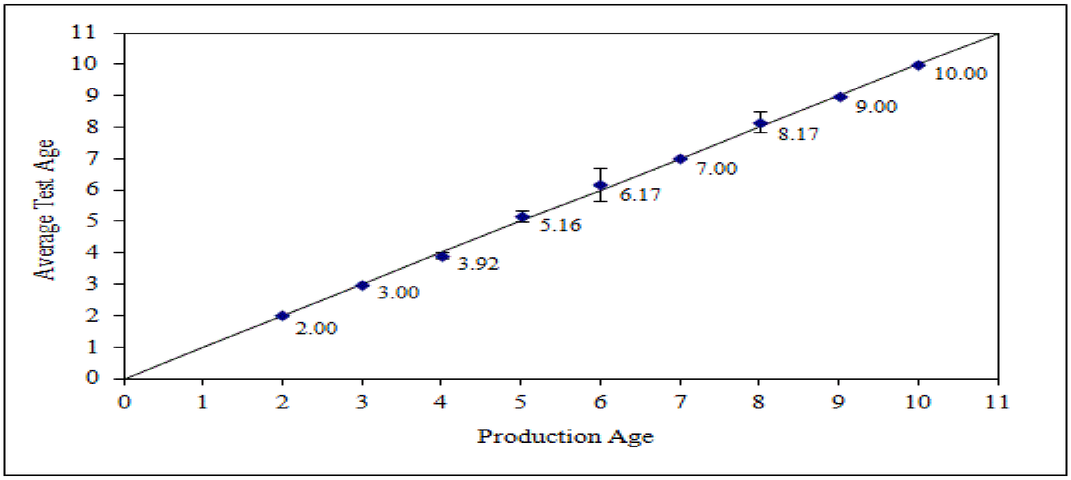


Figure 8. Age bias plot for Northeast Fisheries Science Center (NEFSC) 2011 summer flounder (*Paralichthys dentatus*) quarter 2 commercial ages, 92% agreement.

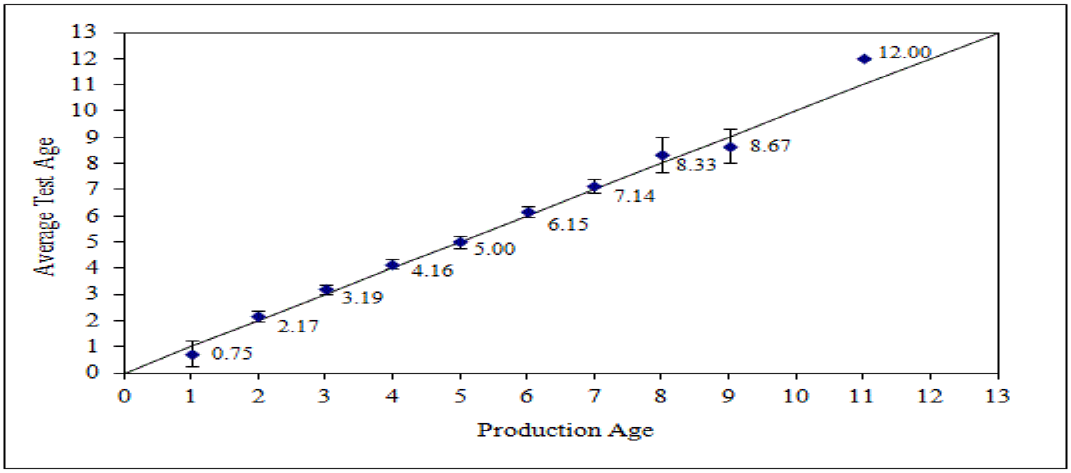


Figure 9. Age bias plot for Northeast Fisheries Science Center (NEFSC) 2011 summer flounder (*Paralichthys dentatus*) quarter 3-4 commercial ages, 80% agreement.

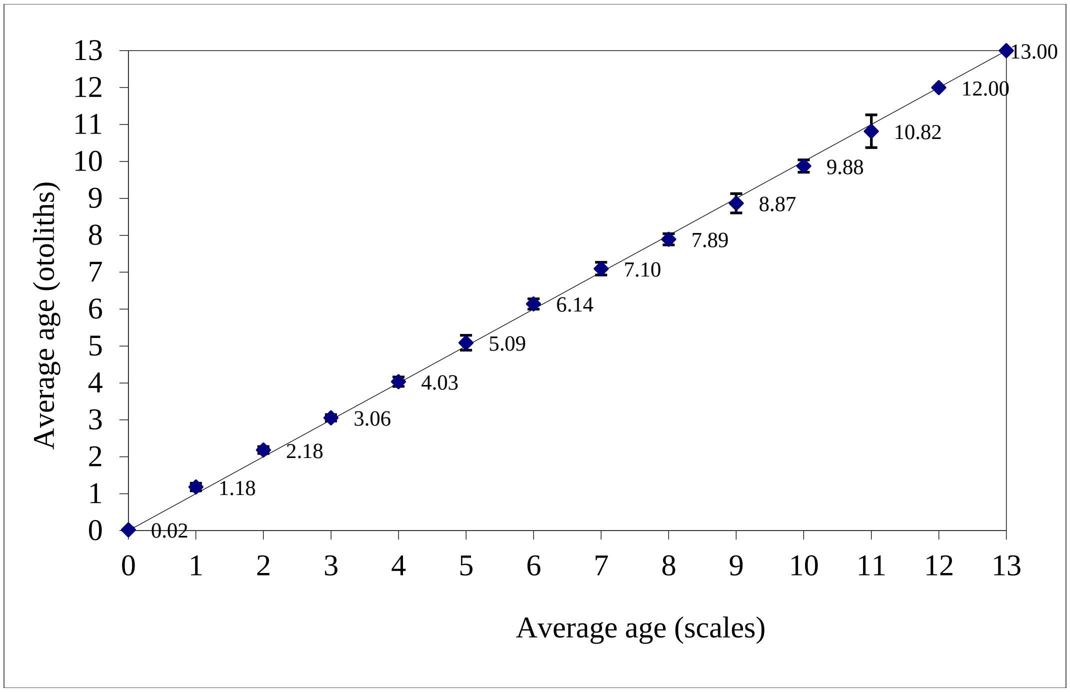


Figure 10. Age bias plot from the Atlantic States Marine Fisheries Commission (ASMFC) 2014 aging workshop comparing scale and otolith ages for 619 summer flounder (*Paralichthys dentatus*) collected during 2009-2013. There was 79% agreement with 4.6% coefficient of variation

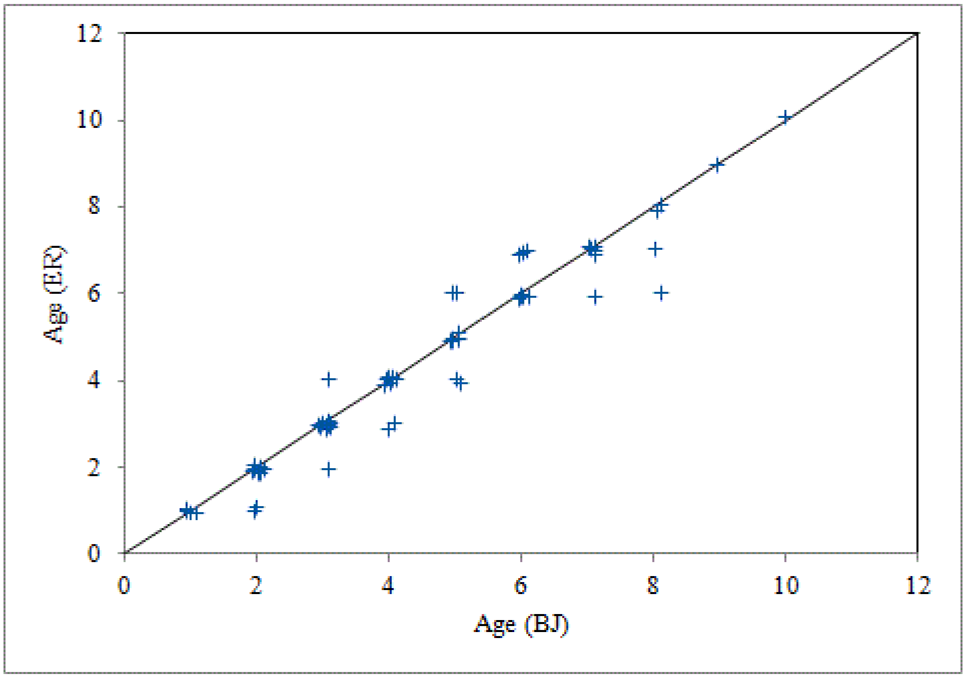


Figure 11. Age bias plot for Northeast Fisheries Science Center (NEFSC) 2016 summer flounder (*Paralichthys dentatus*) spring survey ages, 77% agreement.

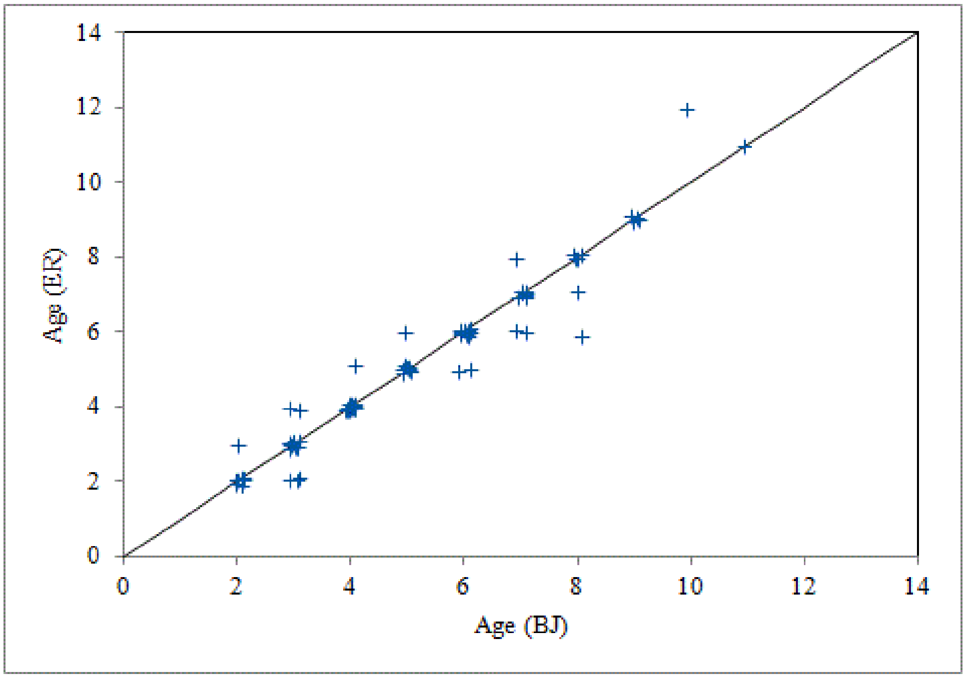


Figure 12. Age bias plot for Northeast Fisheries Science Center (NEFSC) 2016 summer flounder (*Paralichthys dentatus*) quarter 1 commercial ages, 83% agreement.

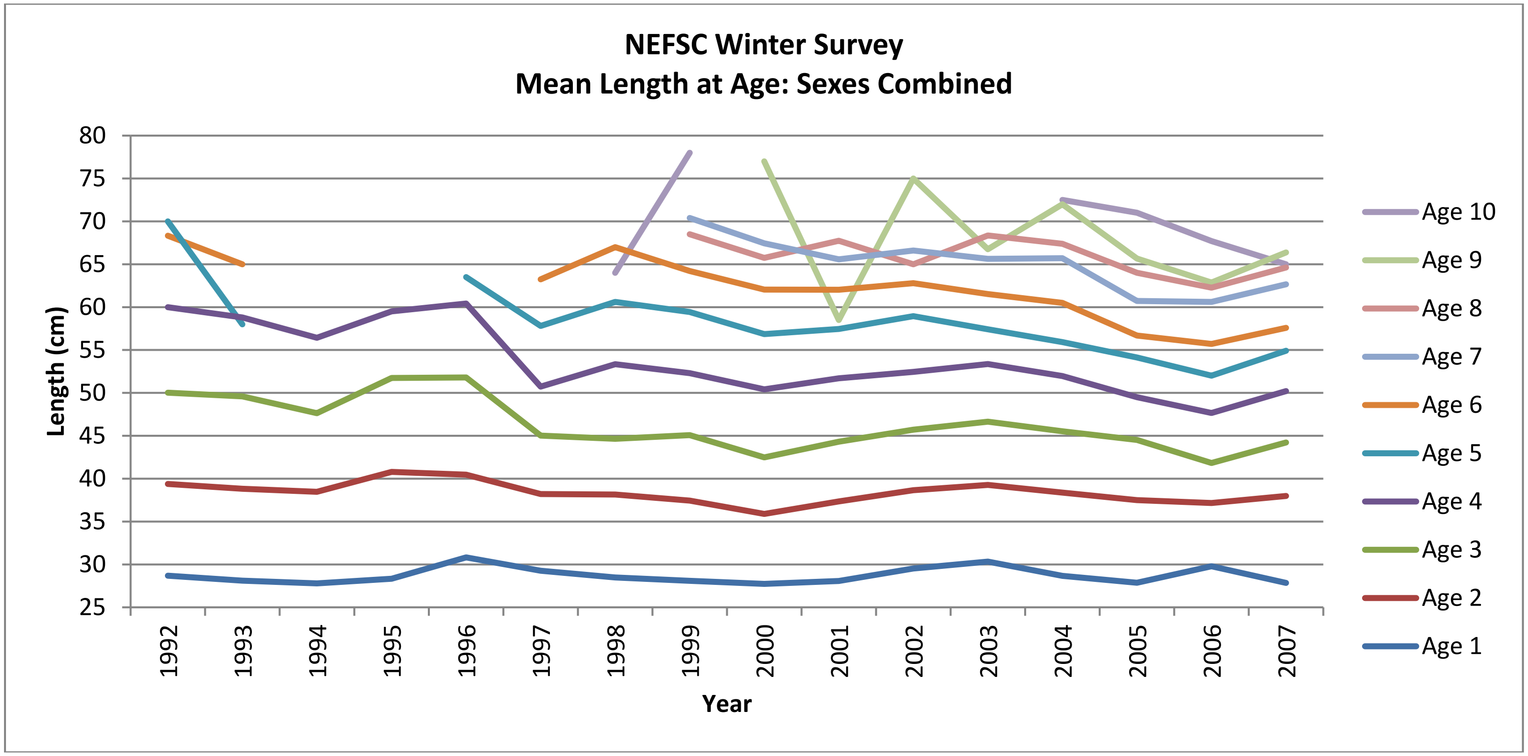


Figure 13. Trend in mean length at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) winter trawl survey: summer flounder (*Paralichthys dentatus*) sexes combined.

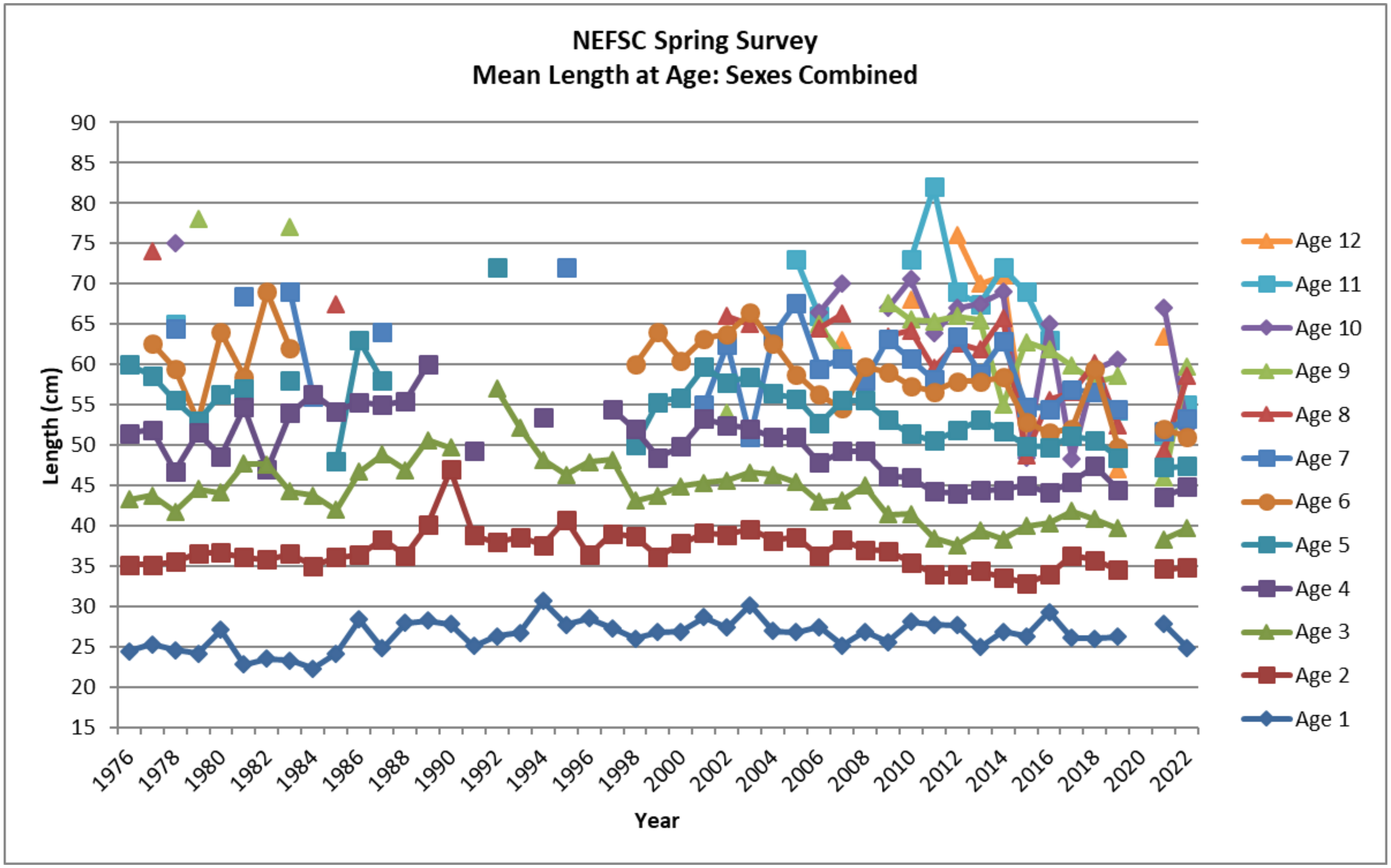


Figure 14. Trend in mean length at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) spring trawl survey: summer flounder (*Paralichthys dentatus*) sexes combined.

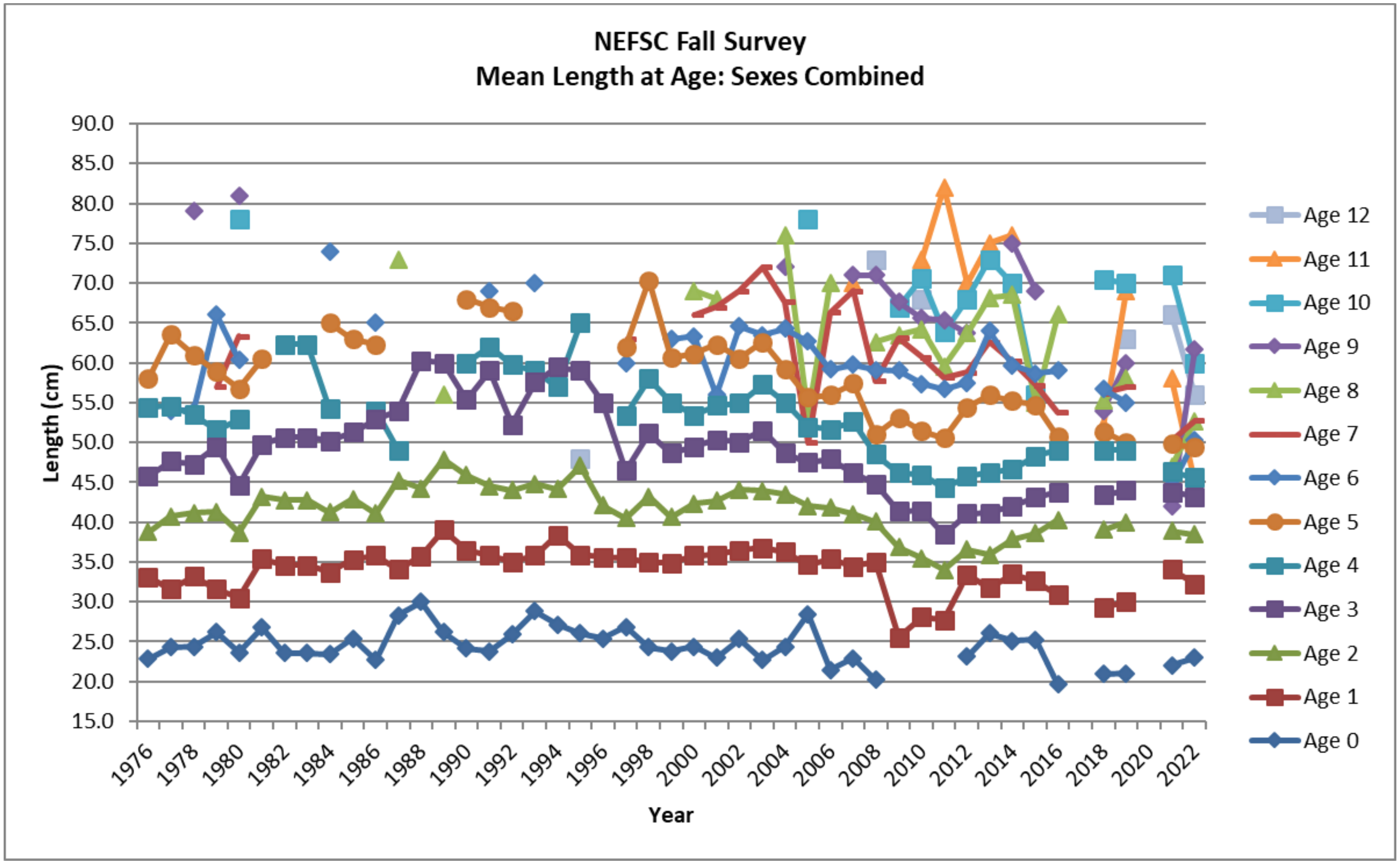


Figure 15. Trend in mean length at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) fall trawl survey: summer flounder (*Paralichthys dentatus*) sexes combined.

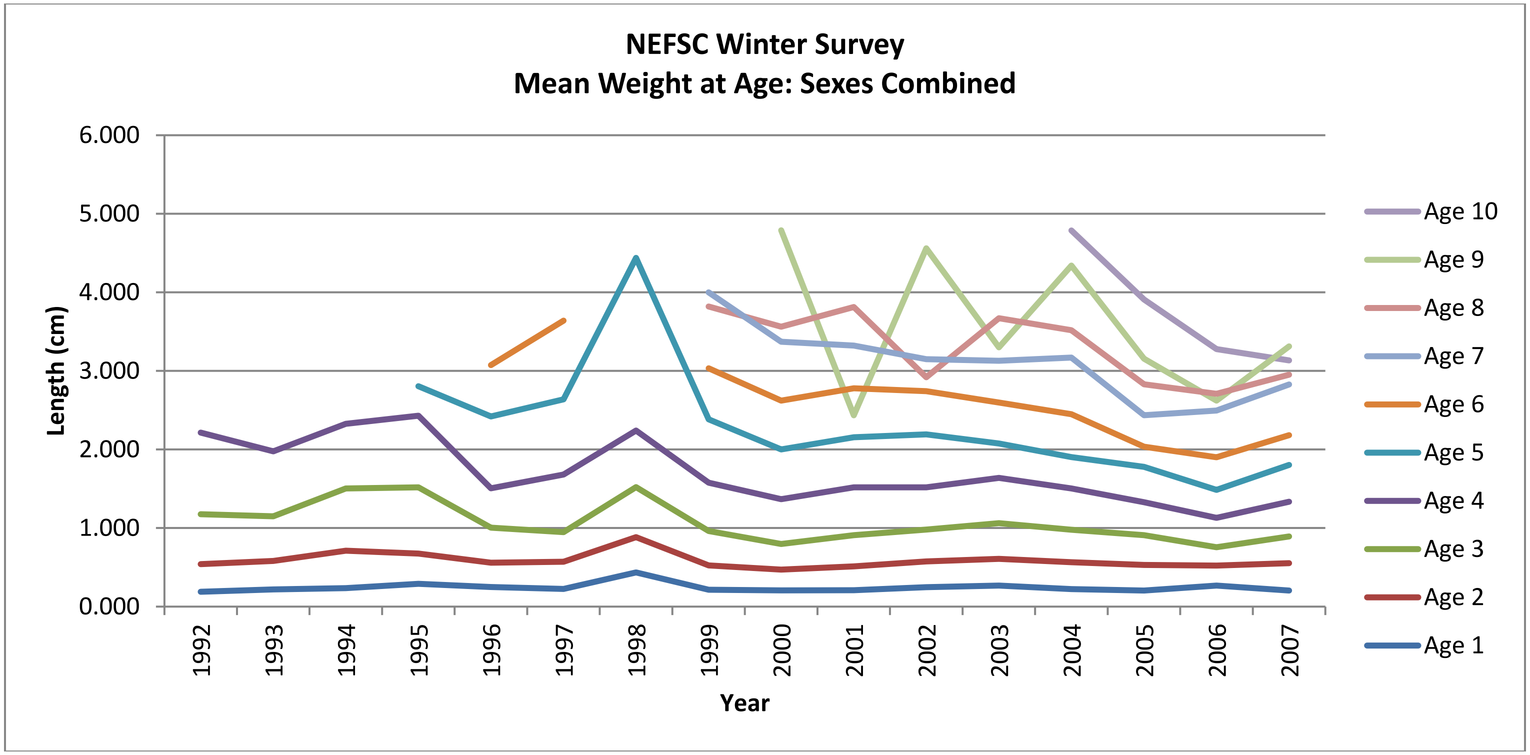


Figure 16. Trend in mean weight at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) winter trawl survey: summer flounder (*Paralichthys dentatus*) sexes combined.

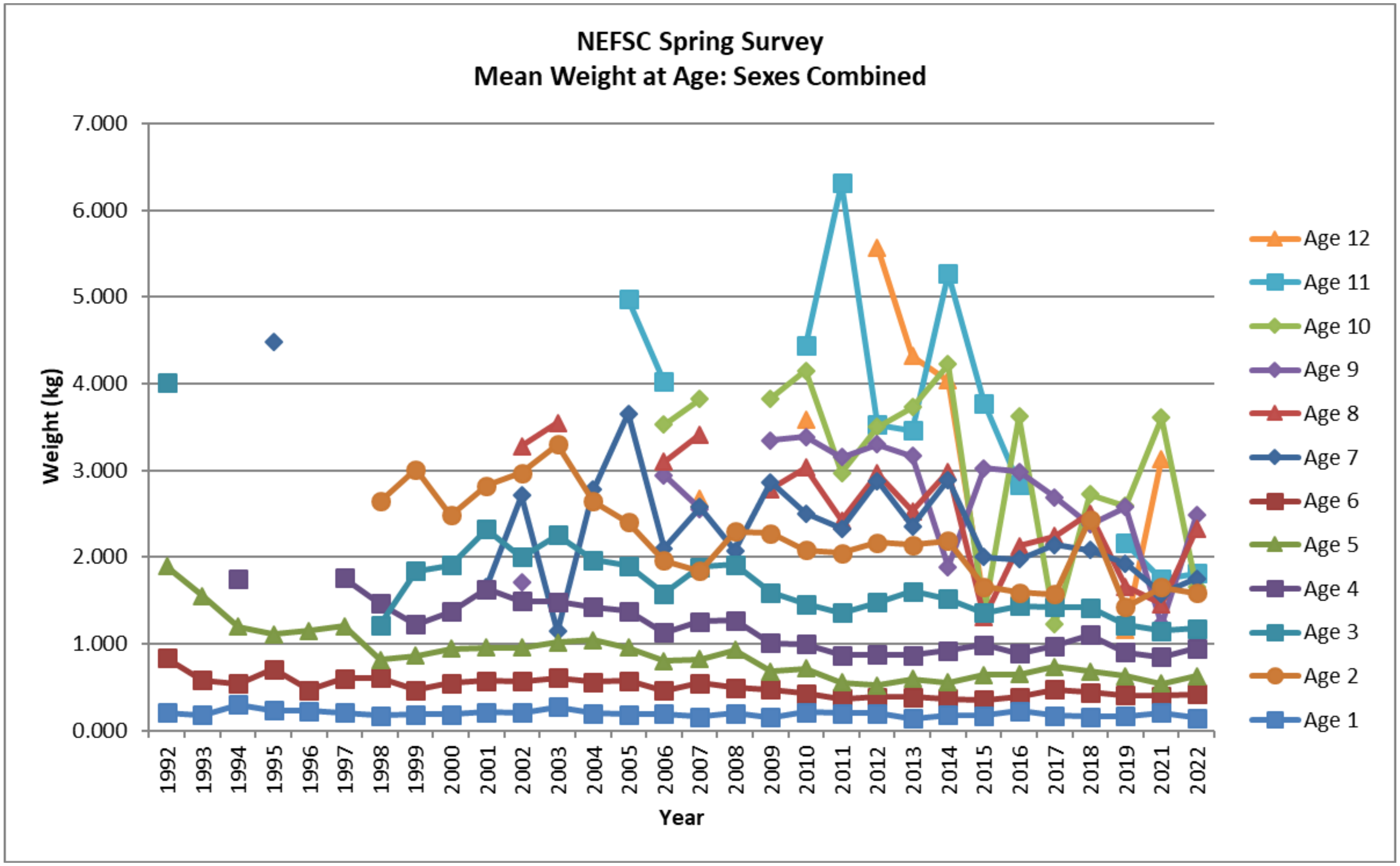


Figure 17. Trend in mean weight at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) spring trawl survey: summer flounder (*Paralichthys dentatus*) sexes combined.

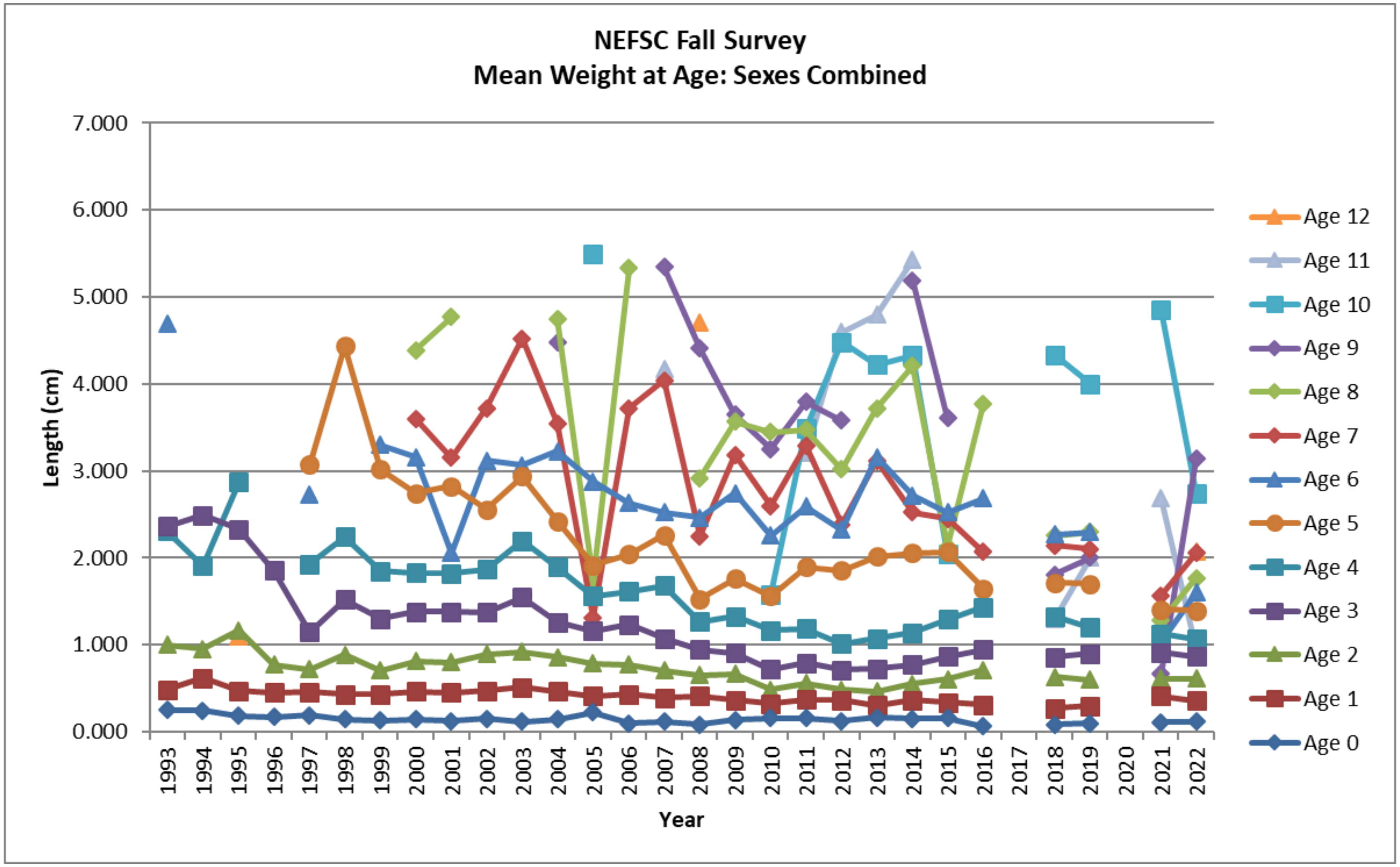


Figure 18. Trend in mean weight at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) fall trawl survey: summer flounder (*Paralichthys dentatus*) sexes combined.

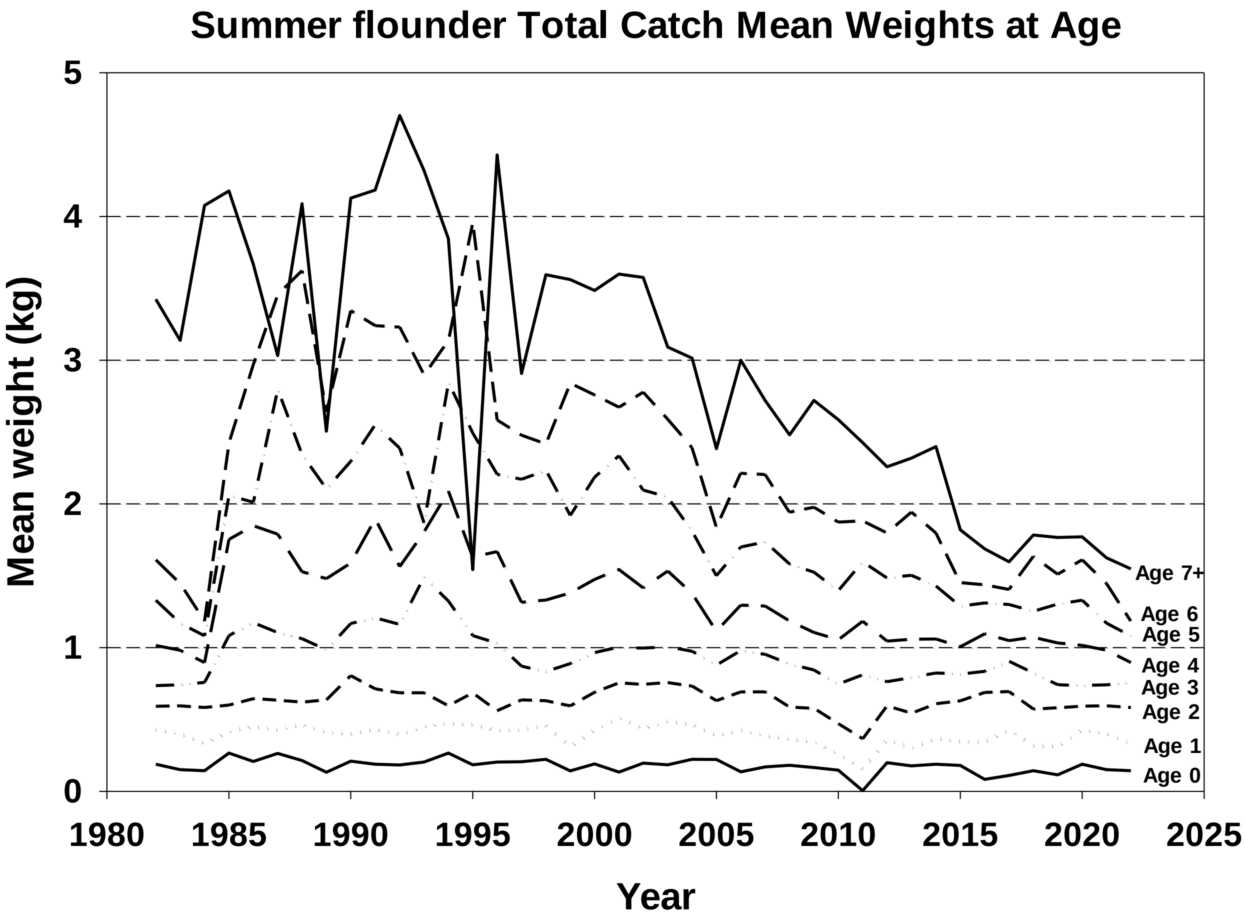


Figure 19. Trend in mean weight at age of summer flounder (*Paralichthys dentatus*) for the fishery total catch (sampled lengths converted to weights): sexes combined.

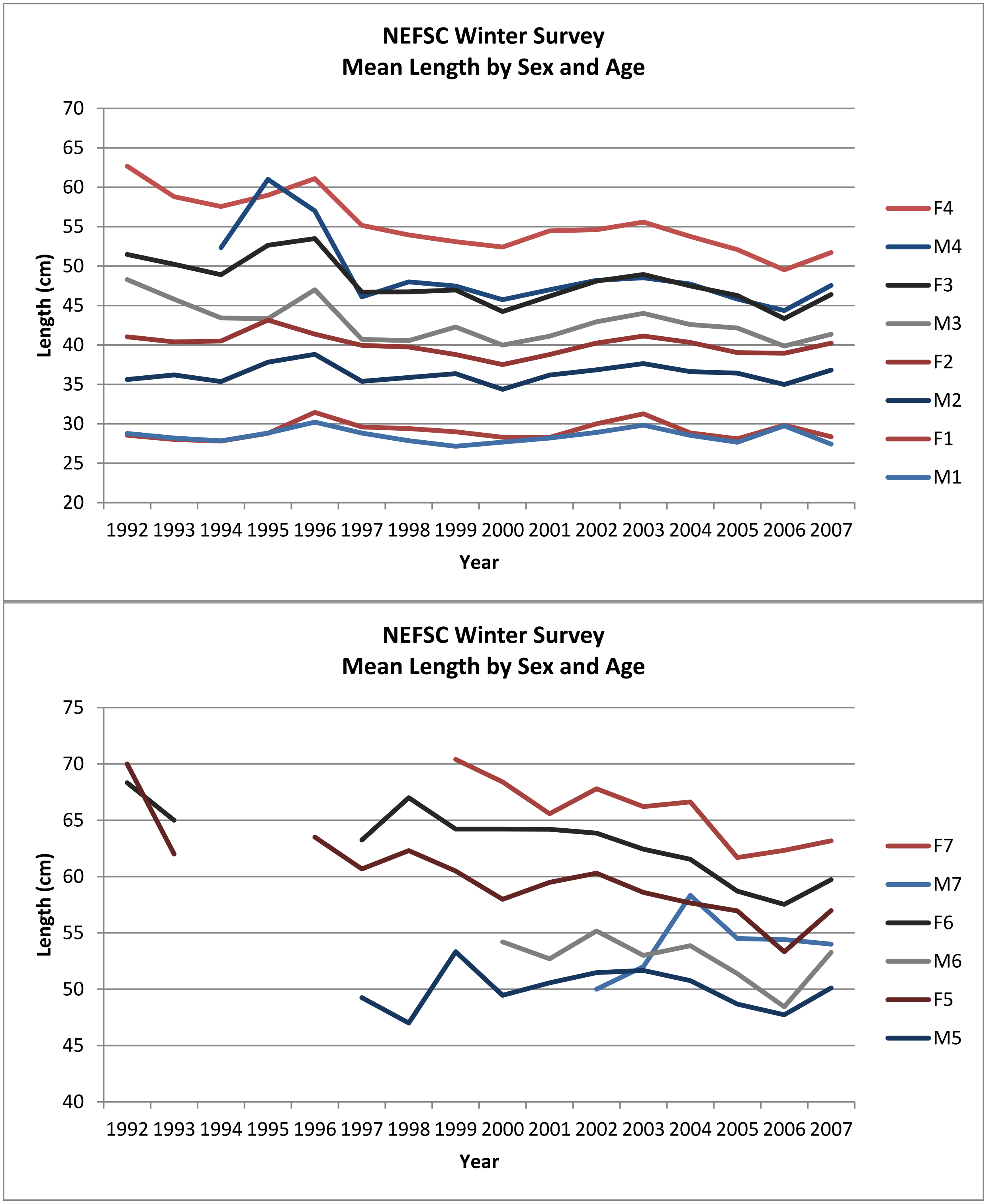


Figure 20. Trend in mean length at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) winter trawl survey: summer flounder (*Paralichthys dentatus*) by sex and age (e.g., M1 = age 1 males, F7 = age 7 females).

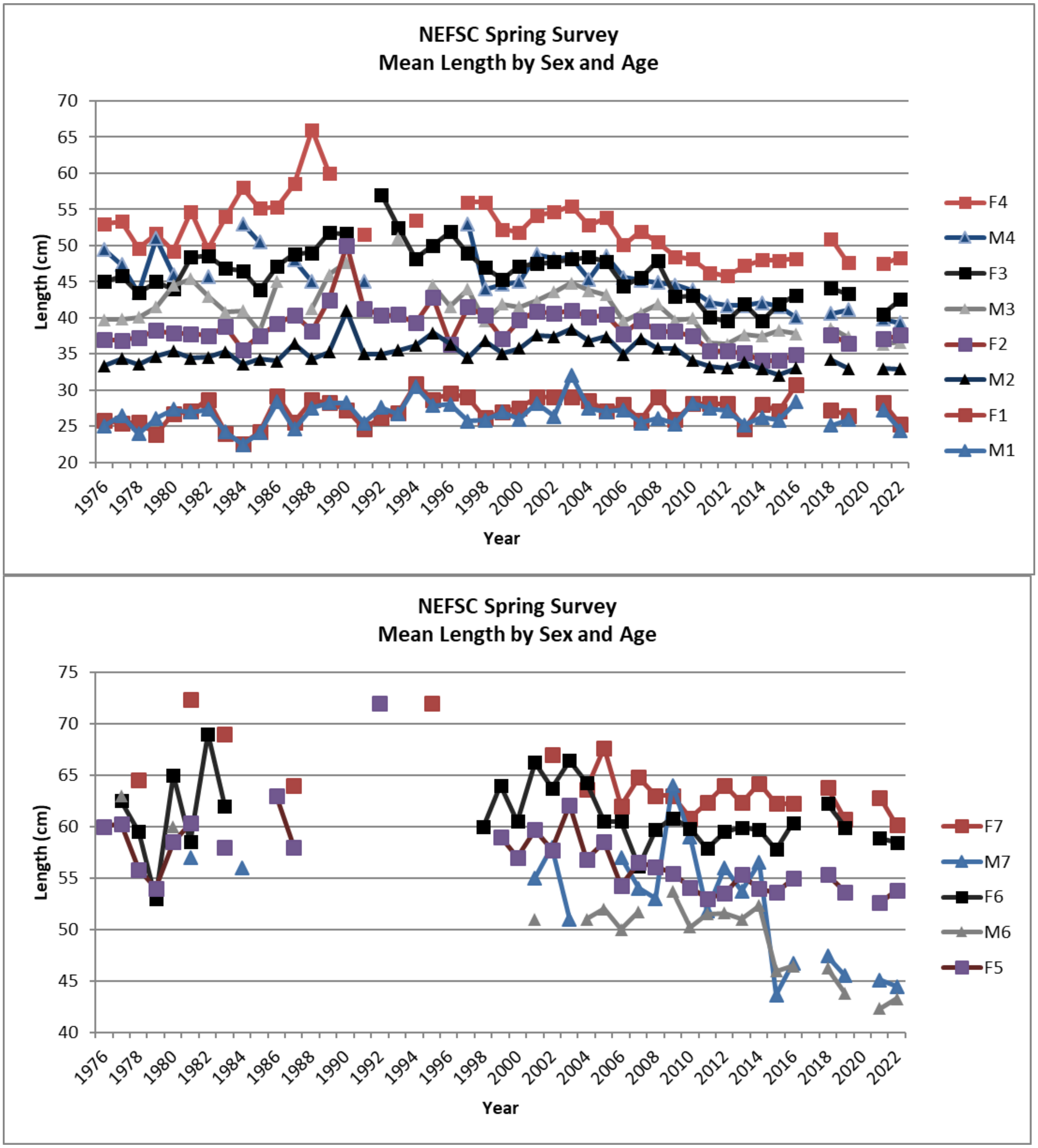
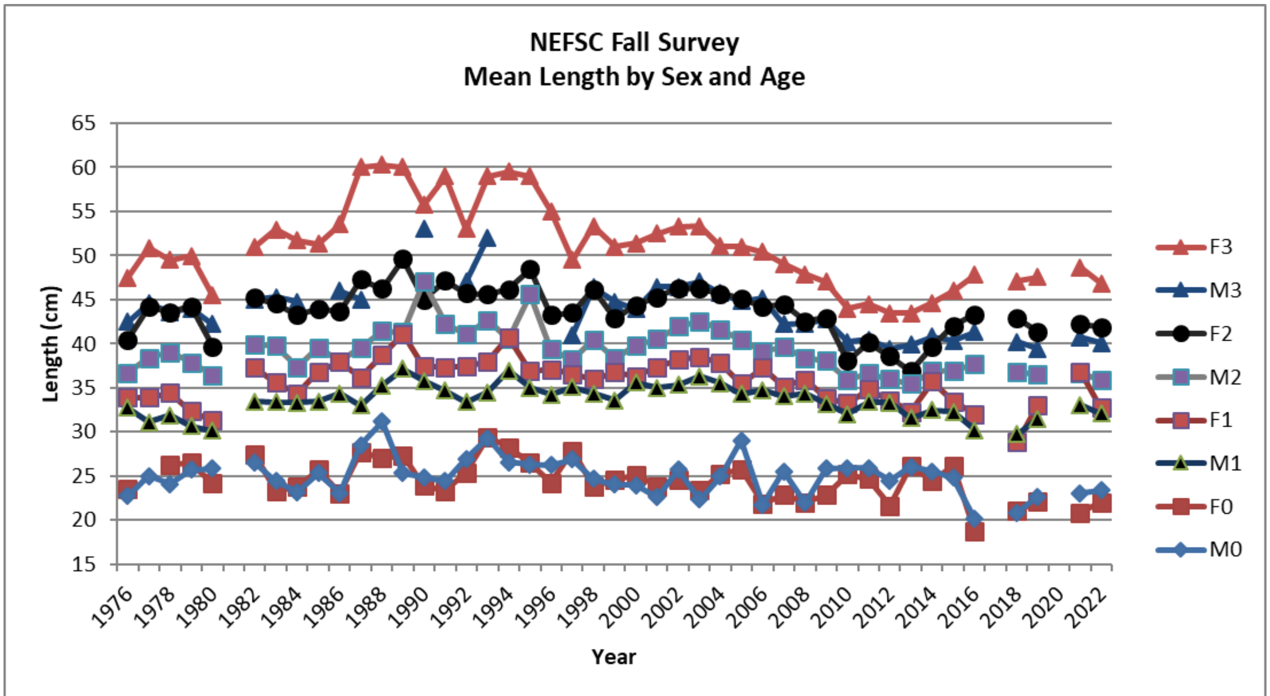


Figure 21. Trend in mean length at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) spring trawl survey: summer flounder (*Paralichthys dentatus*) by sex and age (e.g., M1 = age 1 males, F7 = age 7 females).



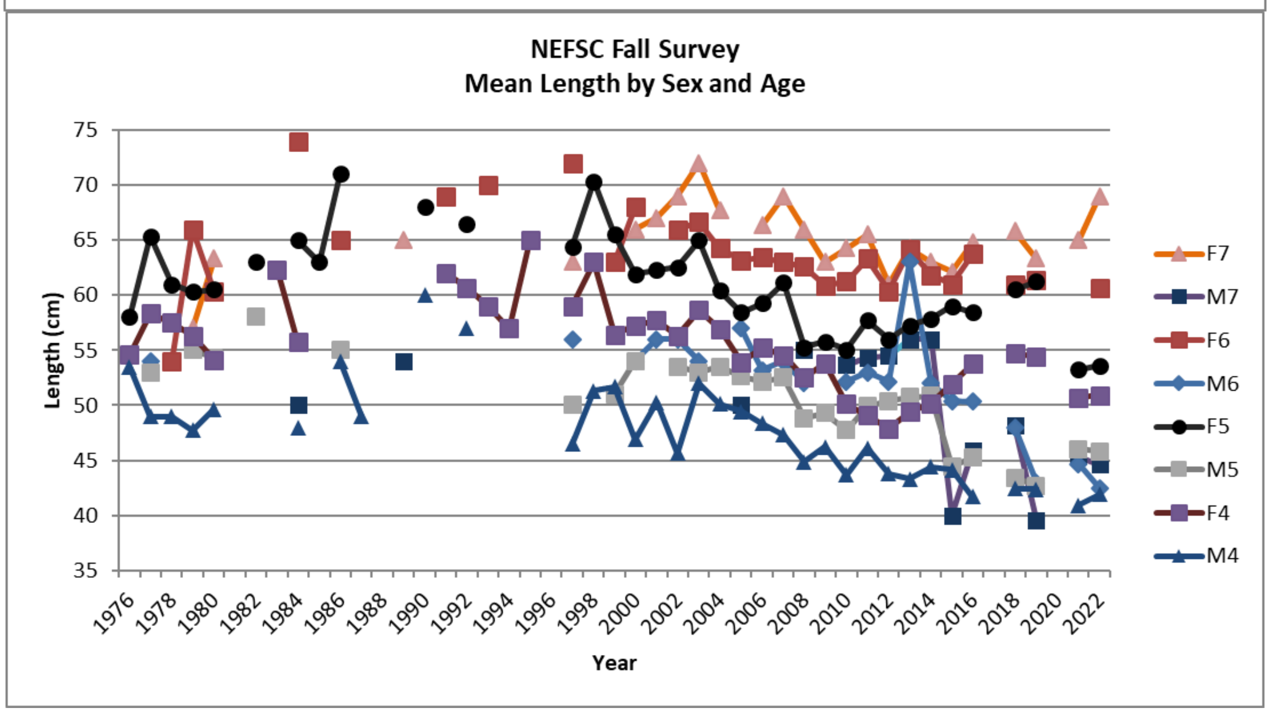


Figure 22. Trend in mean length at age for fish sampled in the Northeast Fisheries Science Center (NEFSC) fall trawl survey: summer flounder (*Paralichthys dentatus*) by sex and age (e.g., M0 = age 0 males, F7 = age 7 females).

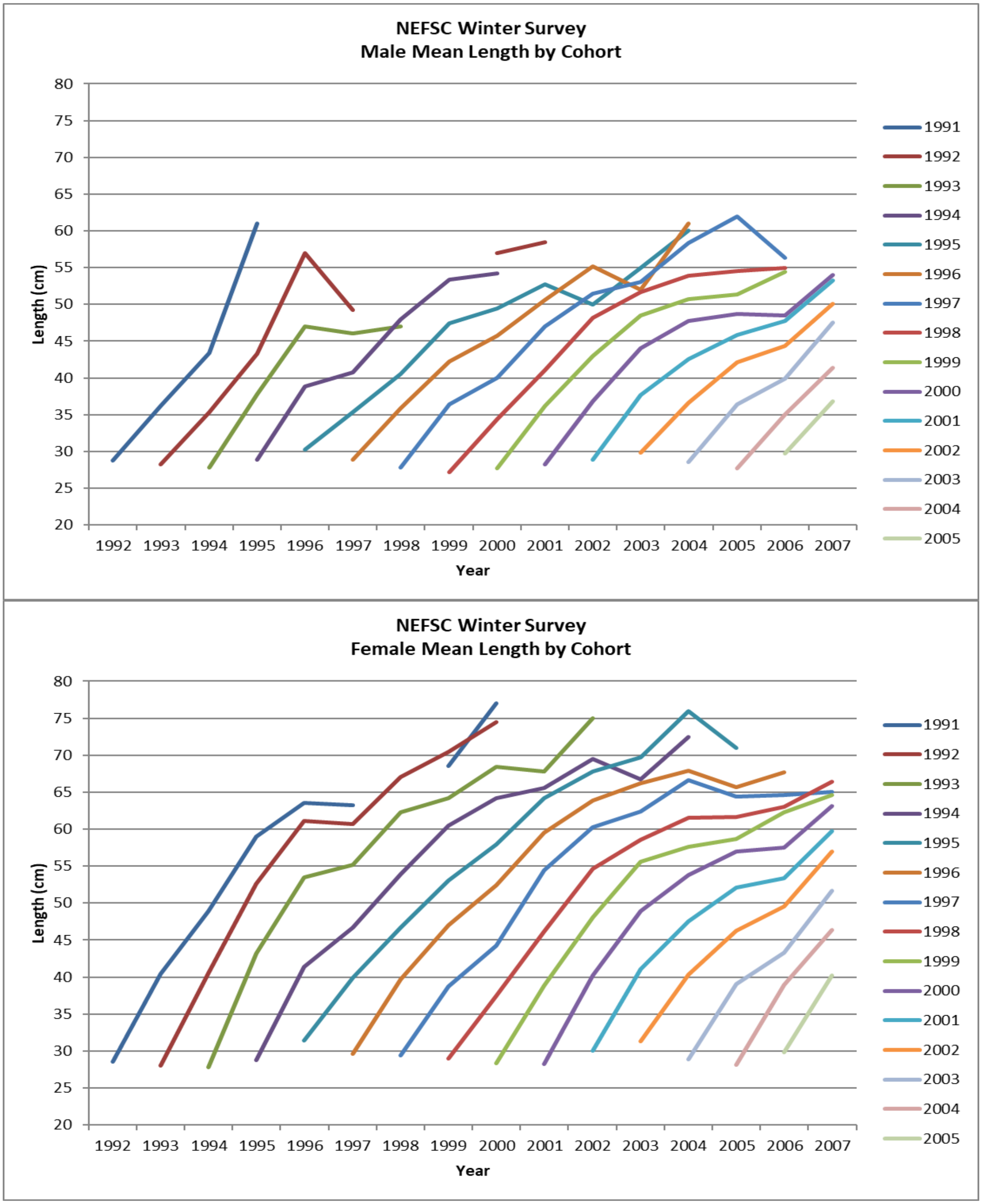


Figure 23. Trend in summer flounder (*Paralichthys dentatus*) mean length by cohort over age by sex in the Northeast Fisheries Science Center (NEFSC) winter trawl survey.

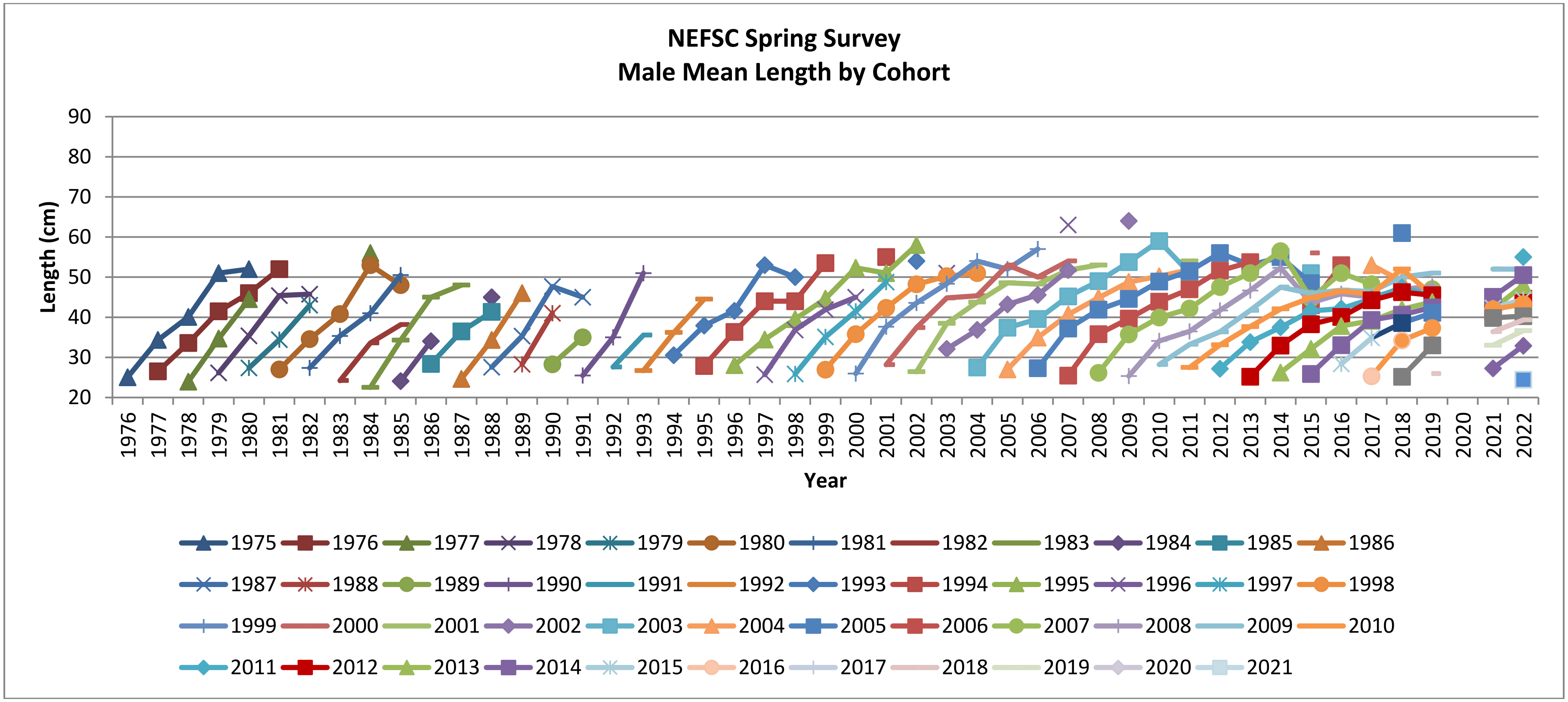


Figure 24. Trend in mean length by cohort over age for male summer flounder (*Paralichthys dentatus*) in the (Northeast Fisheries Science Center (NEFSC) spring trawl survey. No survey in 2020.

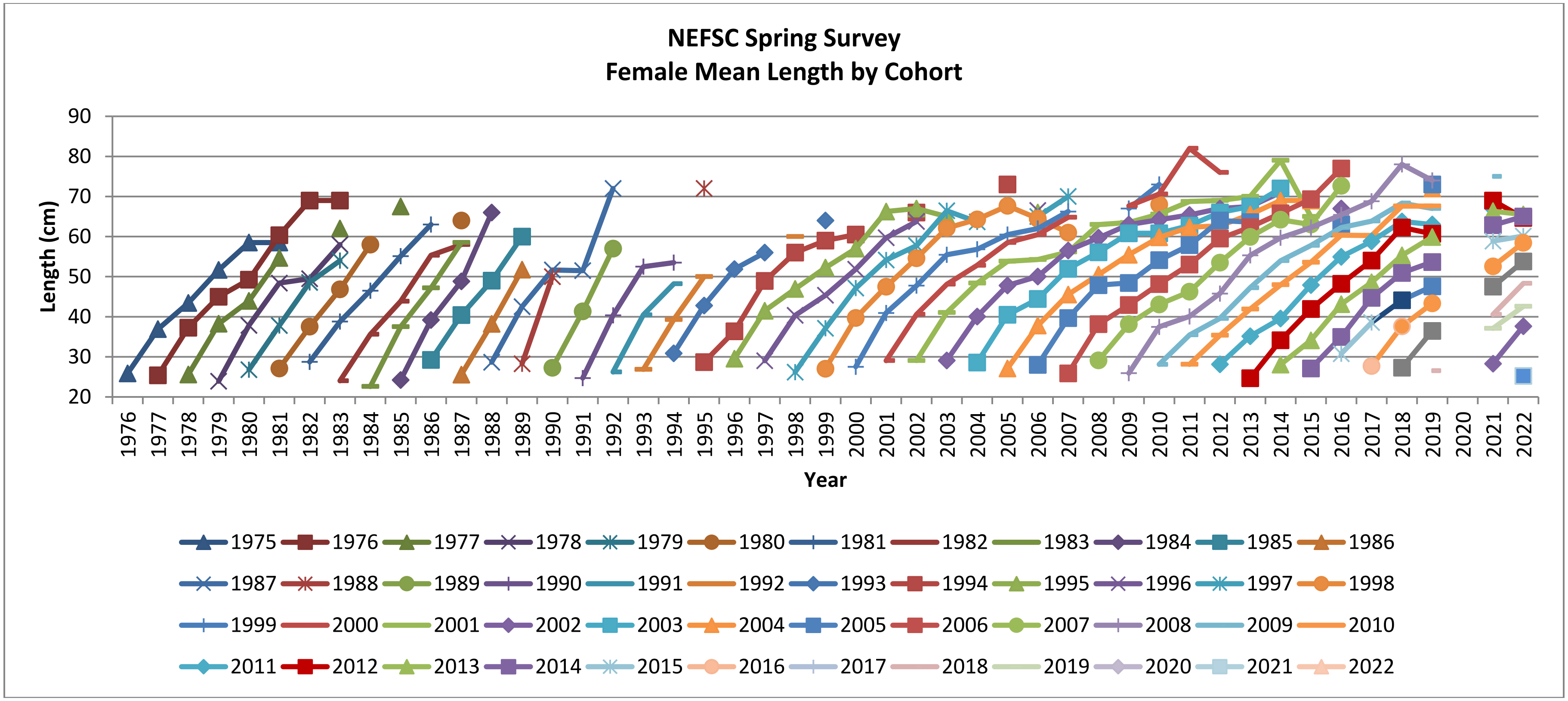


Figure 25. Trend in mean length by cohort over age for female summer flounder (*Paralichthys dentatus*) in the Northeast Fisheries Science Center (NEFSC) spring trawl survey. No survey in 2020.

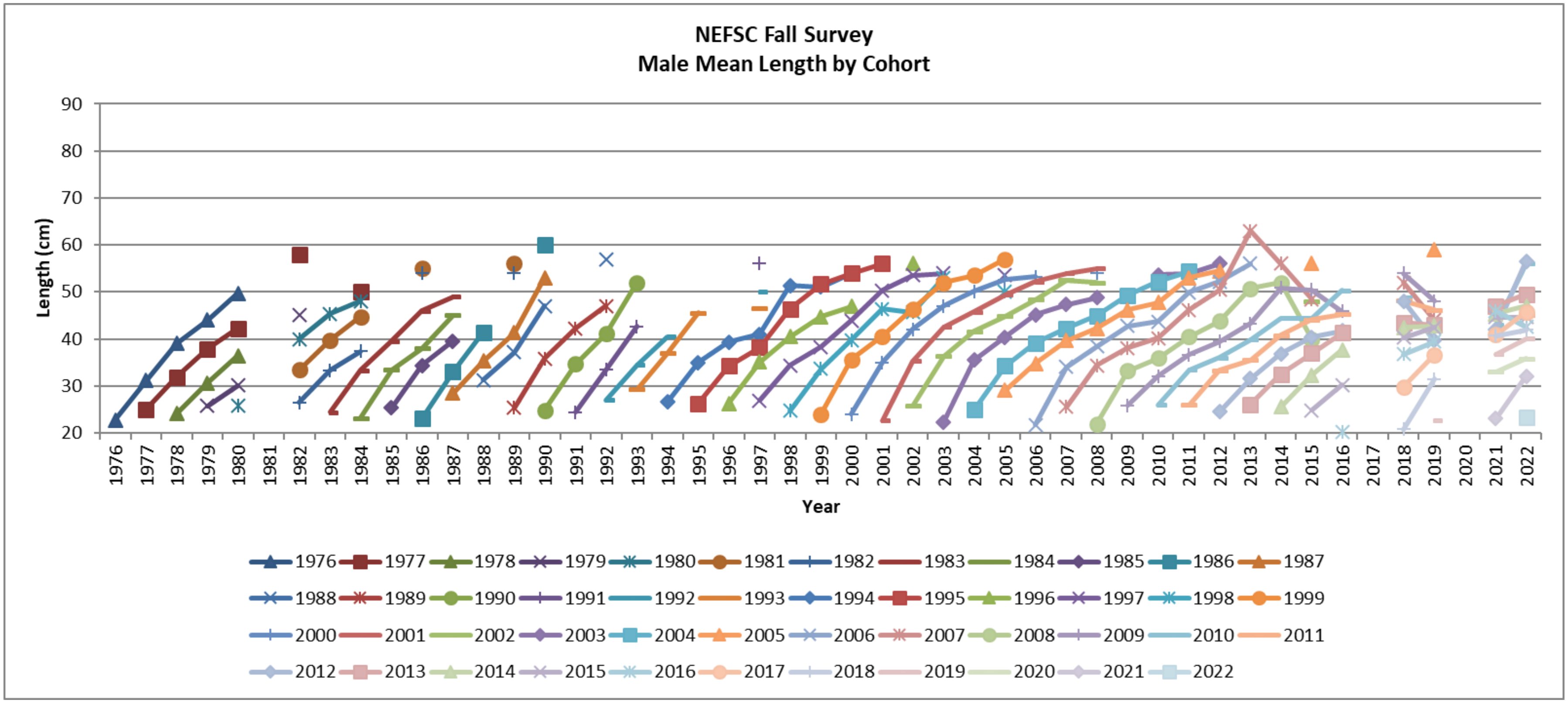


Figure 26. Trend in mean length by cohort over age for male summer flounder (*Paralichthys dentatus*) in the Northeast Fisheries Science Center (NEFSC) fall trawl survey. No survey age data available for 1981. No survey in 2017 and 2020.

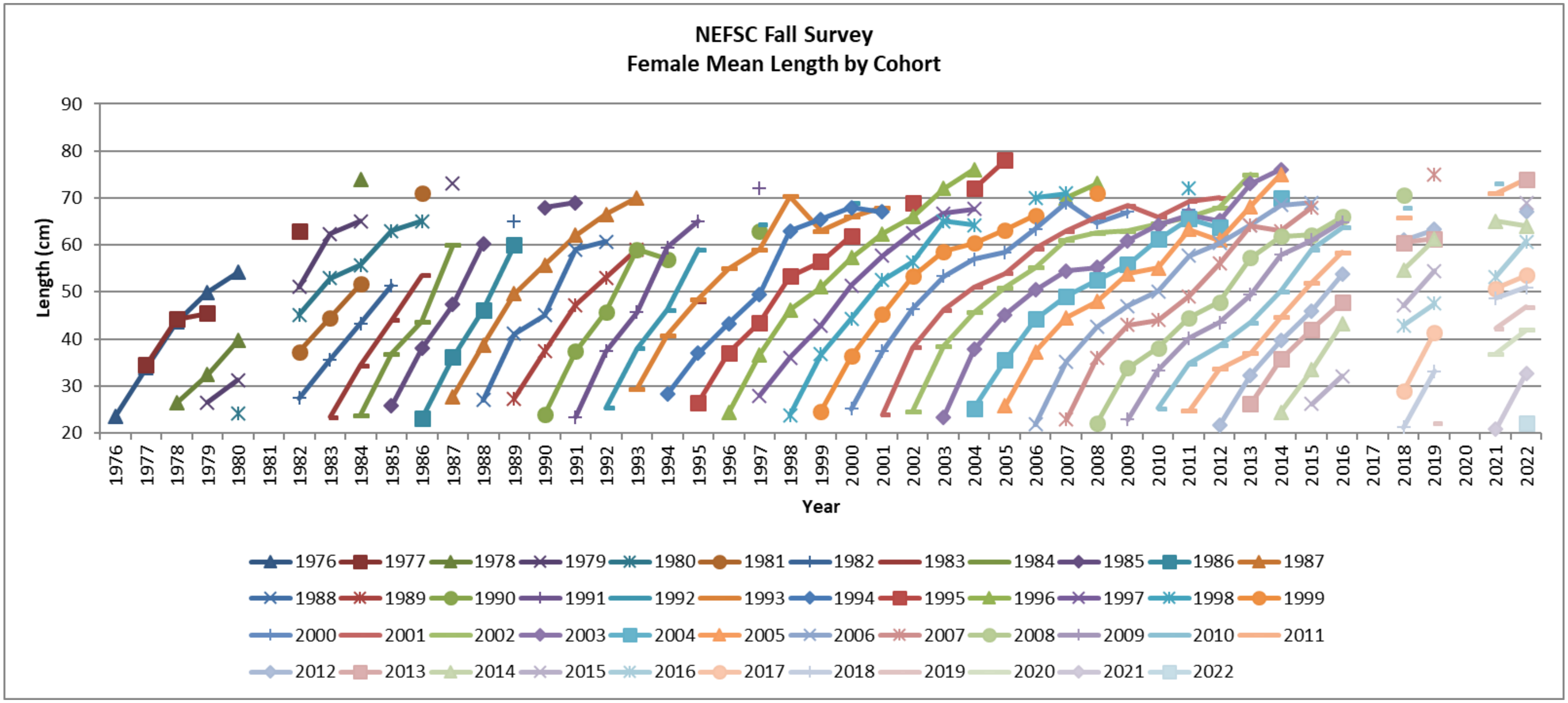


Figure 27. Trend in mean length by cohort over age for female summer flounder (*Paralichthys dentatus*) in the Northeast Fisheries Science Center (NEFSC) fall trawl survey. No survey age data available for 1981. No survey in 2017 and 2020.

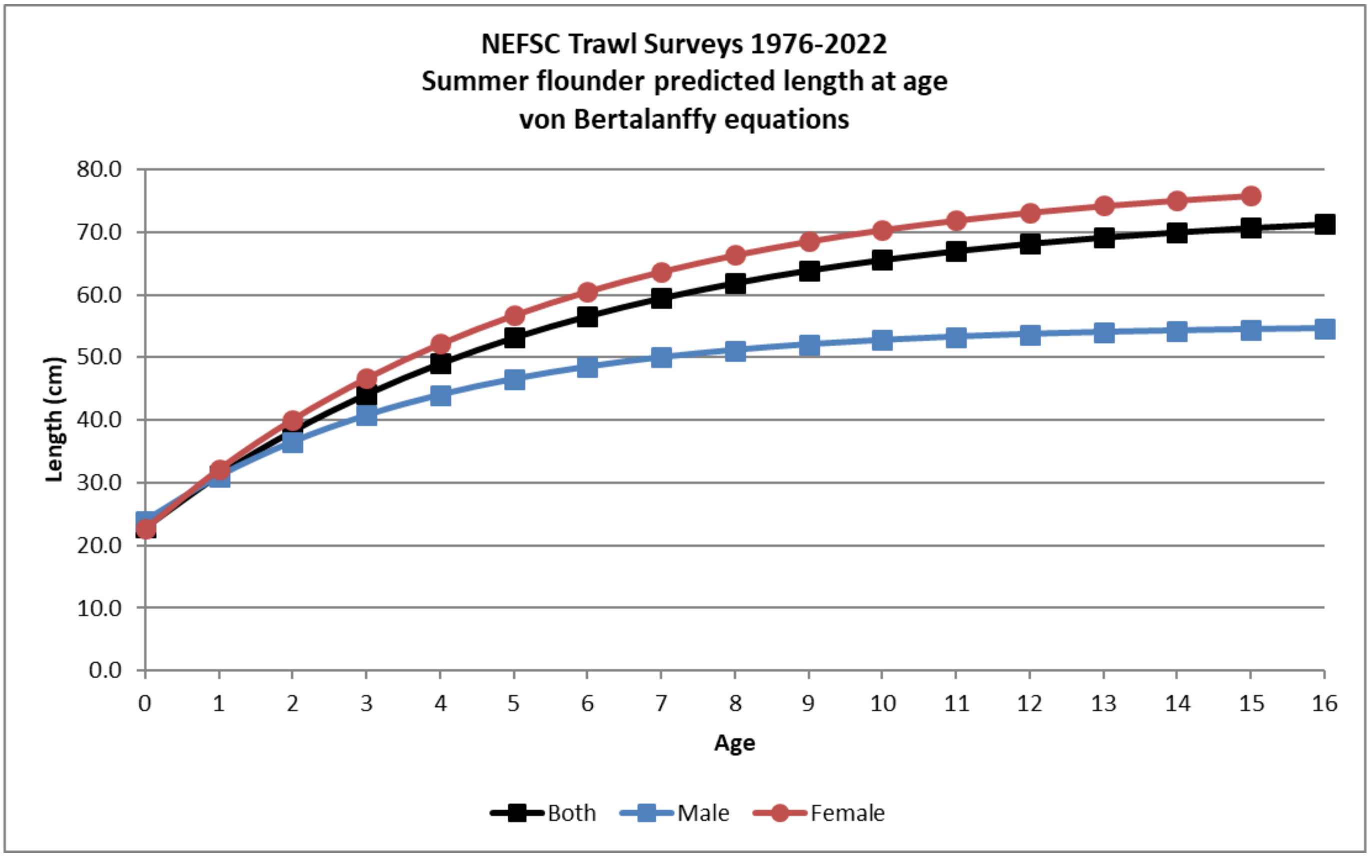
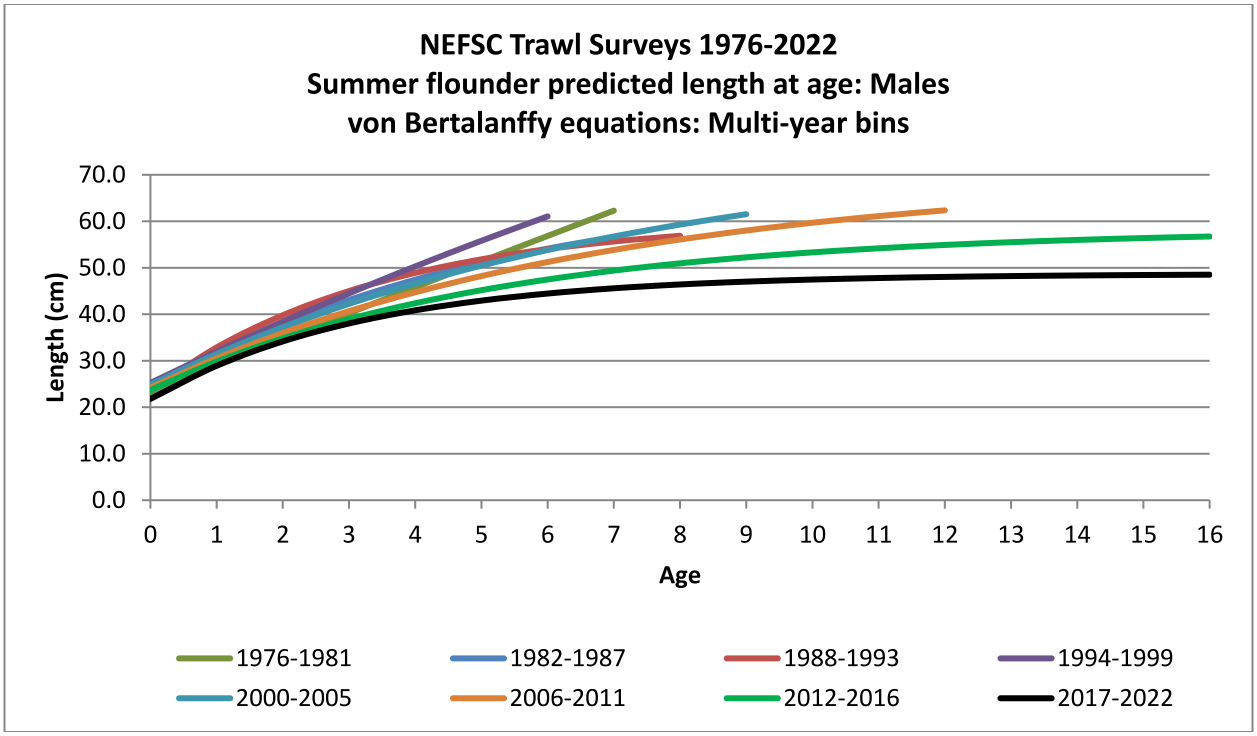


Figure 28. Predicted length at age of summer flounder (*Paralichthys dentatus*) from von Bertalanffy equations parameters estimated from Northeast Fisheries Science Center (NEFSC) trawl survey data for 1976-2022. Maximum observed age for males is age 16 and for females is age 15.



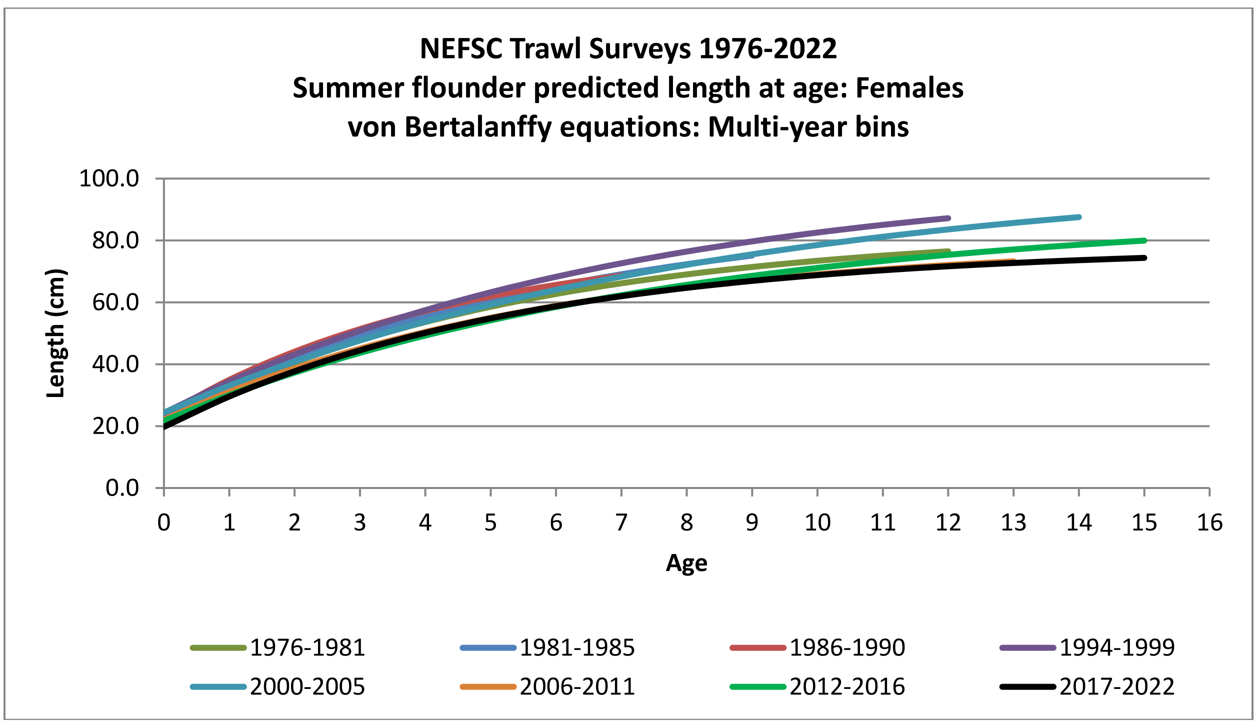


Figure 29. Predicted length at age of summer flounder (*Paralichthys dentatus*) from von Bertalanffy equations parameters estimated from Northeast Fisheries Science Center (NEFSC) trawl survey data for multi-year bins by sex. Curves plotted through the maximum observed ages for each bin and sex.

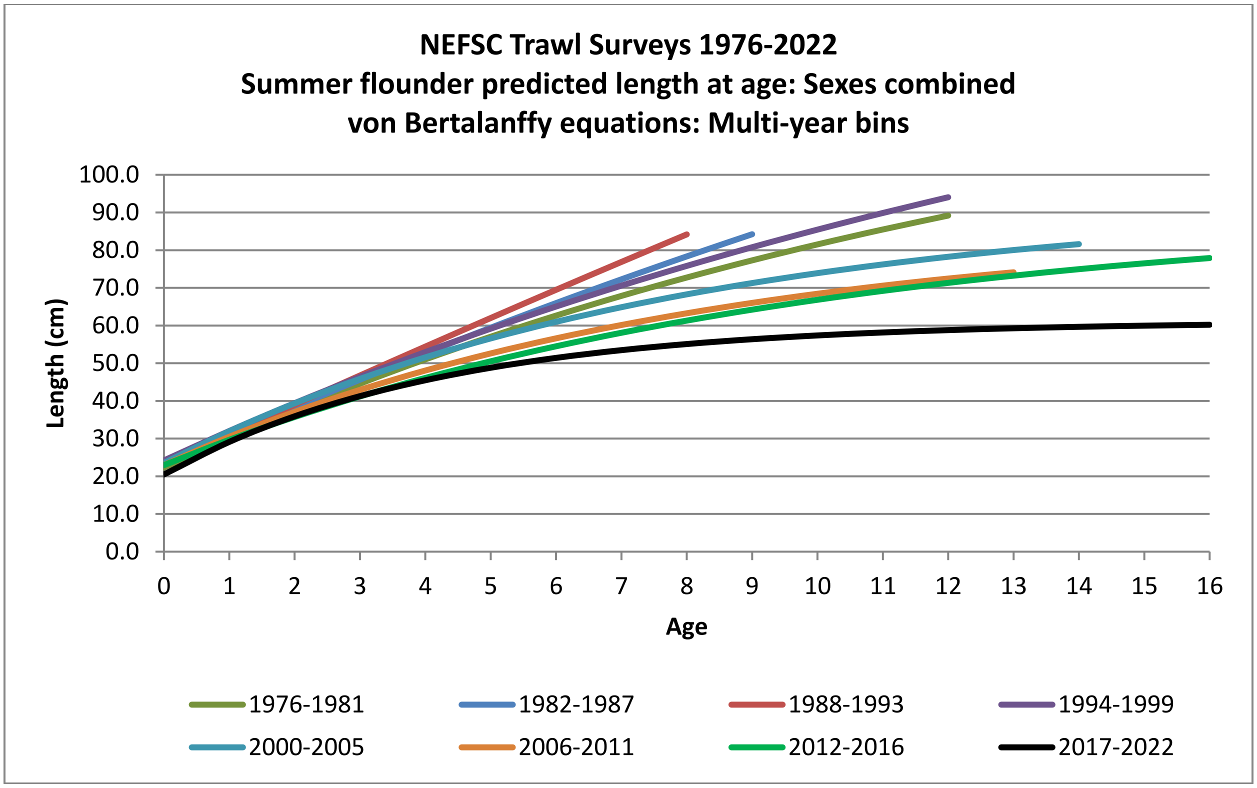


Figure 30. Predicted length at age of summer flounder (*Paralichthys dentatus*) from von Bertalanffy equations parameters estimated from Northeast Fisheries Science Center (NEFSC) trawl survey data for multi-year bins by sexes combined. Curves plotted through the maximum observed ages for each bin.

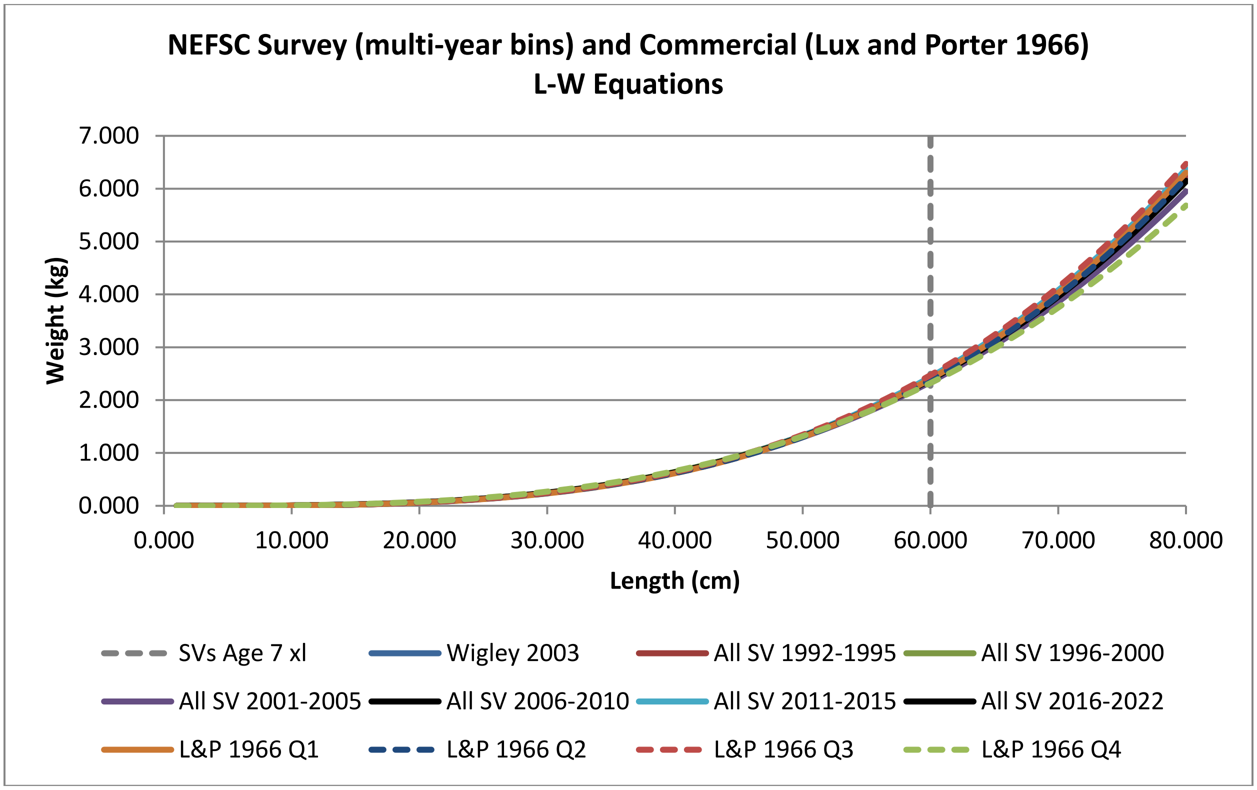


Figure 31. Summer flounder (*Paralichthys dentatus*) length-weight relationships from the works of Lux and Porter (1966; L&P), Wigley et al. (2003; Wigley), and the current work (all surveys combined multi-year bins). Vertical gray line is the mean length of age 7 in Northeast Fisheries Science Center (NEFSC) surveys.

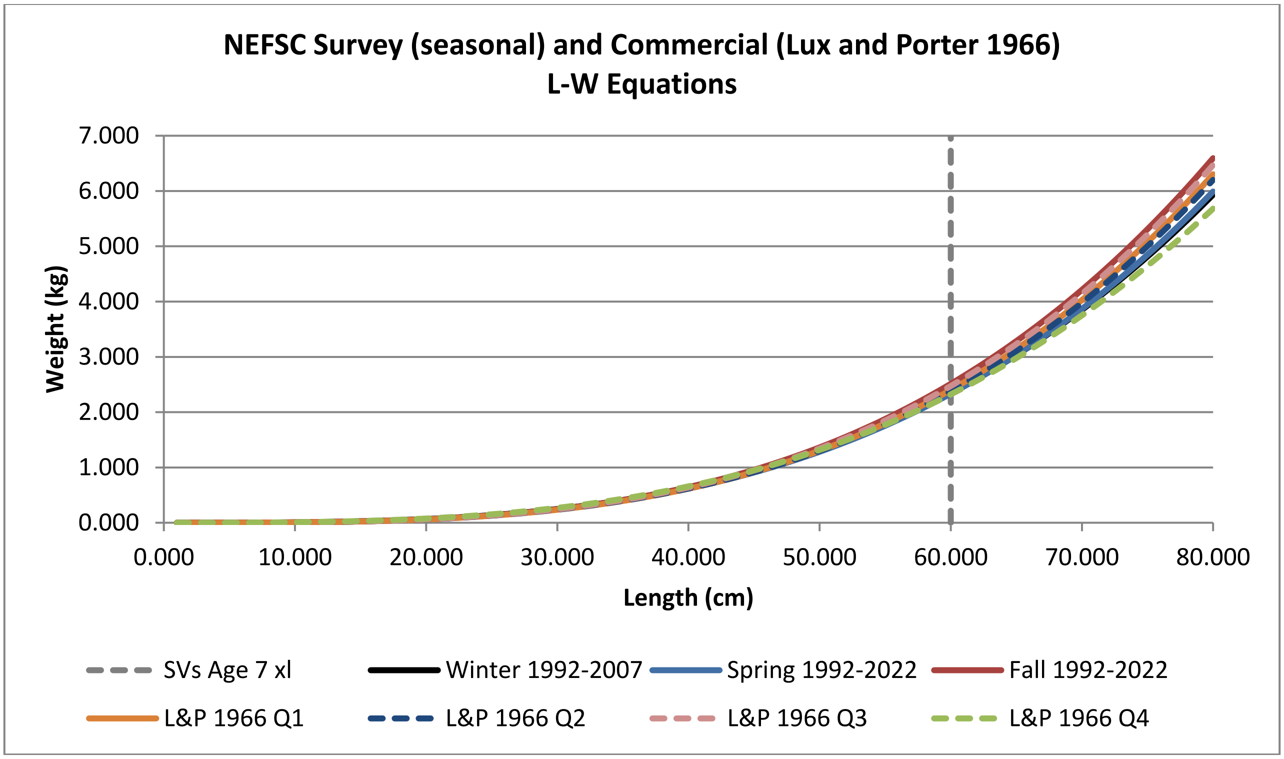


Figure 32. Summer flounder (*Paralichthys dentatus*) length-weight relationships from the works of Lux and Porter (1966; L&P) and the current work (seasonal surveys: winter 1992-2007, spring 1992-2022, fall 1992-2022). Vertical gray line is the mean length of age 7 in Northeast Fisheries Science Center (NEFSC) surveys.

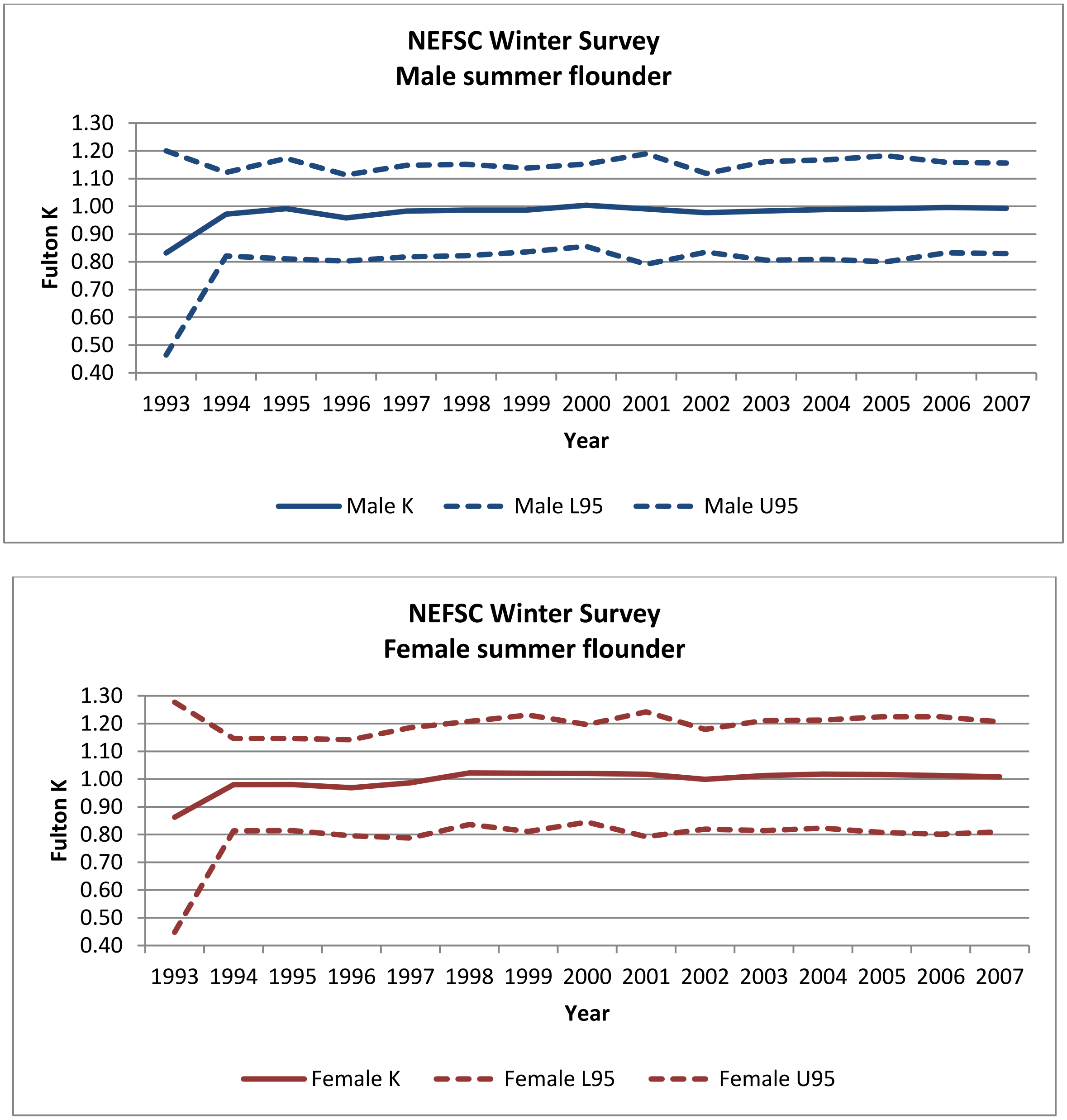
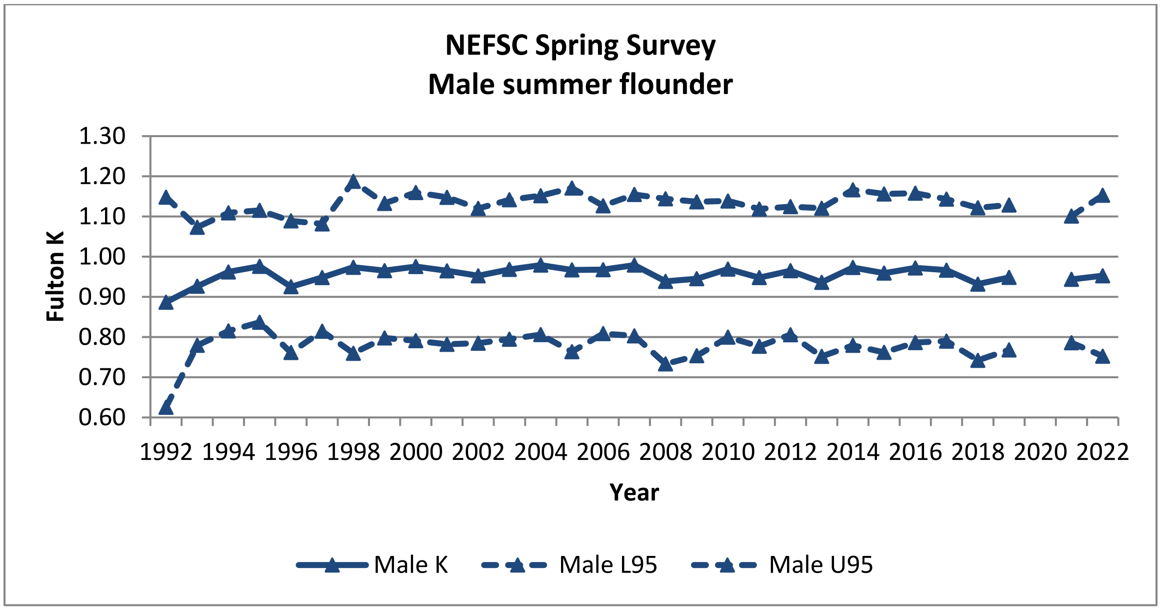


Figure 33. Seasonal condition factor (Fulton K with lower (L95) and upper (U95) confidence intervals) of summer flounder (*Paralichthys dentatus*): Northeast Fisheries Science Center (NEFSC) winter survey by sex.



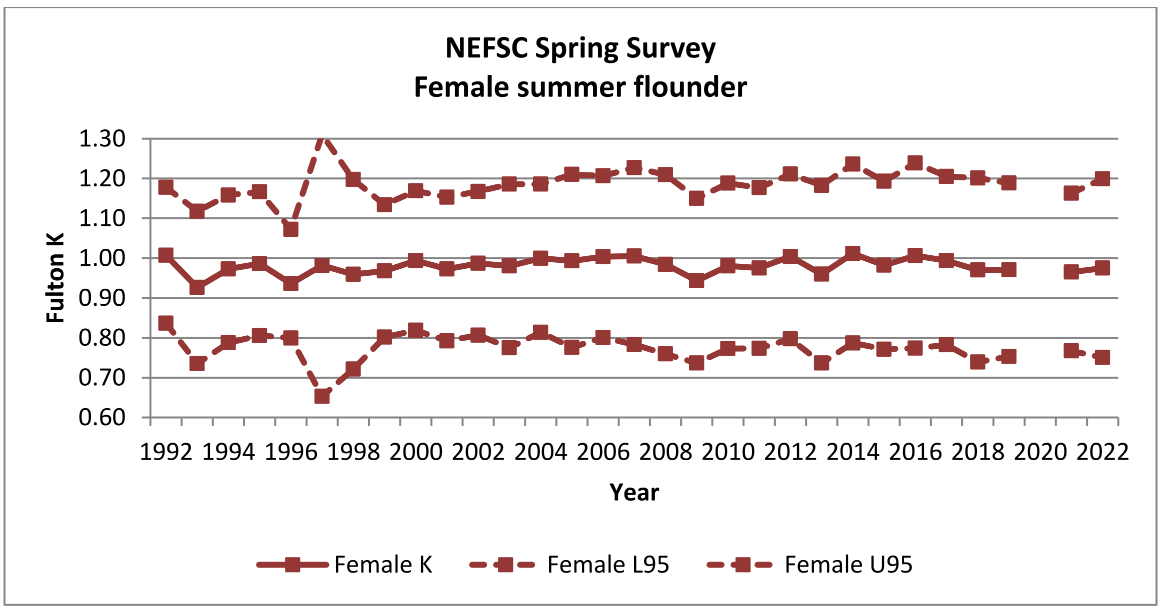
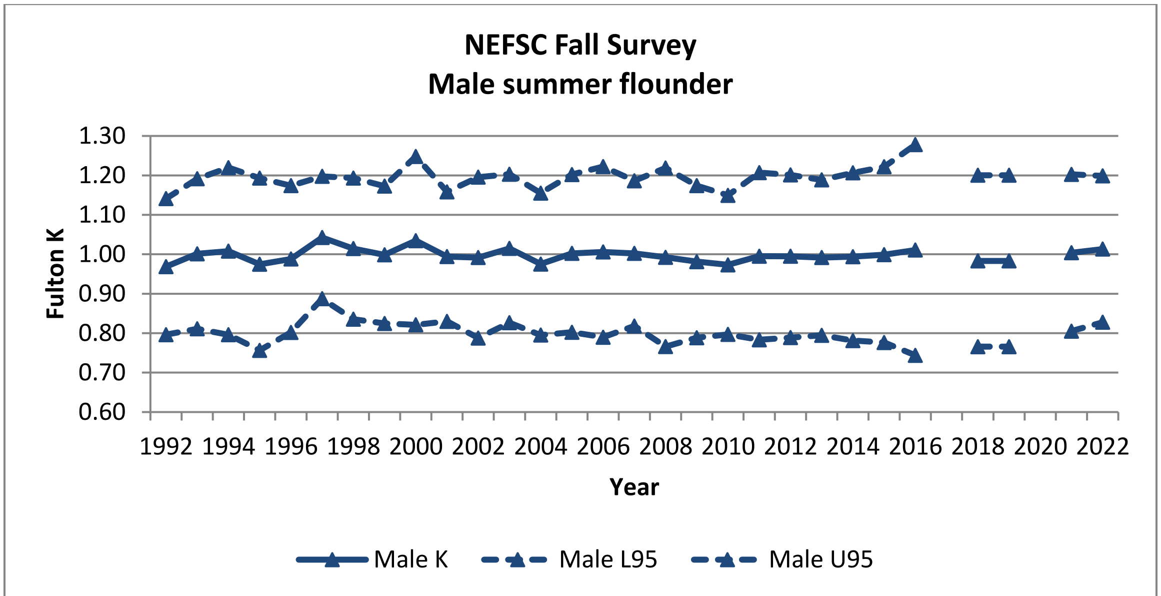


Figure 34. Seasonal condition factor (Fulton K with lower (L95) and upper (U95) confidence intervals) of summer flounder (*Paralichthys dentatus*): Northeast Fisheries Science Center (NEFSC) spring survey by sex. No survey in 2020.



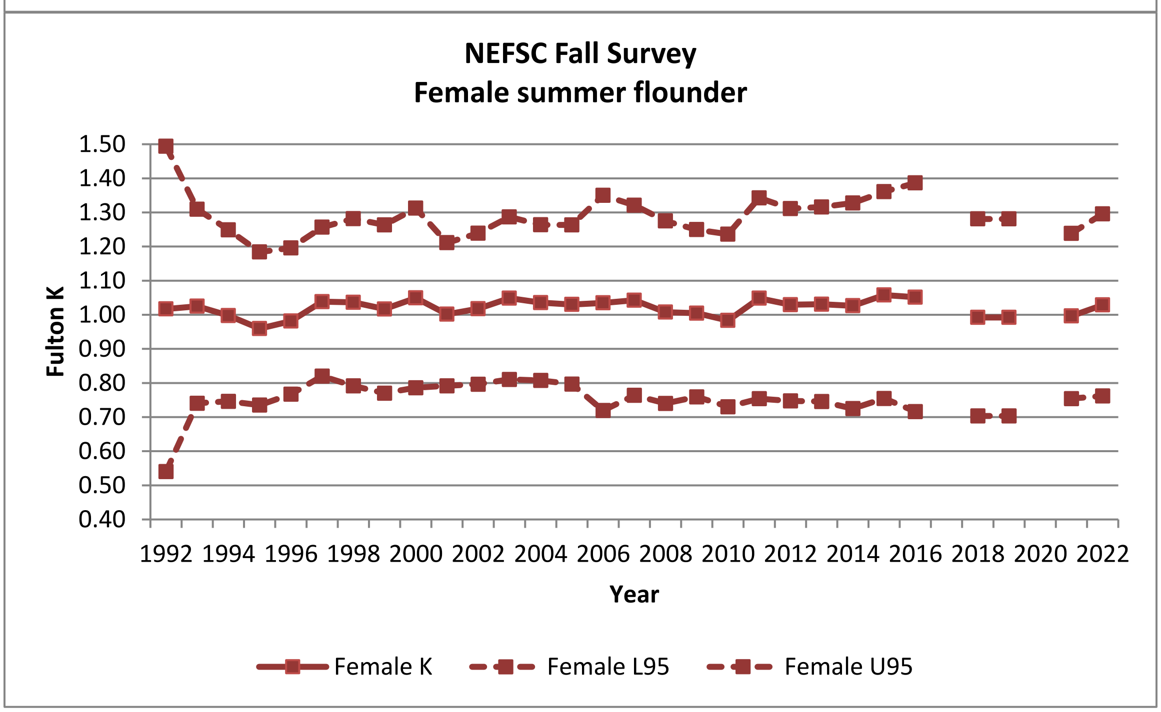
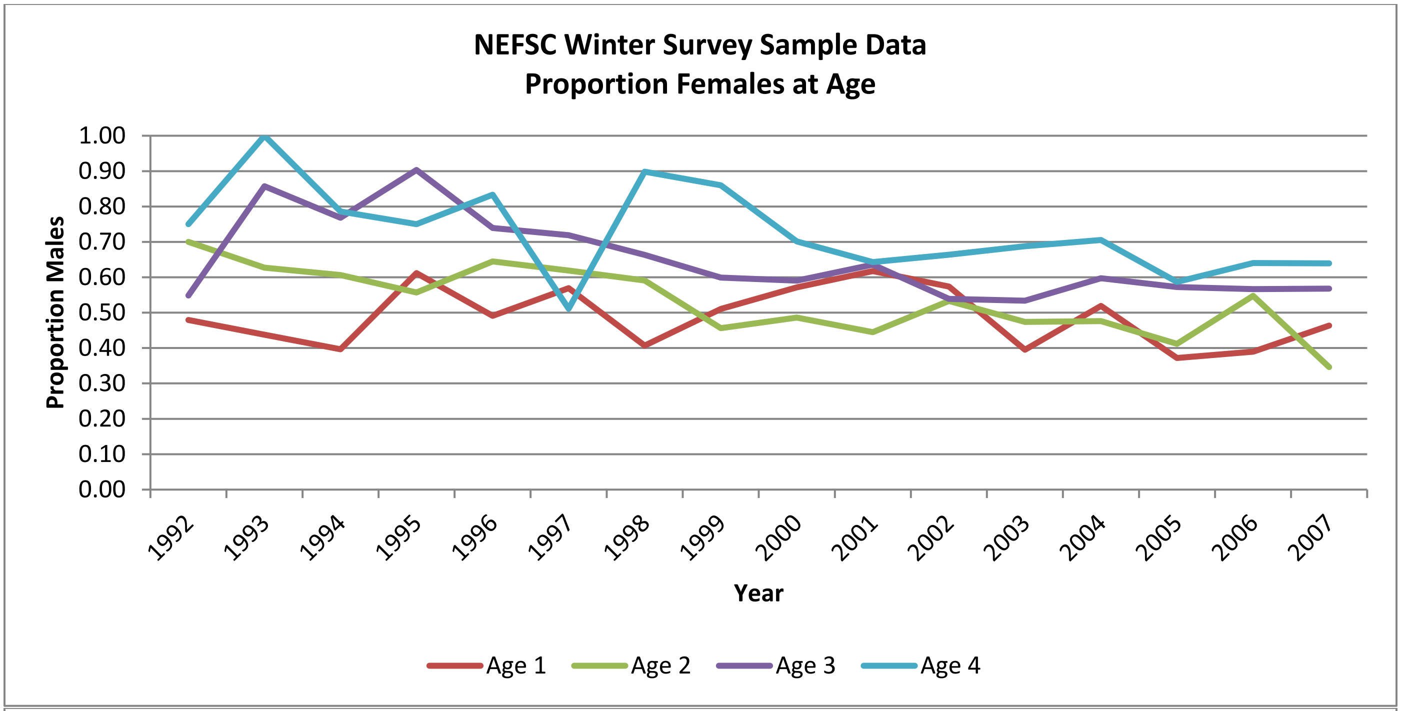


Figure 35. Seasonal condition factor (Fulton K with lower (L95) and upper (U95) confidence intervals) of summer flounder (*Paralichthys dentatus*): Northeast Fisheries Science Center (NEFSC) fall survey by sex. No surveys in 2017 and 2020.



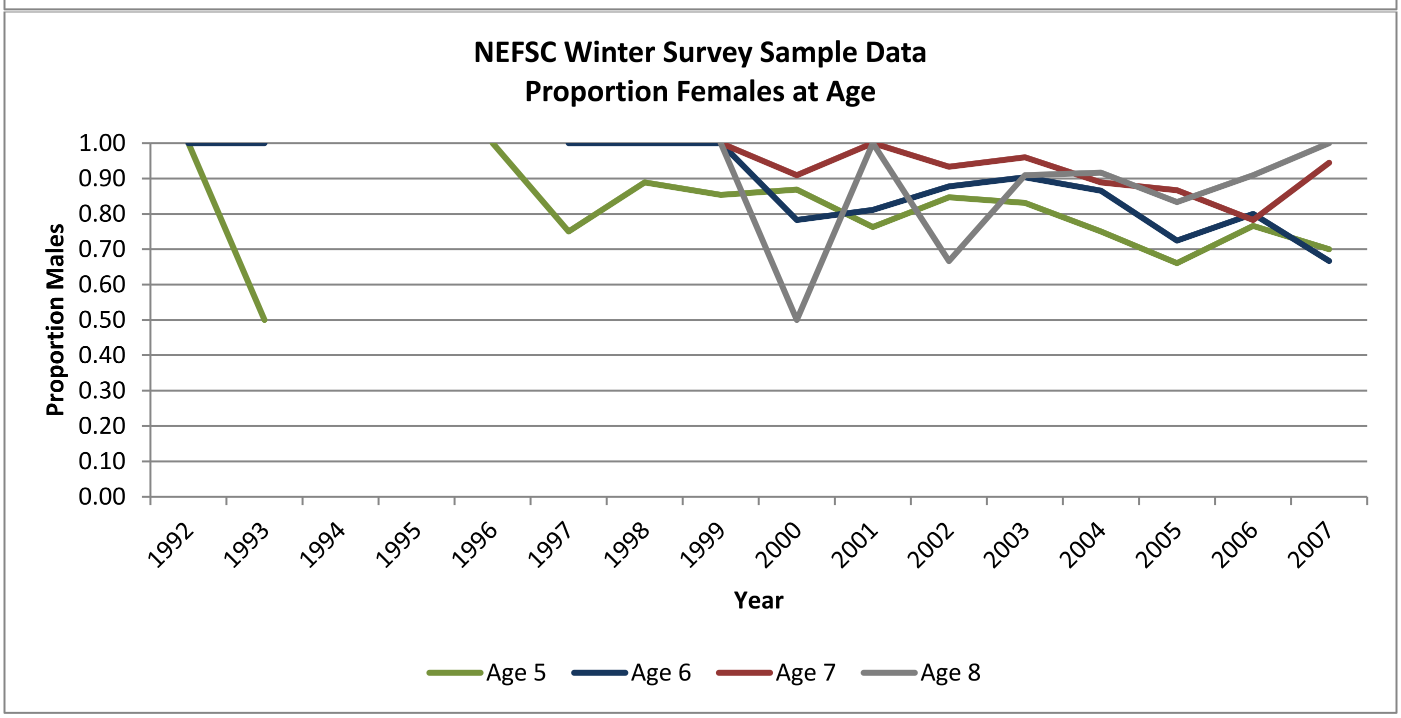
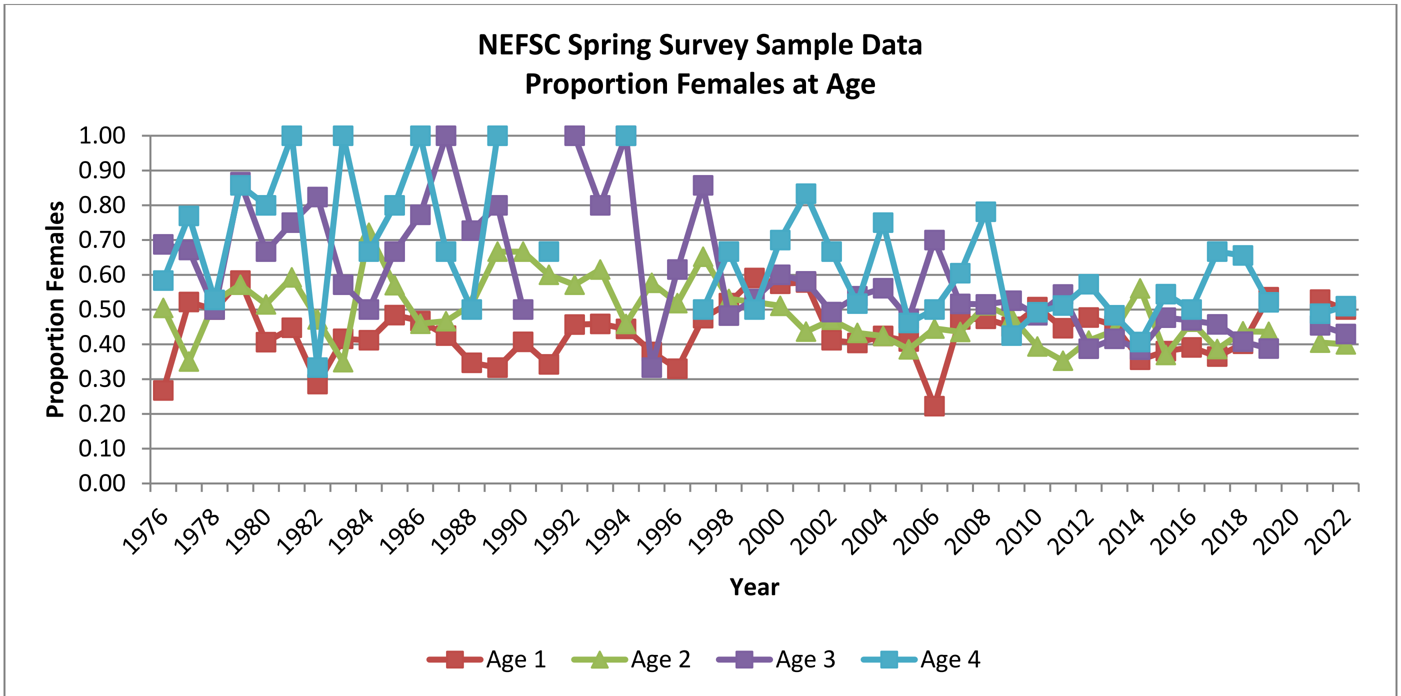


Figure 36. Northeast Fisheries Science Center (NEFSC) winter survey sample data: summer flounder (*Paralichthys dentatus*) proportion female at age.



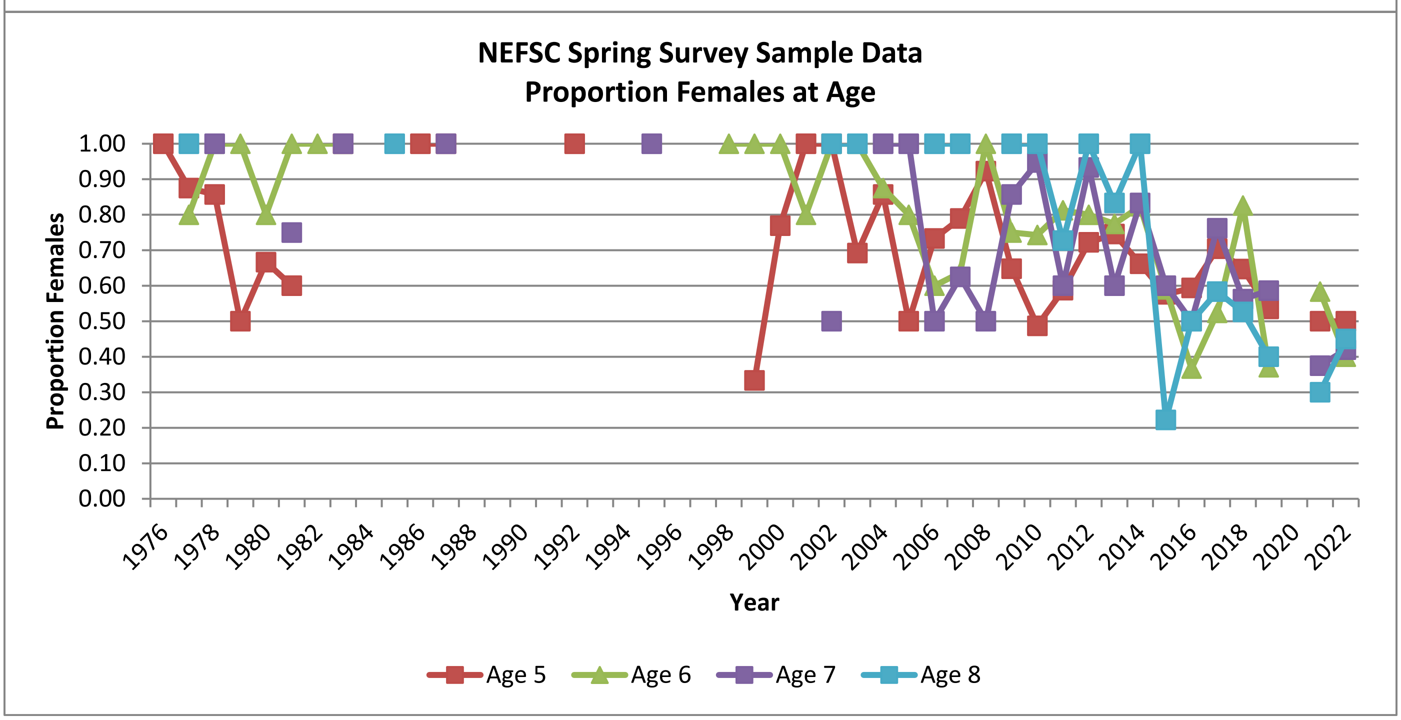
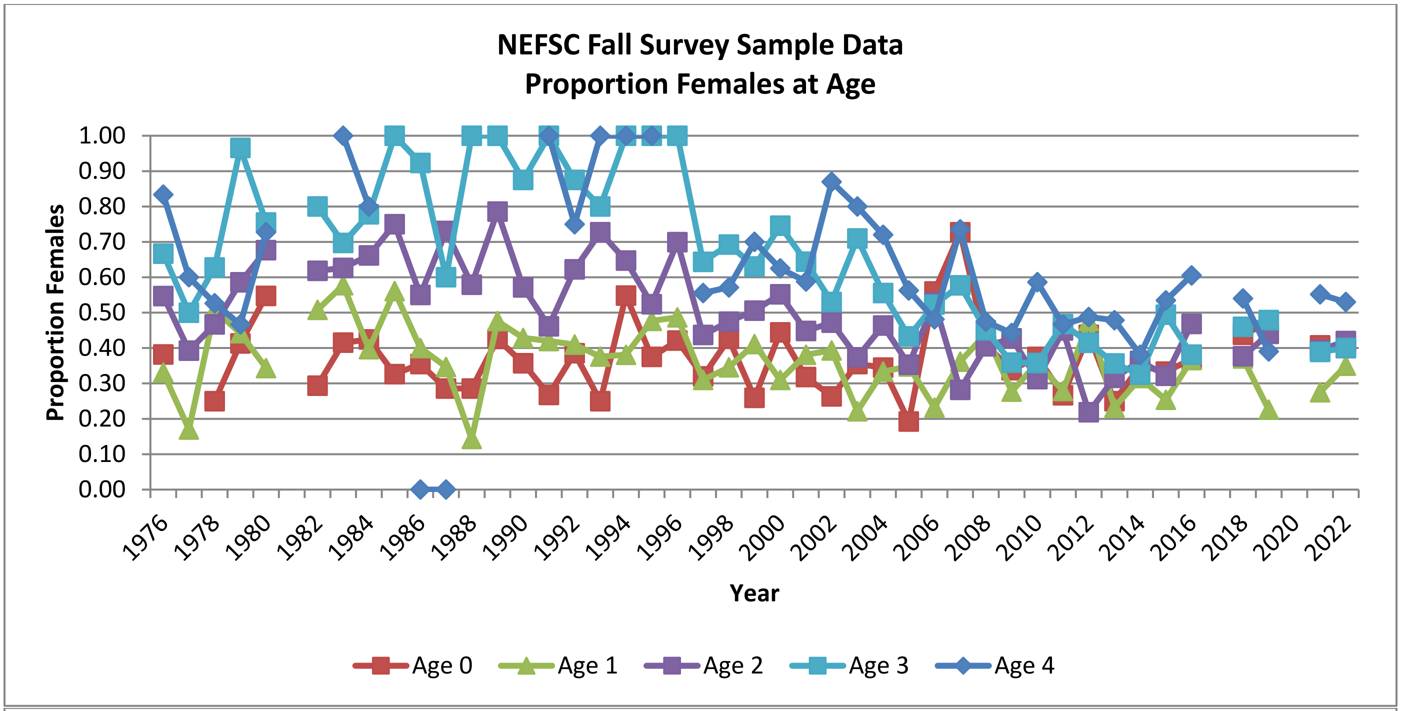


Figure 37. Northeast Fisheries Science Center (NEFSC) spring survey sample data: summer flounder (*Paralichthys dentatus*) proportion female at age. No survey in 2020.



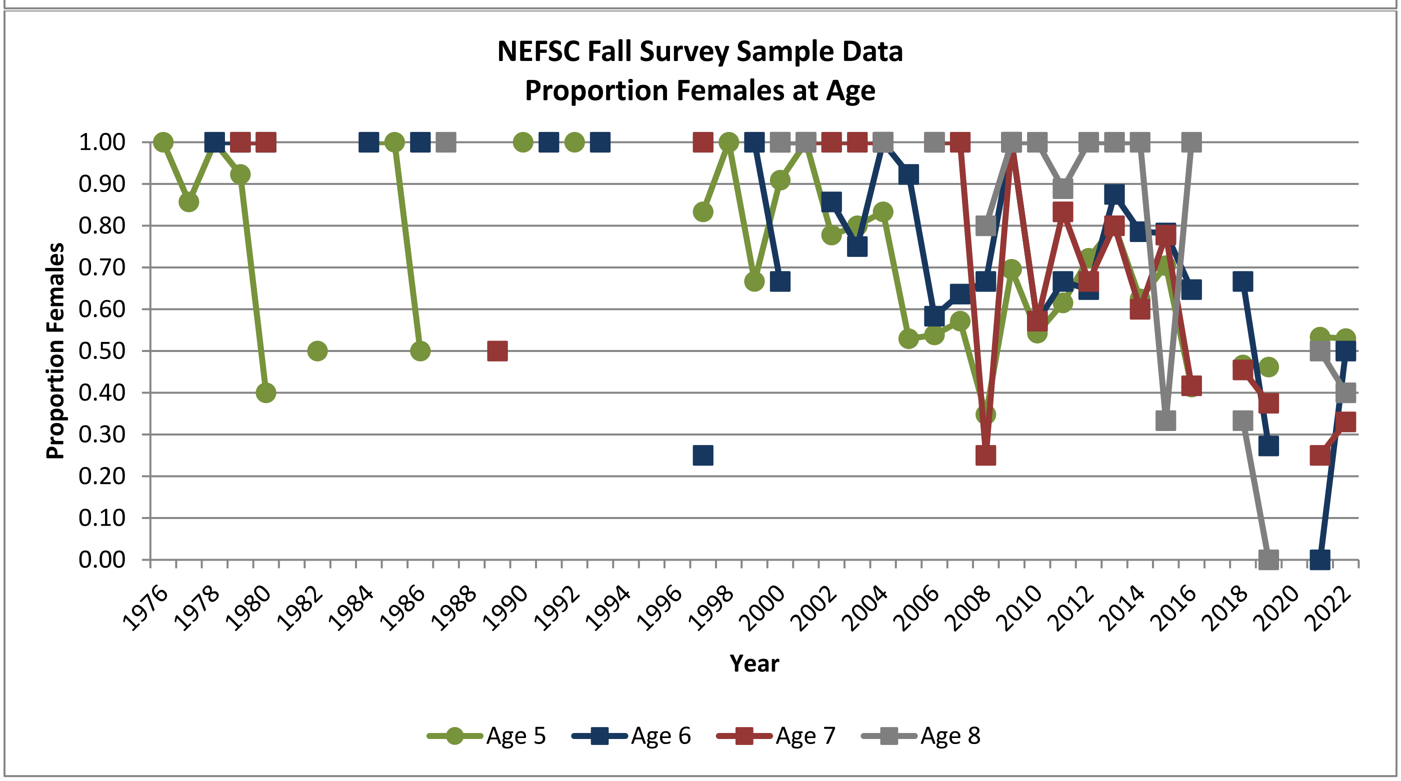


Figure 38. Northeast Fisheries Science Center (NEFSC) fall survey sample data: summer flounder (*Paralichthys dentatus*) proportion female at age. No surveys in 2017 and 2020.

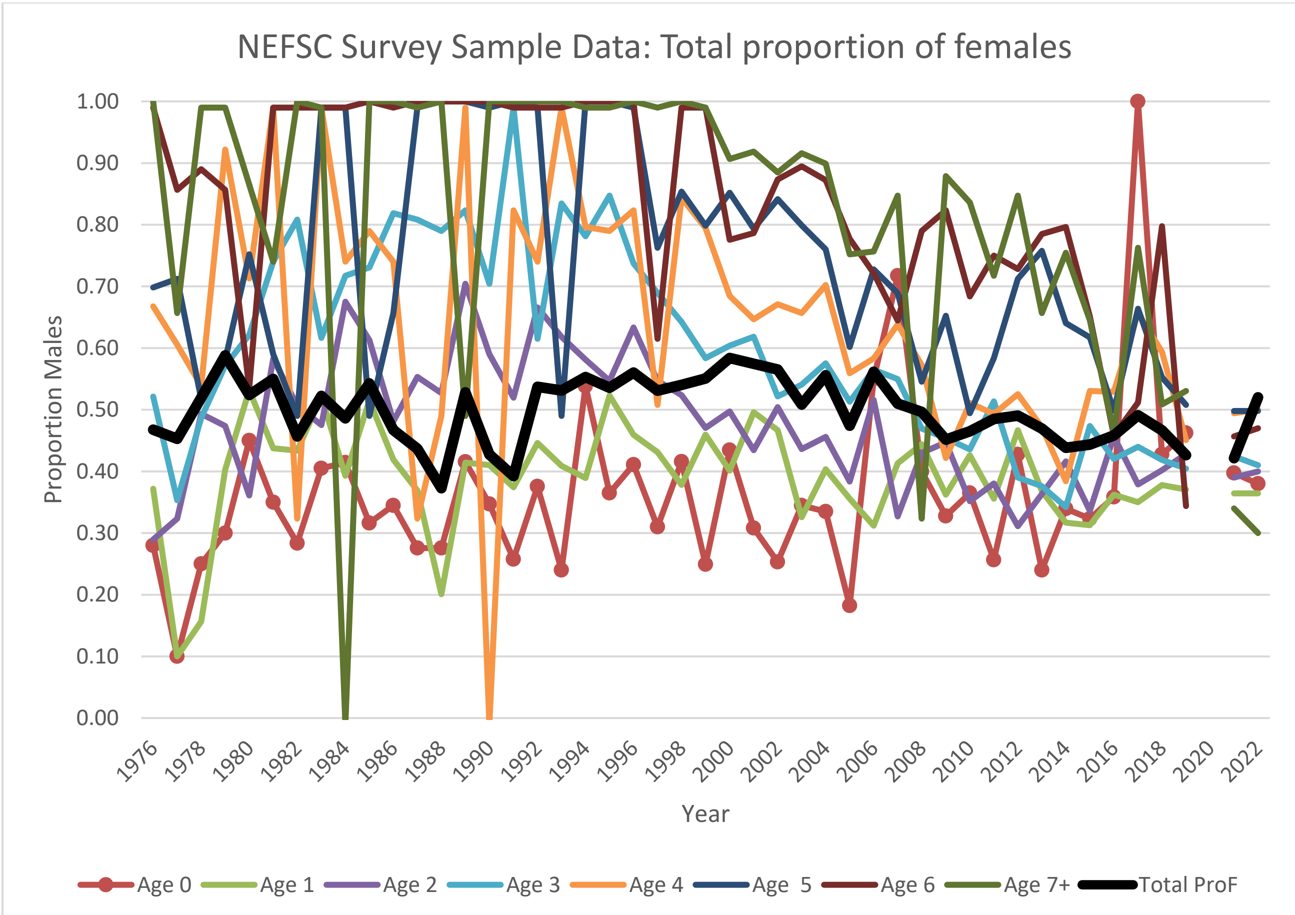
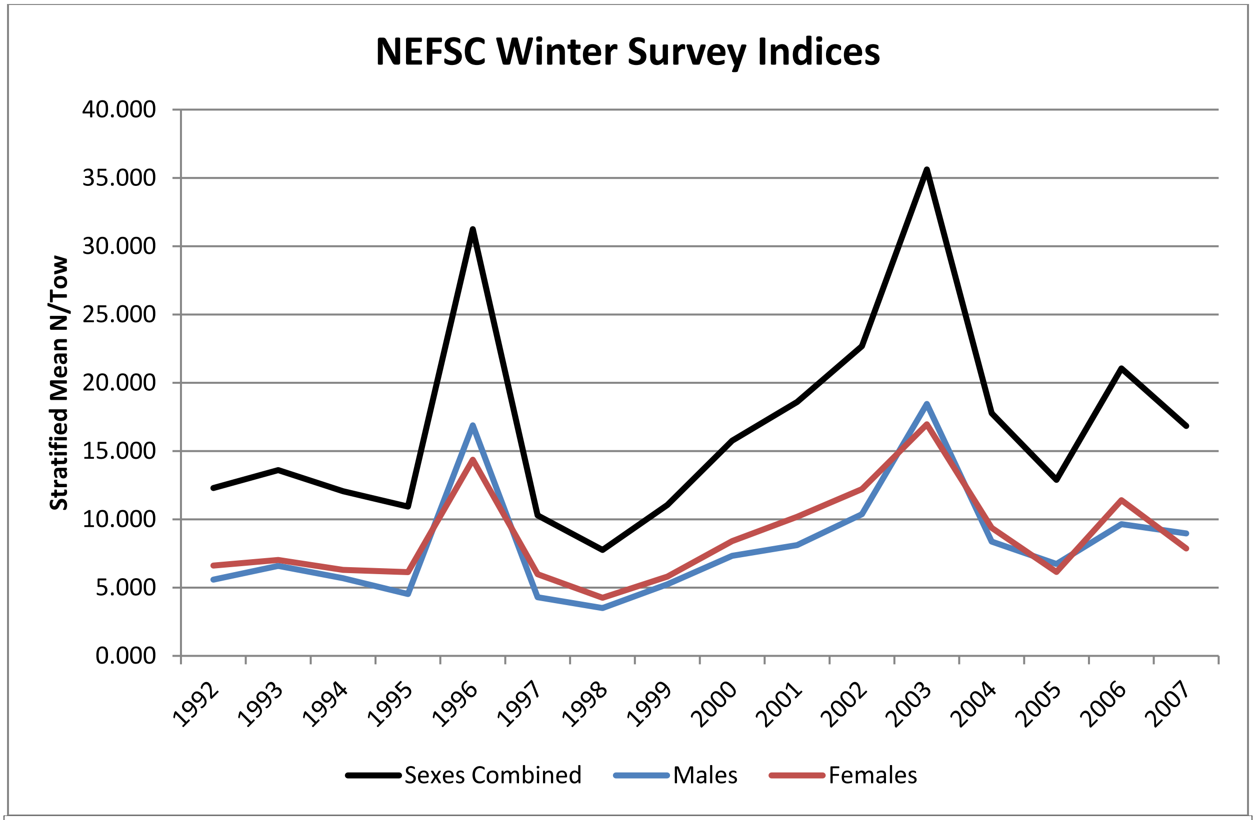


Figure 39. Northeast Fisheries Science Center (NEFSC) trawl surveys all sample data: summer flounder (*Paralichthys dentatus*) proportion female at age. No surveys in 2020.



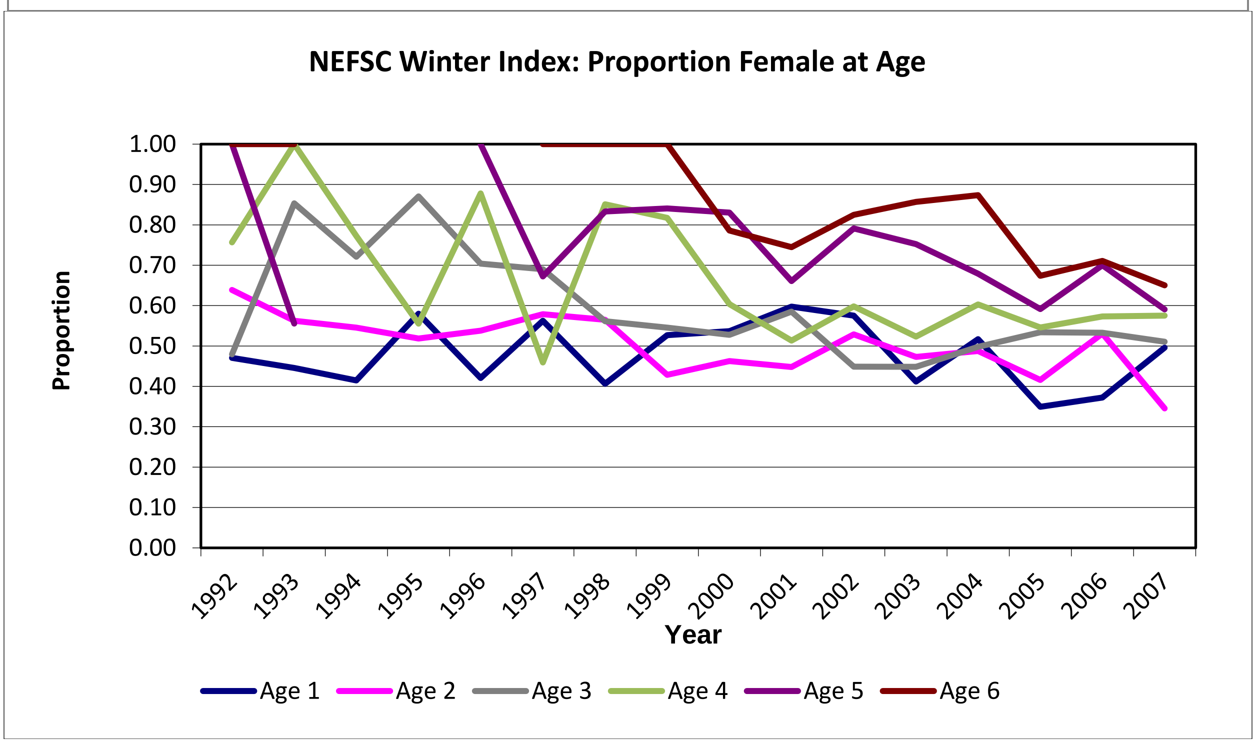
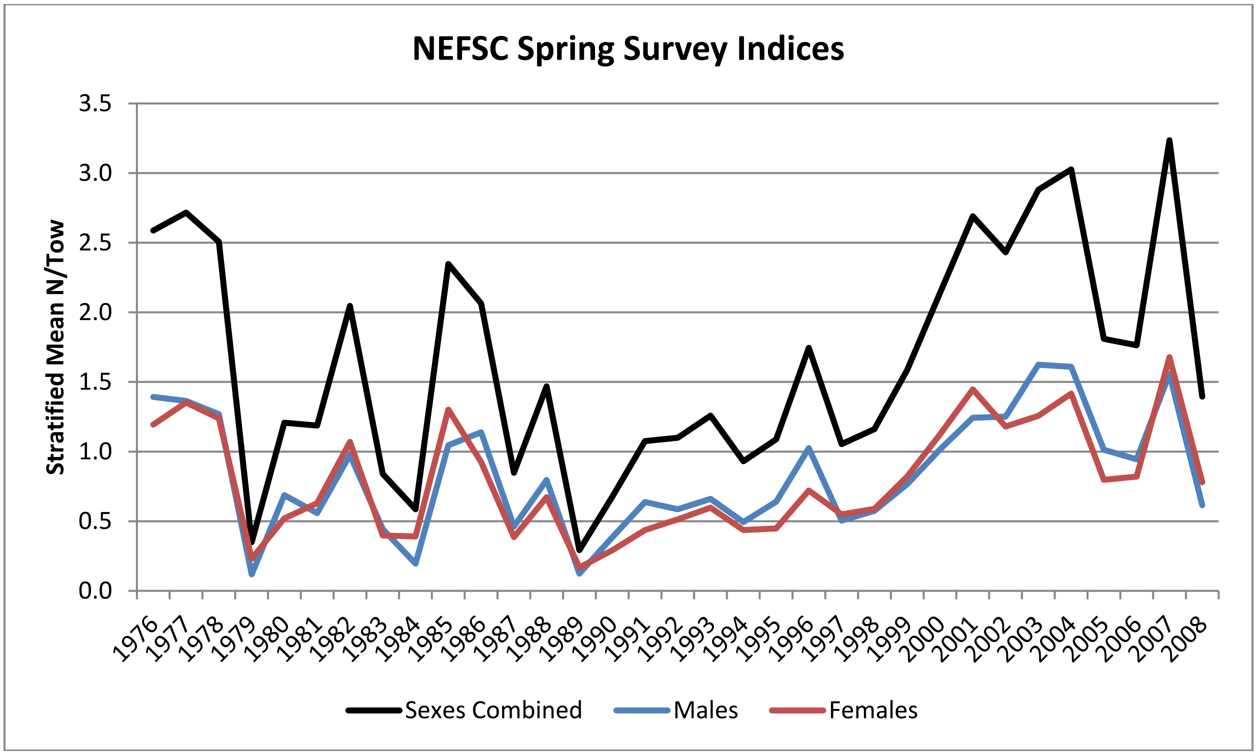


Figure 40. Northeast Fisheries Science Center (NEFSC) winter survey indices of summer flounder (*Paralichthys dentatus*) abundance (number per tow) for males, females, and sexes combined (top) and proportion female by age (bottom).



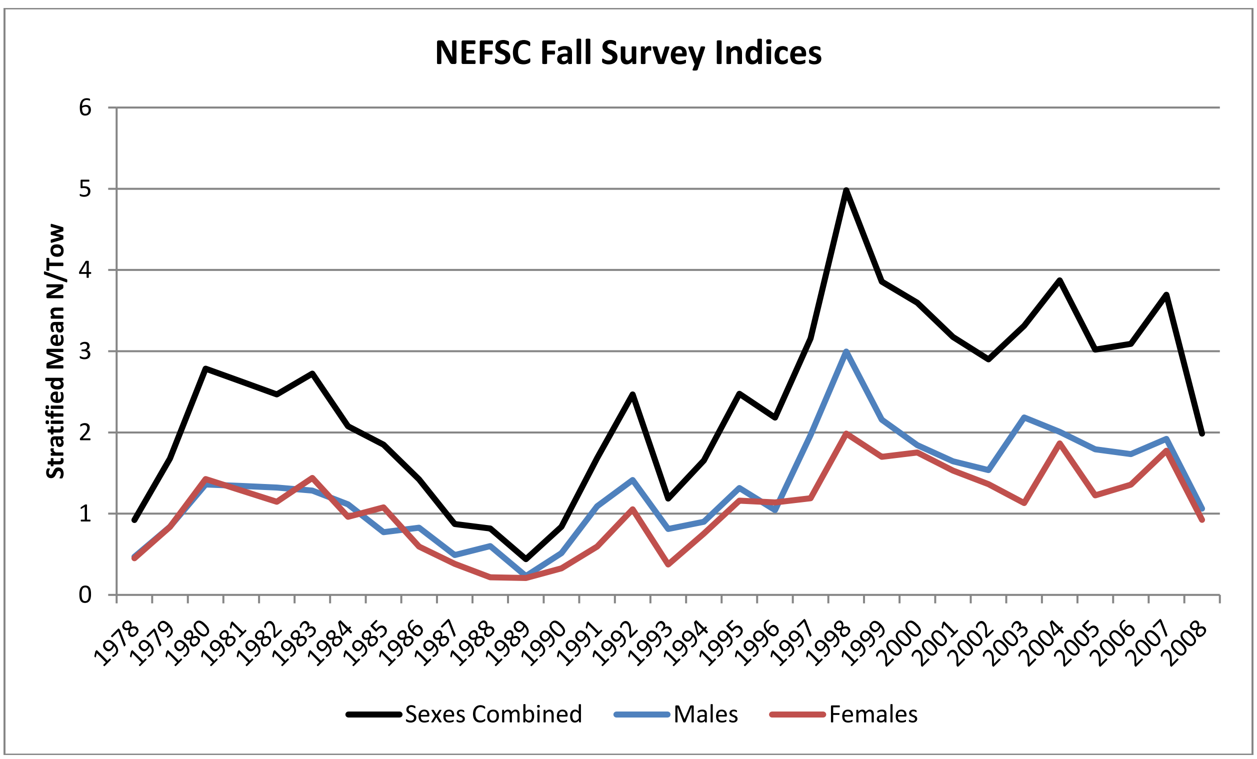


Figure 41. Northeast Fisheries Science Center (NEFSC) Albatross IV spring and fall survey indices of summer flounder (*Paralichthys dentatus*) abundance (number per tow) for sexes combined (summed), males, and females. The series ends in 2008.

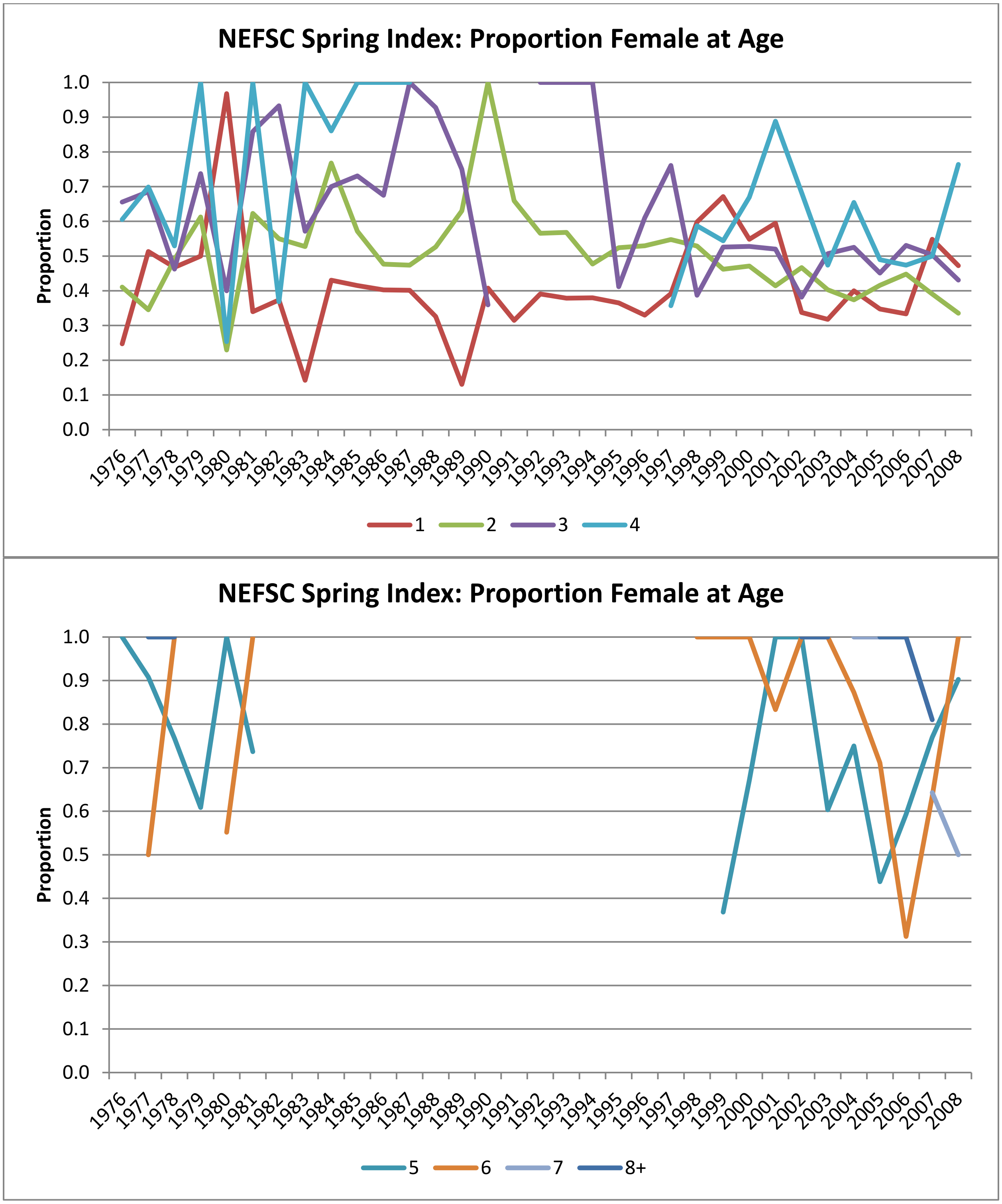
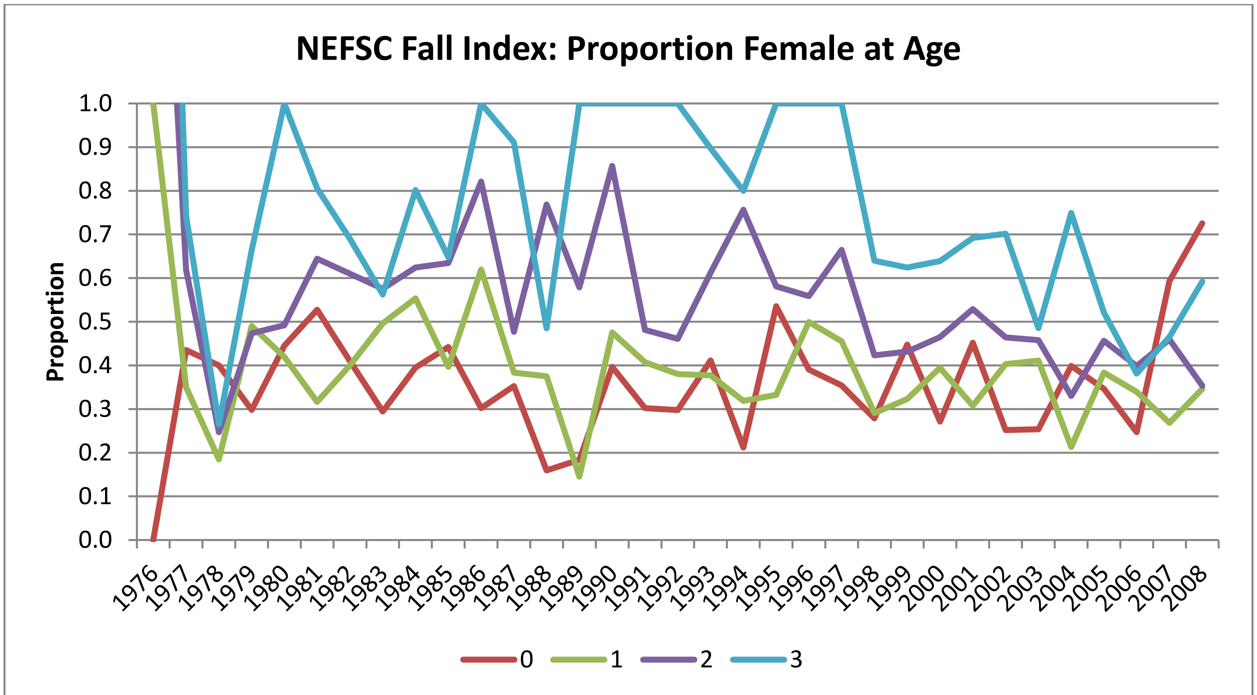


Figure 42. Northeast Fisheries Science Center (NEFSC) Albatross IV spring survey index of summer flounder (*Paralichthys dentatus*) proportion female by age. The series ends in 2008.



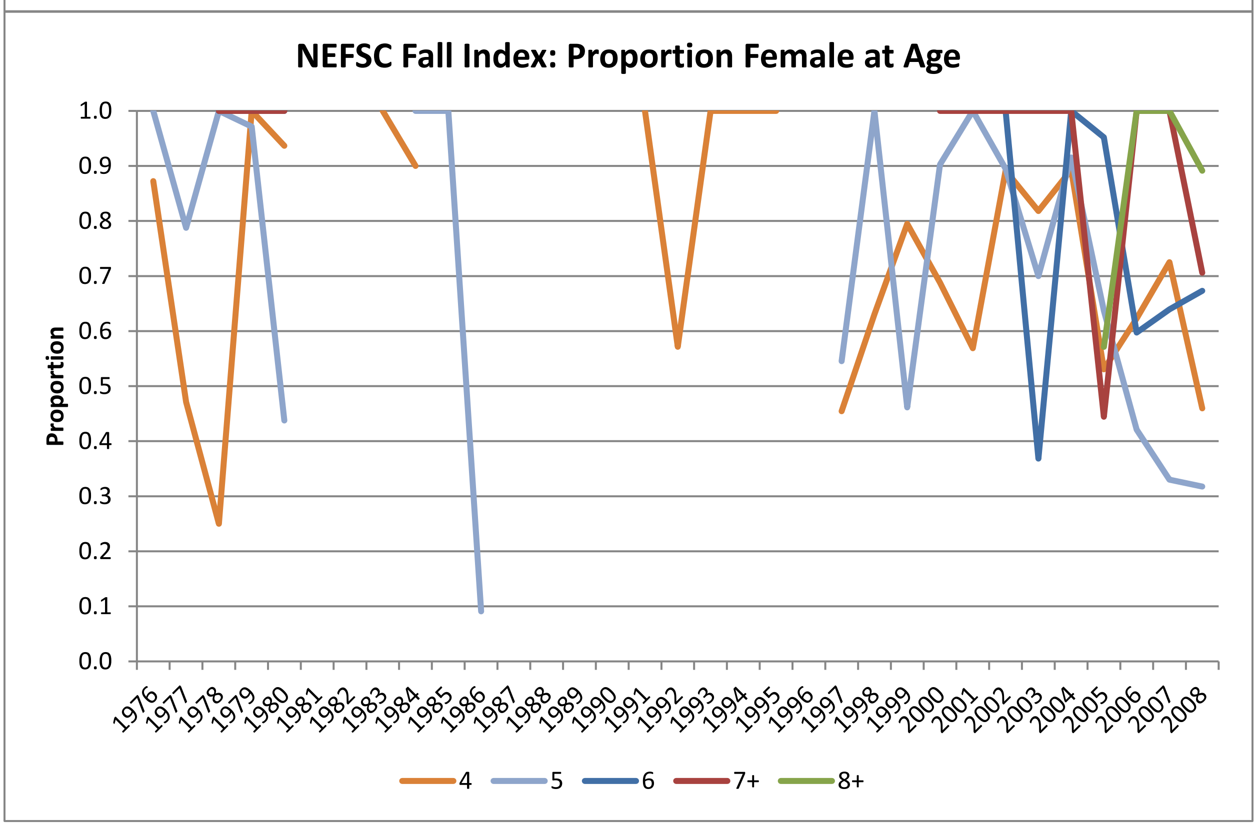


Figure 43. Northeast Fisheries Science Center (NEFSC) Albatross IV fall survey index of summer flounder (*Paralichthys dentatus*) proportion female by age. The series ends in 2008.

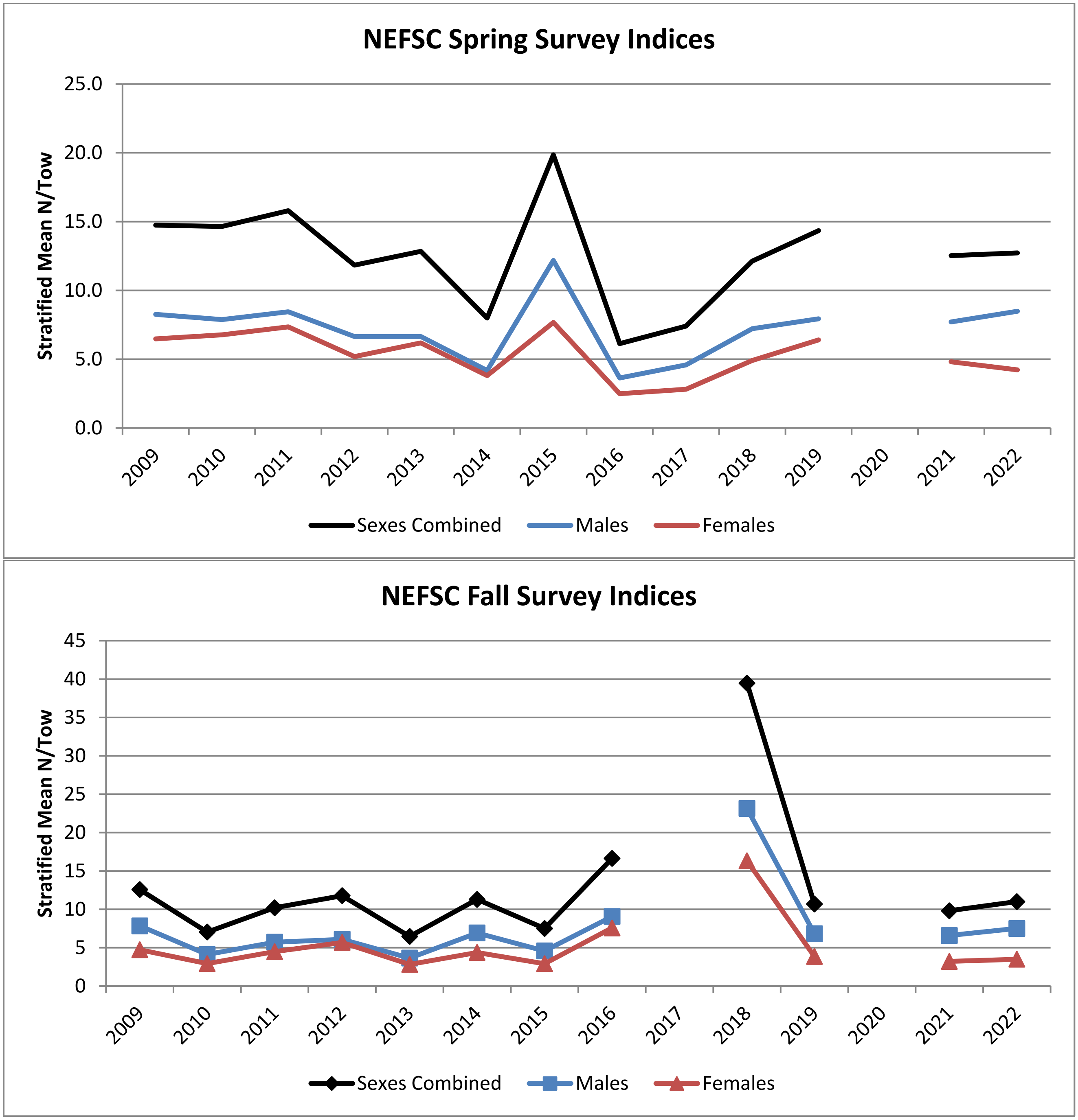


Figure 44. Northeast Fisheries Science Center (NEFSC) HB Bigelow spring and fall survey indices of summer flounder (*Paralichthys dentatus*) abundance (number per tow) for sexes combined (summed), males, and females. No spring survey in 2020, and no fall surveys in 2017 or 2020.

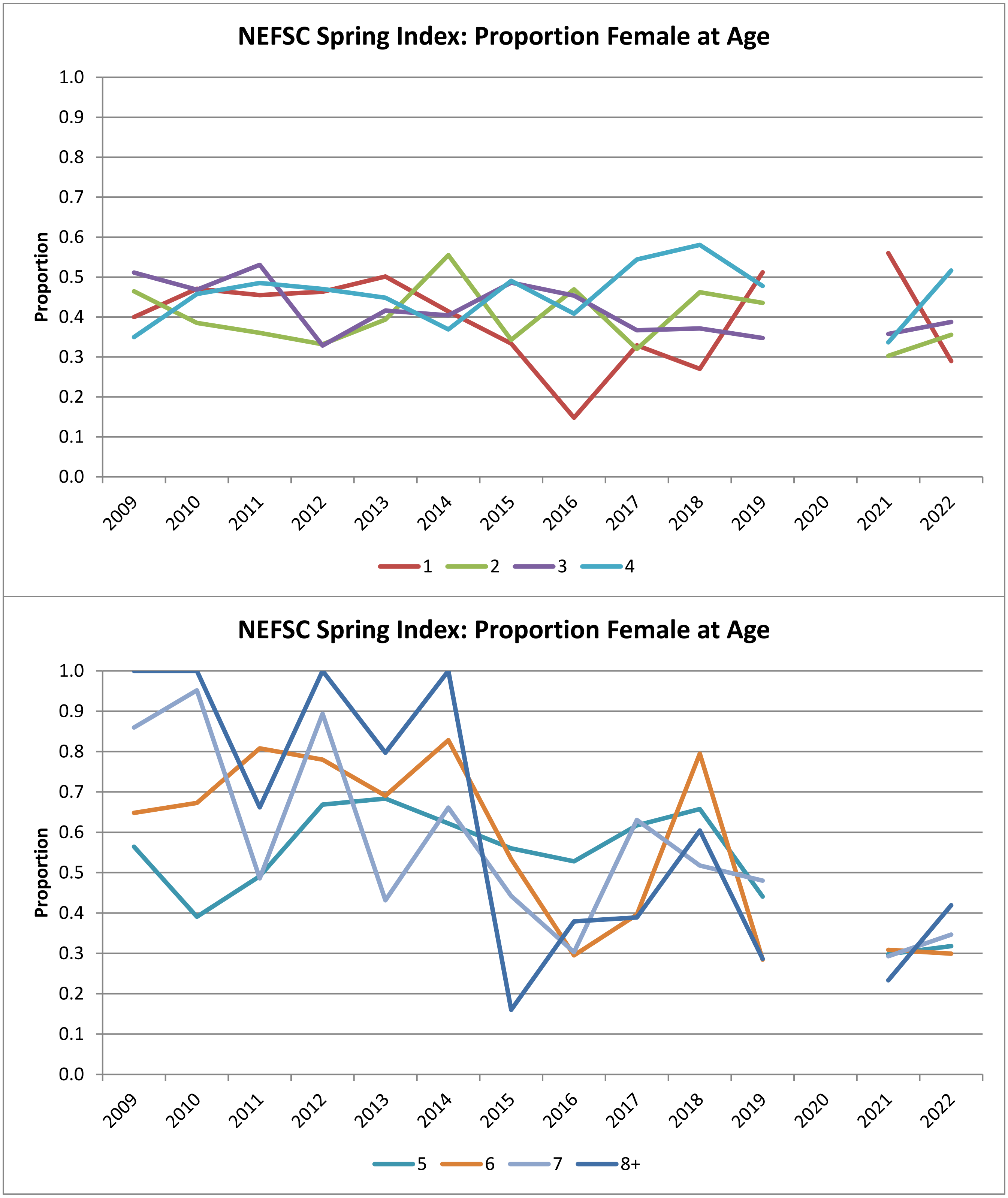


Figure 45. Northeast Fisheries Science Center (NEFSC) HB Bigelow spring survey index of summer flounder (*Paralichthys dentatus*) proportion female by age. No survey in 2020.

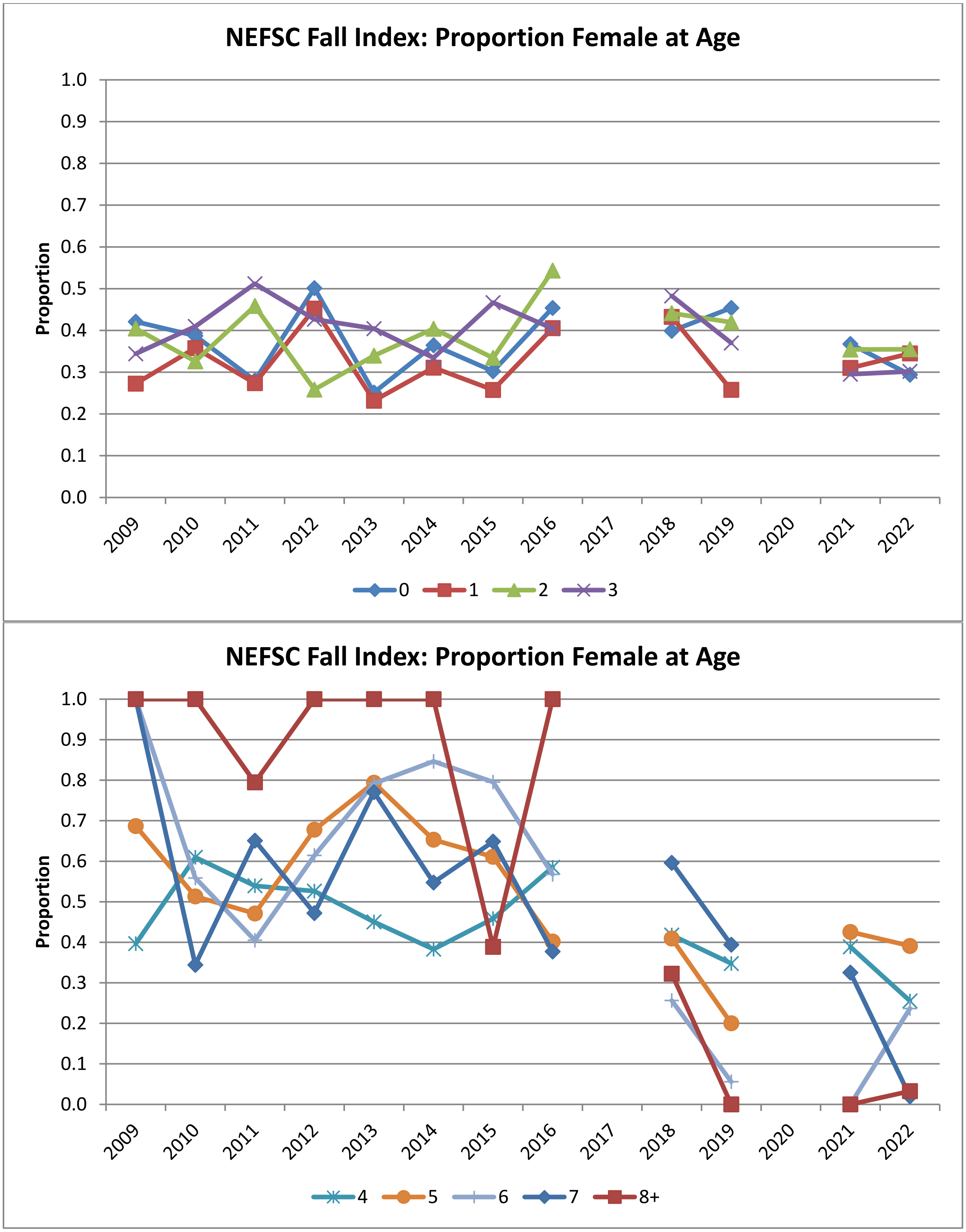


Figure 46. Northeast Fisheries Science Center (NEFSC) HB Bigelow fall survey index of summer flounder (*Paralichthys dentatus*) proportion female by age. No surveys in 2017 or 2020.

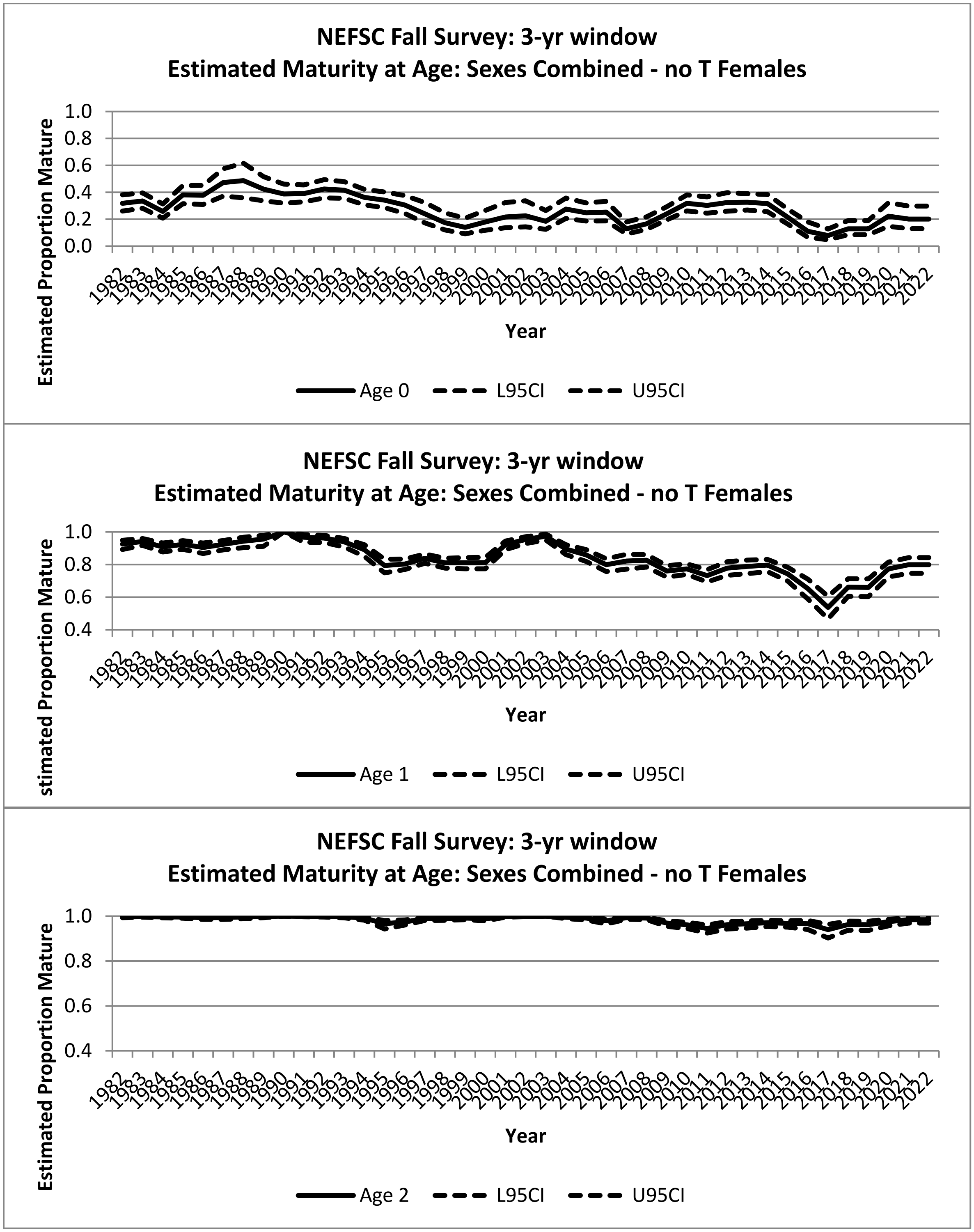


Figure 47. Estimated maturity at ages 0, 1, and 2, for summer flounder (*Paralichthys dentatus*) sexes combined by 3-year moving window; resting (T) females removed.

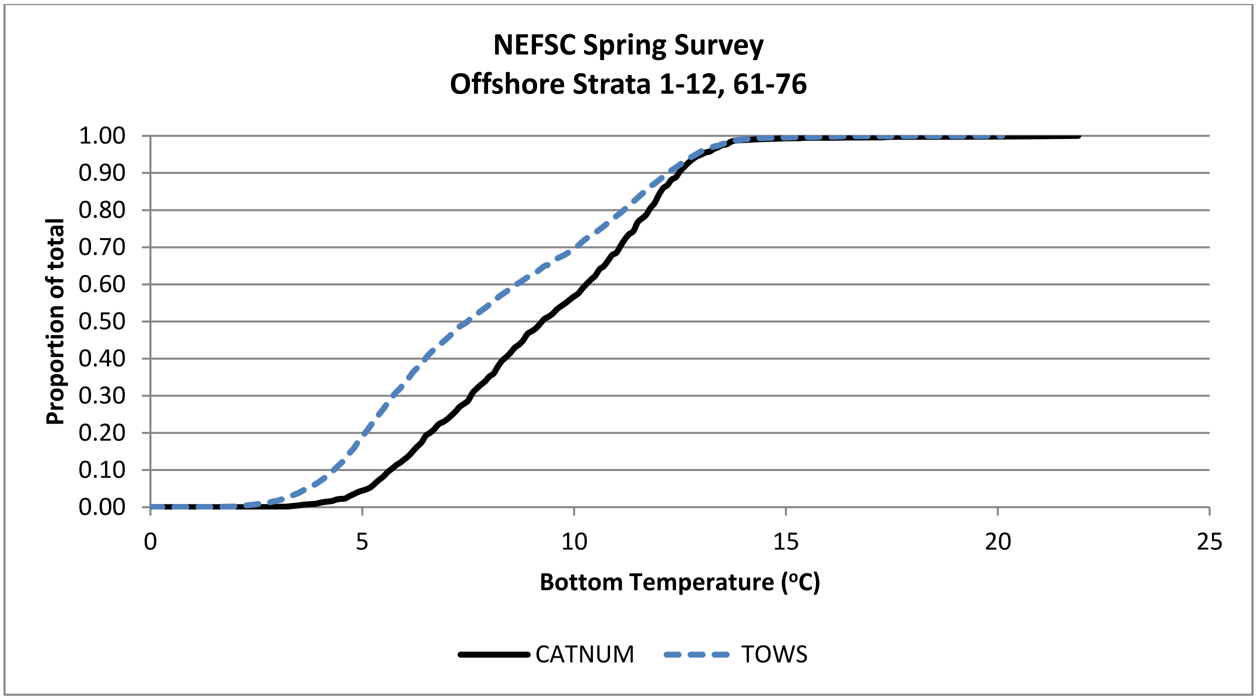


Figure 48. Cumulative proportion of total (expanded catch number per tow [CATNUM] or number of tows) by bottom water temperature for survey stations in the Northeast Fisheries Science Center (NEFSC) spring survey strata set (1968-2022).

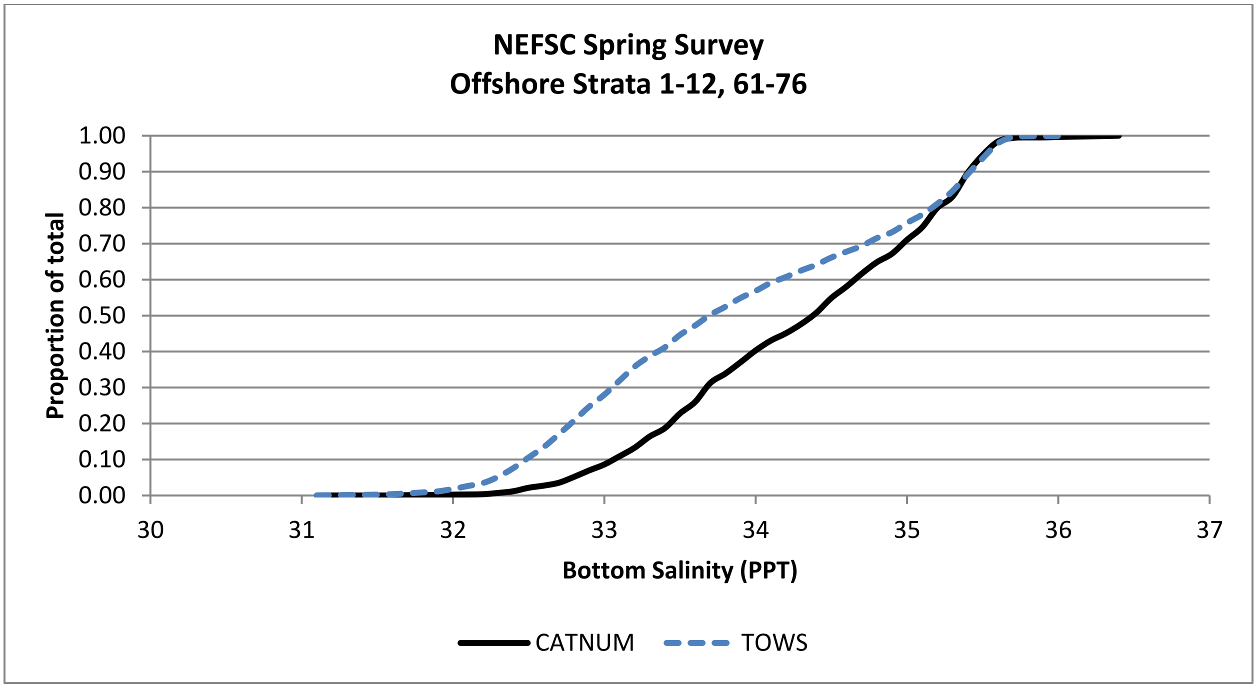


Figure 49. Cumulative proportion of total (expanded catch number per tow [CATNUM] or number of tows) by bottom water salinity for survey stations in the Northeast Fisheries Science Center (NEFSC) spring survey strata set (1968-2022).

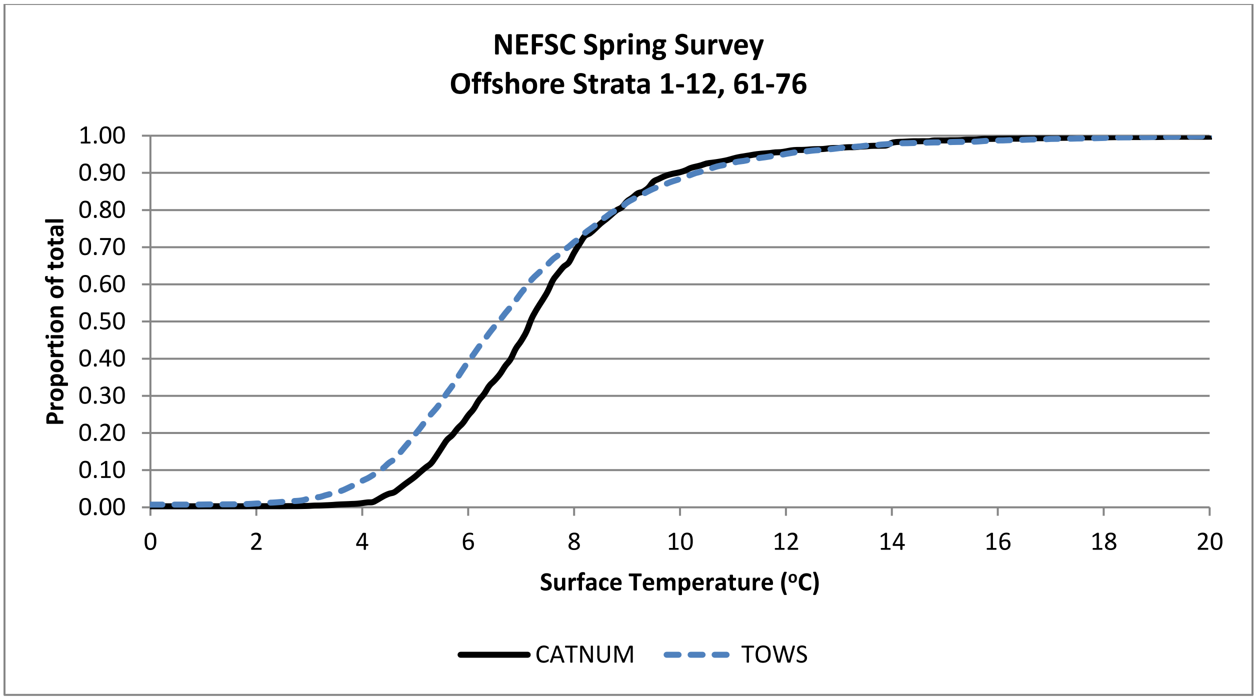


Figure 50. Cumulative proportion of total (expanded catch number per tow [CATNUM] or number of tows) by surface water temperature for survey stations in the Northeast Fisheries Science Center (NEFSC) spring survey strata set (1968-2022).

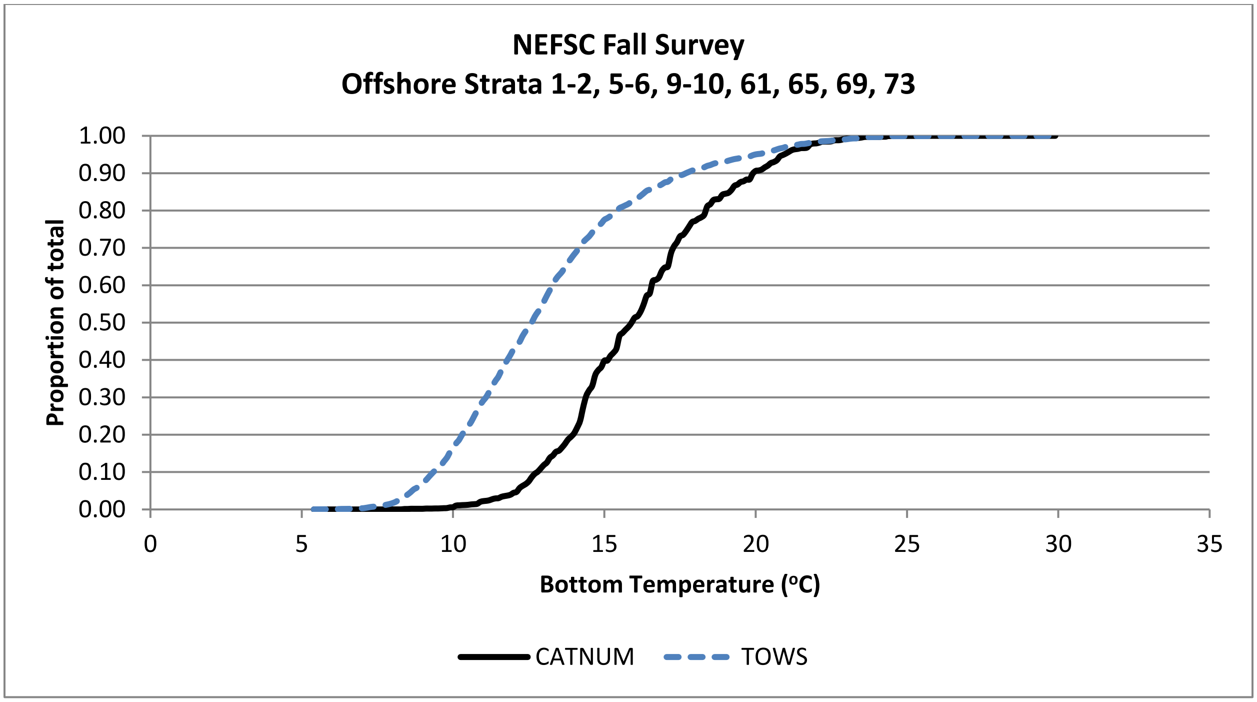


Figure 51. Cumulative proportion of total (expanded catch number per tow [CATNUM] or number of tows) by bottom temperature for survey stations in the Northeast Fisheries Science Center (NEFSC) fall survey strata set (1968-2022).

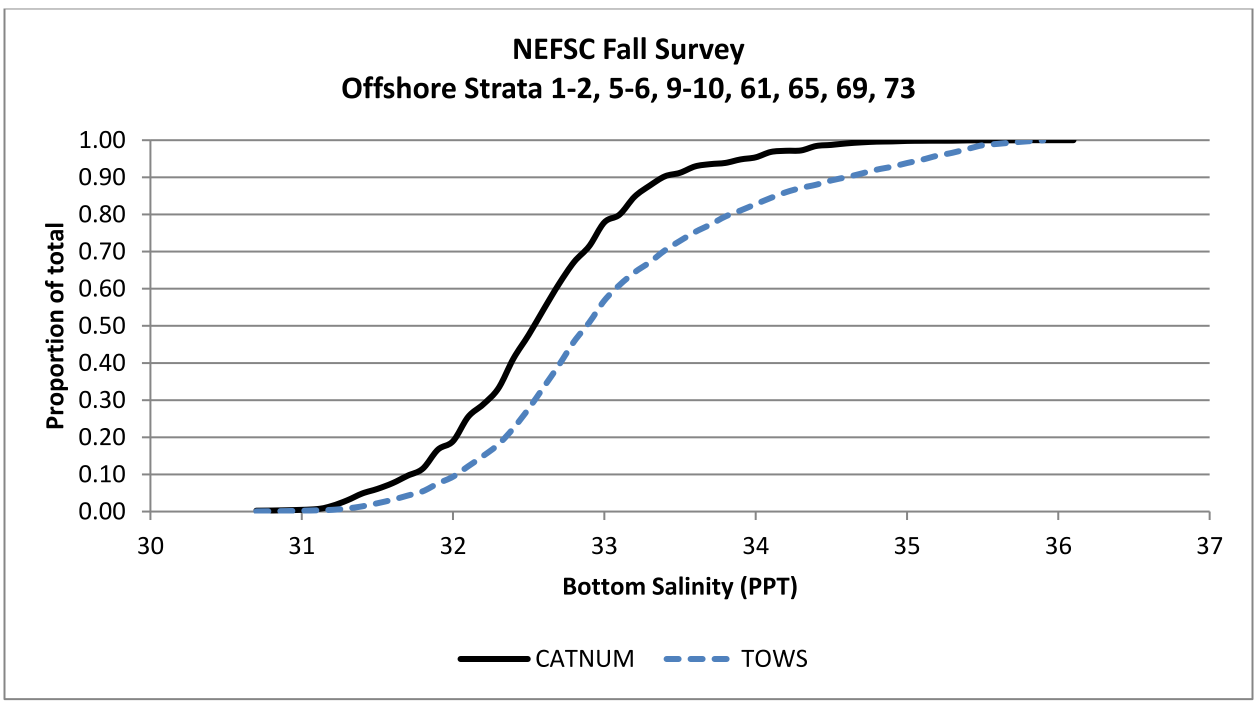


Figure 52. Cumulative proportion of total (expanded catch number per tow [CATNUM] or number of tows) by bottom salinity for survey stations in the Northeast Fisheries Science Center (NEFSC) fall survey strata set (1968-2022).

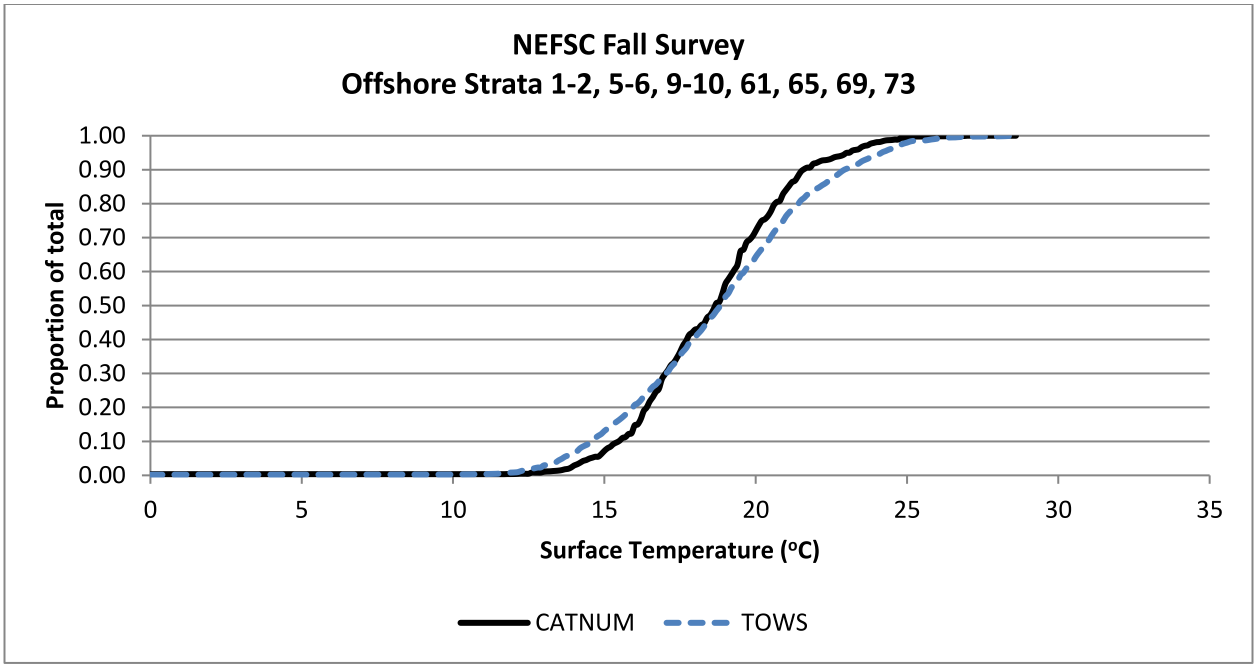


Figure 53. Cumulative proportion of total (expanded catch number per tow [CATNUM] or number of tows) by surface temperature for survey stations in the Northeast Fisheries Science Center (NEFSC)fall survey strata set (1968-2022).

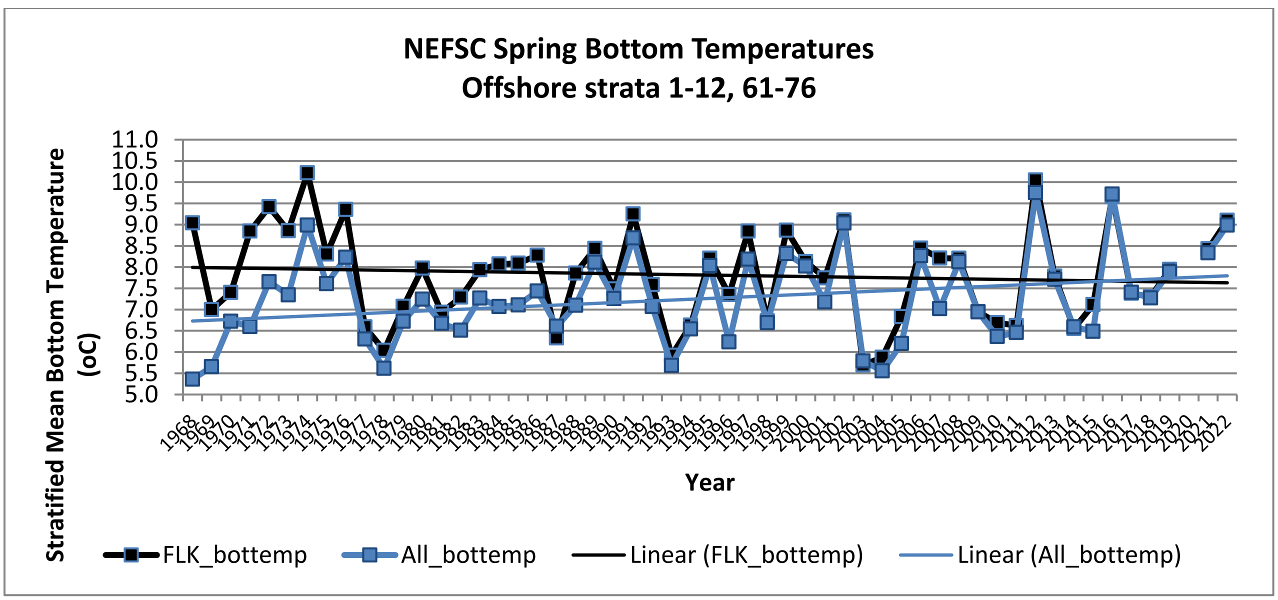


Figure 54. Spring stratified mean values of the bottom temperature for positive summer flounder (*Paralichthys dentatus*) catch tows (expcatchnum > 0; FLK_bottemp) compared with the stratified mean values for all tows (All_bottemp). Straight lines are linear smooths.

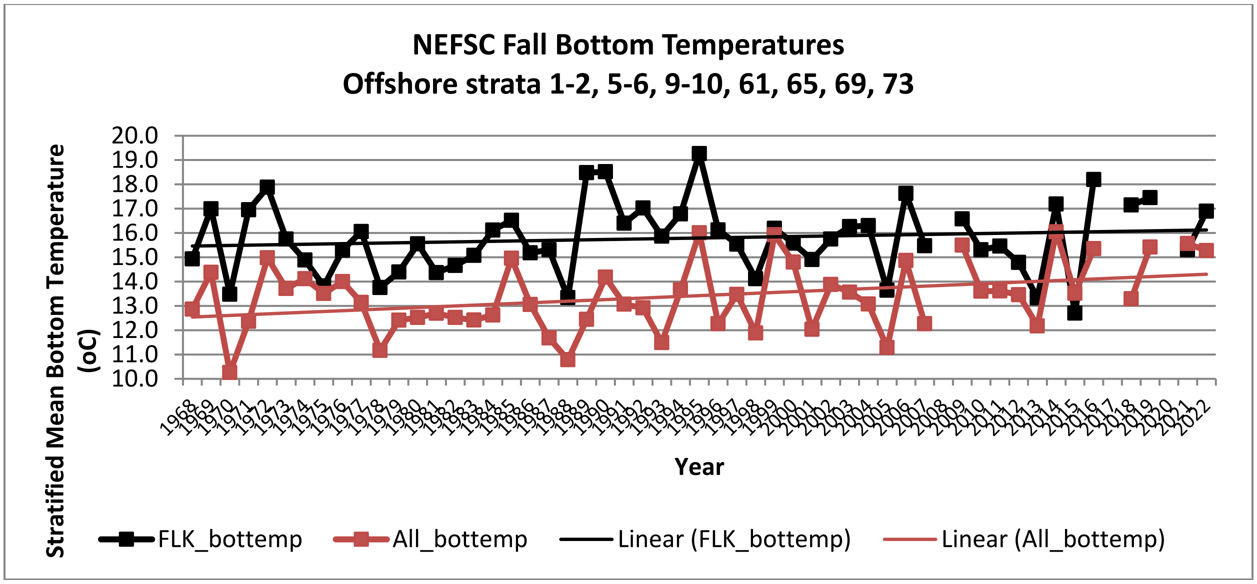


Figure 55. Fall stratified mean values of the bottom temperature for positive summer flounder (*Paralichthys dentatus*) catch tows (expcatchnum > 0; FLK_bottemp) compared with the stratified mean values for all tows (All_bottemp). Straight lines are linear smooths.

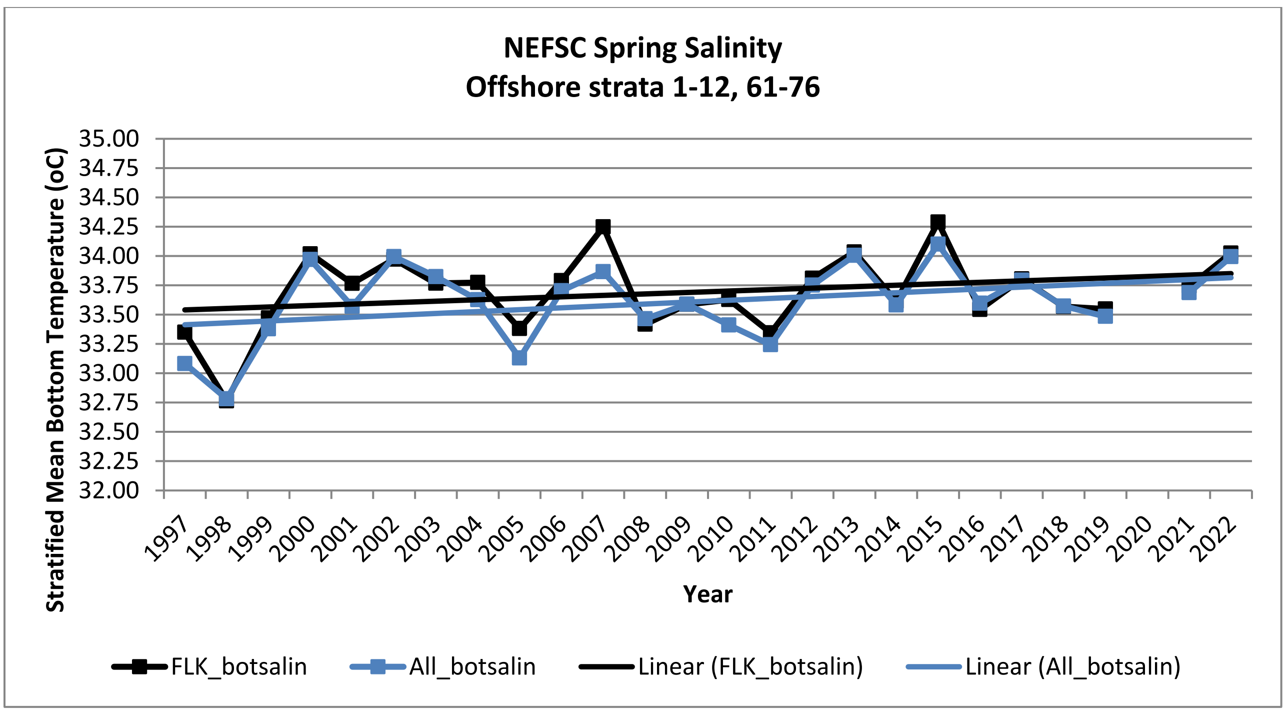


Figure 56. Spring stratified mean values of the bottom salinity for positive summer flounder (*Paralichthys dentatus*) catch tows (expcatchnum > 0; FLK_botsalin) compared with the stratified mean values for all tows (All_botsalin). Straight lines are linear smooths.

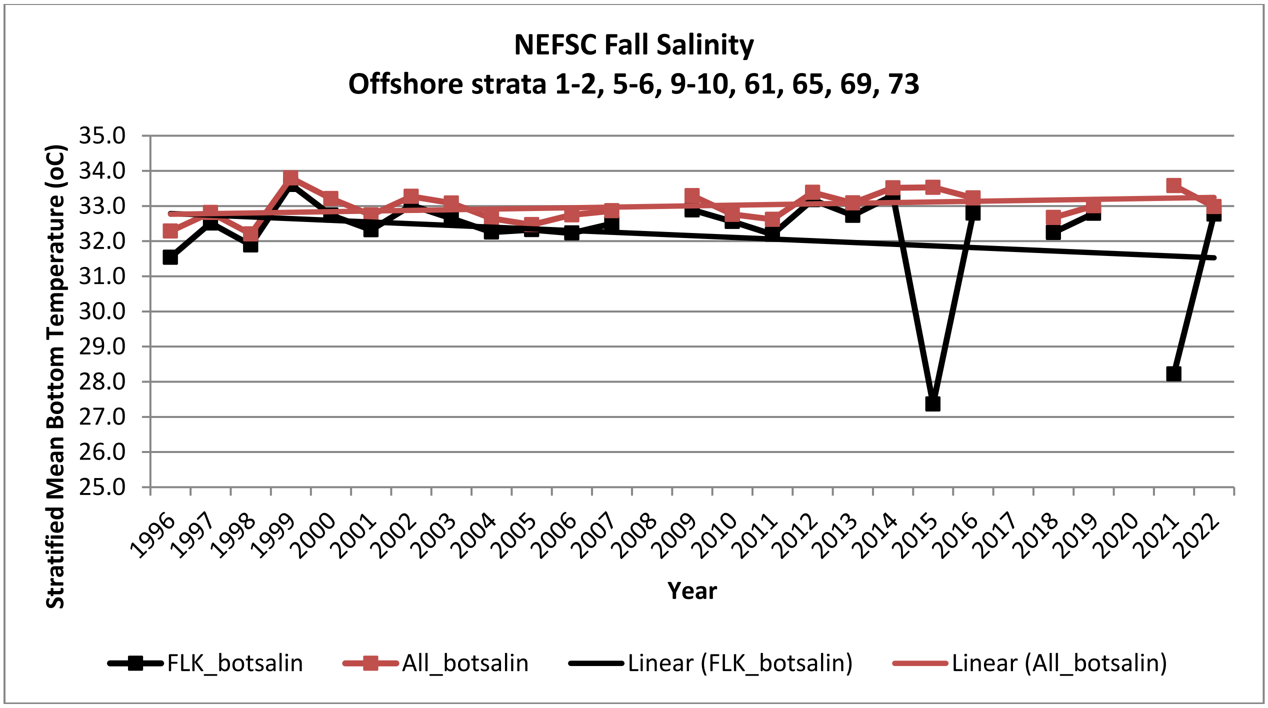


Figure 57. Fall stratified mean values of the bottom salinity for positive summer flounder (*Paralichthys dentatus*) catch tows (expcatchnum > 0; FLK_botsalin) compared with the stratified mean values for all tows (All_botsalin). Straight lines are linear smooths.

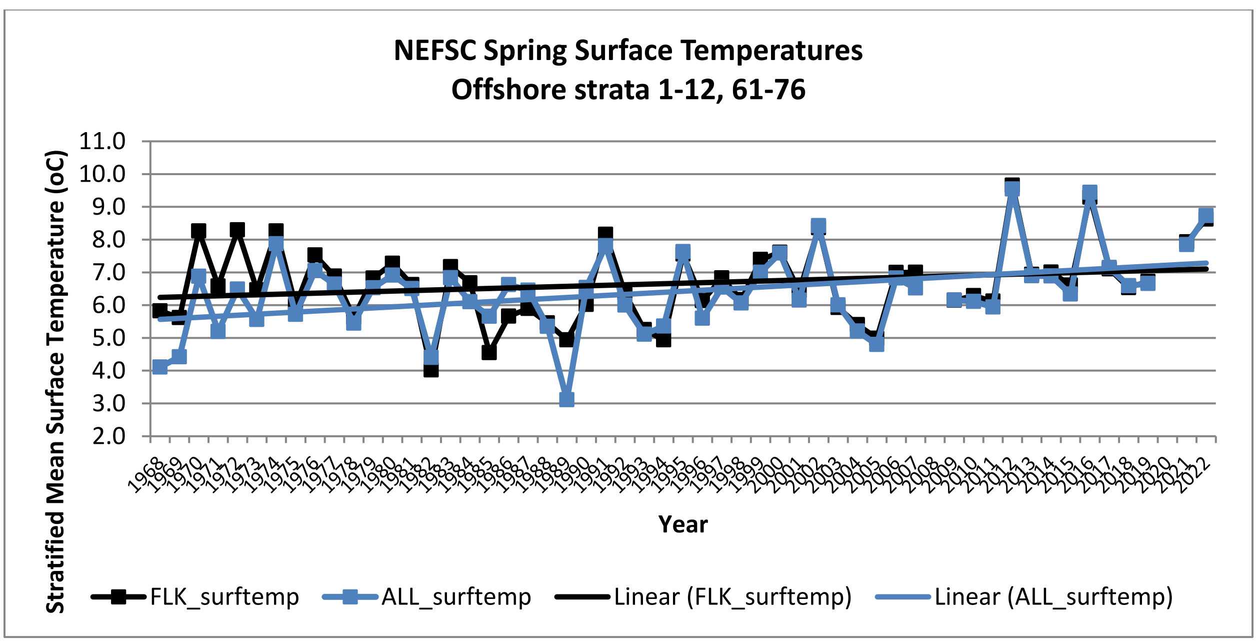


Figure 58. Spring stratified mean values of the surface temperature for positive summer flounder (*Paralichthys dentatus*) catch tows (expcatchnum > 0; FLK_surftemp) compared with the stratified mean values for all tows (All_surftemp). Straight lines are linear smooths.

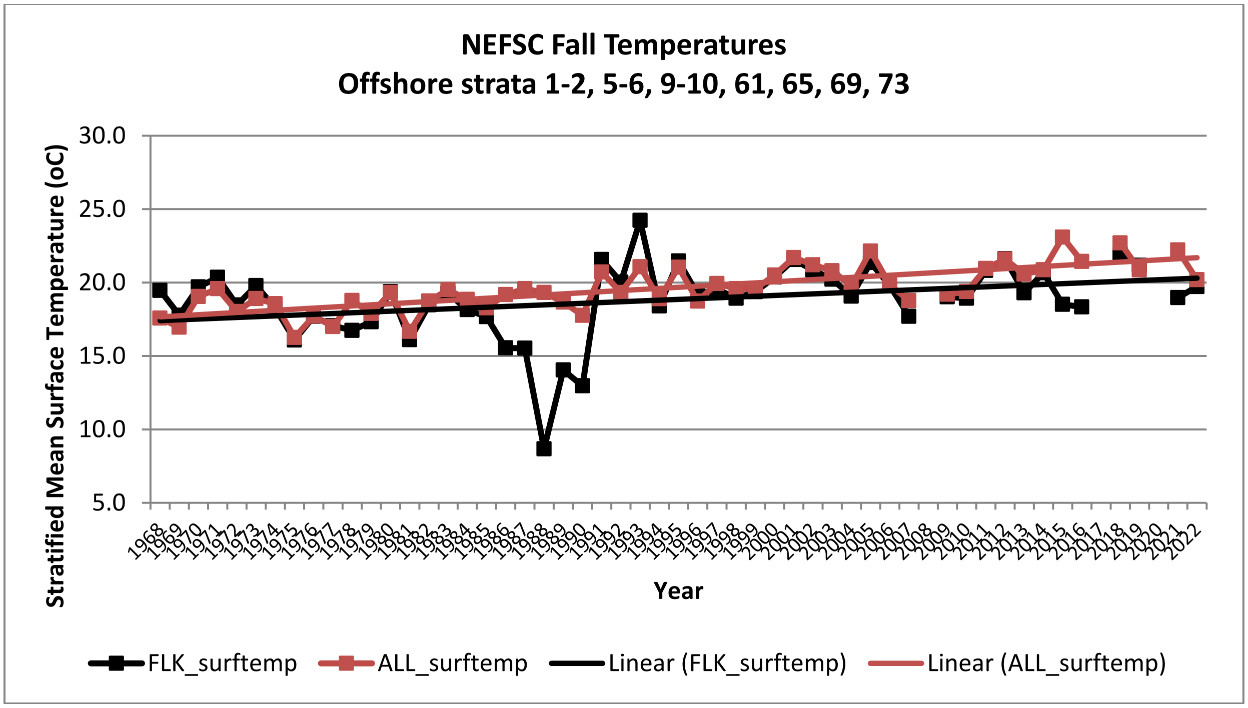


Figure 59. Fall stratified mean values of the surface temperature for positive summer flounder (*Paralichthys dentatus*) catch tows (expcatchnum > 0; FLK_surftemp) compared with the stratified mean values for all tows (All_surftemp). Straight lines are linear smooths.

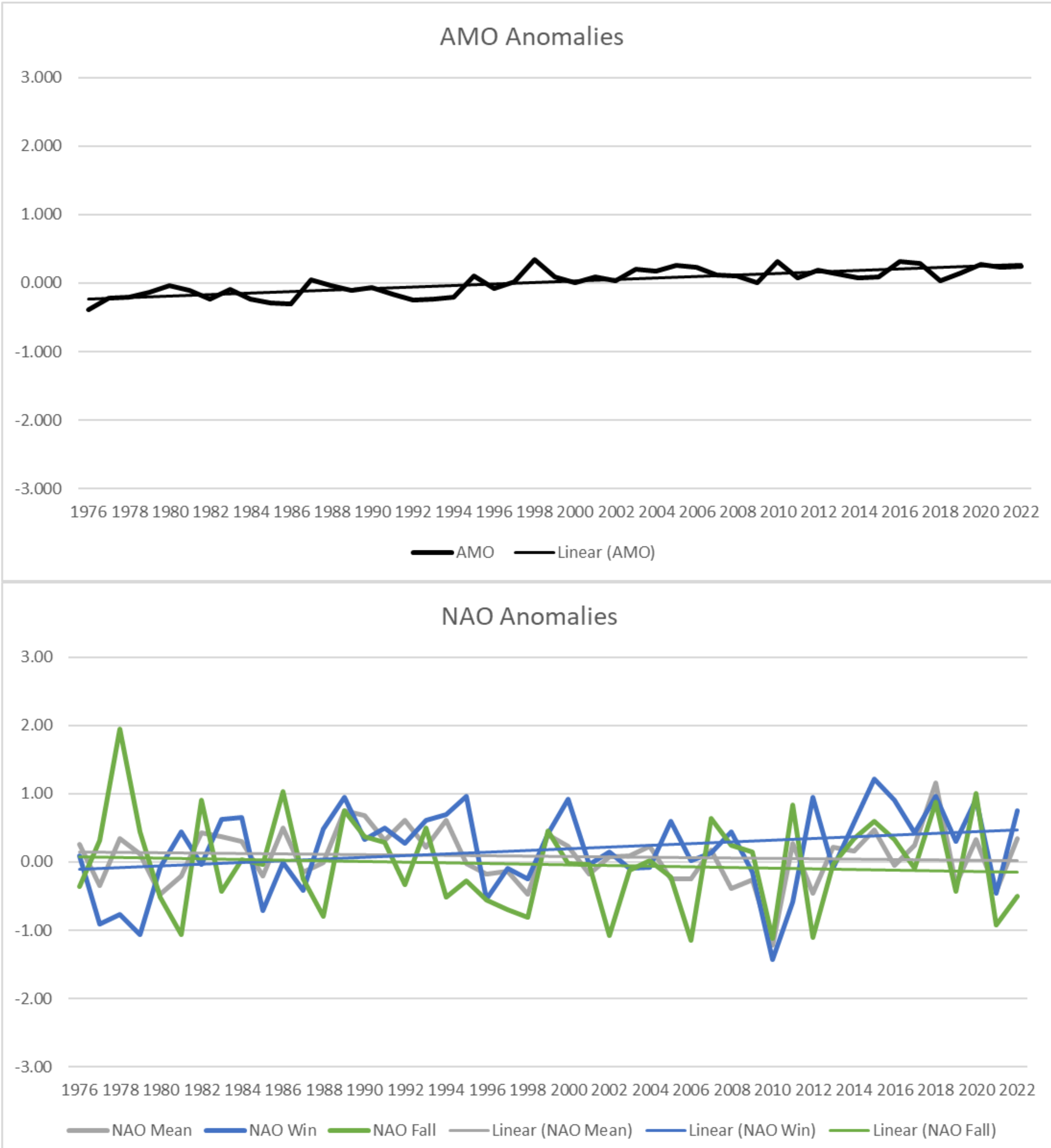


Figure 60. Top: Time series of the Atlantic Multidecal Oscillation (AMO). Bottom: Time series of the North Atlantci Oscillation (NOA Mean, NAO Win, and NAO Fall are annual, December-March, and September-November averages). Straight lines are linear smooths.

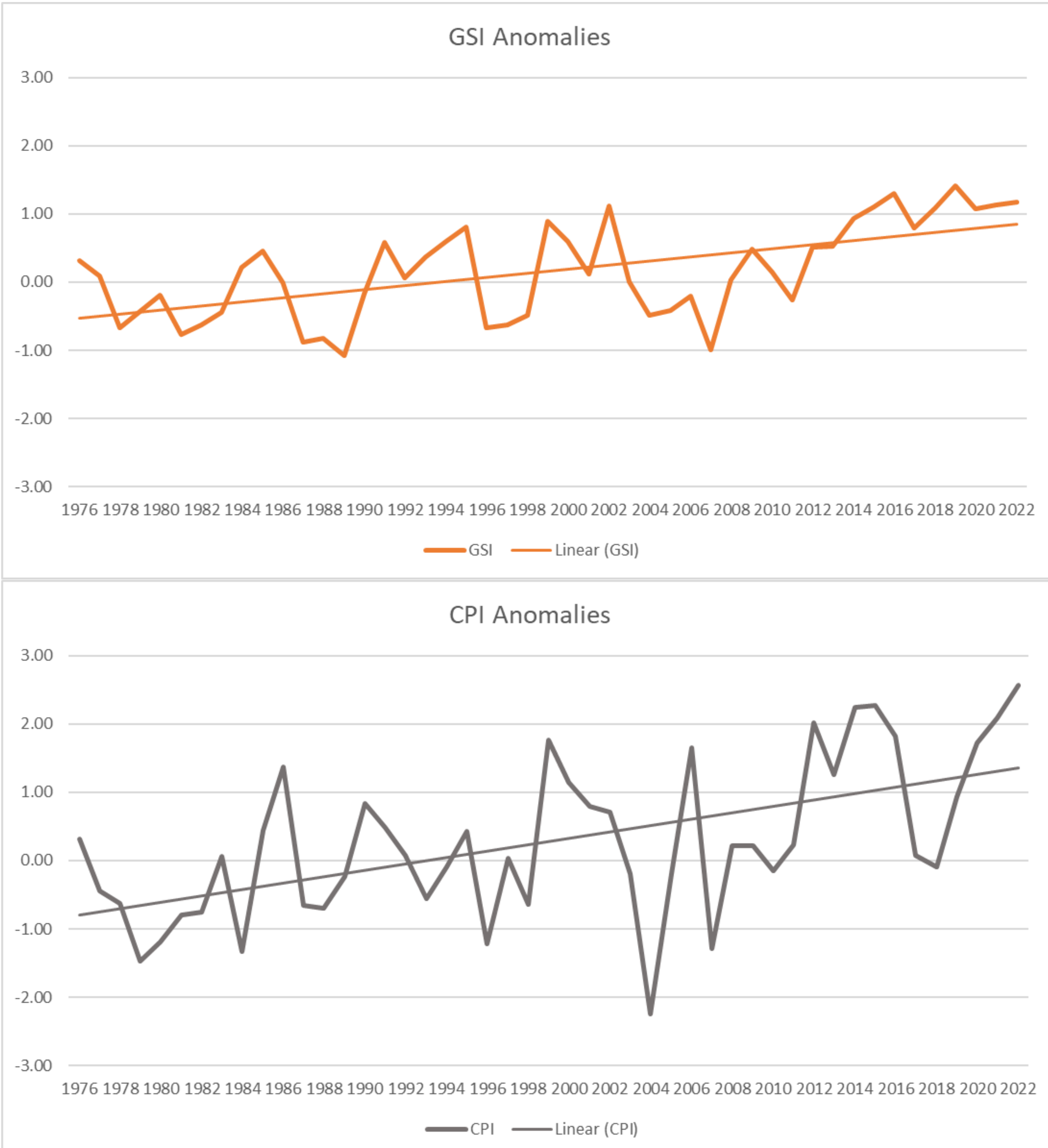


Figure 61. Top: time series of the Gulf Stream Index (GSI). Bottom: time series of the Cold Pool Index (CPI). Straight lines are linear smooths.

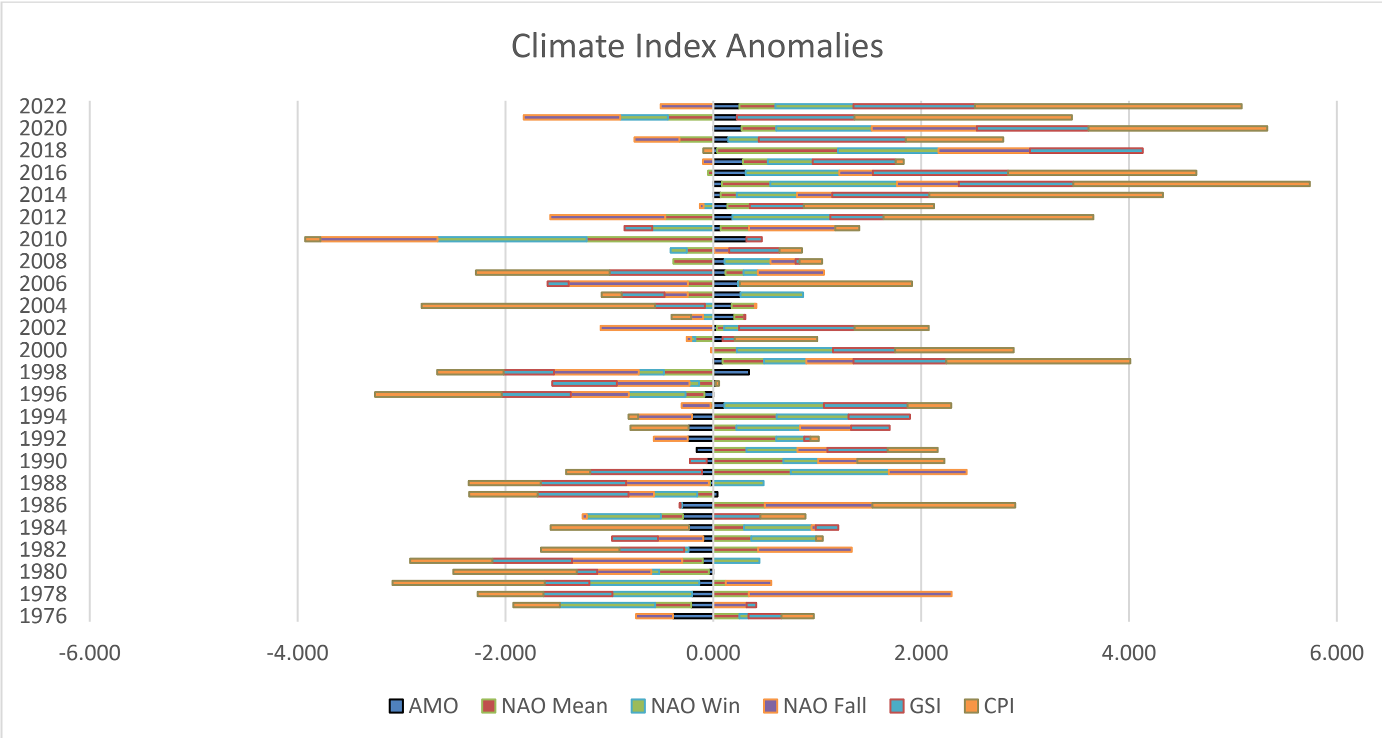


Figure 62. Time series of the Climate Indices anomalies. AMO is the Atlantic Multidecadal Oscillation; North Atlantic Oscillation [NAO] Mean, NAO Win, and NAO Fall are annual, December-March, and September-November avarages of the NAO; GSI is the Gulf Stream Index; CPI is the Cold Pool Index.

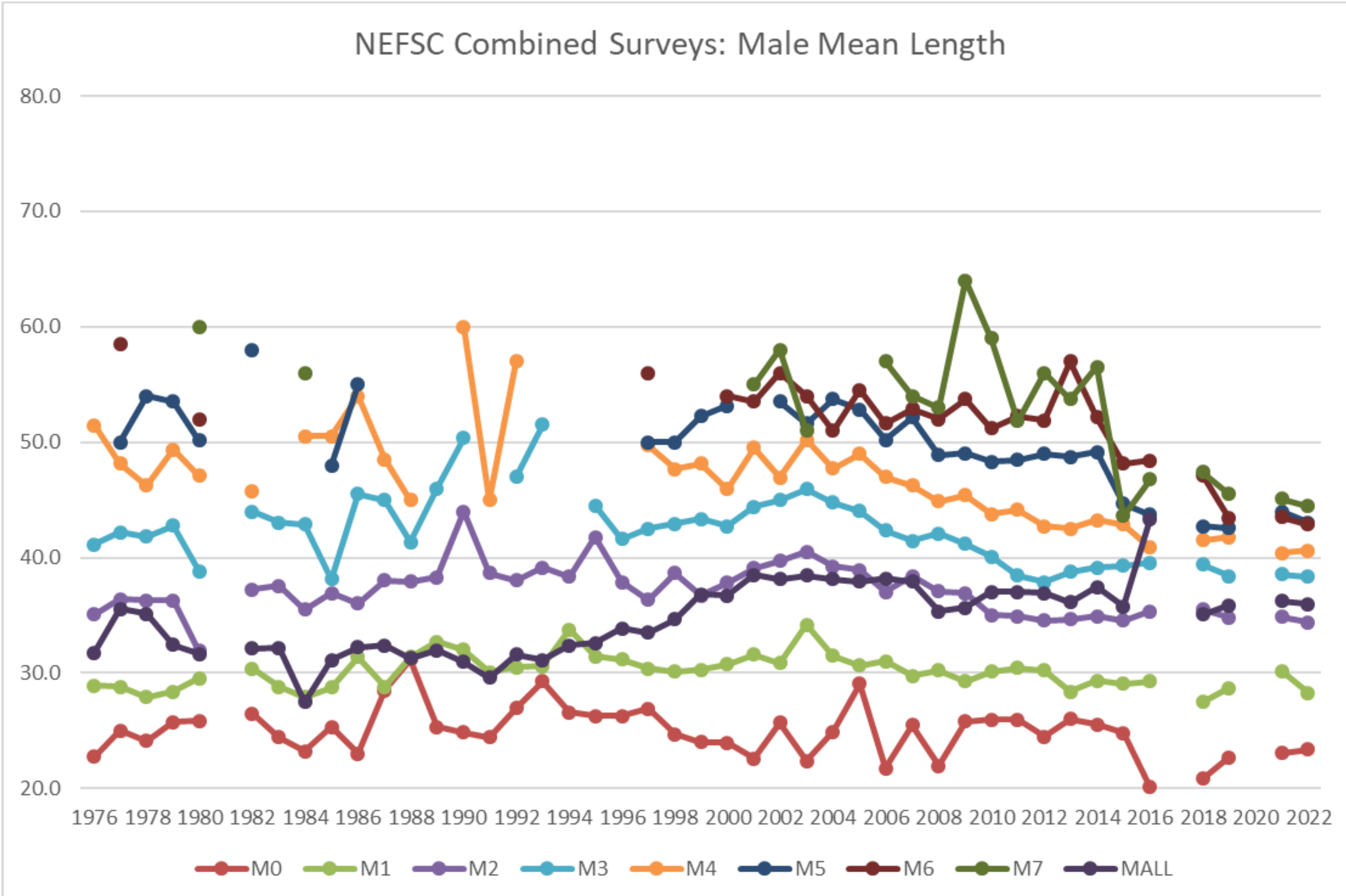


Figure 63. Trend in summer flounder (*Paralichthys dentatus*) mean length at age (M0 = age 0) and for all ages (MALL) for male fish sampled in the Northeast Fisheries Science Center (NEFSC) trawl survey: annual average over all winter, spring, and fall surveys. Data omitted for 2017 and 2020 due to missing surveys.

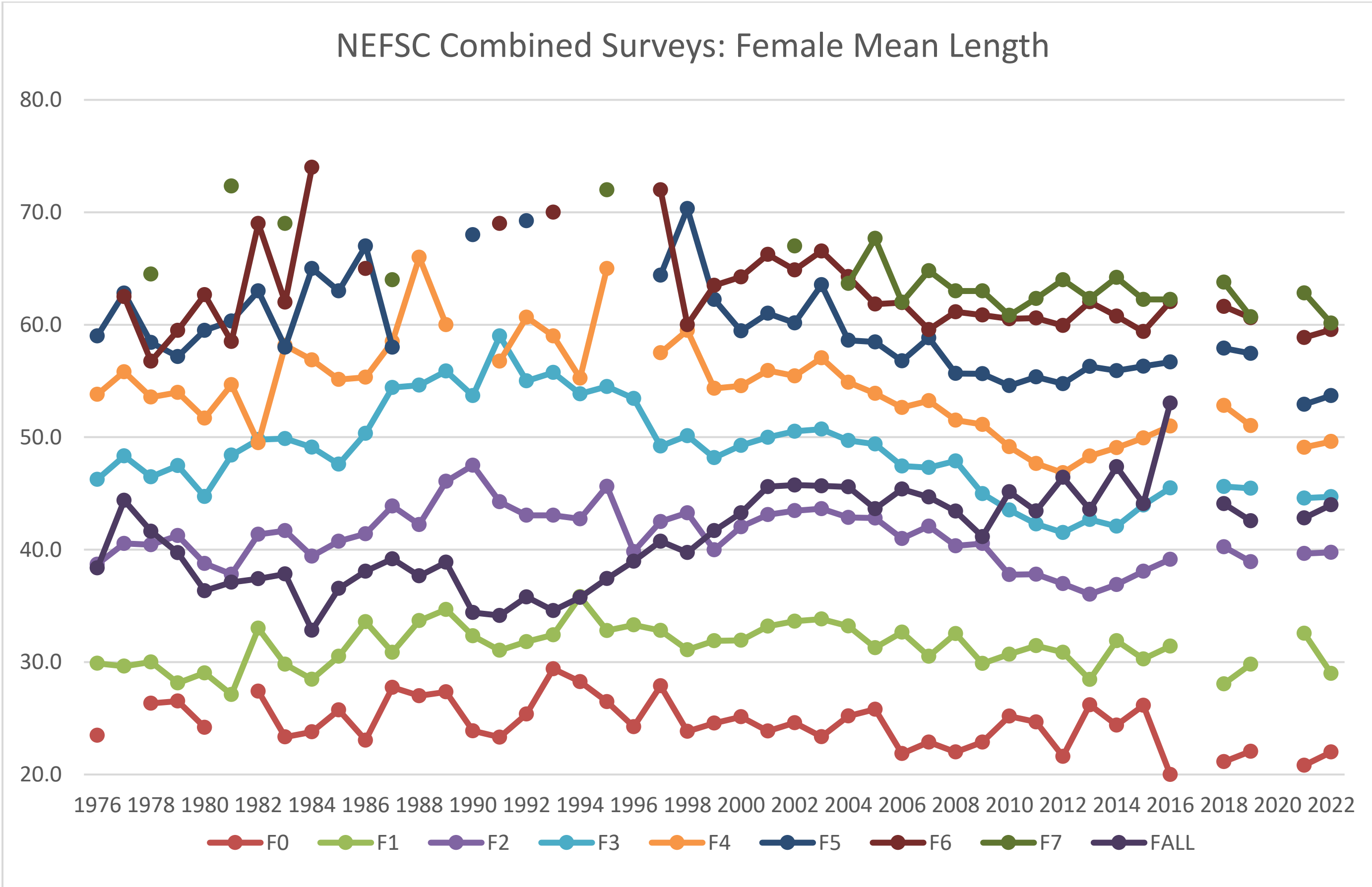


Figure 64. Trend in summer flounder (*Paralichthys dentatus*) mean length at age (F0 = age 0) and for all ages (FALL) for female fish sampled in the Northeast Fisheries Science Center (NEFSC) trawl survey: annual average over all winter, spring, and fall surveys. Data omitted for 2017 and 2020 due to missing surveys.

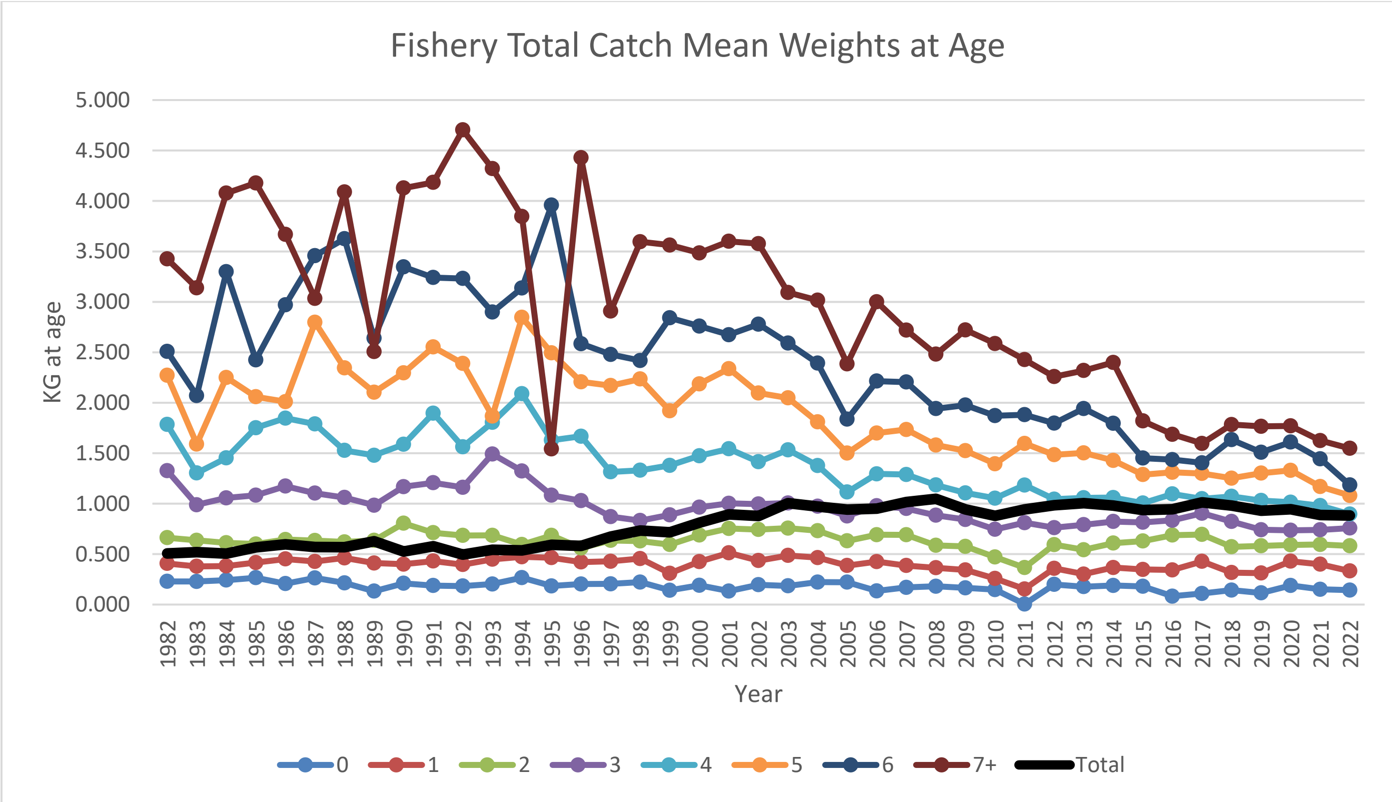


Figure 65. Trend in summer flounder (*Paralichthys dentatus*) mean weight at age and for all ages (Total) for combined sexes estimated for the total fishery catch.

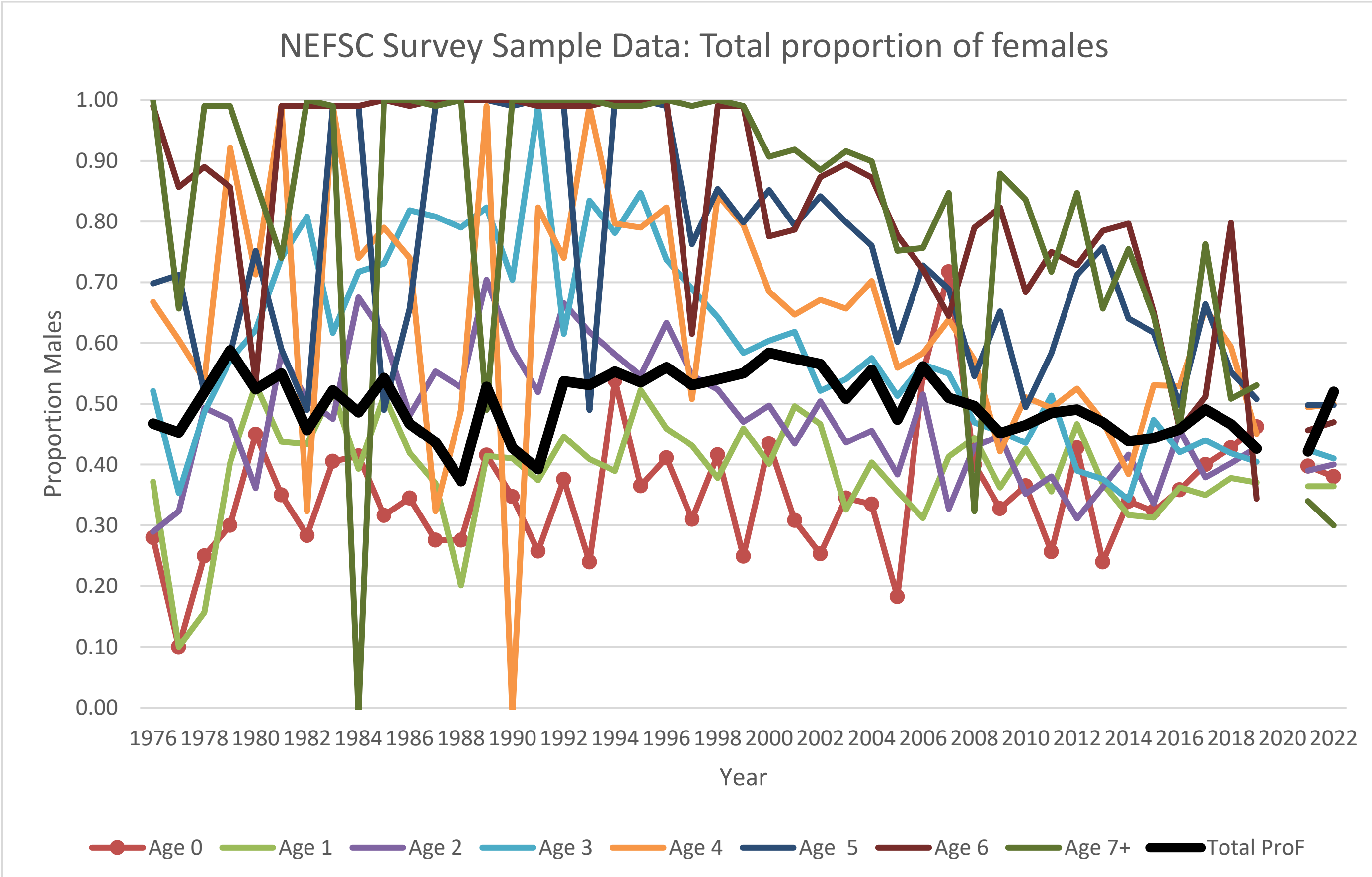


Figure 66. Trend in summer flounder (*Paralichthys dentatus*) proportion female (sex ratio) at age and for all ages (Total ProF) for fish sampled in the Northeast Fisheries Science Center (NEFSC) trawl survey: annual average over all winter, spring, and fall surveys.

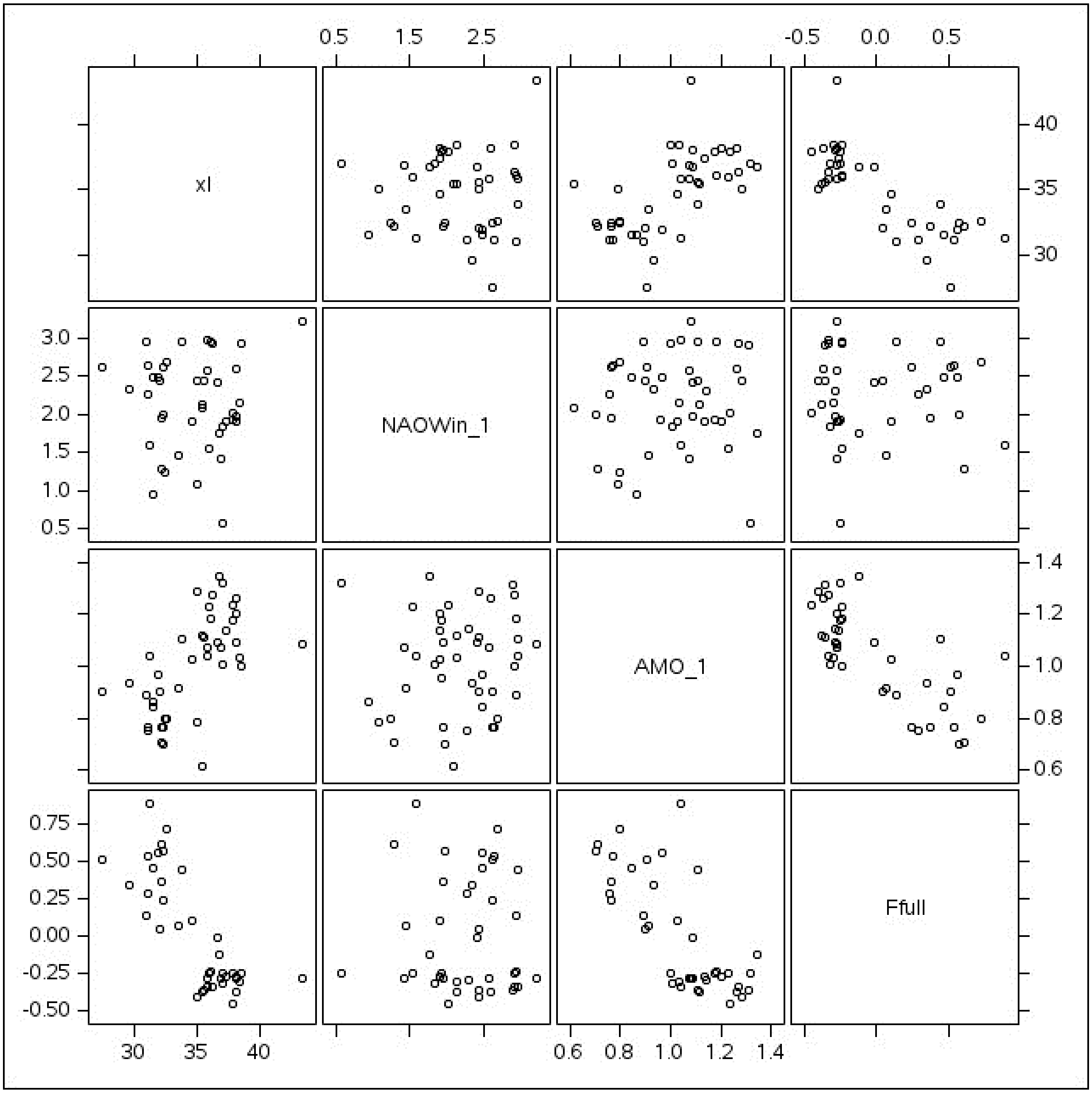


Figure 67. Scatter plot for summer flounder (*Paralichthys dentatus*) male aggregate mean length (xl) and the top 3 significant model factors.

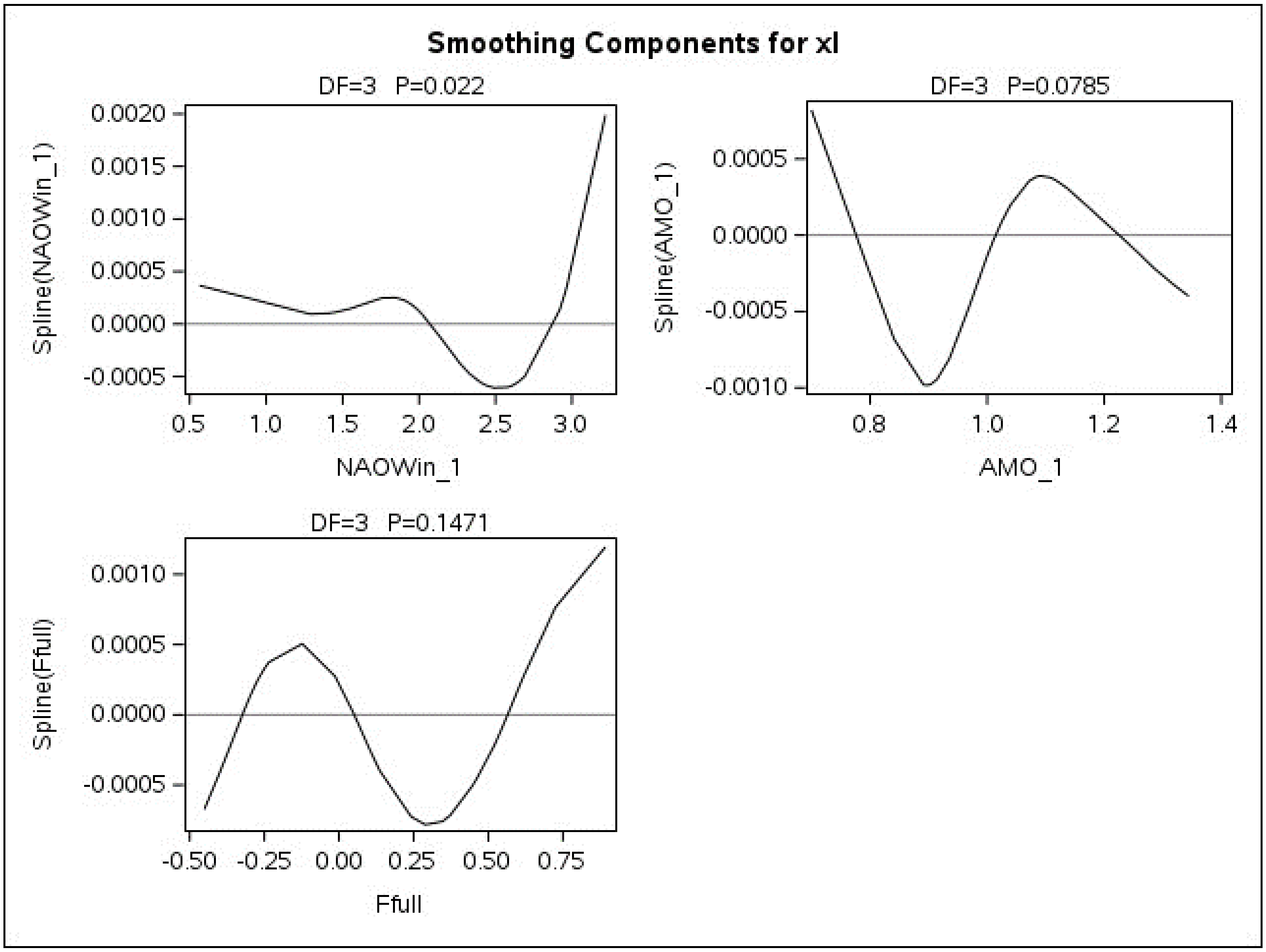


Figure 68. Smoothing component model results for summer flounder (*Paralichthys dentatus*) male aggregate mean length (xl) and the top 3 significant model factors.

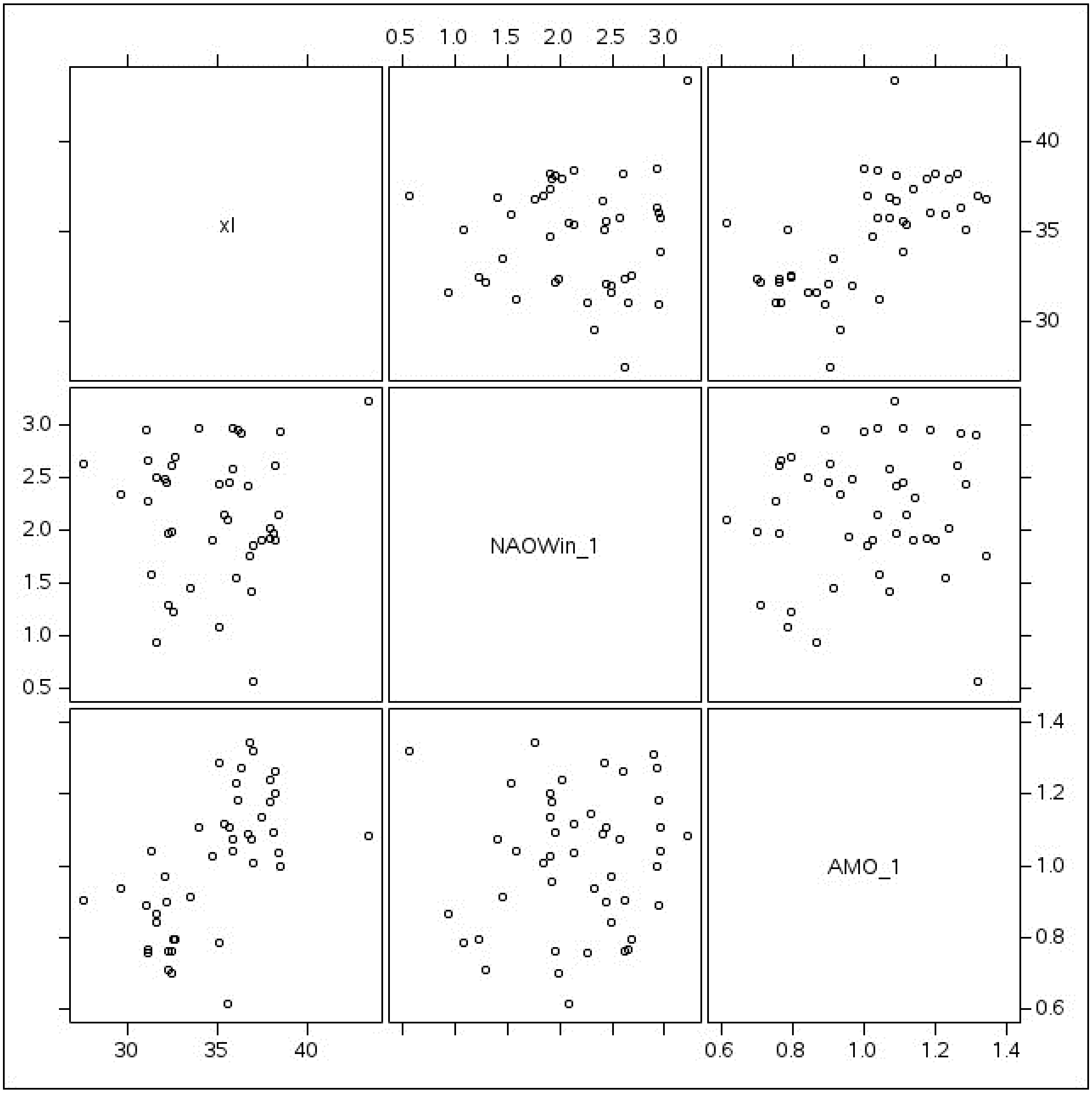


Figure 69. Scatter plot for summer flounder (*Paralichthys dentatus*) male aggregate mean length (xl) and the top 2 significant model factors.

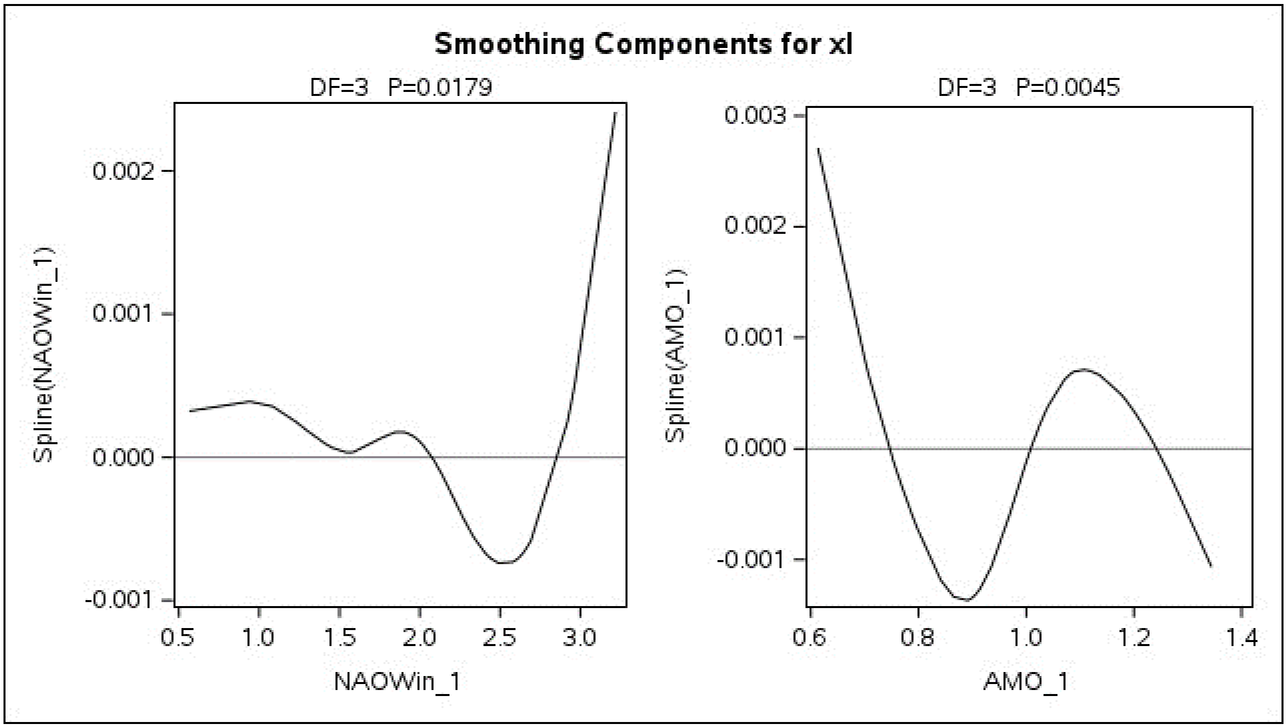


Figure 70. Smoothing component model results for summer flounder (*Paralichthys dentatus*) male aggregate mean length (xl) and the top 2 significant model factors.

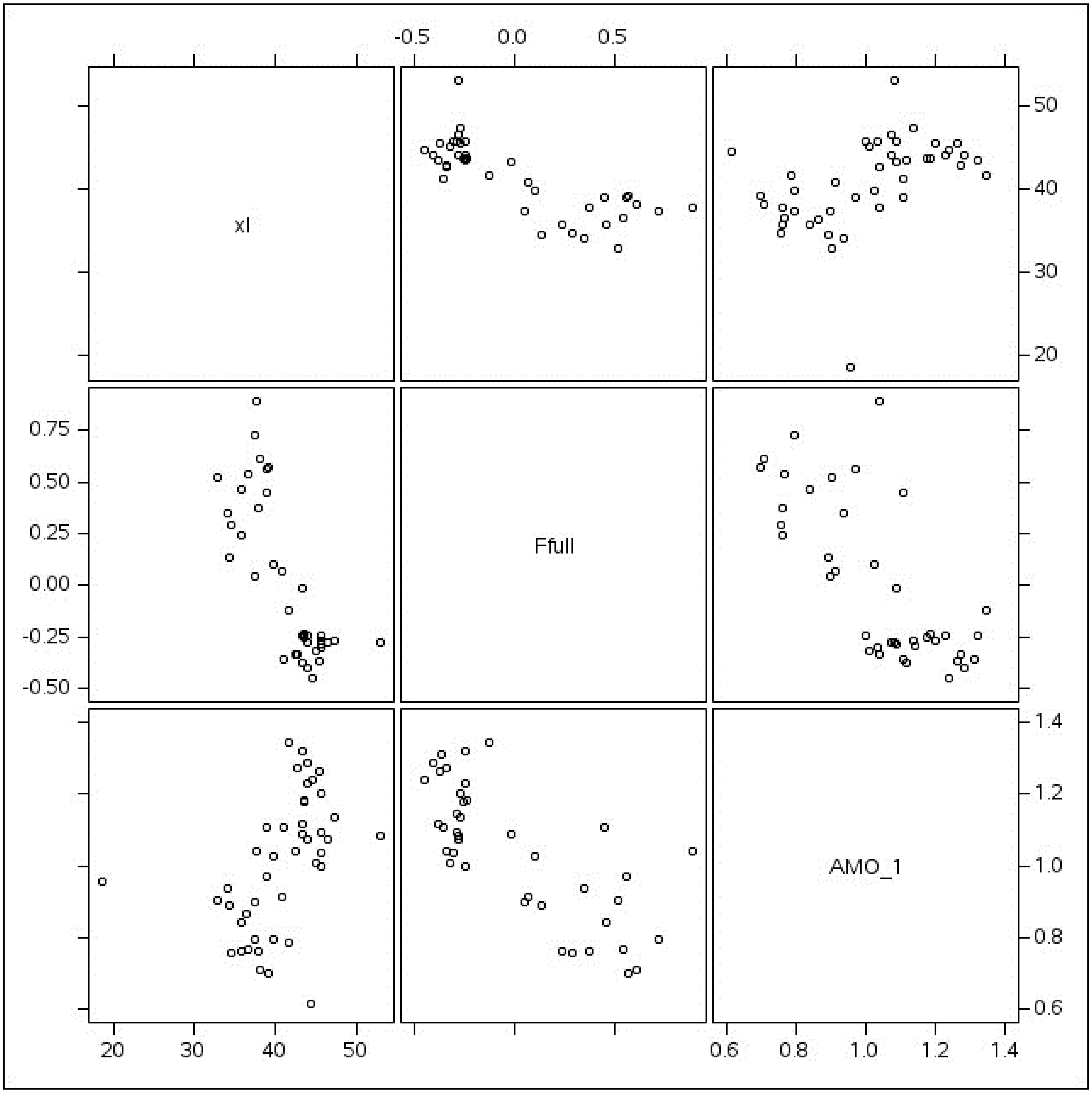


Figure 71. Scatter plot for summer flounder (*Paralichthys dentatus*) female aggregate mean length (xl) and the top 2 significant model factors.

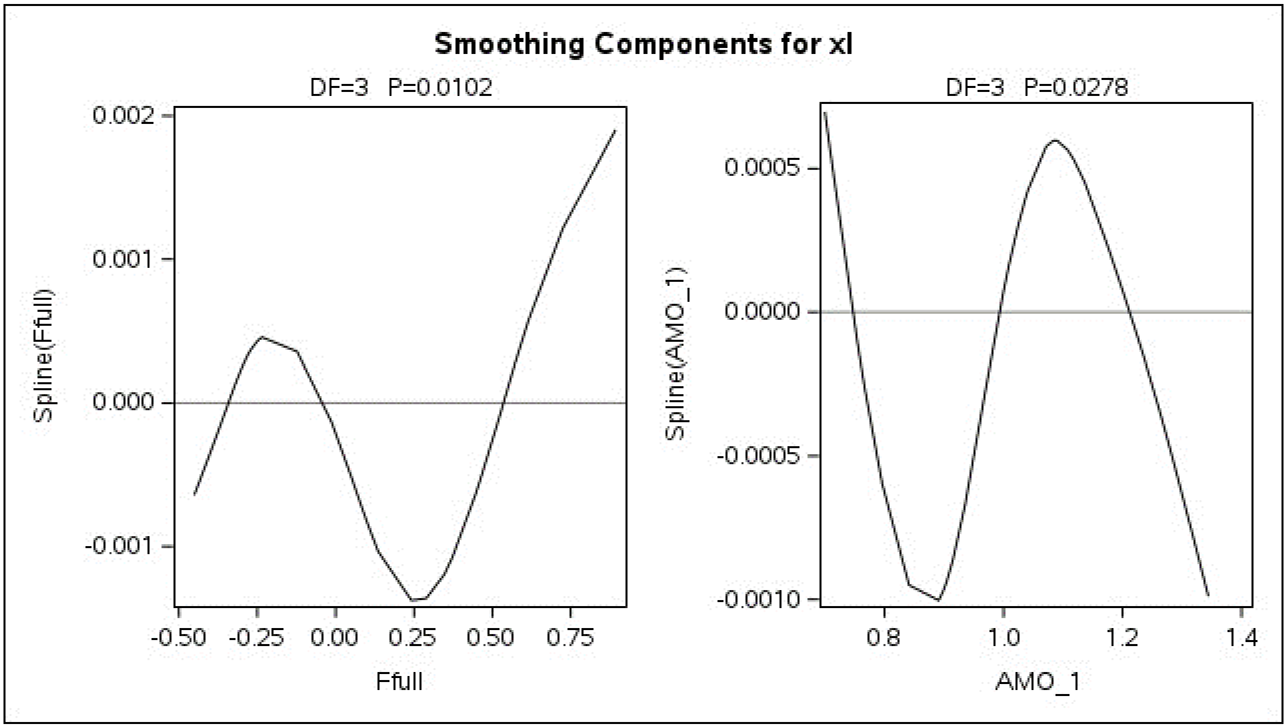


Figure 72. Smoothing component model results for summer flounder (*Paralichthys dentatus*) female aggregate mean length (xl) and the top 2 significant model factors.

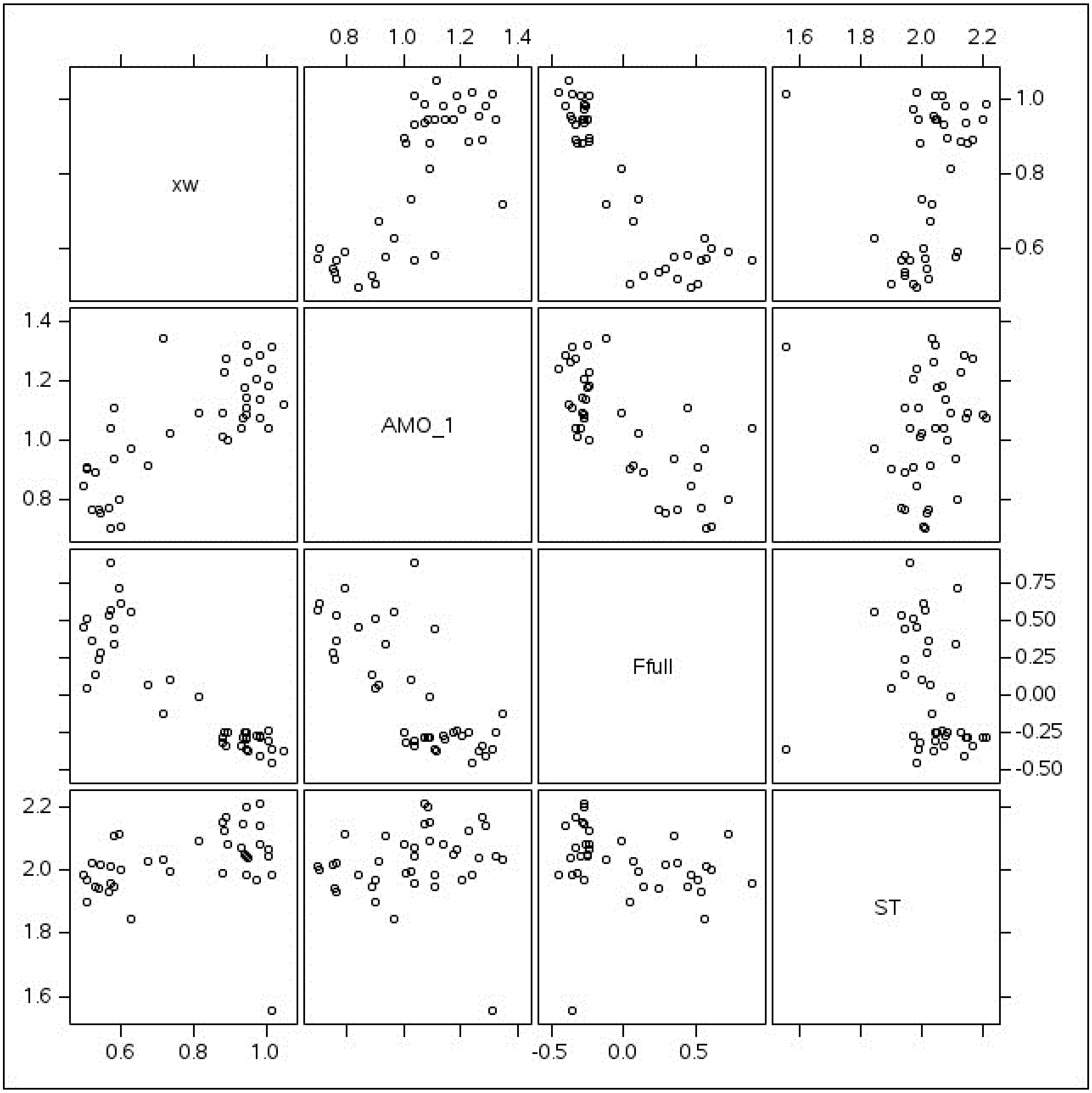


Figure 73. Scatter plot for summer flounder (*Paralichthys dentatus*) fishery aggregate mean weight (xw) and the top 3 significant model factors.

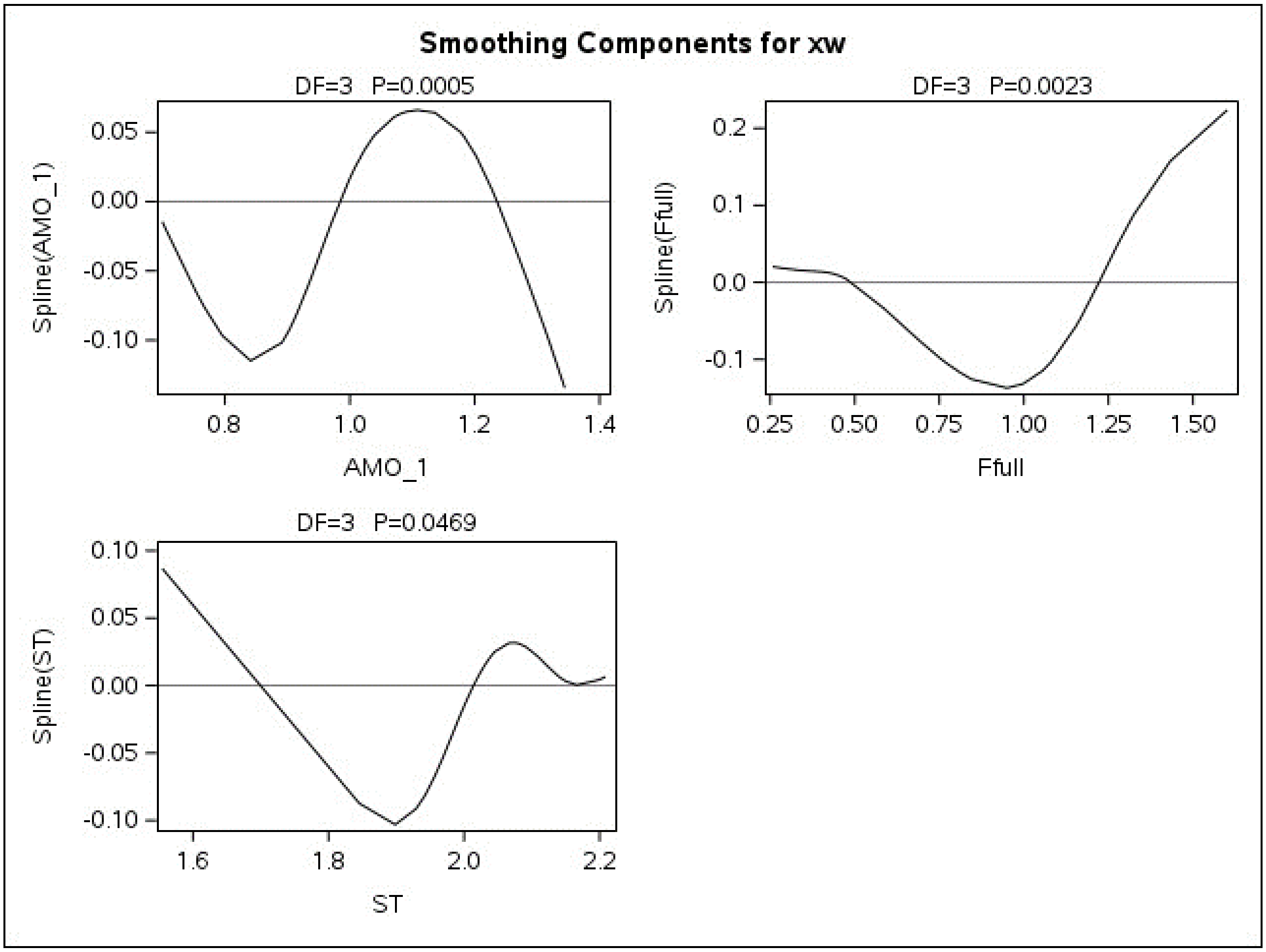


Figure 74. Smoothing component model results for summer flounder (*Paralichthys dentatus*) fishery aggregate mean weight (xw) and the top 3 significant model factors.

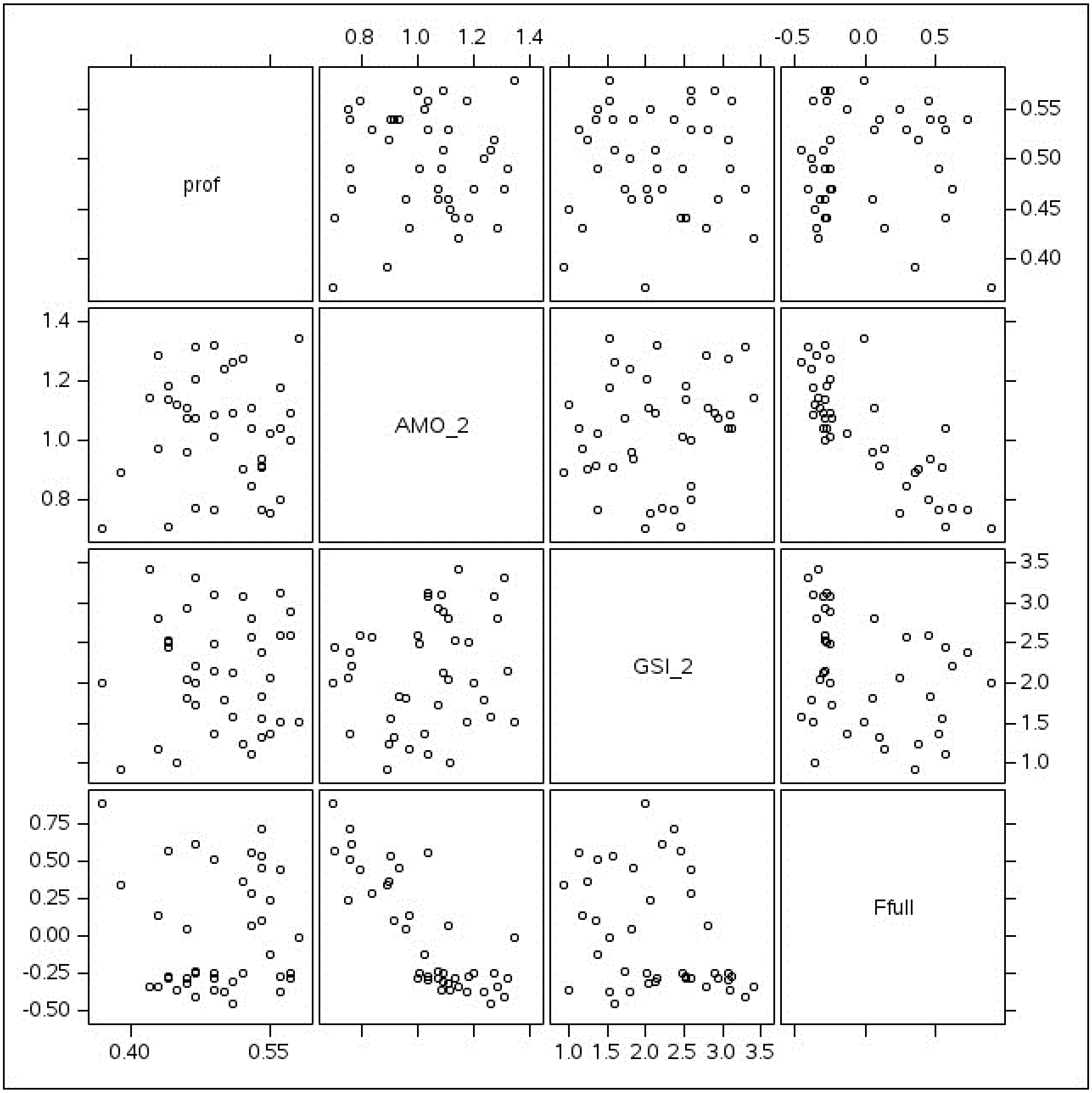


Figure 75. Scatter plot for summer flounder (*Paralichthys dentatus*) aggregate proportion female (prof) and the top 3 significant model factors.

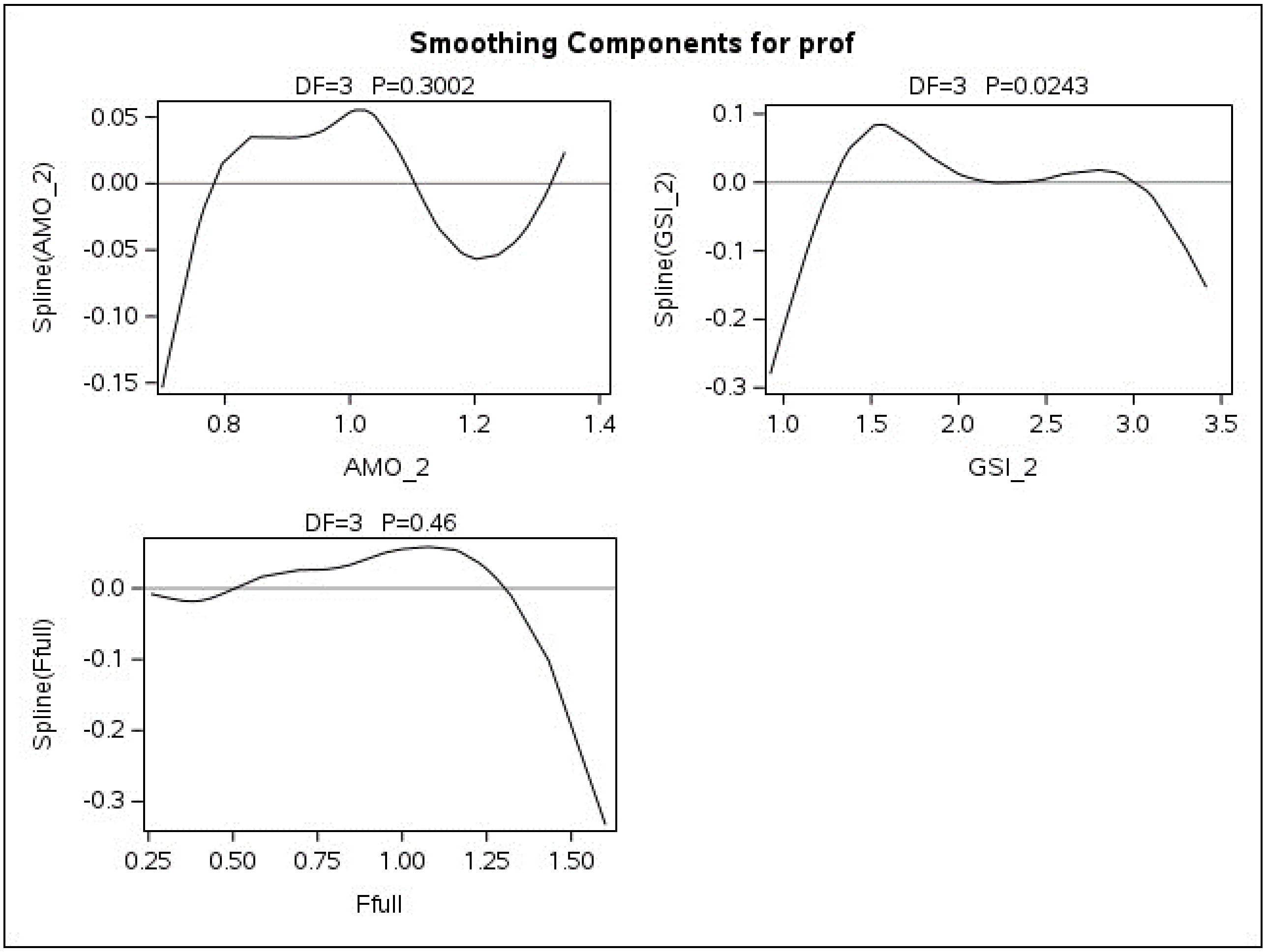


Figure 76. Smoothing component model results for summer flounder (*Paralichthys dentatus*) aggregate proportion female (prof) and the top 3 significant model factors.

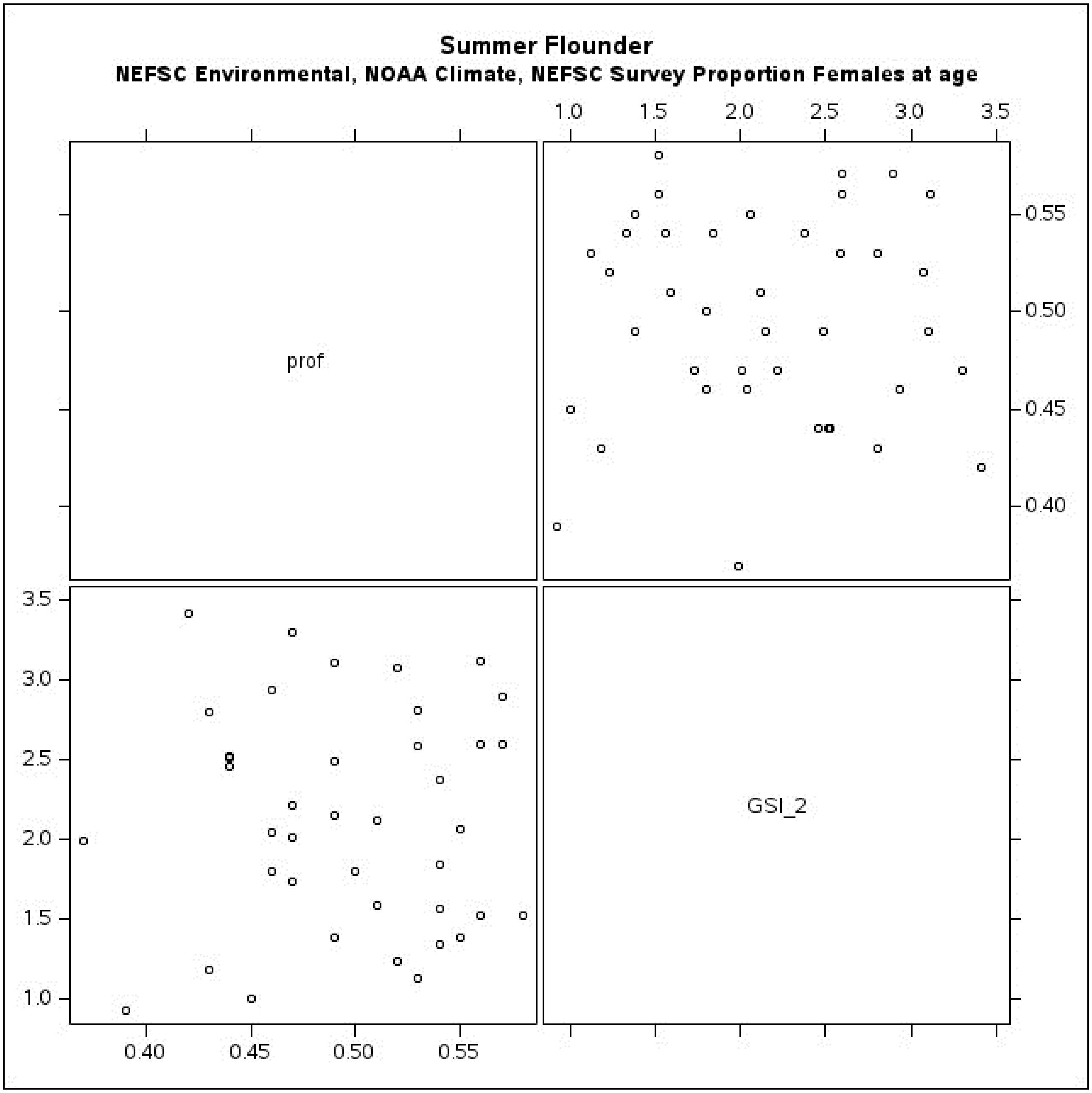


Figure 77. Scatter plot for Northeast Fisheries Science Center (NEFSC) survey index aggregate proportion of female (prof) summer flounder (*Paralichthys dentatus*) and the NEFSC environmental and National Oceanic and Atmospheric Administration (NOAA) climate top significant model factor.

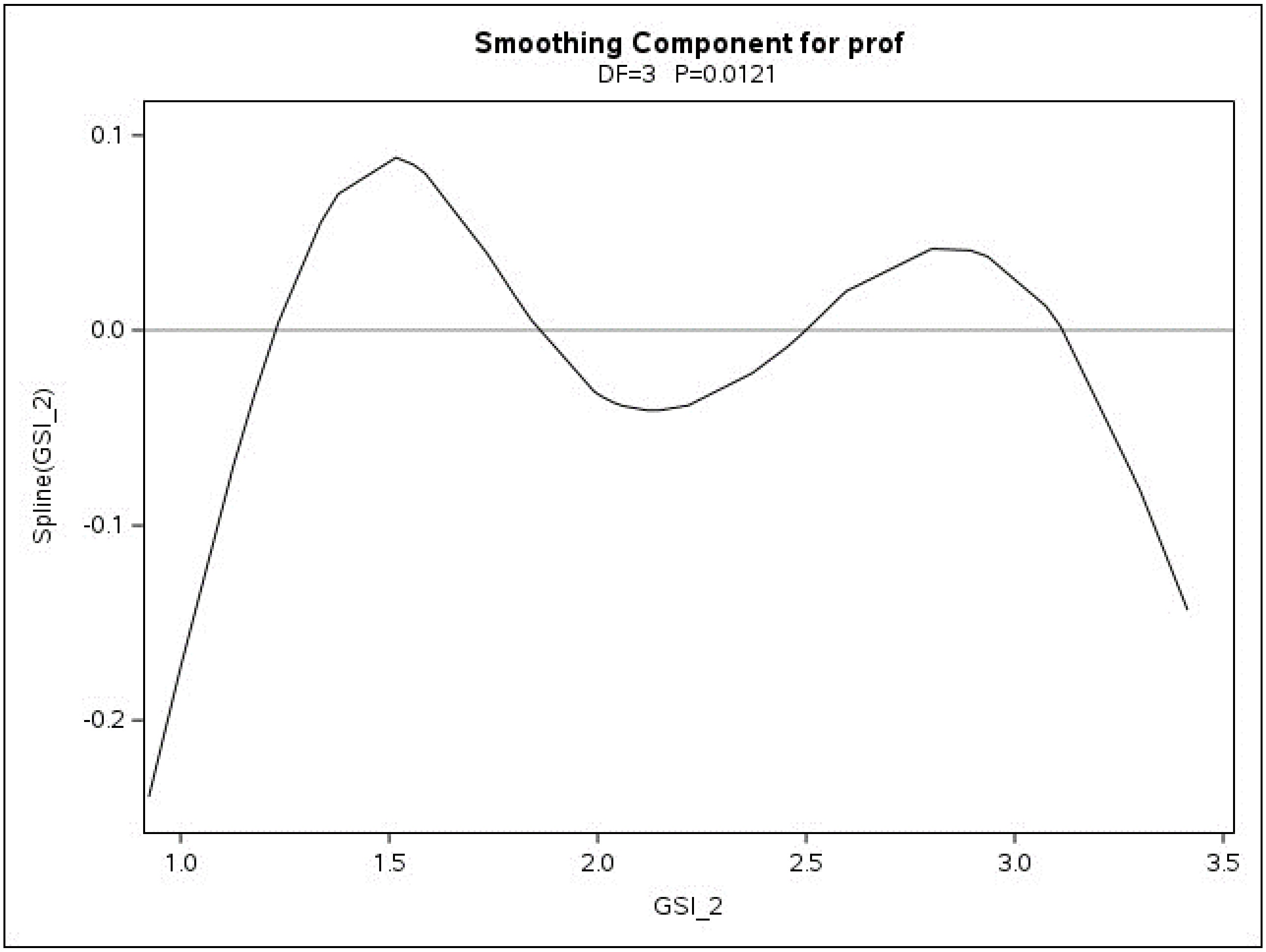


Figure 78. Smoothing component model results for aggregate proportion female (prof) and the top significant model factor.

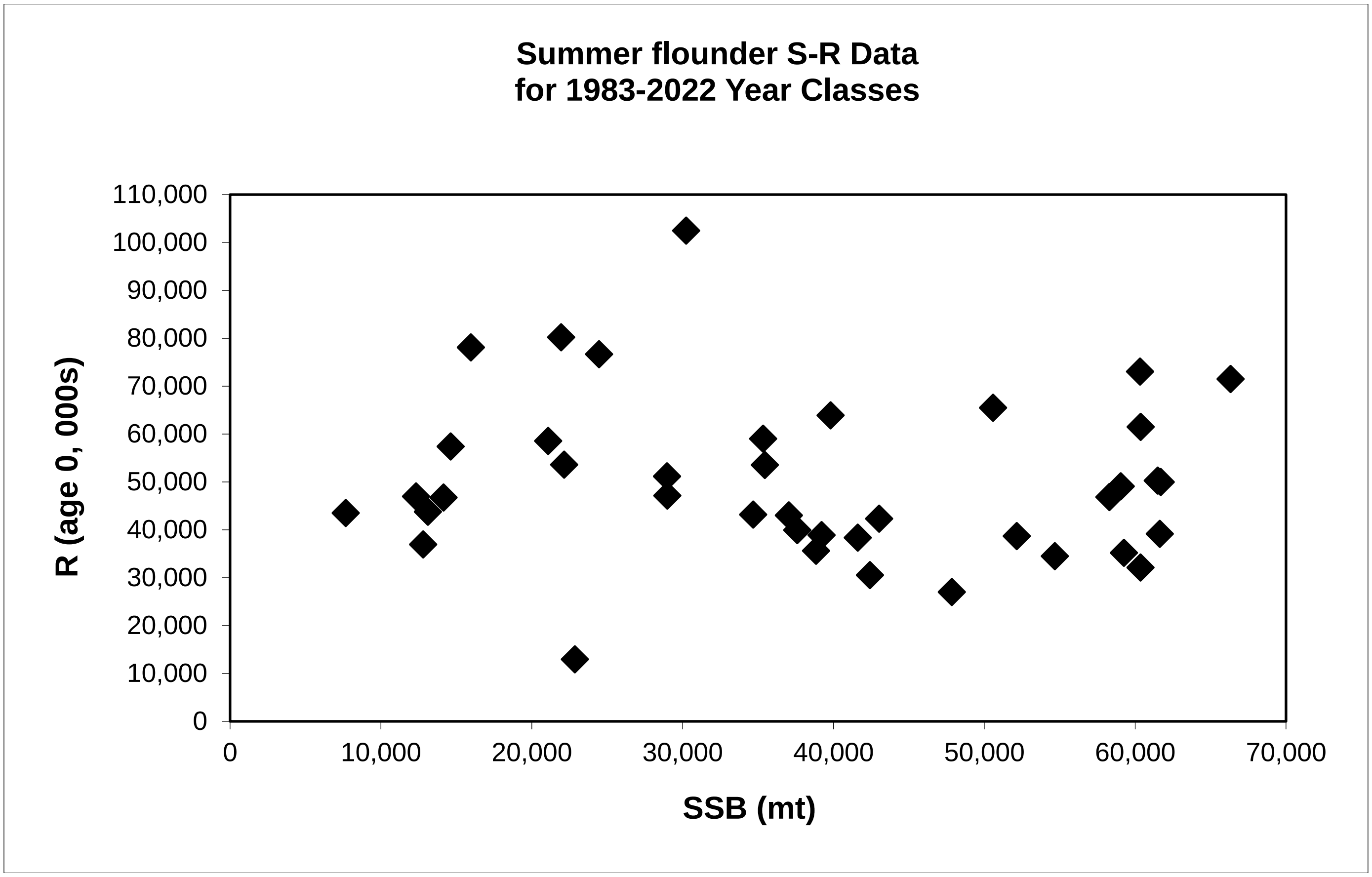


Figure 79. Estimates of summer flounder (*Paralichthys dentatus*) recruitment at age 0 (R in 000s) and spawning stock biomass (SSB in metric tons [mt]) through 2022 (NEFSC 2023).

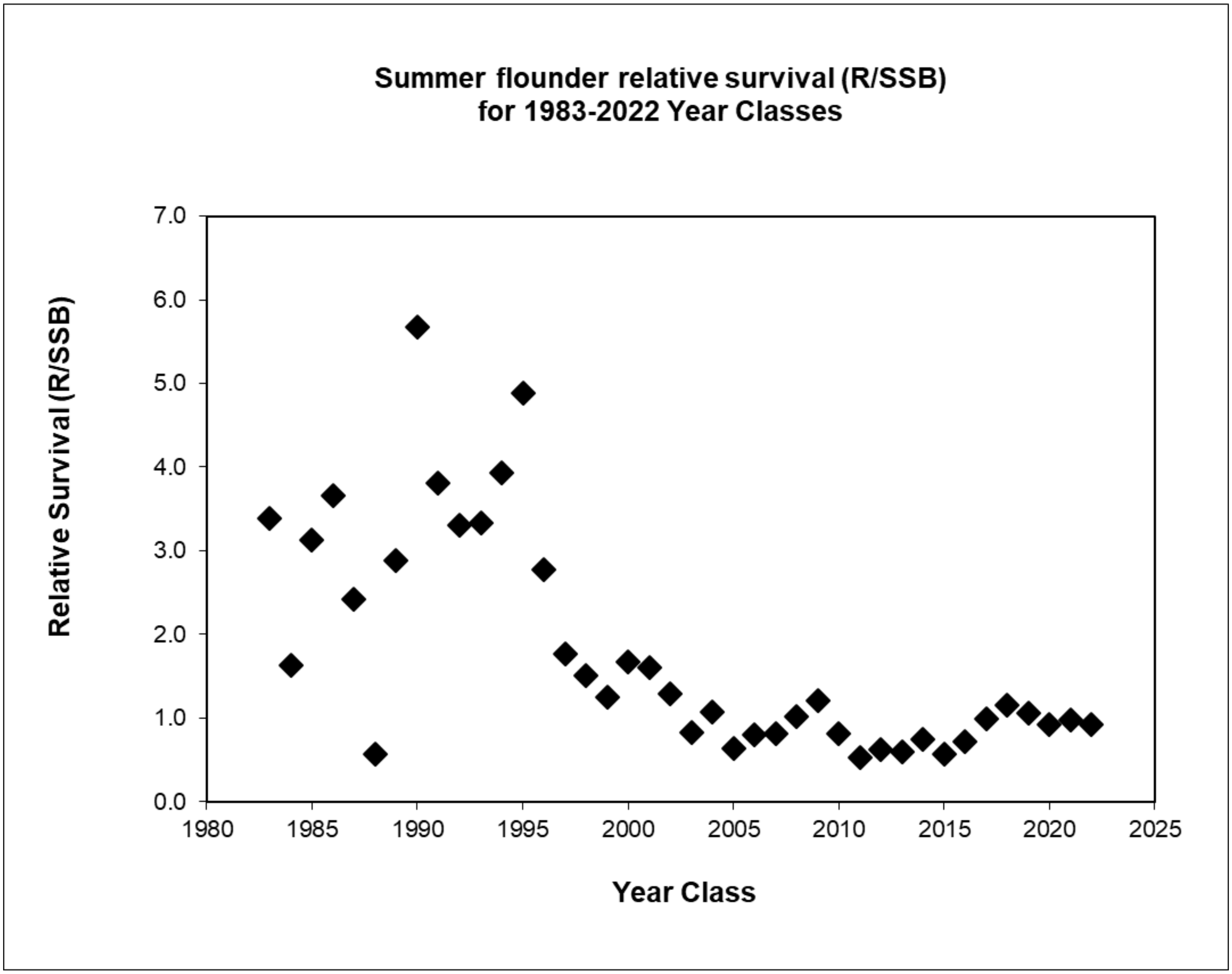


Figure 80. Estimates of summer flounder (*Paralichthys dentatus*) relative survival: recruits per spawning stock biomass (R/SSB) through 2022 (NEFSC 2023).

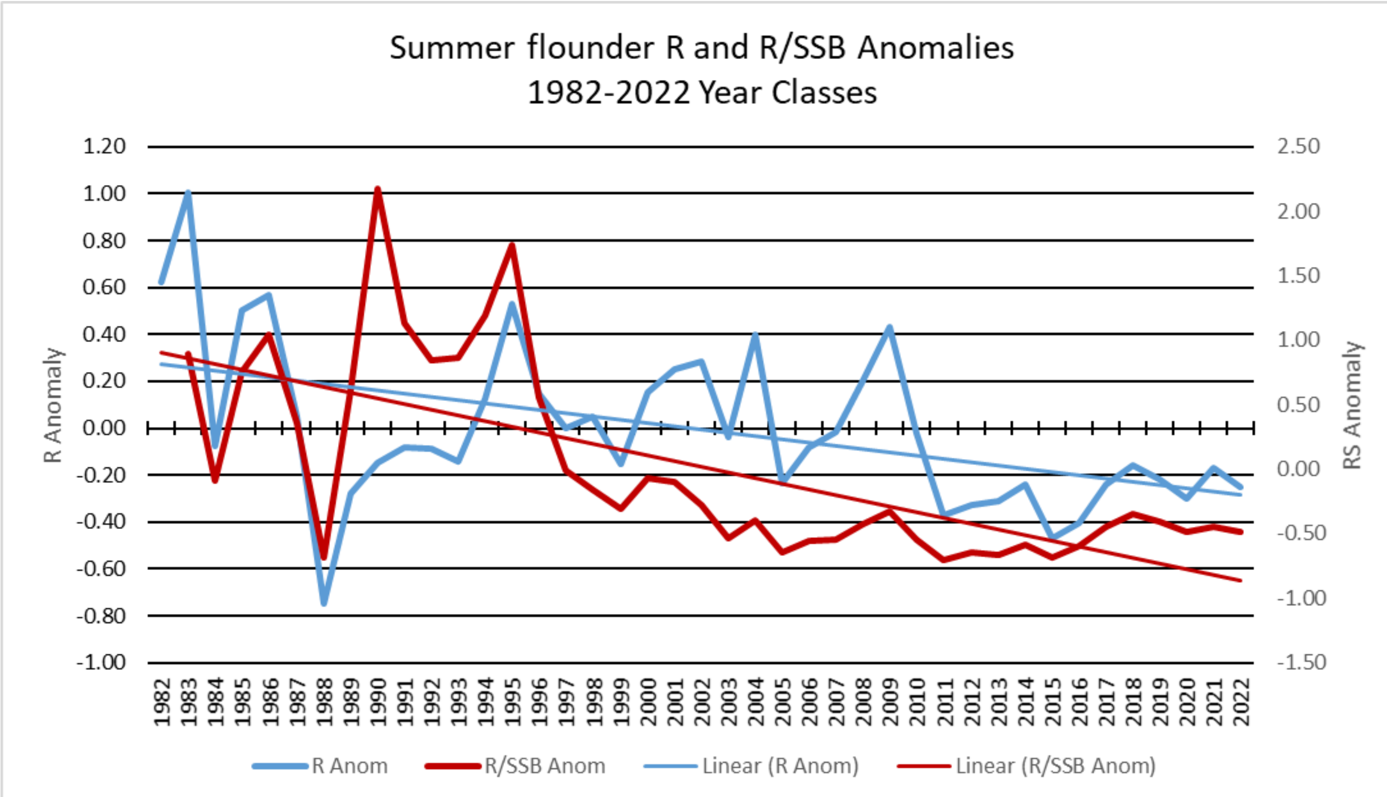


Figure 81. Summer flounder (*Paralichthys dentatus*) recruitment at age 0 (R) and recruits per spawning stock biomass (R/SSB) anomalies through 2022.

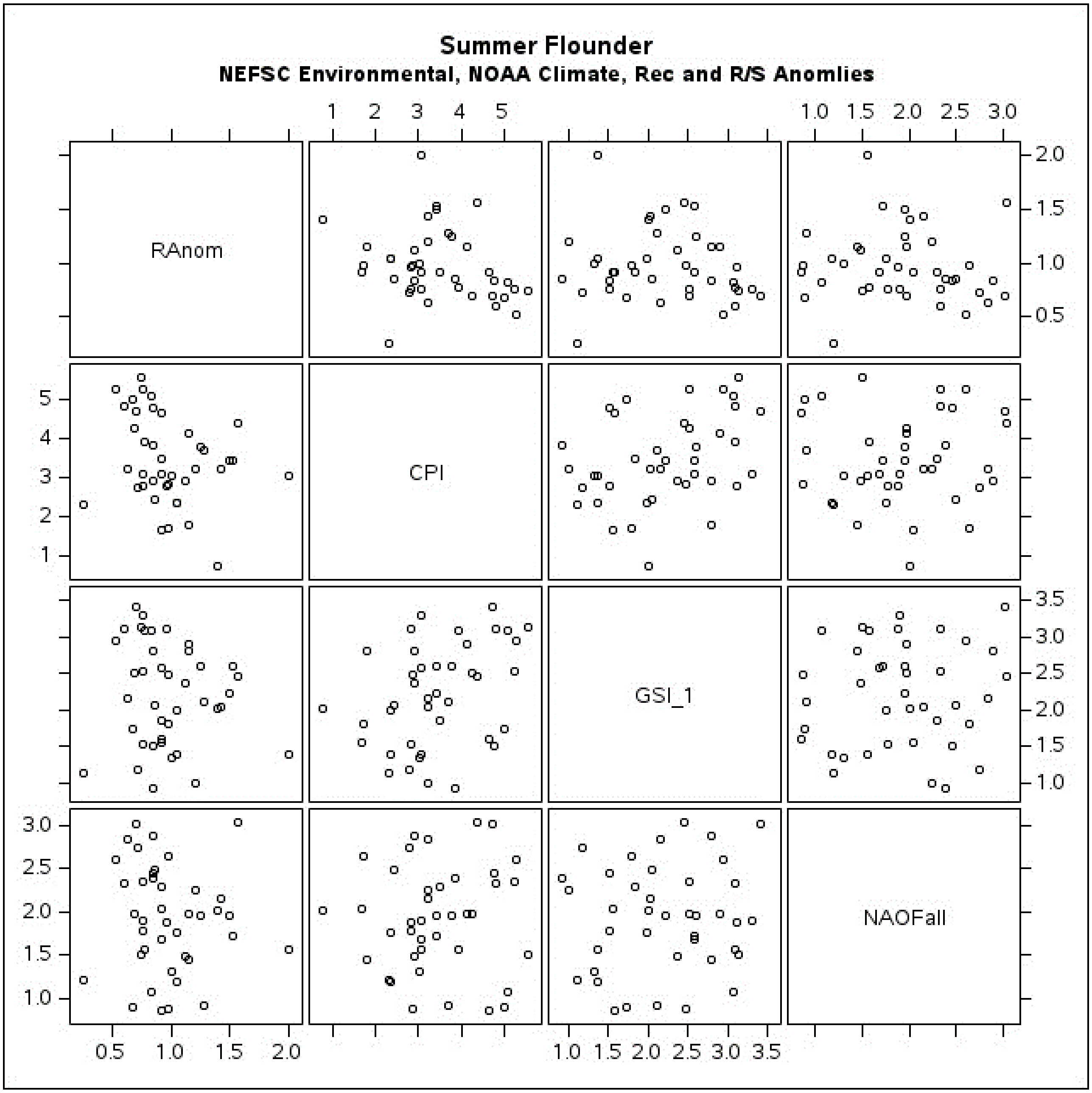


Figure 82. Scatter plot for absolute recruitment (RAnom) of summer flounder (*Paralichthys dentatus*) and the Northeast Fisheries Science Center (NEFSC) environmental and National Oceanic and Atmospheric Administration (NOAA) climate top 3 significant model factors.

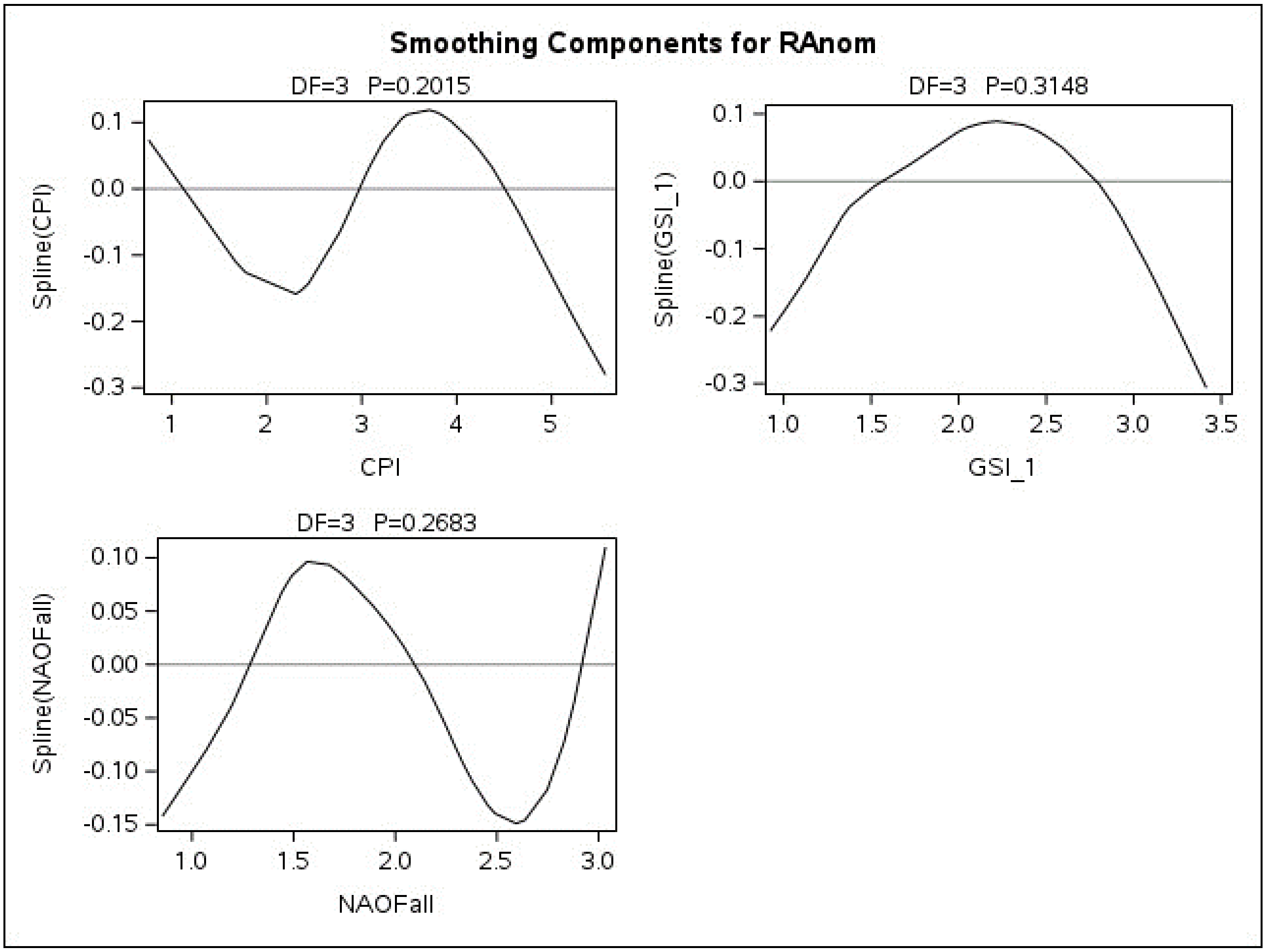


Figure 83. Smoothing component model results for absolute recruitment (RAnom) and the top 3 significant model factors.

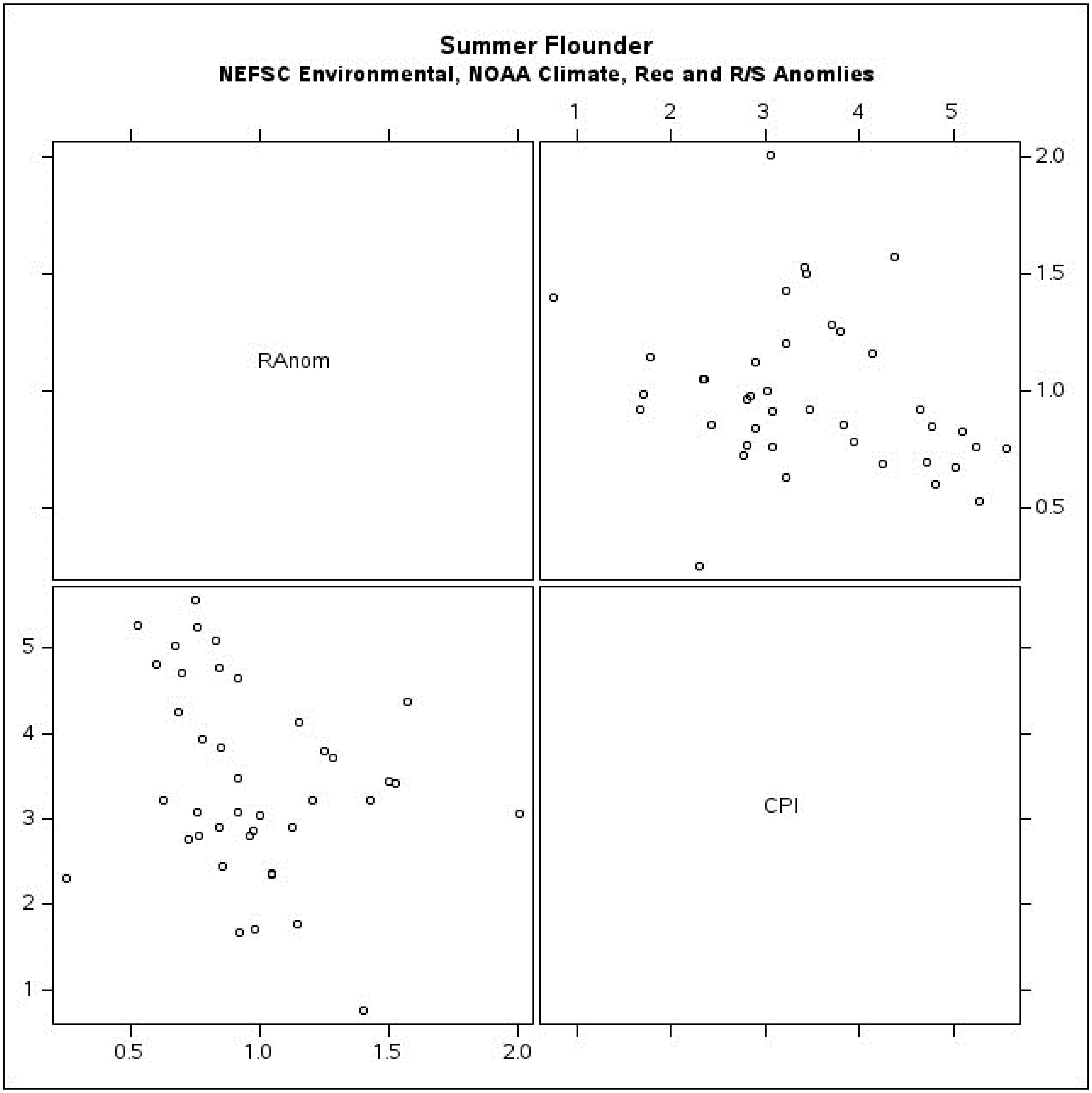


Figure 84. Scatter plot for absolute recruitment (RAnom) of summer flounder (*Paralichthys dentatus*) and the Northeast Fisheries Science Center (NEFSC) environmental and National Oceanic and Atmospheric Administration (NOAA) climate top significant model factor.

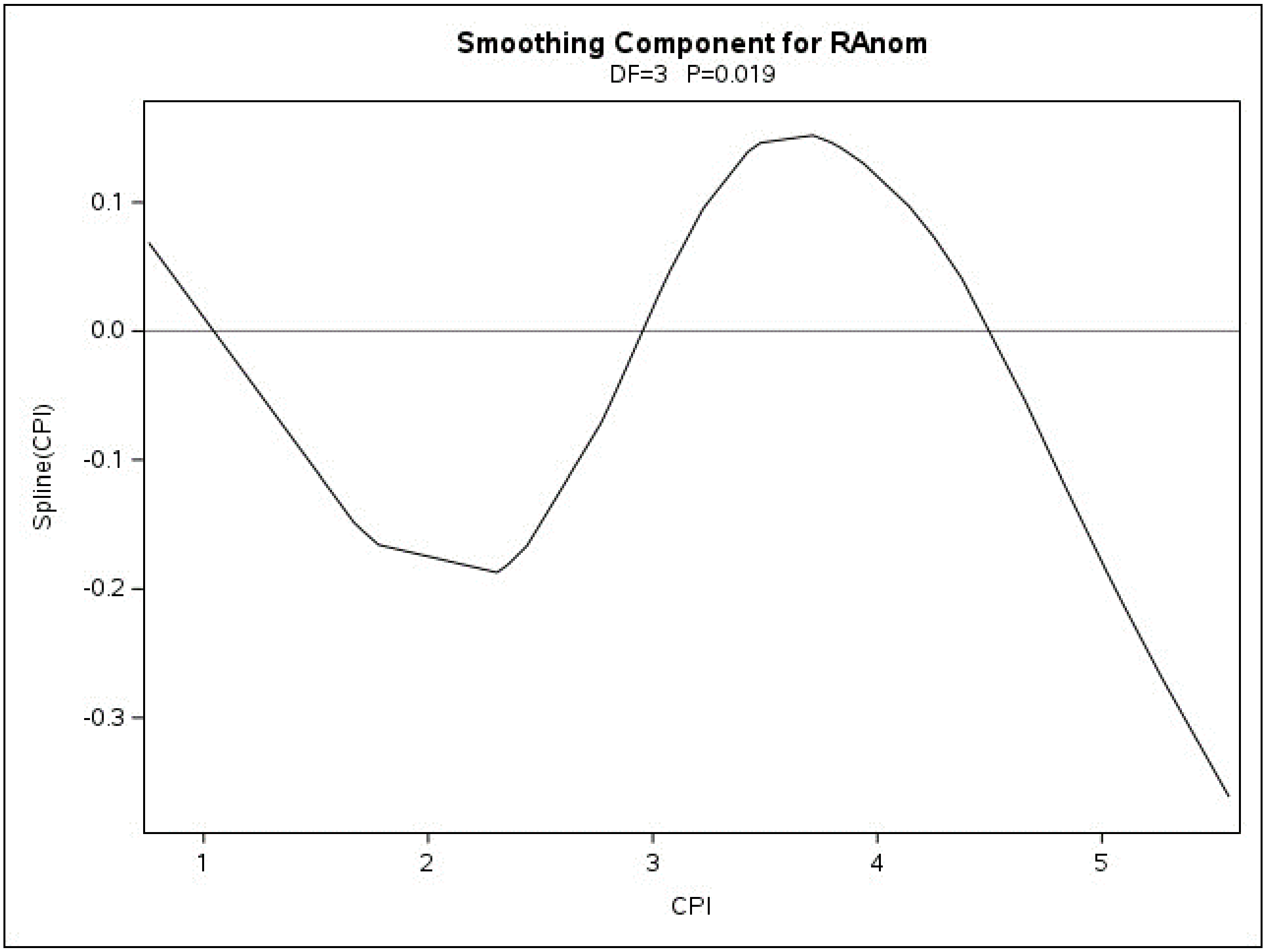


Figure 85. Smoothing component model results for absolute recruitment (RAnom) and the top significant model factor.

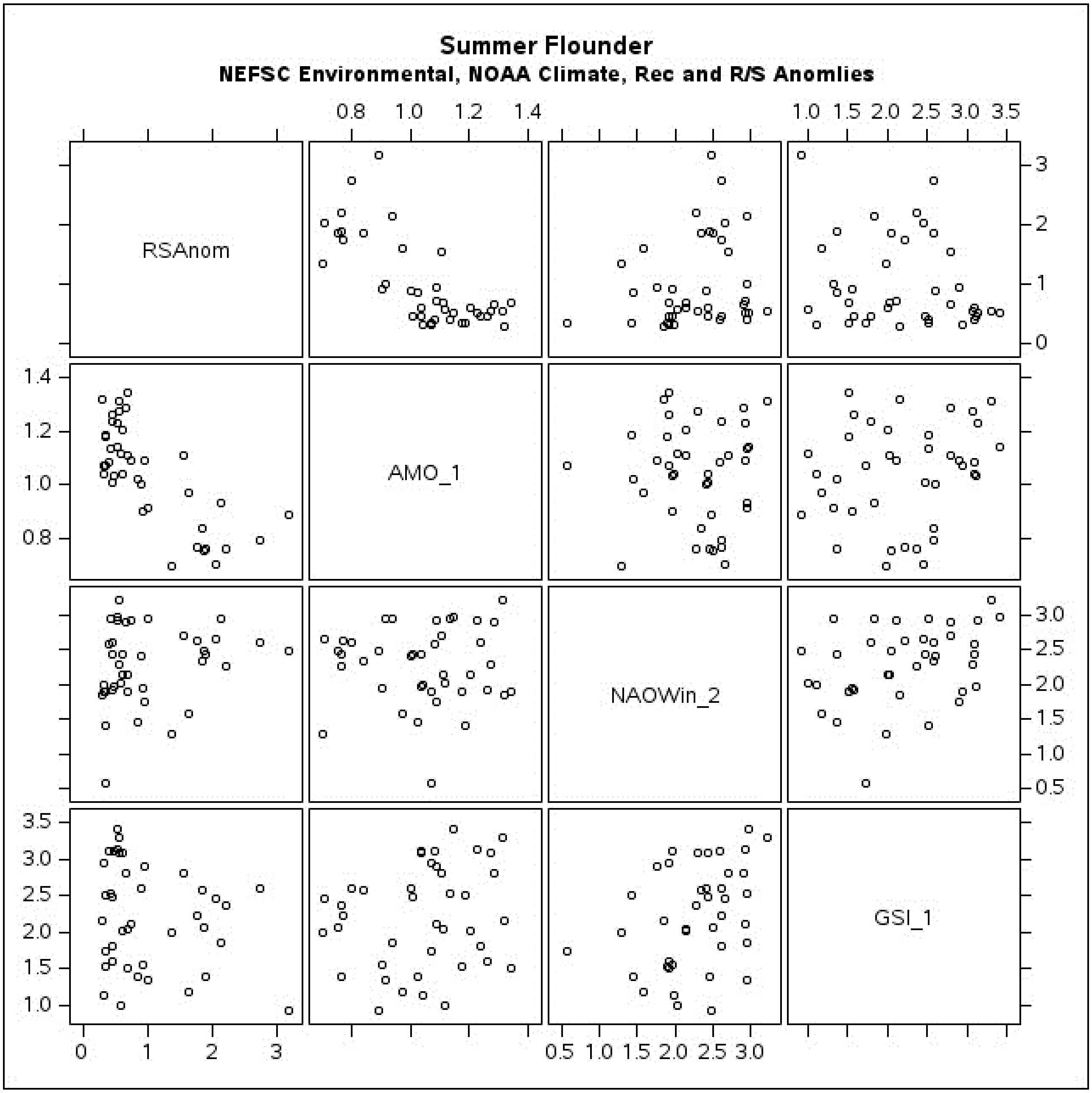


Figure 86. Scatter plot for recruits per spawning stock biomass (RSAnom) of summer flounder (*Paralichthys dentatus*) and the Northeast Fisheries Science Center (NEFSC) environmental and National Oceanic and Atmospheric Administration (NOAA) climate top 3 significant model factors.

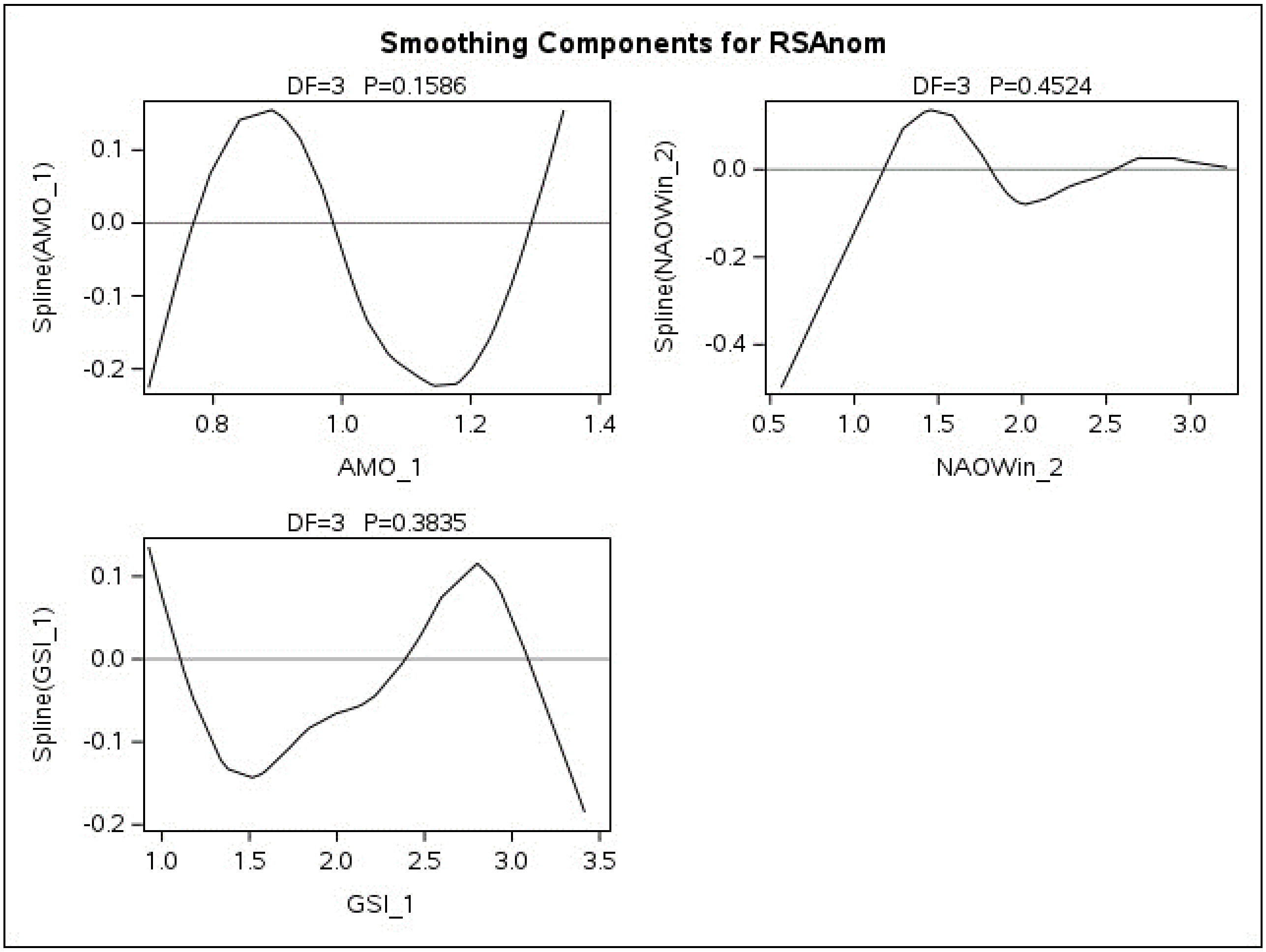


Figure 87. Smoothing component model results for recruits per spawning stock biomass (RSAnom) and the top 3 significant model factors.

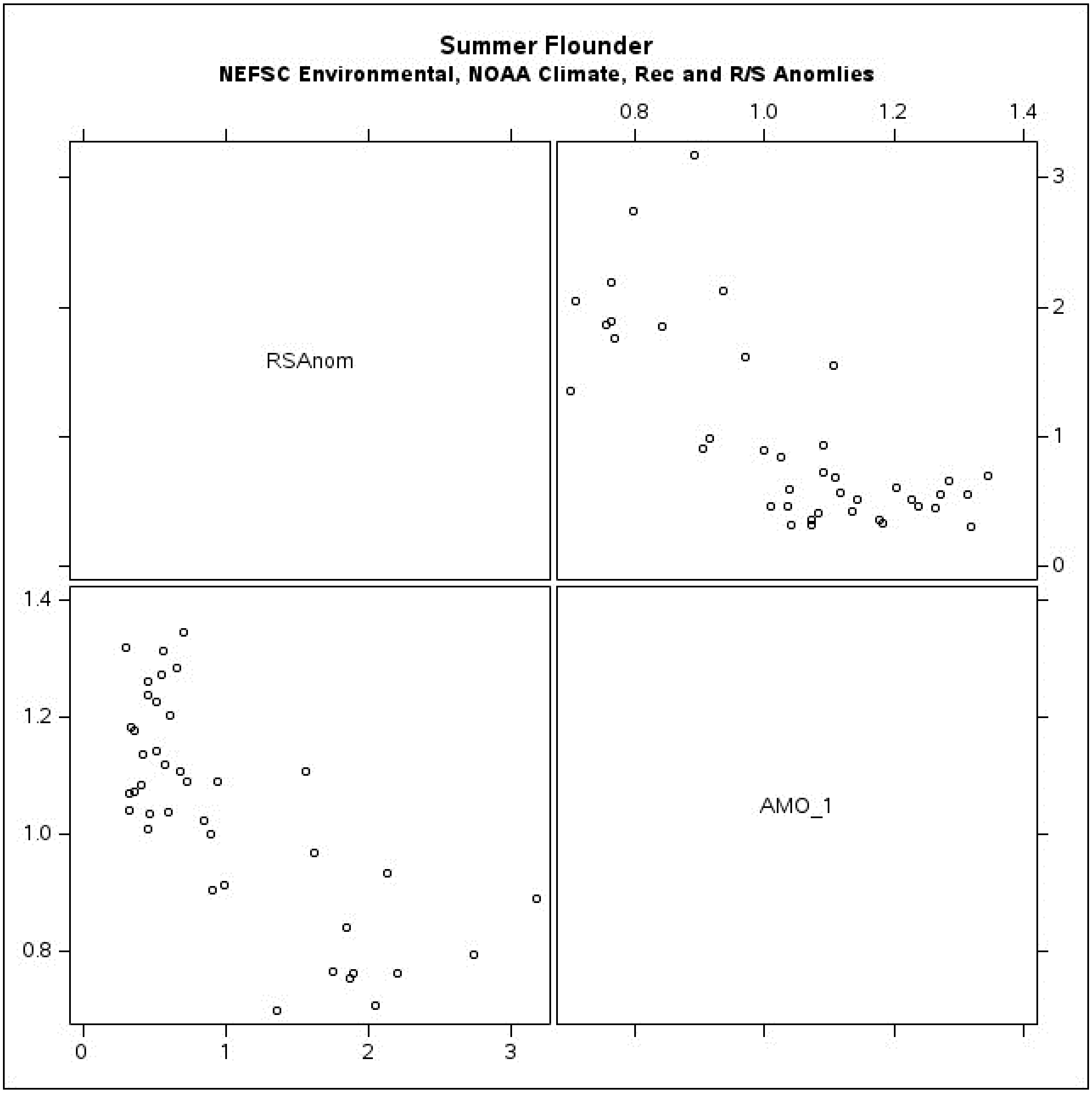


Figure 88. Scatter plot for recruits per spawning stock biomass (RSAnom) of summer flounder (*Paralichthys dentatus*) and the Northeast Fisheries Science Center (NEFSC) environmental and National Oceanic and Atmospheric Administration (NOAA) climate top significant model factor.

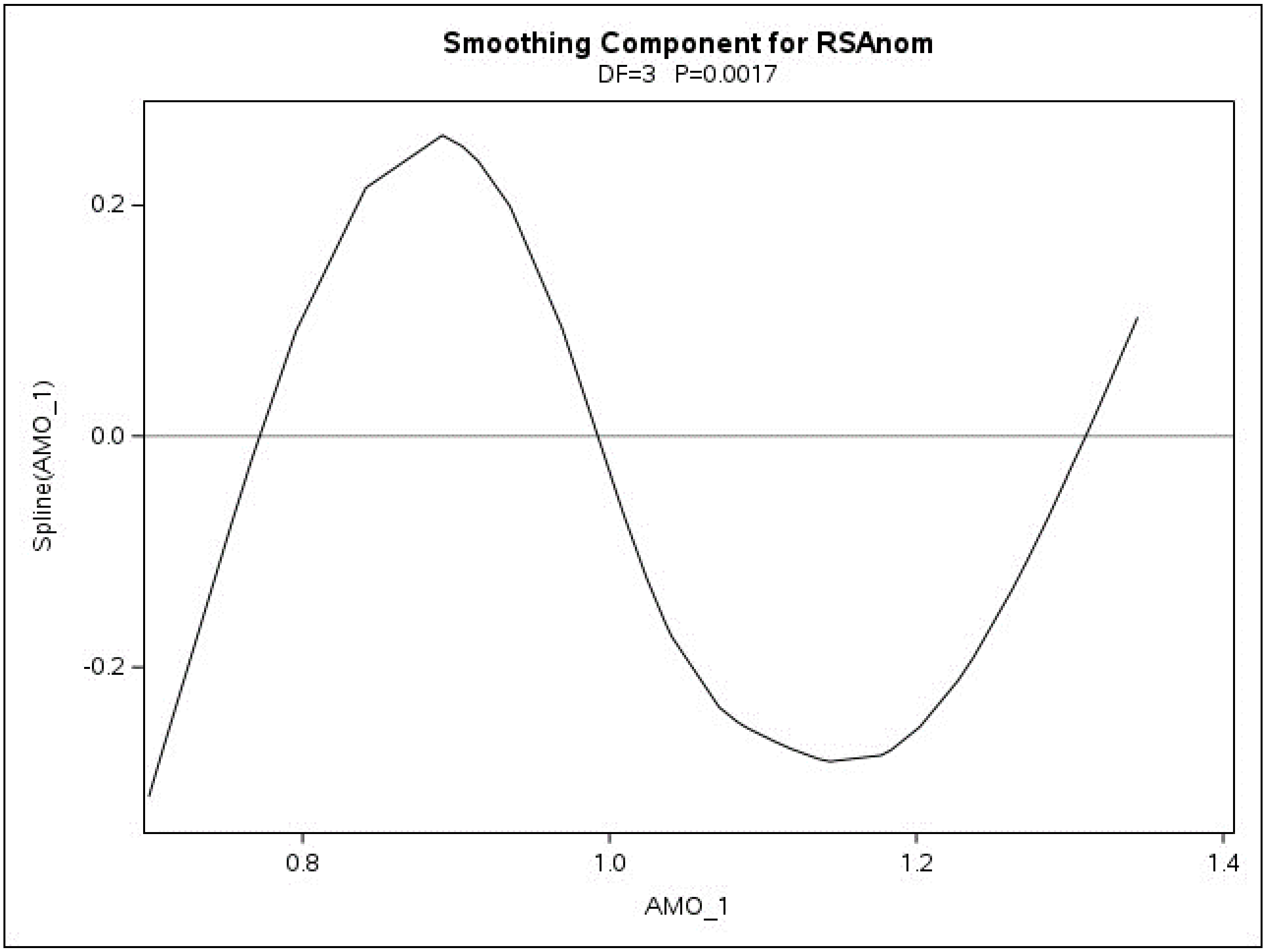


Figure 89. Smoothing component model results for recruits per spawning stock biomass (RSAnom) and the top significant model factor.

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