

Stock Synthesis For Atlantic Spiny Dogfish

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1 Introduction

An Atlantic spiny dogfish stock assessment model was developed in Stock Synthesis version 3.30.18 (SS3; Methot and Wetzel 2013) to provide an alternative for the index-based approach (Stochastic Estimator; NEFSC 2006) that was used in the previous assessments. SS3 is a statistical length-based age-structured population modeling framework. It is one of the most widely used stock assessment packages in the U.S. and globally (Dichmont 2016, 2021) and has many essential features of next-generation stock assessment models (Punt et al. 2020). Unlike most age-structured stock assessment models, SS3 can tune directly to length data, which is necessary when age data are lacking, as in Atlantic spiny dogfish. Additionally, SS3 can model sexes separately, an essential feature for a sexually dimorphic species such as spiny dogfish where the fishery targets only females. SS3 was recently used to assess Pacific spiny dogfish (Gertseva and Taylor 2021).

A sex-specific SS3 model was constructed for the Atlantic spiny dogfish to account for the life history and fishing differences between sexes. The SS3 runs were conducted solely on length data with assumed/estimated growth parameters within the model, without age data. While there was an effort to age Atlantic spiny dogfish and provide up-to-date age information for this assessment, due to several potential issues for the new age data, the Working Group decided not to use it for this assessment (Passerotti and McCandless 2022). Since growth is likely the primary uncertainty of this assessment, extensive sensitivity and profile analyses on various growth assumptions were conducted.

2 Model Configuration

2.1 Time Series Data

2.1.1 Catch

Commercial catch data (metric tons) available for SS3 modeling including U.S. and distant water commercial fisheries and U.S. recreational landings from 1962 to 2019, and discards

from U.S. commercial fisheries and U.S. recreational landings from 1989 to 2019 (see TOR2). Both landings and discards data are available by gear type and summarized in Table 1. The discards were converted into dead discards using gear-specific discard mortalities and modeled as "catch" in SS3 (see TOR2). The commercial data by gear were aggregated into five modeling fleets (two fleets for landings and three fleets for discards) based on examining the similarities of their length compositions (Table 1 and Figures 1-2).

2.1.2 Abundance and Biomass Indices

The Northeast Fisheries Sciences Center (NEFSC) bottom trawl survey data was used as the primary abundance index for the SS3 modeling since it is the only resource-wide survey available for this stock (see TOR3). The survey has operated in the spring and fall since 1968. Like the previous assessments, only the spring bottom trawl data were used because a portion of dogfish are outside of the bottom trawl survey domain in the fall due to seasonal migrations. The 2014 spring bottom trawl survey data were excluded from SS3 modeling because of missing data from critical survey strata in the Mid-Atlantic region. The annual stratified mean number per tow index was expanded using a factor of 5,260,450, the ratio of the total area surveyed divided by the swept area of a tow (wings only), the same expansion factor used in the Stochastic Estimator. This expansion allows the survey catchability q estimated in SS3 to be interpretable as gear efficiency combined with availability.

Additional abundance/biomass indices considered in SS3 modeling were the NEFSC bottom longline survey data (2014-2021; Nieland and McElroy 2022) and a vector auto-regressive spatio-temporal model-based index (VAST) that combined four trawl surveys from NEFSC (1980-2021), Massachusetts Division of Marine Fisheries (1980-2021); Maine/New Hampshire (2005-2021); and Northeast Area Monitoring and Assessment Program (NEAMAP; 2007-2021; Hansell and McManus 2022; see TOR3). These abundance/biomass indices, along with the NEFSC fall bottom trawl survey index, were included in SS3 as sensitivity runs.

The abundance/biomass indices are assumed to have a lognormal error structure, and the standard error of $\sqrt{\ln(1 + (CV)^2)}$ where CV is the coefficient of variation. A constant parameter added to the inputted standard error of the survey indices was estimated in SS3 for each survey.

2.1.3 Length Composition

Sex-specific length composition data from catch and survey for all fleets and years, except for the 2014 NEFSC spring bottom trawl survey, were available for this assessment. Total length data were partitioned into 31 length bins, from 20 to 110+ cm with a 3 cm increment. The SS3 estimated population numbers at length (population length bins) were structured the same as the length composition data. Length composition data were excluded and not used in the modeling when the effective sample size was one, or the number of length bins covered was less than five, as they are less credible (Figure 2). Comparing preliminary model runs using the complete data versus the reduced data showed no difference in population estimates, suggesting that the excluded data were not informative.

2.2 Initial Population State

SS3 model runs started in 1989, the first year quantitative discards information was available from observer data. Discards before 1989 were a significant source of mortality for spiny dogfish (NEFSC 1994); thus, the Working Group was reluctant to start the model before 1989 without accurate discards information. Since fishing for dogfish occurred before 1989, an initial equilibrium catch was assumed, and initial fishing mortality was estimated for each fleet in SS3. The initial equilibrium catch by fleet was estimated using an average of the 1962-1988 catch data. Total landings from 1962 to 1988 were obtained from Sosebee (2019). Total discards from 1962 to 1988 were hindcasted using the observed ratio of discarded dogfish to landings of all species in 1989 from otter trawl and gill nets fishery (NEFSC 2006). Hindcasted total discards are likely underestimated because they only rely on two types of gears. Total landings and hindcasted total discards were assigned to each fleet using the averaged by-fleet proportion from the 1989-1993 catch data. An SS3 run of starting the model from 1962 and assuming fishing mortality to be negligible prior to 1962 was conducted in the sensitivity analysis.

2.3 Life History

Life history characteristics, including sex-specific length-weight relationship, female maturity, and fecundity relationship, were updated using NEFSC bottom trawl survey data during this assessment and fixed at the updated values in SS3 (Hart and Sosebee 2022; Sosebee 2022). During the preliminary model explorations, the Working Group found evidence of changing life history characteristics, including growth, maturity, and fecundity for Atlantic spiny dogfish in recent years. In particular, the estimated length at 50% maturity declined from 80 cm in 1998-2011 to 73 cm during 2012-2019 (Sosebee 2022). Therefore, time blocks of 1989-2011 and 2012-2019 (referred to as biology blocks) were implemented in SS3 to allow growth, maturity, and fecundity to vary through time. Different growth, maturity, and fecundity parameter values were assumed/estimated for each block in SS3. Several sensitivity runs were conducted to examine the biology block assumption.

2.3.1 Growth

In the past assessments, the sex-specific growth for Atlantic spiny dogfish was assumed to follow a von Bertalanffy (VB) relationship estimated by Nammack et al. (1985; Table 2). A new growth study was conducted during this assessment to provide up-to-date growth information for this stock (Passerotti and McCandless 2022). During the preliminary model explorations, the new age data was compiled as conditional distributions of age-at-length, and VB growth parameters were estimated for each sex in SS3 (Figure 3). However, due to the high variability in length by age classes, especially for older females (Figure 3), the estimated standard deviations around the estimated growth curve were unrealistically large. As a result, the estimated selectivities for landings and surveys became dome-shaped, which the Working Group found to be unreasonable. SS3 runs that fixed the growth parameters at the values estimated by Passerotti and McCandless (2022) using the new growth data were

also conducted. However, the results were similarly unrealistic. Given the uncertainties of the new growth data identified in Passerotti and McCandless (2022), and the unrealistic SS3 model results, the new growth data were not used in this assessment.

Performances of the model using Nammack et al. (1985) growth and models with time-varying growth where the VB parameters were estimated for the biology block 2012-2019 were examined during the preliminary model explorations. The results showed a significant improvement in Akaike information criterion (AIC), resulted from the reduced VB asymptotic length (L_∞), especially for the females (Table 2). The reduction of L_∞ reflects the absence of large females in both catch and survey data for recent years (Figure 4). The Working Group decided to estimate L_∞ for both sexes in SS3 for the 2012-2019 period but fix the VB length at age-0 (L_{Amin}) and growth coefficient (k) at the values of Nammack et al. (1985) for the base case model. Sensitivity and profile analyses with various growth assumptions were conducted. The maximum age in SS3 was fixed at 50 yr based on the approximate maximum age observed (Passerotti and McCandless 2022).

2.3.2 Length-Weight, Maturity, and Fecundity Relationships

Sex-specific length-weight relationships in SS3 were estimated using NEFSC bottom trawl survey data from 1993 to 2019 from generalized linear mixed-effects models (Hart and Sosebee 2022; Figure 5):

$$W = 1.899348e - 06L^{3.188} \text{ for females,} \quad (1)$$

$$W = 3.656515e - 06L^{3.006} \text{ for males,} \quad (2)$$

where W is total weight (kg) and L is total length (cm).

Female maturity relationships were estimated for 1998-2011 and 2012-2019, respectively, using NEFSC bottom trawl survey data and used in SS3 (Sosebee 2022; Figure 6):

$$Mat = \frac{1}{1 + \exp(-0.4098361(79.9 - L))} \text{ for biology block: 1989-2011,} \quad (3)$$

$$Mat = \frac{1}{1 + \exp(-0.2832861(73.1 - L))} \text{ for biology block: 2012-2019,} \quad (4)$$

where Mat is proportion mature and L is total length (cm).

Fecundity relationships were estimated for 1998-2011 and 2012-2019, respectively, using the pups/embryo data found in a subsample of female dogfish in the NEFSC bottom trawl survey and used in SS3 (Hart and Sosebee 2022; Figure 7):

$$P = 5.525074e - 06L^{3.046335} \text{ for biology block: 1989-2011,} \quad (5)$$

$$P = 7.893089e - 06L^{2.950182} \text{ for biology block: 2012-2019,} \quad (6)$$

where P is number of pups (age-0) and L is total length (cm).

2.4 Natural Mortality

The past Atlantic spiny dogfish assessments assumed a natural mortality (M) of 0.092 (Hoenig 1983; Rago et al. 1998). For this assessment, sex- and age-specific natural mortality was fixed at values derived using Lorenzen (1996) method and scaled to the average of Then et al. (2015) estimate ($M = 0.102$; Anstead 2022; Figure 8). Sensitivity runs were conducted to examine various M assumptions.

2.5 Spawner-Recruitment Relationship

Stock-recruit (SR) relationship in SS3 models the relationships between age-0 fish and spawning output, i.e., the number of pups the mature females produced (1,000s) at the beginning of each year (Methot et al. 2021). Ricker, Beverton-Holt, and survivorship SR relationships were explored during this assessment. The survivorship SR relationship developed by Taylor et al. (2013) is an SR model that explicitly models the survival between embryos and age-0 recruits, which is particularly useful for low fecundity species that produce fewer offspring per litter and exhibit a more direct relationship between spawning output and recruitment (Taylor et al. 2013; Methot et al. 2021). The survivorship SR relationship was assumed for the Pacific spiny dogfish assessment (Gertseva et al. 2021) and is parameterized as (Taylor et al. 2013):

$$R_y = SSB_y e^{\ln(S_0)(1 - Z_{frac}(1 - \frac{SSB_y^\beta}{SSB_0}))}, \quad (7)$$

where R_y is recruitment in year y , SSB_y is spawning output in year y , $S_0 = \frac{R_0}{SSB_0}$ is survival of per-recruit individuals at unfished equilibrium, R_0 is unexploited equilibrium recruitment, SSB_0 is the corresponding equilibrium spawning output, β is a shape parameter controlling the shape of the density-dependent relationship between $\frac{SSB_y}{SSB_0}$ and S_0 (with limit $\beta > 1$), and Z_{frac} is a fraction of pre-recruit instantaneous mortality rate at equilibrium ($-\ln(S_0)$) and range $0 < Z_{frac} < 1$.

During the preliminary model explorations, the parameters for all three SR models were estimated within SS3, and model results were compared. The SS3 model with the Beverton-Holt SR relationship failed to converge, and the models that assumed Ricker and survivorship SR relationships showed very differently estimated stock trajectories. Thus, the Working Group decided to estimate the SR relationship outside of SS3, fix the SR parameters in SS3 at these values, and then compare their model performances.

The Ricker and Beverton-Holt SR relationships parameterized by a and b were estimated using the NEFSC bottom trawl survey data (McManus et al. 2022). The survivorship SR relationship was explored using the same data set (with S_0 and SSB_0 estimated by averages

of various SS3 preliminary runs) but failed to converge because the two parameters Z_{frac} and β are highly correlated. Therefore, the survivorship SR parameters estimated in a preliminary model run ($Z_{frac} = 0.93$ and $\beta = 1.6$) were assumed for exploratory SS3 runs.

In SS3, the Ricker and Beverton-Holt SR models were parameterized using $\ln(R_0)$, the steepness parameter (h ; Methot and Wetzel 2013). To estimate the Ricker and Beverton-Holt steepness from the a and b form models, S_0 is required (Miller and Brooks 2021):

$$h = \frac{a\phi_0}{4 + a\phi_0} \text{ for Beverton-Holt SR model,} \quad (8)$$

$$h = \frac{(a\phi_0)^{4/5}}{5} \text{ for Ricker SR model,} \quad (9)$$

where $\phi_0 = \frac{1}{S_0}$ can be interpreted as unexploited spawning per recruit. The survivorship SR relationship is not parameterized in the form of steepness in SS3, but steepness was calculated for comparison purposes. S_0 is also required to estimate steepness for the survivorship SR parameters (Taylor et al. 2013):

$$h = 0.2e^{S_0 Z_{frac}(1-0.2^\beta)} \quad (10)$$

To get an estimate of S_0 , various preliminary SS3 runs were examined. The estimated S_0 in SS3 is invariant with different model settings, e.g., growth, maturity, fecundity, SR relationships, etc., but varies with natural mortality. Therefore, three S_0 values derived using three M assumptions, static $M = 0.092$ (Hoenig 1983), static $M = 0.102$ (Then et al. 2015), and Lorenzen (1996) M scaled to an average of 0.102, were assumed, steepness were estimated from these values for the Ricker and Beverton-Holt SR models, and SS3 runs were conducted with the fixed steepness values. For the survivorship SR relationship, parameters were fixed at $Z_{frac} = 0.93$ and $\beta = 1.6$, and model runs were conducted with three different M assumptions.

The estimated steepness was around 0.4 for $M = 0.092$, around 0.3 for $M = 0.102$, and around 0.2 for scaled Lorenzen (1996) M for both Ricker and Beverton-Holt SR models. However, the steepness is around 1 for $M = 0.092$, around 0.8 for $M = 0.102$, and around 0.6 for scaled Lorenzen M for the survivorship SR models. AIC values from these runs suggested that survivorship SR outperformed Ricker and Beverton-Holt models regardless of M assumptions; the survivorship SR model coupled with $M = 0.102$ performed the best, followed by the scaled Lorenzen (1996) M . These conclusions were the same with or without estimating recruitment deviations in the model.

Because assuming $M = 0.102$ resulted in an unrealistically high steepness/productivity for spiny dogfish, a long-lived and low fecundity stock, the Working Group decided to assume a survivorship SR relationship, coupled with the Lorenzen (1996) M scaled to an average of 0.102 as the base case model configuration. The survivorship SR parameters were updated

based on a profile analysis and fixed at $Z_{frac} = 0.9$, $\beta = 1.5$, and $\sigma_R = 0.3$ (standard deviation of log recruitment deviations) for the base case model. Recruitment deviations were estimated for the entire time series and bias-adjusted so that the estimated recruitments are mean unbiased (Methot and Taylor 2011; Methot et al. 2021). Uncertainty of the SR relationship assumptions were further explored in the sensitivity and profile analysis.

2.6 Selectivity

A double normal selectivity function was assumed for all six fleets in SS3 to fit the length composition data for its ability to estimate either an asymptotic or a domed-shaped selectivity pattern from data (Methot and Wetzel 2013; Methot et al. 2021). The double normal selectivity function has six parameters: p1 - peak value, p2 - top logistic, p3 - ascending width, p4 - descending width, p5 - selectivity at first length bin, and p6 - selectivity at last length bin. The sex-specific selectivity was estimated using a parameter offset approach with a maximal selectivity greater than or equal to one for the dominant sex and an additional parameter to determine the relative apical selectivity value for the offset sex. The selectivity parameters allowed to be offset in SS3 are p1, p3, p4, and p6. For the catch fleets 1-5, male selectivity was estimated as an offset from the female parameters, so the maximum selectivity for both sexes is one; thus, the resulting apical fishing mortality is comparable among fleets. The shape of the selectivities was freely estimated in SS3 for all fleets. Parameters p5 and p6 were skipped for all fleets, except for p5 for the discard fleet 5 and survey because they caught small dogfish. The offset of descending parameter p4 for landings fleets and the survey was turned off because it was estimated at zero during the preliminary model explorations. Selectivity time blocks were implemented for the NEFSC spring bottom trawl survey to estimate different selectivities for the two different research vessels conducting the survey: RV *Albatross IV* (1989-2008) and FRV *Henry B. Bigelow* (2009-2019). A sensitivity run was conducted to examine the selectivity time block assumption.

2.7 Data Weighting

Three data weighting approaches, McAllister-Ianelli, Francis, and Dirichlet-Multinomial (McAllister and Ianelli 1997; Francis and Hilborn 2011; Thorson et al. 2017), were explored to rescale the effective sample size to reduce conflicts between data sources during the preliminary model exploration. The scalars estimated using McAllister-Ianelli and Francis data weighting approach significantly down-weighted the survey length composition data relative to the catch length composition data. Thus, the Working Group decided to use the Dirichlet-Multinomial data weighting approach, which involves estimating a parameter (θ) to scale each fleet's inputted effective sample size. For comparison purposes, the θ parameter was fixed at the base case value for the jitter and profile analysis but re-estimated for the retrospective analysis. Sensitivity analysis was conducted without weighting the length composition data.

2.8 Parameters

In summary, the parameters fixed in SS3 include length-weight, maturity, fecundity, SR relationships, growth for the first biology block, and the fixed p4-6 parameters mentioned in the selectivity paragraph above. Within the estimated parameters, the peak, ascending, and apical selectivity parameters were time-varying for fleet 6, and L_∞ for both sexes were estimated for biology block 2012-2019. Non-informative priors were used for all the parameters except for the θ parameter for the Dirichlet-Multinomial error distribution used to weight the length data. A Normal $N(0, 1.813)$ prior was assumed for $\ln(\theta)$ to counteract the log transformation effect between θ and data weighting (Methot et al. 2021).

3 Model Convergence and Diagnostic

The model convergence was evaluated based on whether the final gradient is < 0.0001 and whether the Hessian matrix for the parameter estimates is positive definite. Parameters estimated at a bound were examined, and correlations between estimated parameters were produced to see if highly correlated parameter pairs or non-informative parameters exist for possible unstable model or model misspecification. The residual analysis proposed by Carvalho et al. (2021) was performed on indices and length composition data to check for model fits. Profile of R_0 , jitter, and retrospective analyses were also conducted to check for data consistency and model stability (Carvalho et al. 2021).

4 Model Results

4.1 Base Case Model

4.1.1 Convergence

The base case model converged (gradient 2.3×10^{-5}) and the Hessian matrix was positive definite. All parameters were estimated within their bounds, correlations between parameters were low (< 0.95), and all parameters were informative (correlation > 0.01). The 100 iterations of jittering the starting values by 10% resulted in 60% of the runs converging at the total likelihood value of the base case (-23409.9) and above the base case total likelihood value for the rest of the runs with a maximum change of 36.6 in likelihood. This result indicated that the base case model is slightly sensitive to starting values but stable and is likely to converge at a global rather than a local minimum.

4.1.2 Overall Goodness of Fit

The overall model fit of the abundance index data and length composition data was evaluated using joint-index residual plots from the fit to the index data and the mean length of the length composition data (Carvalho et al. 2021). The residual plot for the NEFSC spring bottom trawl survey index showed a residual pattern where the residuals are positive during

the 1990s, negative during the 2000s, and positive in recent years, with $\text{RMSE} = 39.6\%$ (Figure 9). The residual plot for mean length of the length composition data showed a good fit with $\text{RMSE} = 6.3\%$. The loess-smoother of this plot indicated a positive residual pattern at the beginning of the time series but no apparent residual pattern for recent years (Figure 10). The above analysis indicated a reasonably good overall fit to the data for the base case model.

4.1.3 Growth

The time-varying growth curve and the assumed/estimated VB growth parameters by sex are shown in Table 2 and Figure 11. The estimated L_∞ for the biology block 2012-2019 were smaller than those estimated by Nammack et al. (1985) for both sexes. The reduction is more significant for females (11.26 cm) than males (3.35 cm) and is likely reflecting the absence of large females in both catch and survey data (Figure 4).

4.1.4 Abundance Index

The observed and model-predicted NEFSC spring bottom trawl abundance index is shown in Figure 12. The predicted index is within the 95% uncertainty level, except for 2004. The estimated catchability q was 0.83 for this survey.

4.1.5 Selectivity

The estimated selectivities by sex and fleet are shown in Figures 13-18. The estimated selectivities were asymptotic (logistic) for all landings fleets and NEFSC spring bottom trawl survey (fleets 1, 2, and 6) and dome-shaped for all discard fleets (3-5; Table 1). Estimated apical male selectivity was smaller than females for landings and discard fleets (1-5; Table 1), which is reasonable for a female-targeted fishery. Time-varying selectivity for the NEFSC spring bottom trawl survey showed an increased selectivity for small dogfish and reduced selectivity for the large females during the *Bigelow* period (2009-2019), which is consistent with the survey data. Figure of length compositions from 2005 to 2012 showed systematic changes between the *Albatross* to *Bigelow* period for both sexes (Figure 19).

4.1.6 Length Composition

The observed and model-predicted length compositions aggregated by fleet, year, and sex are shown in Figure 20. The fits to the aggregated length compositions appear to be fairly accurate, suggesting that the estimated fisheries and survey selectivities are reasonable.

The observed and model-predicted annual length composition data and the residuals from the fits by fleet and sex are shown in Figures 21-32. Fit to the annual length composition data showed some systematic poor fit for the large females for the landings fleets (1 and 2) and the survey, as well as the median size males for the survey. There were large residuals for small (around 30 cm) dogfish for fleets 1, 3, and 4 and large dogfish for fleets 3 and 4.

4.1.7 Recruitment

The fixed survivorship SR relationship, along with the estimated recruitment from both the SR relationship and recruitment deviations, are shown in Figure 33. The estimated recruitment decreased from 1989 to the early 2000s, when the lowest recruitments of the entire time series were estimated, followed by a large increase through 2010, and then dropped to half of the peak value and stayed stable since (Table 4 and Figure 34).

4.1.8 Total Biomass and Spawning Output

The estimated time series of total biomass by sex and spawning output are provided in Table 4 and Figure 35. The estimated spawning output declined during the beginning of the time series, increased starting in the early 2000s, peaked in 2012, and then decreased since.

4.1.9 Fishing Mortality

The estimated annual fishing mortality, which is defined as the number-based exploitation rate for age 12+ dogfish (roughly age at 50% fishery selectivity), peaked around 1989 to 1990, decreased to the lowest point in 2003, and stayed below 0.02 since 2003, except for 2014, which is slightly above 0.02 (Table 4 and Figure 35).

4.2 Sensitivity Analysis

4.2.1 Growth for 2012-2019 Period

For the base case model, L_∞ was the only growth parameter estimated for the biology block 2012-2019. The sensitivity of this assumption was examined with three additional runs:

- estimating L_∞ and k but fixing L_{Amin} at the Nammack et al. (1985) values,
- estimating all three growth parameters L_∞ , k , and L_{Amin} , and
- fixing L_∞ , k , and L_{Amin} at the Nammack et al. (1985) values

for both sexes for the biology block 2012-2019. The estimated spawning output from the two growth scenarios with estimating two or all three VB parameters are similar to the estimates from the base case model, with slightly higher terminal spawning outputs (Figure 36). However, the run assuming Nammack et al. (1985) growth produced a very different spawning output trajectory than the base case model (Figure 36).

The estimated L_∞ is similar with or without estimating k and L_{Amin} (Table 2). The estimated k is slightly higher than that k estimated by the Nammack et al. (1985) study. Although runs estimating two or all three VB parameters performed better than the base-case model, the differences in AIC were small (Table 3). When the VB growth parameters were fixed

at the Nammack et al. (1985) values, the AIC was much worse. These results support the Working Group’s decision on estimating the L_∞ for the biology block 2012-2019 for the base case model.

4.2.2 Natural Mortality

Sensitivity runs were performed assuming:

- $M = 0.092$ (Hoenig 1983) for all ages and sexes, as used in the previous assessments,
- $M = 0.102$ for all ages and sexes derived using Then et al. (2015) method, and
- the sex- and age-specific Lorenzen (1996) M scaled to asymptote at 0.102.

There were compared to the base case model where the sex- and age-specific Lorenzen (1996) M was scaled to an average of 0.102. A summary of performance statistics and several critical parameter estimates for these runs can be found in Table 3. The two static natural mortality runs performed better than the base case in AIC, likely contributed by the higher M for older dogfish (Figure 37). However, the estimated NEFSC spring bottom trawl survey q and steepness h were both over 1 for the static natural mortality runs, indicating possible model misspecifications. This supports the Working Group’s decision not to use static natural mortality for the base case model. The run with Lorenzen (1996) M scaled to asymptote at 0.102, which assumed the highest natural mortality at age of all the runs, performed worse than the base case. The estimated spawning output for this run is much higher than the two static M runs and the base case model (Figure 38).

4.2.3 Spawner-Recruitment Relationship

The performance of the base case model with a fixed survivorship SR relationship and estimated recruitment deviations was compared to two additional sensitivity runs:

- fixed Ricker SR parameters with recruitment deviations and
- fixed Beverton-Holt SR parameters with recruitment deviations.

The Ricker and Beverton-Holt SR relationship parameters were derived from the NEFSC bottom trawl survey and translated into steepness using the ϕ_0 estimated from the base case model. The estimated steepness was 0.28 for both Ricker and Beverton-Holt SR and 0.68 for the survivorship SR from the base case model. Different SR assumptions resulted in different trajectories of spawning output and likely different management advice (Figure 39). These two SR sensitivity runs performed worse than the base case model in terms of AIC (Table 3). The recruitment likelihood increased when assuming a Ricker (recruitment likelihood = 126.99) or a Beverton-Holt (recruitment likelihood = 107.97) SR relationship, reflecting a poorer fit to the recruitment data compared to the base case model (recruitment likelihood

= 0.24). The recruitment time series estimated from the Ricker and Beverton-Holt models were far from what was observed in the NEFSC spring bottom trawl survey (Figure 40; see McManus et al. 2022, Figure 1). In both cases, the estimated NEFSC spring bottom trawl survey q was over 1, which indicated possible model misspecifications (Table 3).

4.2.4 Time Block

Sensitivity runs were conducted with different time block assumptions:

- biology block 2011-2019,
- biology block 2013-2019,
- no biology block, and
- no survey block.

These were compared to the base case model where the biology block 2012-2019 and survey block 2009-2019 was assumed. For the runs with plus and minus one year of the base case biology block (2012-2019), the maturity and fecundity relationships remain the same as the base case model, and L_∞ was estimated for both sexes within the model. The run with no biology block, maturity, fecundity, and growth was assumed to be the same as the settings for the biology block 1989-2011 in the base case model.

The model run with no biology block could not track the large population increases observed in surveys around 2010, and performed worse in terms of AIC (Table 3 and Figure 41; see TOR3). Assuming different lengths of the biology block only affected the earlier years' spawning output and did not change the terminal estimates (Figure 41). Therefore, even though the 2011-2019 biology block slightly outperformed the base case model, given that the terminal year estimates are insensitive to this assumption, the Working Group decided to proceed with the base case model configuration. The fit for length composition data was worse with no survey blocks in the model (Table 3).

4.2.5 1962-2019 Model

A sensitivity run was conducted that examined a longer time series 1962-2019. The population is assumed to be unfished prior to 1962. Landings and discards from 1962 to 1988 were estimated using the same method used to derive the initial equilibrium catch for each fleet in the base case model. NEFSC spring bottom trawl survey time series data were available from 1979 for this run. The estimated spawning output is smaller for the 1962-2019 model; however, the trend is similar to the base case model (Figure 42).

4.2.6 Survey Data

Sensitivity runs were conducted using different survey data:

- NEFSC fall bottom trawl survey (as an additional abundance index),
- NEFSC spring longline survey (as an additional abundance index),
- NEFSC fall longline survey (as an additional abundance index), and
- VAST spring index (as the sole biomass index).

These were compared to the base case model that used only the NEFSC spring bottom trawl survey index. The estimated spawning output trend is similar to the base case model in all cases (Figure 43). The NEFSC fall bottom trawl survey was split into *Albatross* and *Bigelow* time series and entered as separate fleets in the model because their length composition is distinctly different (see TOR3). The estimated survey q for the NEFSC fall bottom trawl is much smaller than the spring survey (Table 3), reflecting the seasonal migration of dogfish out of the survey domain in the fall. The estimated selectivity for the NEFSC fall bottom trawl survey is logistic for the *Albatross* years but flat domed-shaped for the *Bigelow* period. Further investigations regarding the fall survey data and the model are required to examine whether this result is reasonable. Adding the NEFSC longline survey to the model did not change the spawning output (Figure 43). The model constructed using the model-based VAST index performed worse than the base case model in AIC (Table 3). The VAST length composition was estimated at a 6 cm length bin and was interpolated to a 3 cm length bin using a moving average method. It is not clear whether this mismatch is the cause of its low performance. The Working Group suggested continuing to develop the VAST index, and this index should be reevaluated in future assessments.

4.3 Profile Analysis

4.3.1 R_0

For the R_0 profile analysis, the $\ln(R_0)$ parameter was fixed at values above and below the value estimated by the base case model (9 to 15 with an increment of 0.5, base case $\ln(R_0) = 12$) and the models were refitted. The results indicated that the length composition data was the most informative and the survey index was the least informative for estimating R_0 (Figure 44). Among the length composition data, the catch data support the base case R_0 ; however, the survey data slightly favored a smaller R_0 value (Figure 45). This result indicated a slight conflict between catch and survey length composition data and that the maximum likelihood estimate of R_0 landed at the spot where conflicts between different sources of data were balanced (Figure 45).

4.3.2 Female Growth for 2012-2019 Period

Likelihood profiling was conducted over a wide range of values for the female VB growth parameters L_∞ and k while the rest of the VB parameters were fixed at the Nammack et al. (1985) values. The model had a tendency to favor smaller L_∞ and slightly larger k values compared to Nammack et al. (1985; Figure 46). The run with the smallest total likelihood

was $L_\infty = 88$ and $k = 0.12$, which is close to the maximum likelihood estimates (Tables 2-3 and Figure 46), suggesting that the estimated growth parameters in the base case model or sensitivity analysis are likely global instead of local minimums.

4.3.3 Survivorship Spawner-Recruitment Parameters

The survivorship SR parameters, Z_{frac} , β , and σ_R were profiled over a wide range of values, and the resulting total likelihoods are in Figure 47. Among the combination of parameters tested, the parameter values fixed in the base case model ($Z_{frac} = 0.9$, $\beta = 1.5$, and $\sigma_R = 0.3$) produced the smallest total likelihood. The β parameter is the least influential to the model, which is likely why this parameter is hard to estimate in SS3. The model performance is the most sensitive to Z_{frac} , where larger Z_{frac} values were favored.

4.4 Retrospective Analysis

A 7-year peel retrospective analysis was conducted for the base case model. The results indicated that the model has a minor retrospective pattern with Mohn's $\rho = 0.06$ for the spawning output and -0.05 for the fully recruited fishing mortality (Figures 48-49).

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Table 1: Summary of Atlantic spiny dogfish data by gear and fleet used in SS3.

Type	Gear	Fleet	Label in SS3
Landings	Sink Gill Net + Others Recreational	1	Landings_SGN_Rec_Others
Landings	Longline Otter Trawl + Foreign Fleet	2	Landings_LL_OT_Foreign
Discard	Sink Gill Net Scallop Dredge	3	Discard_SGN_SD
Discard	Longline Large Mesh Otter Trawl Recreational	4	Discard_LMOT_LL_Rec
Discard	Small Mesh Otter Trawl	5	Discard_SMOT
Survey	NEFSC Spring Bottom Trawl	6	NEFSC_Spring_BTS

Table 2: Summary of von Bertalanffy (VB) growth parameters assumed/estimated in SS3 for Atlantic spiny dogfish. Shaded cell indicated an estimated value.

Sex	VB Parameters	Base Case 1989-2011	Base Case 2012-2019	Sensitivity	
		Nammack et al. (1985)	Est L_∞	Est L_∞ and k	Est L_∞ , k , and L_{Amin}
Female	L_∞	100.50	89.24	88.64	88.67
	k	0.1057	0.1057	0.1258	0.1259
	L_{Amin}	26.53	26.53	26.53	27.33
Male	L_∞	82.49	79.14	78.02	78.02
	k	0.1481	0.1481	0.1657	0.1666
	L_{Amin}	26.94	26.94	26.94	27.46

Table 3: Summary of Atlantic spiny dogfish SS3 model runs.

Version	Sensitivity Category	Scenario	AIC	Delta AIC	Catchability q	Steepness h
3.6.2.1.5	Base Case Model	Dirichlet-Multinomial Data Weighting	-46624	-	0.83	0.68
3.6.2.1		No Data Weighting	5504	0	0.88	0.68
3.6.2.2	Growth	Nammack et al. (1985)/Est L_∞ and k	5488	-17	0.85	0.68
3.6.2.3		Nammack et al. (1985)/Est L_∞ , k , and L_{Amin}	5485	-19	0.85	0.68
3.6.2.4		Nammack et al. (1985)	5931	427	1.03	0.68
3.6.2.8.1	Natural Mortality	$M = 0.092$ (Hoenig 1983)	5108	-396	1.11	1.23
3.6.2.8		$M = 0.102$ (Then et al. 2015)	5059	-446	1.13	1.01
3.6.2.8.2		Lorenzen (1996) scaled asymptote 0.102	5938	433	0.47	0.36
3.6.2.6	SR Relationship	Ricker SR with recruitment deviation	5833	328	1.21	0.28
3.6.2.5		Beverton-Holt SR with recruitment deviation	5804	300	1.18	0.28
3.6.2.10	Time Block	Biology Block 2011-2019	5387	-117	0.86	0.68
3.6.2.11		Biology Block 2013-2019	5601	96	0.89	0.68
3.6.2.1.2		No Biology Block	5938	434	1.02	0.68
3.6.2.9		No Survey Block	5648	143	0.95	0.68
3.6.2.13.1	Model Starting Year	1962-2019 Model	6974	-	0.87	0.68
3.6.2.14	Survey Data	Additional NEFSC fall bottom trawl survey	7202	-	0.94/0.33/0.48	0.68
3.6.2.15		Additional NEFSC spring longline survey	5606	-	0.89/0.0004	0.68
3.6.2.16		Additional NEFSC fall longline survey	5590	-	0.89/0.0002	0.68
3.6.2.18		VAST spring index	5778	274	0.03	0.68

Table 4: Summary of total biomass by sex, spawning output, recruitment (in 1,000, age 0+) and fishing mortality (age 12+) by year estimated by SS3 for Atlantic spiny dogfish.

Year	Total Biomass (mt)		Spawning Output	Recruitment (1,000s)	F
	Male	Female			
1989	379672	432328	228469	218249	0.076
1990	386663	437351	232245	223706	0.118
1991	382068	440461	221779	213925	0.087
1992	384717	447807	217034	209429	0.170
1993	373117	447218	199000	192048	0.107
1994	371731	453841	187884	181317	0.084
1995	376160	461839	183010	176608	0.109
1996	375467	466877	174570	168454	0.101
1997	373842	472231	165600	159660	0.068
1998	380404	478322	167817	156426	0.079
1999	381356	480471	169694	102990	0.067
2000	384201	480566	178975	99774	0.044
2001	389329	478825	196331	73343	0.031
2002	395526	474807	219984	76663	0.029
2003	398997	468448	244437	74109	0.017
2004	403791	461401	271988	87065	0.020
2005	405289	452780	296758	85641	0.016
2006	406741	444746	319904	115680	0.020
2007	406047	436859	338467	122918	0.024
2008	404749	431073	351125	176522	0.019
2009	406500	429058	360845	196595	0.023
2010	410016	430333	364526	234935	0.017
2011	418240	435756	365877	235805	0.026
2012	425115	444996	388326	288488	0.029
2013	409991	443991	353179	120648	0.027
2014	401195	445024	325491	167354	0.041
2015	389002	444033	296337	123237	0.028
2016	383112	444474	276850	137889	0.039
2017	375398	444646	256708	159111	0.032
2018	371603	444323	245197	136947	0.026
2019	371635	445385	239877	176963	0.032

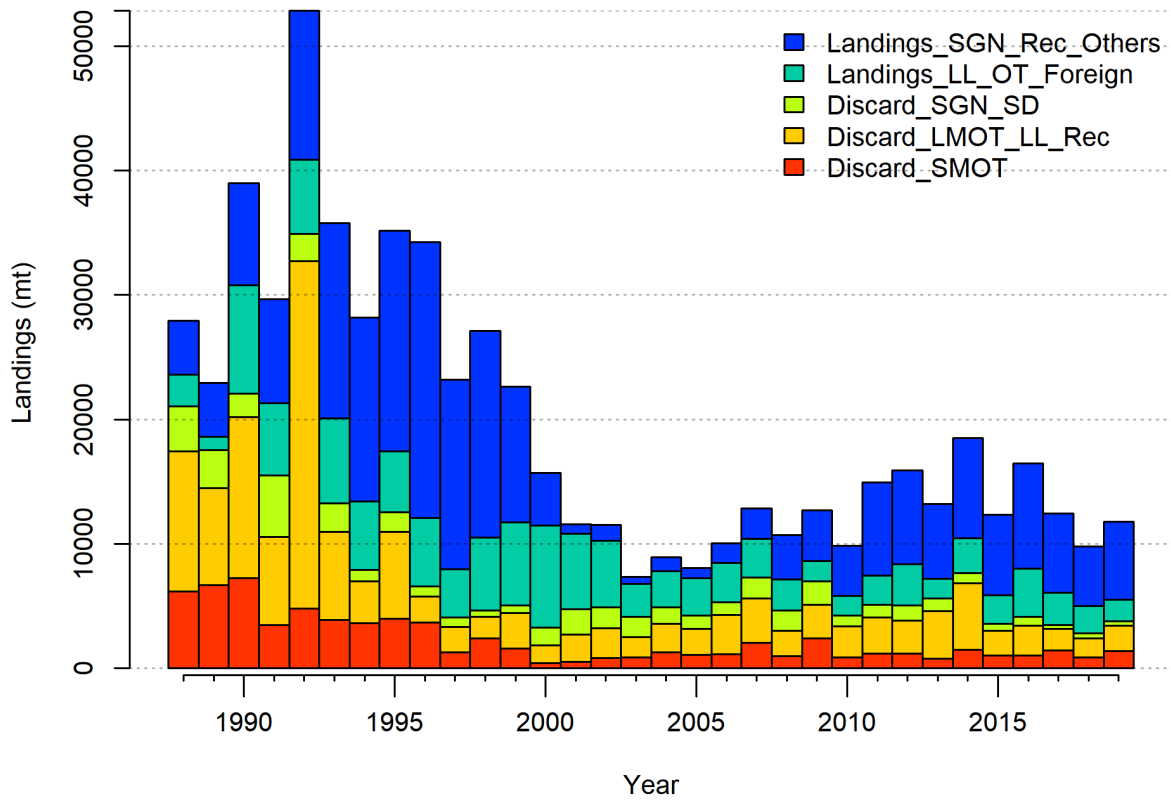


Figure 1: Time series of Atlantic spiny dogfish catch by fleet.

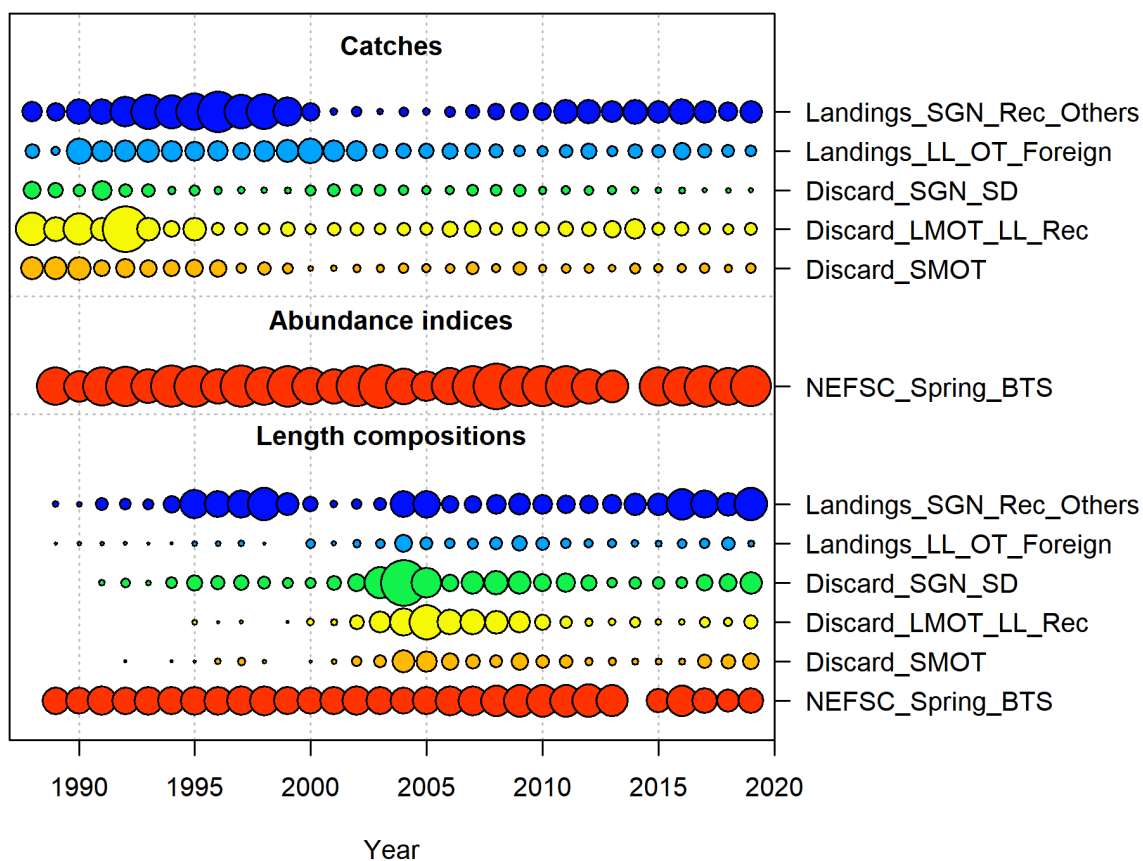


Figure 2: Catch and survey data by year for each fleet used in SS3. Circle area is relative within a data type. Circles are proportional to total catch for catches, to precision for indices, and to total sample size for length compositions. Note that since the circles are scaled relative to the maximum within each type, the scaling within separate plots should not be compared.

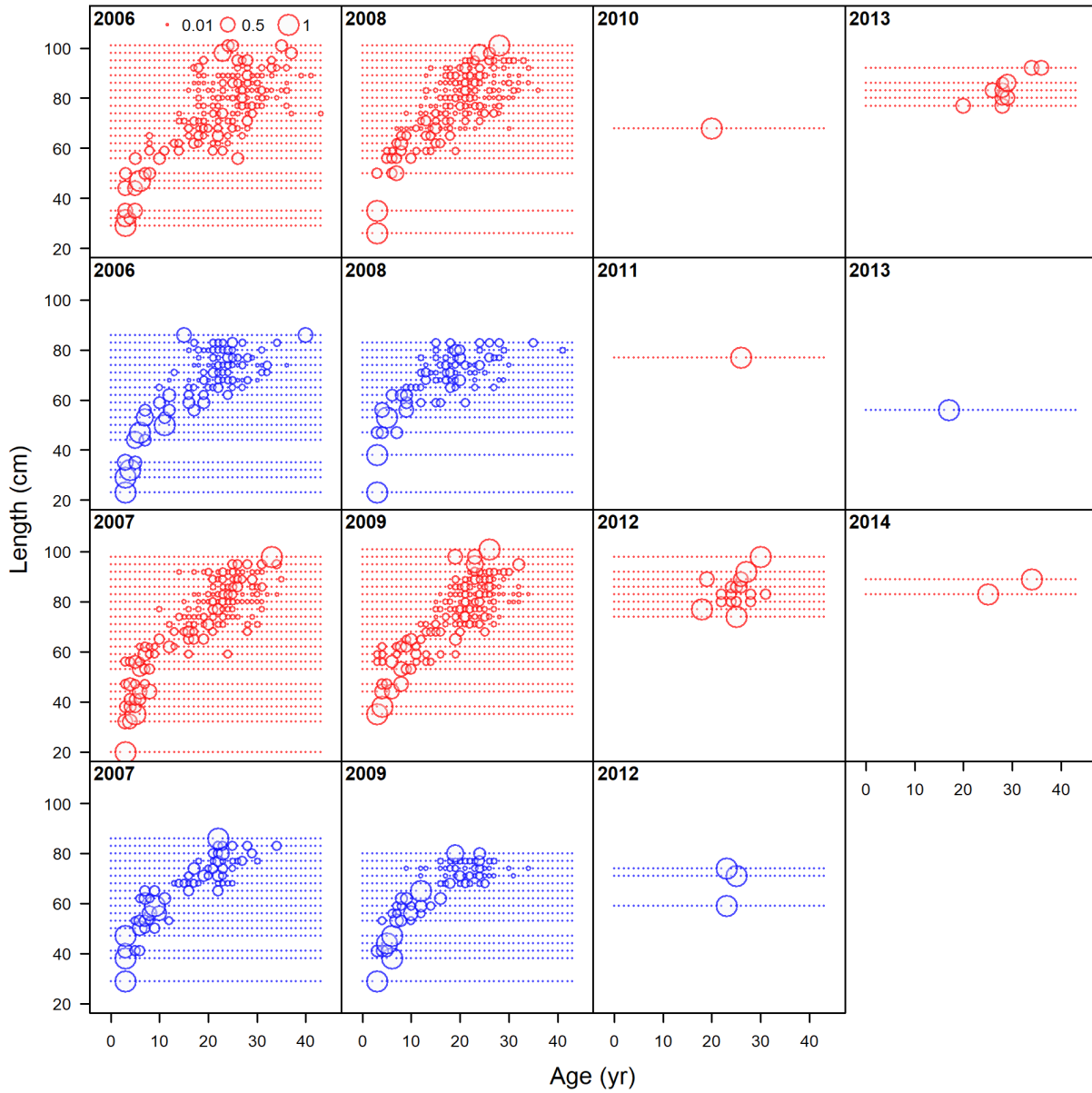


Figure 3: Conditional age-at-length data from NEFSC spring bottom trawl survey.

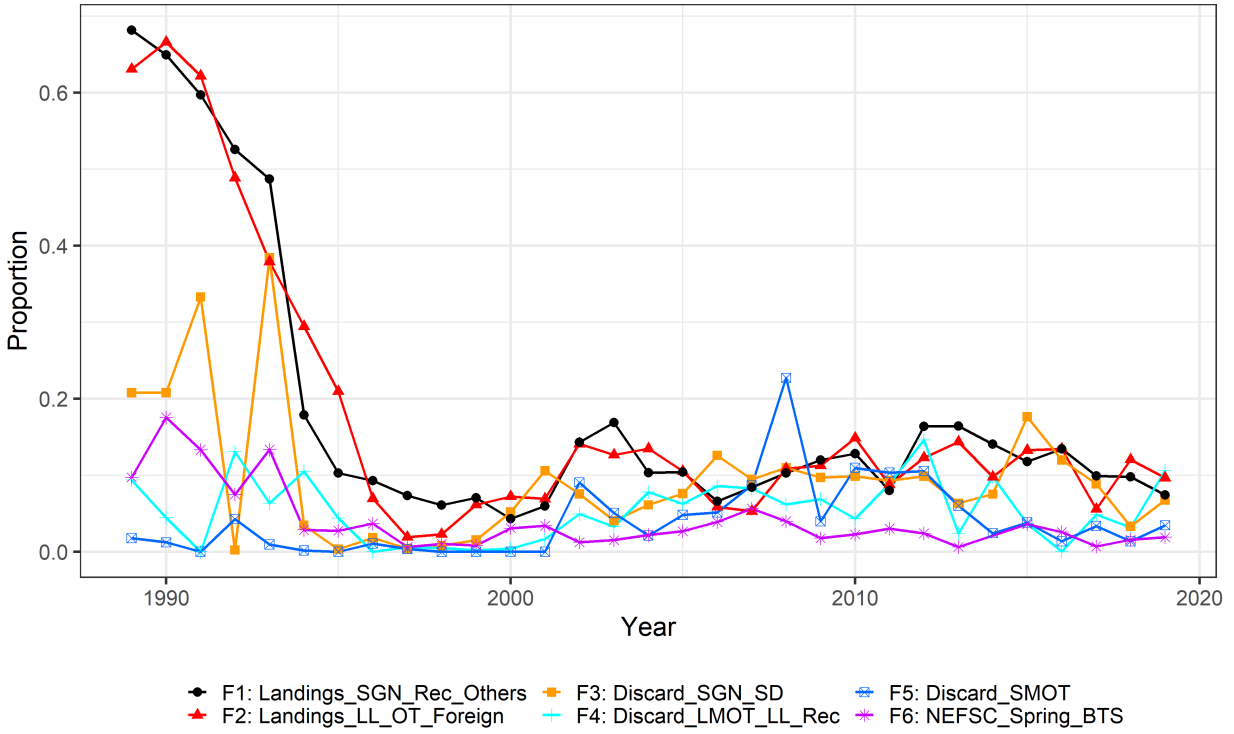


Figure 4: Proportion of 90+ cm females by fleet and year.

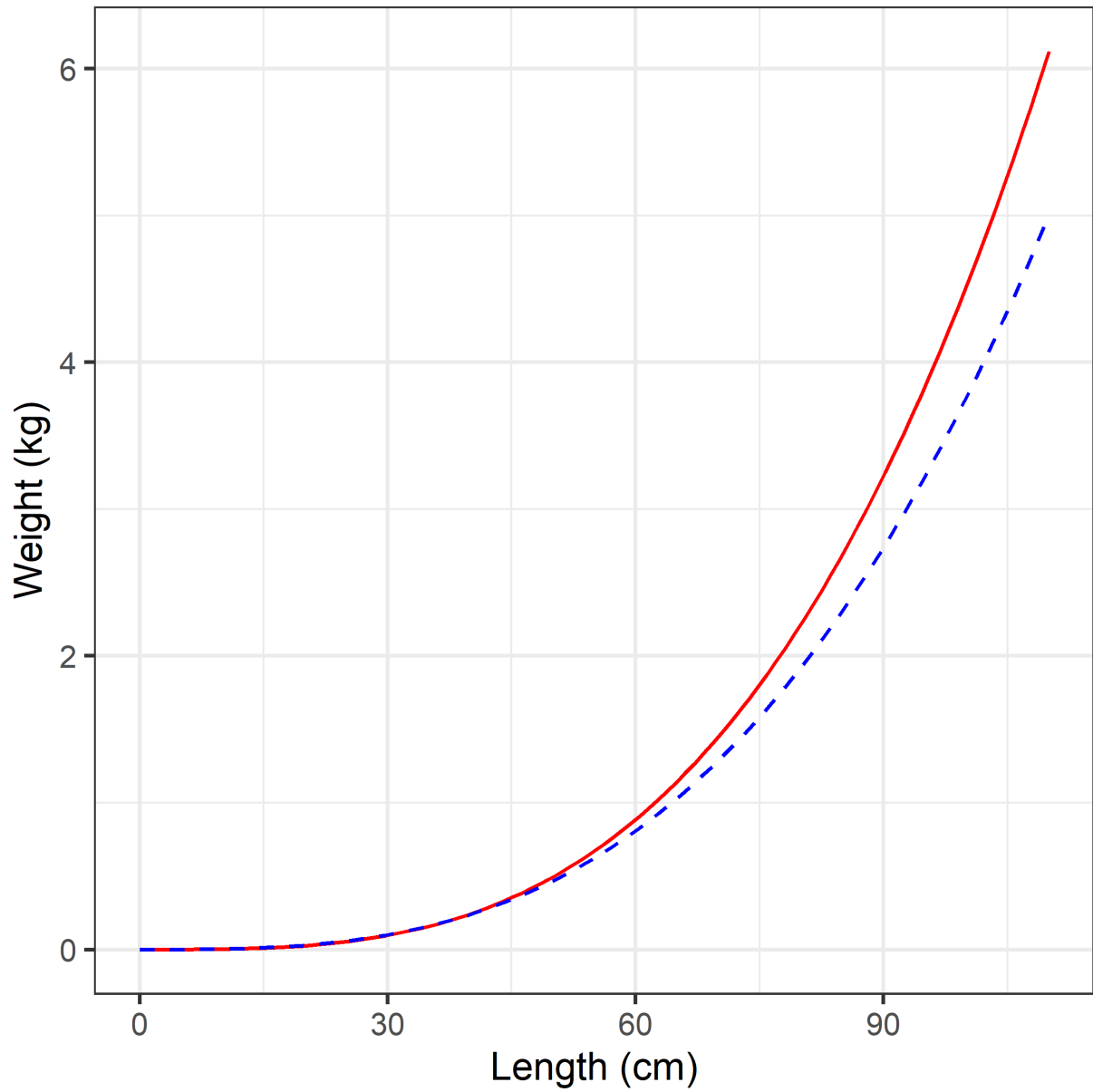


Figure 5: Length-weight relationships for females (red solid line) and males (blue dash line).

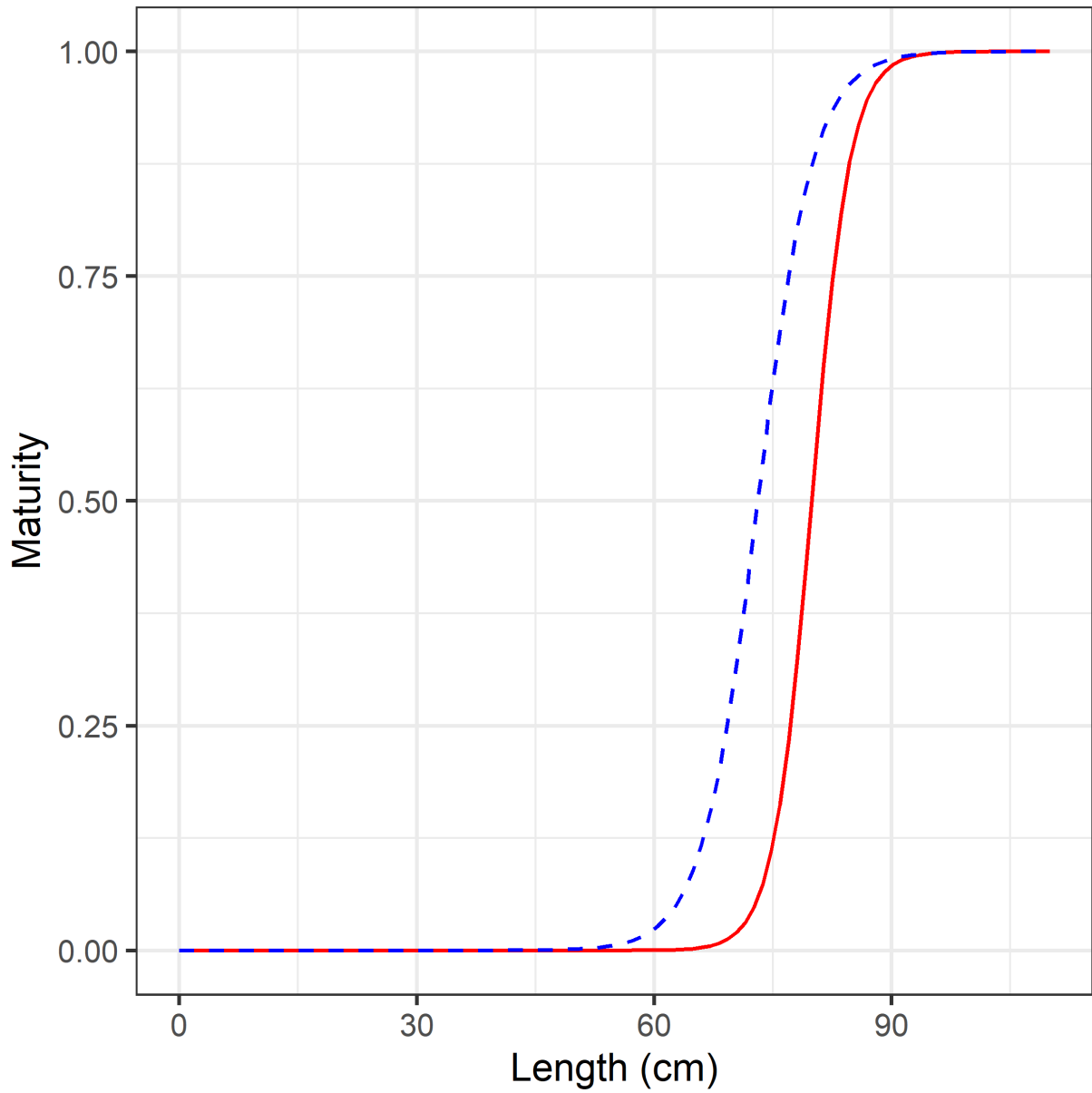


Figure 6: Maturity at length for biology blocks 1989-2011 (red solid line) and 2012-2019 (blue dash line).

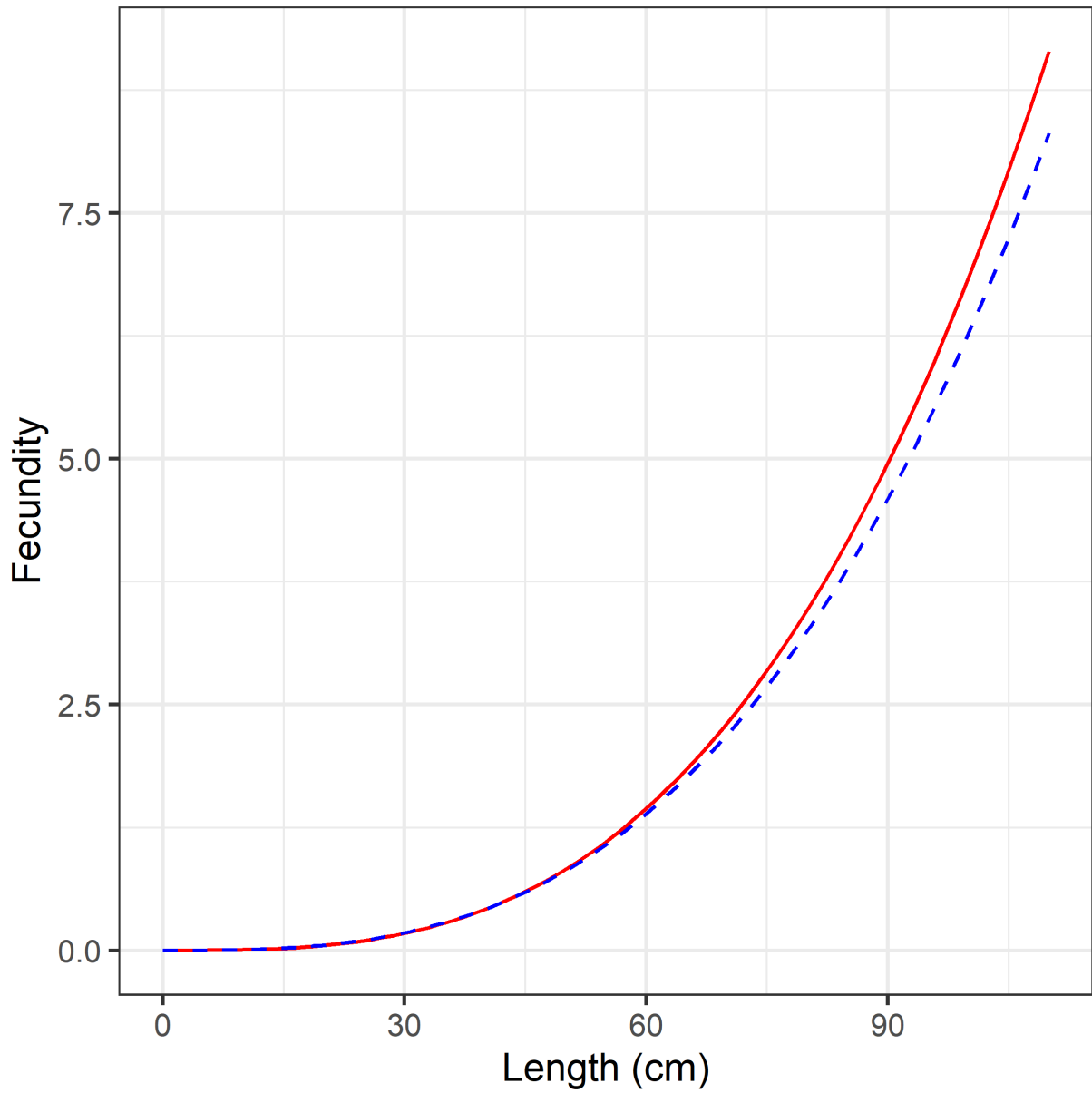


Figure 7: Fecundity at length for biology blocks 1989-2011 (red solid line) and 2012-2019 (blue dash line).

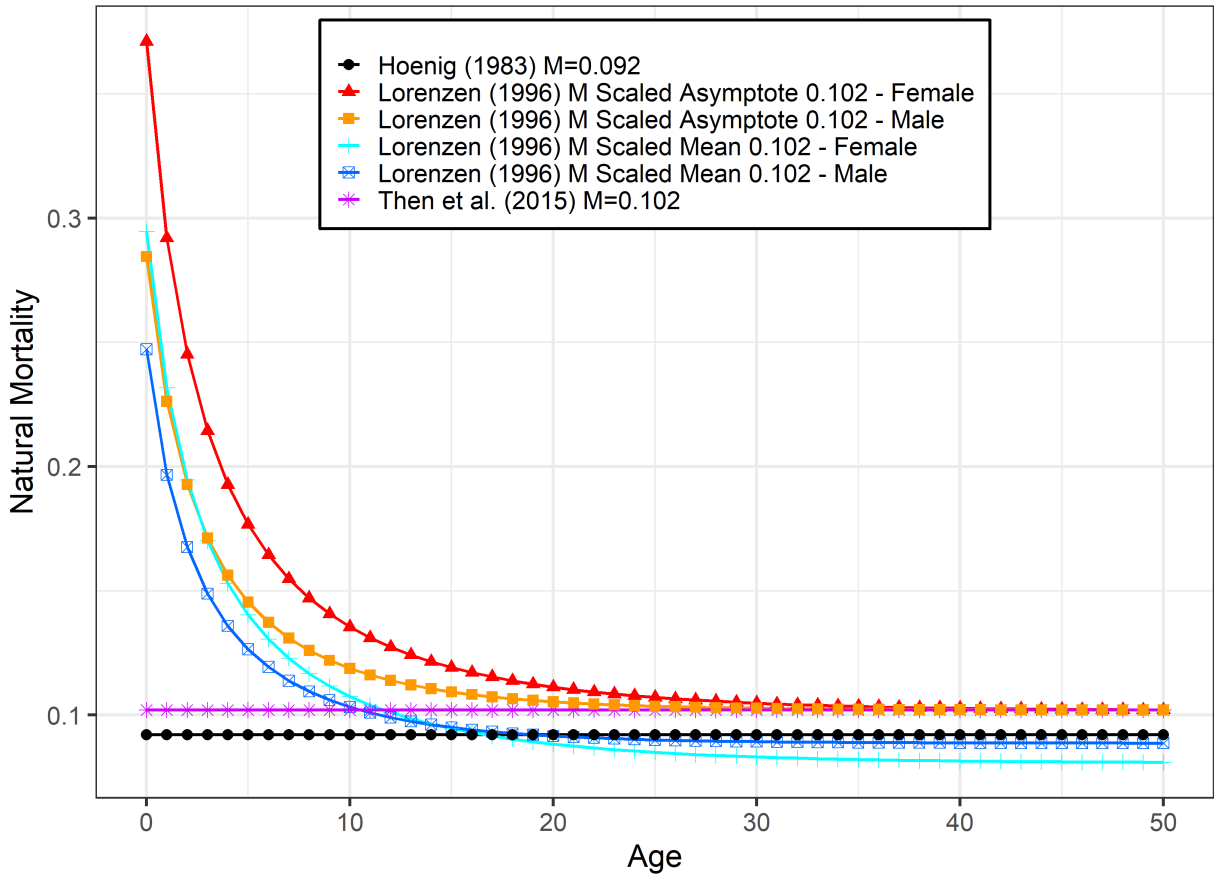


Figure 8: Natural mortality estimates explored in SS3 for Atlantic spiny dogfish.

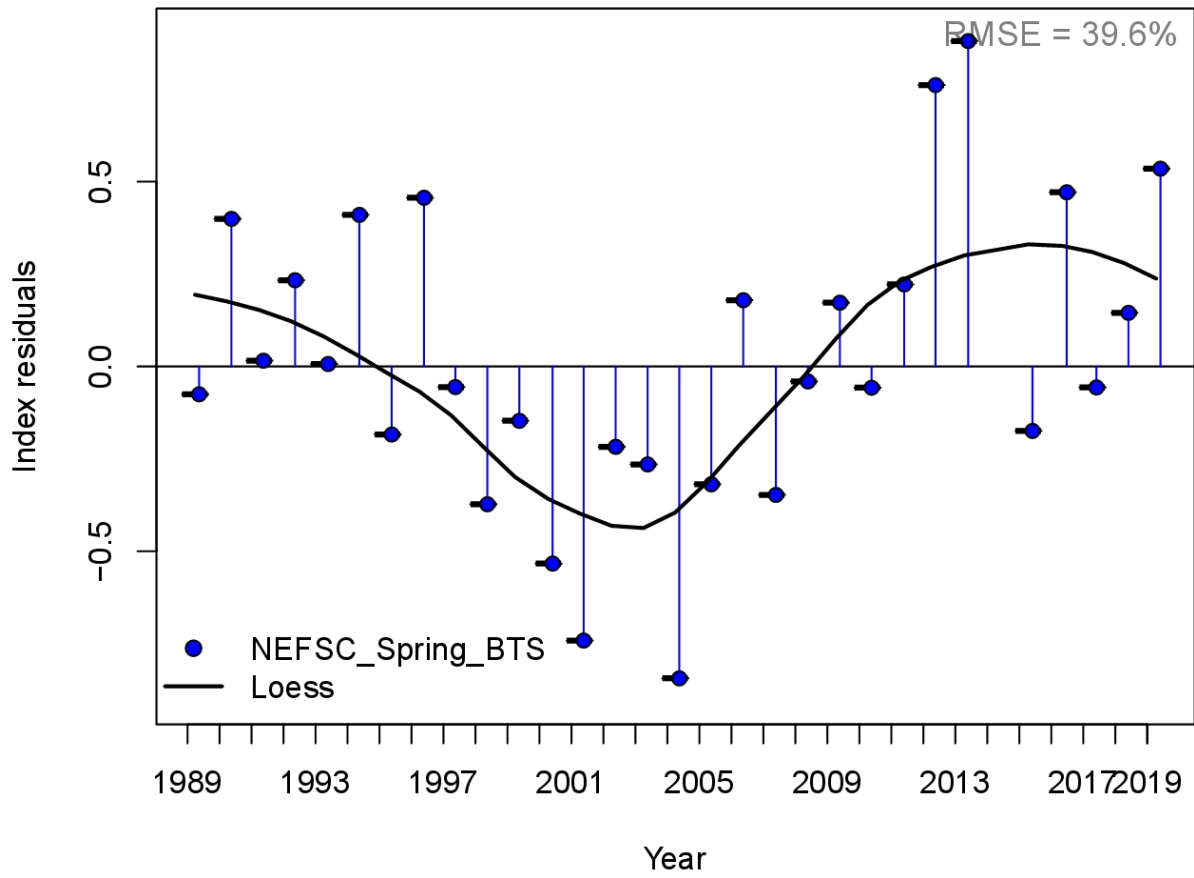


Figure 9: Joint residual plot from fit to annual index data.

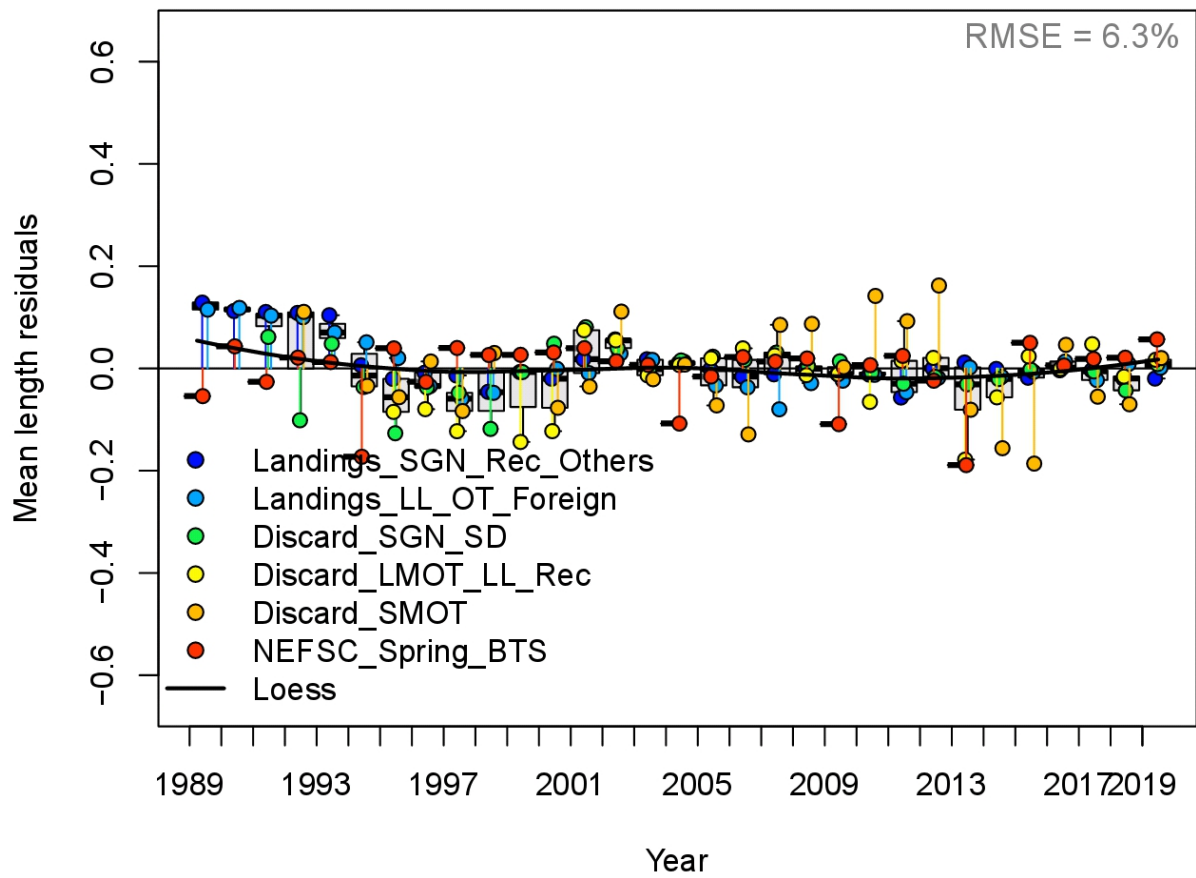


Figure 10: Joint residual plot from fit to annual mean length from length composition data.

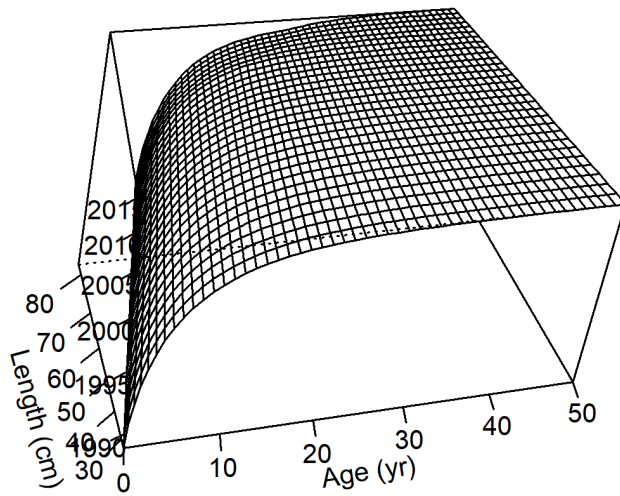
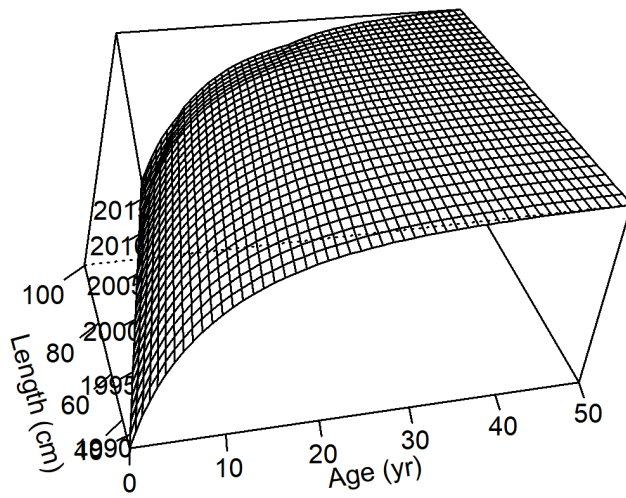


Figure 11: Surface plot of time-varying growth for females (top) and males (bottom) from 1989 to 2019.

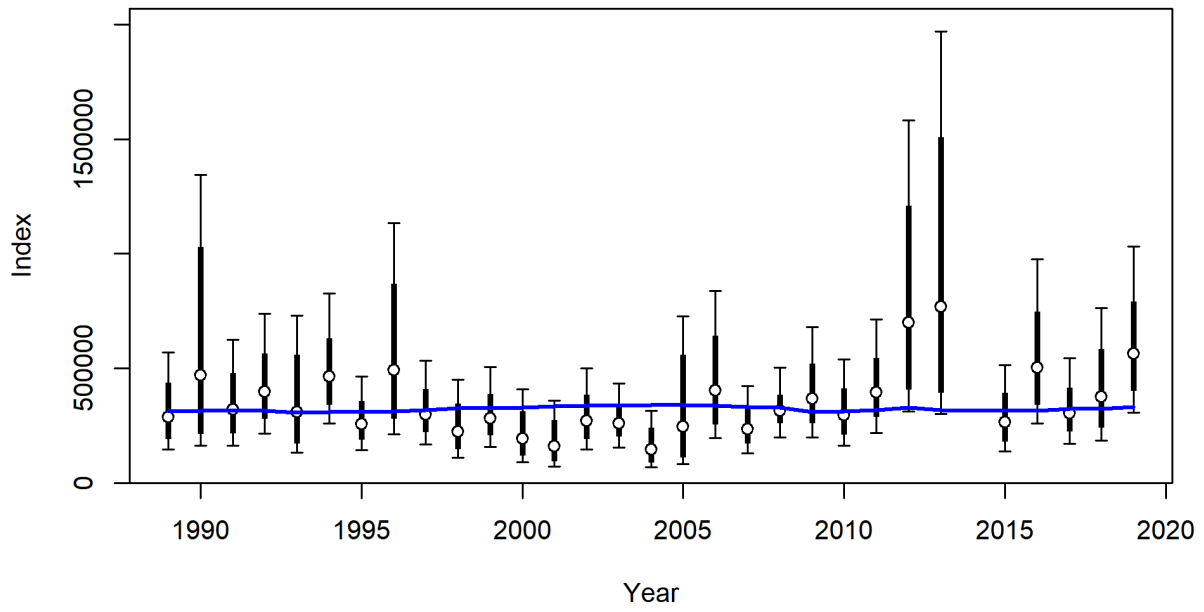


Figure 12: Observed and model-predicted abundance index (1,000s) for the NEFSC spring bottom trawl survey. Lines indicate 95% uncertainty interval around index values based on the model assumption of lognormal error. Thicker lines indicate input uncertainty before addition of estimated additional uncertainty parameter.

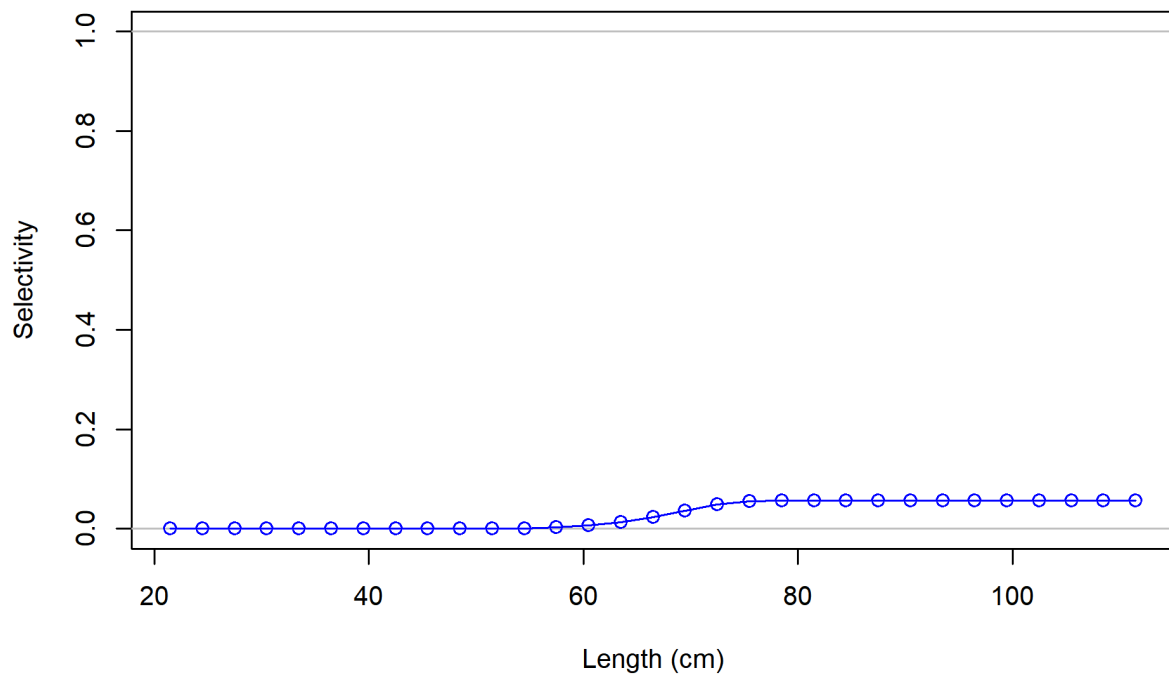
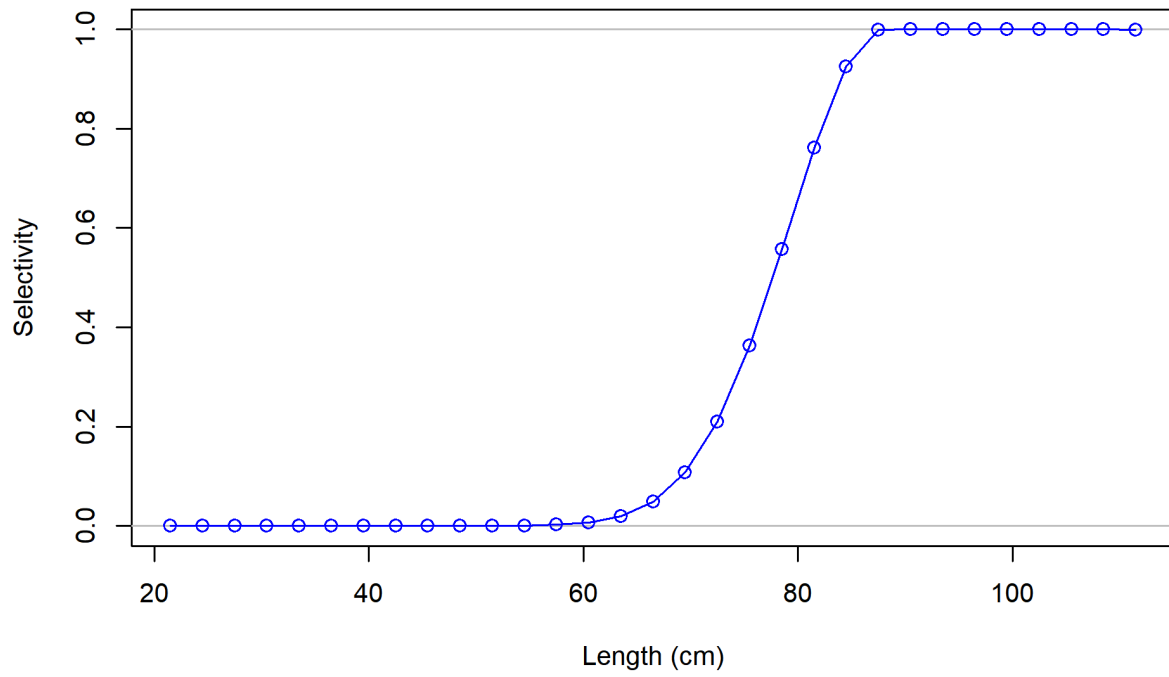


Figure 13: Estimated selectivity for females (top) and males (bottom) for fleet 1: Landings_SGN_Rec_Others.

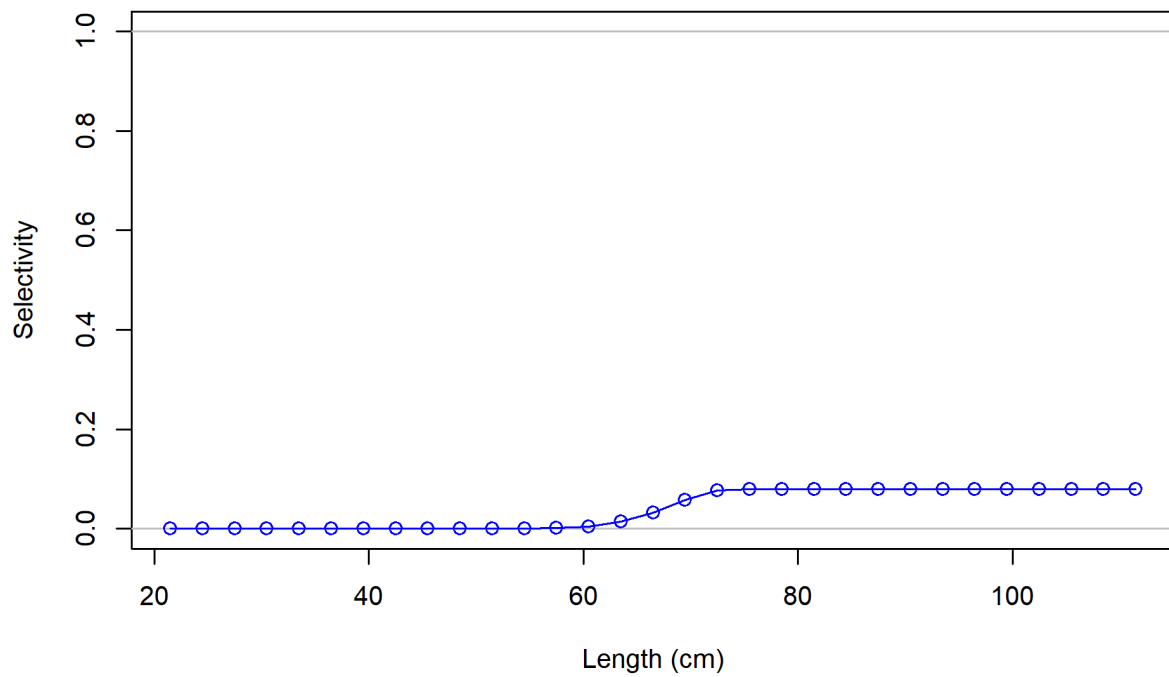
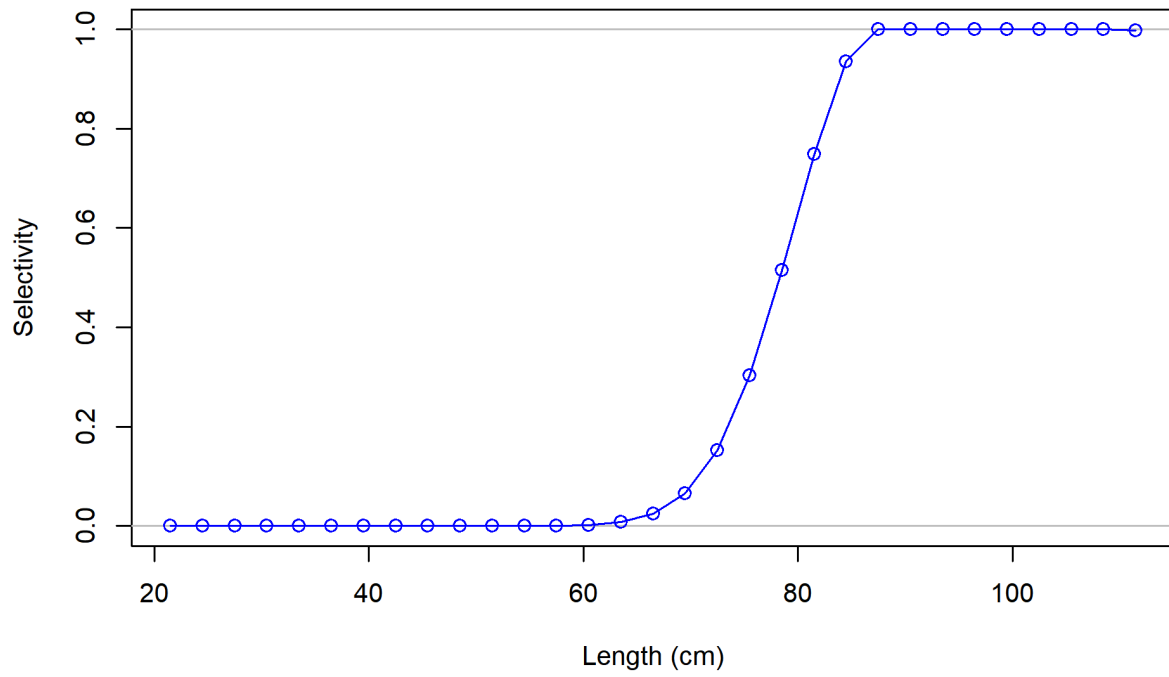


Figure 14: Estimated selectivity for females (top) and males (bottom) for fleet 2: Landings_LL_OT_Foreign.

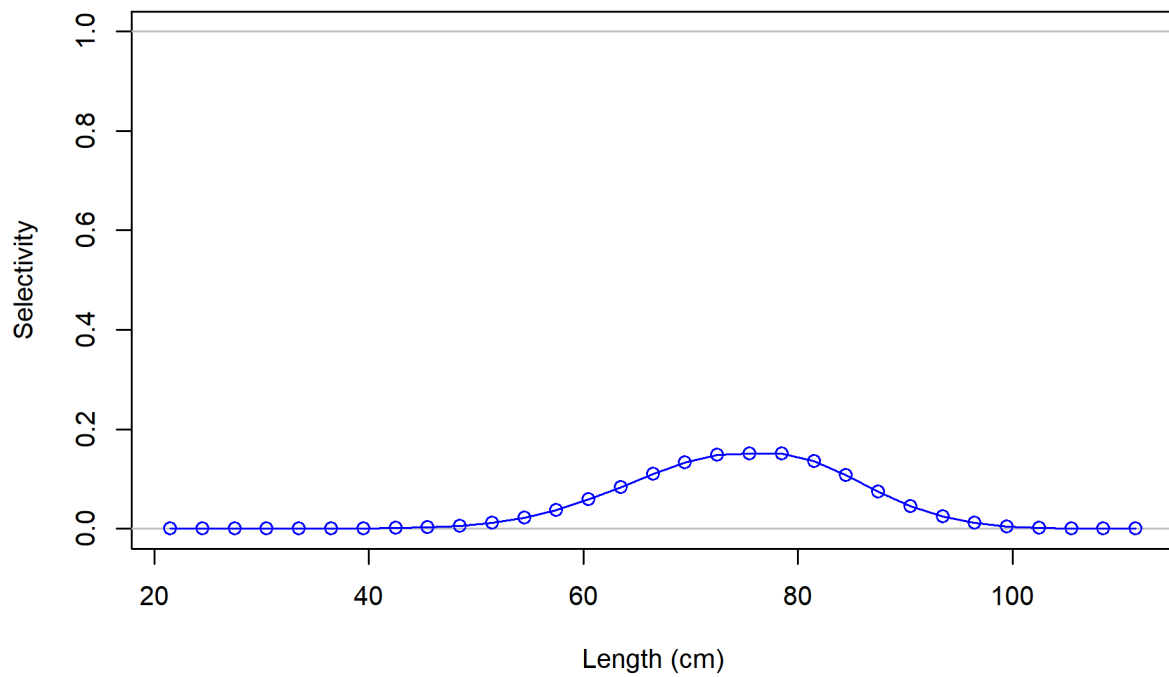
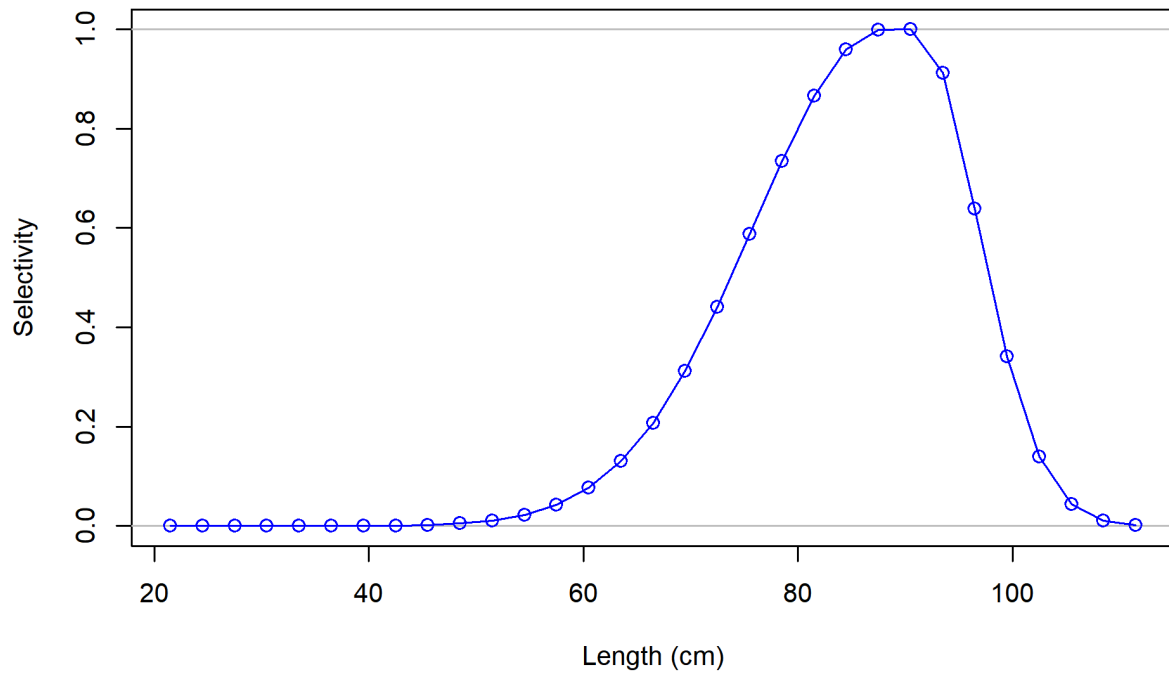


Figure 15: Estimated selectivity for females (top) and males (bottom) for fleet 3: Discard_SGN_SD.

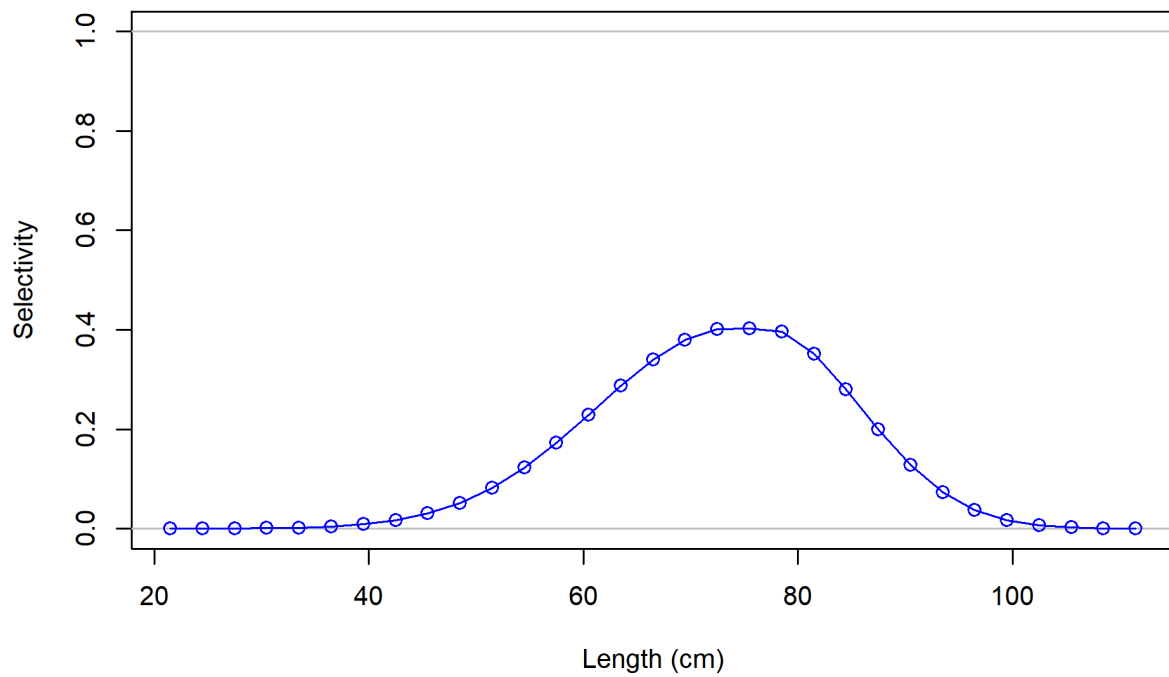
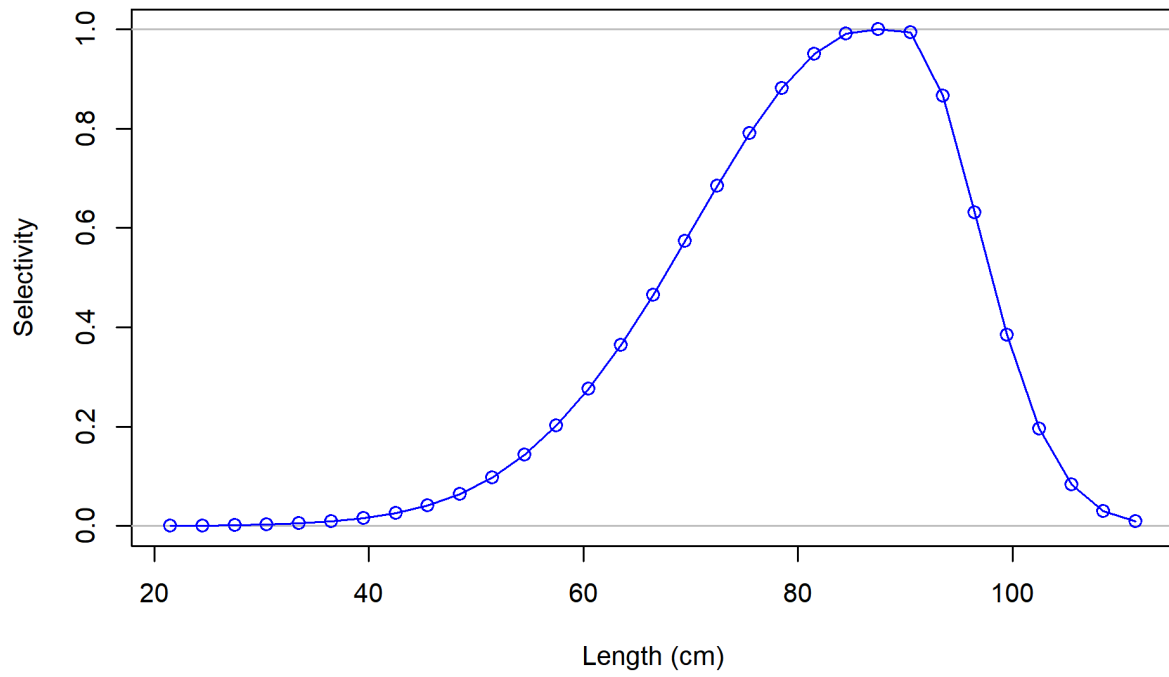


Figure 16: Estimated selectivity for females (top) and males (bottom) for fleet 4: Discard_LMOT_LL.Rec.

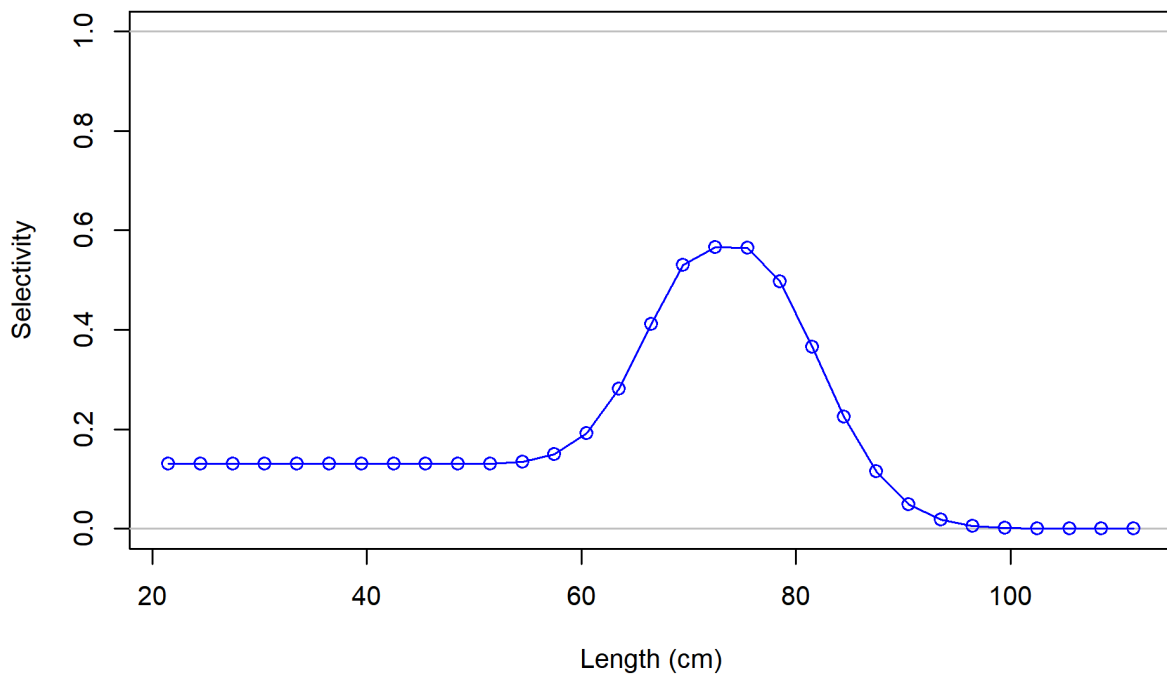
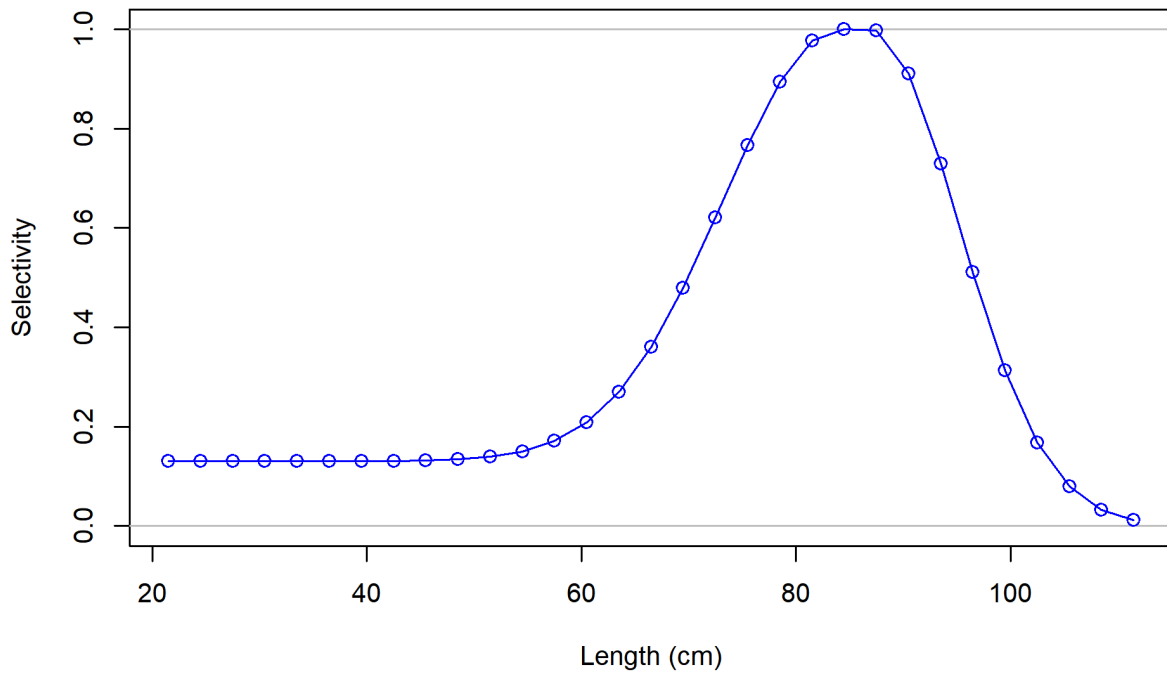


Figure 17: Estimated selectivity for females (top) and males (bottom) for fleet 5: Discard_SMOT.

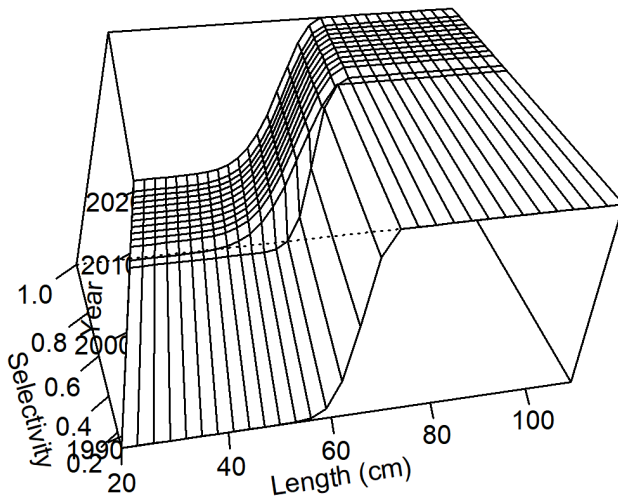
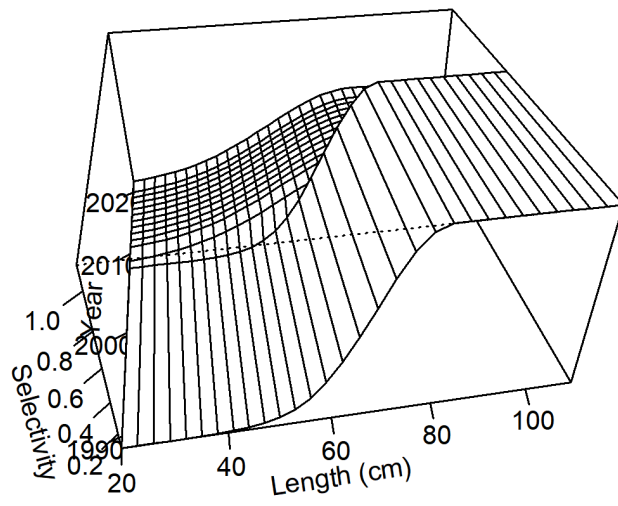


Figure 18: Surface plot of time-varying selectivity for females (top) and males (bottom) from 1989 to 2019 for NEFSC spring bottom trawl survey.

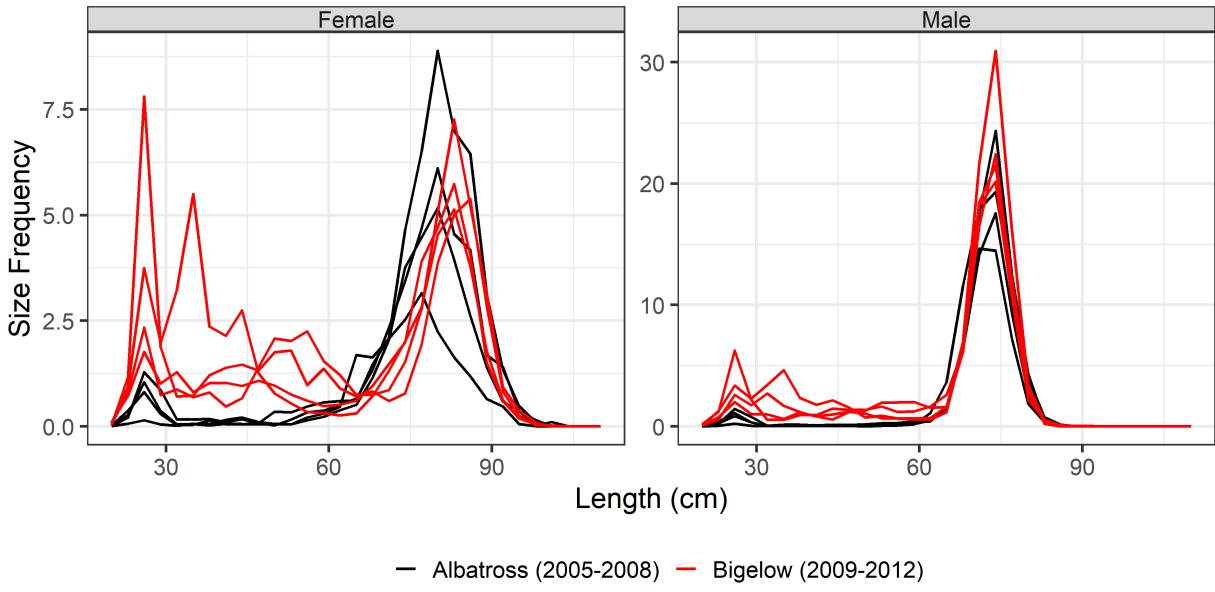


Figure 19: Observed length composition data from 2005 to 2012 for the NEFSC spring bottom trawl survey by *Albatross* and *Bigelow* period.

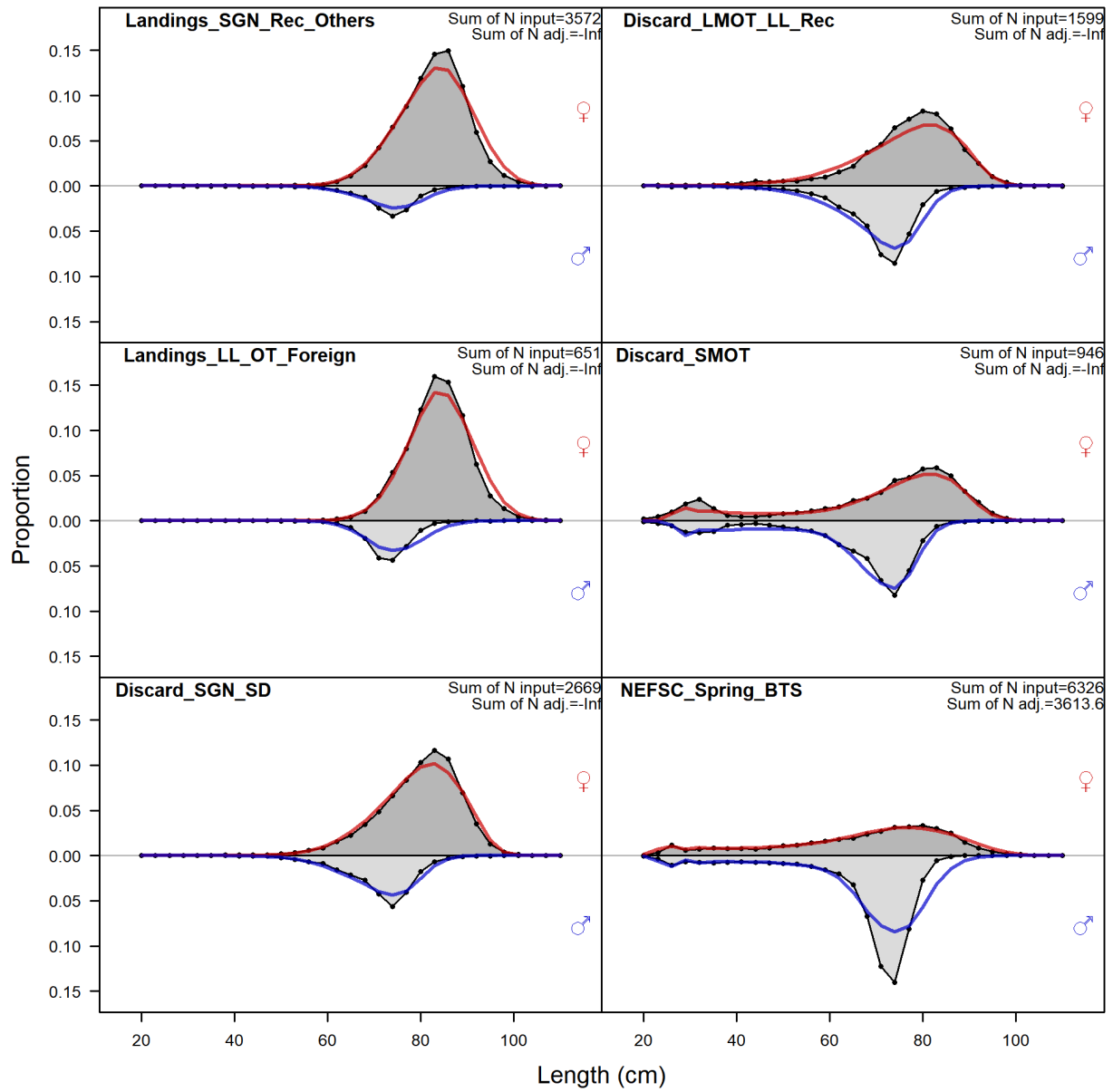


Figure 20: Observed (shaded) and model-predicted (line) length compositions, aggregated across time by fleet and sex.

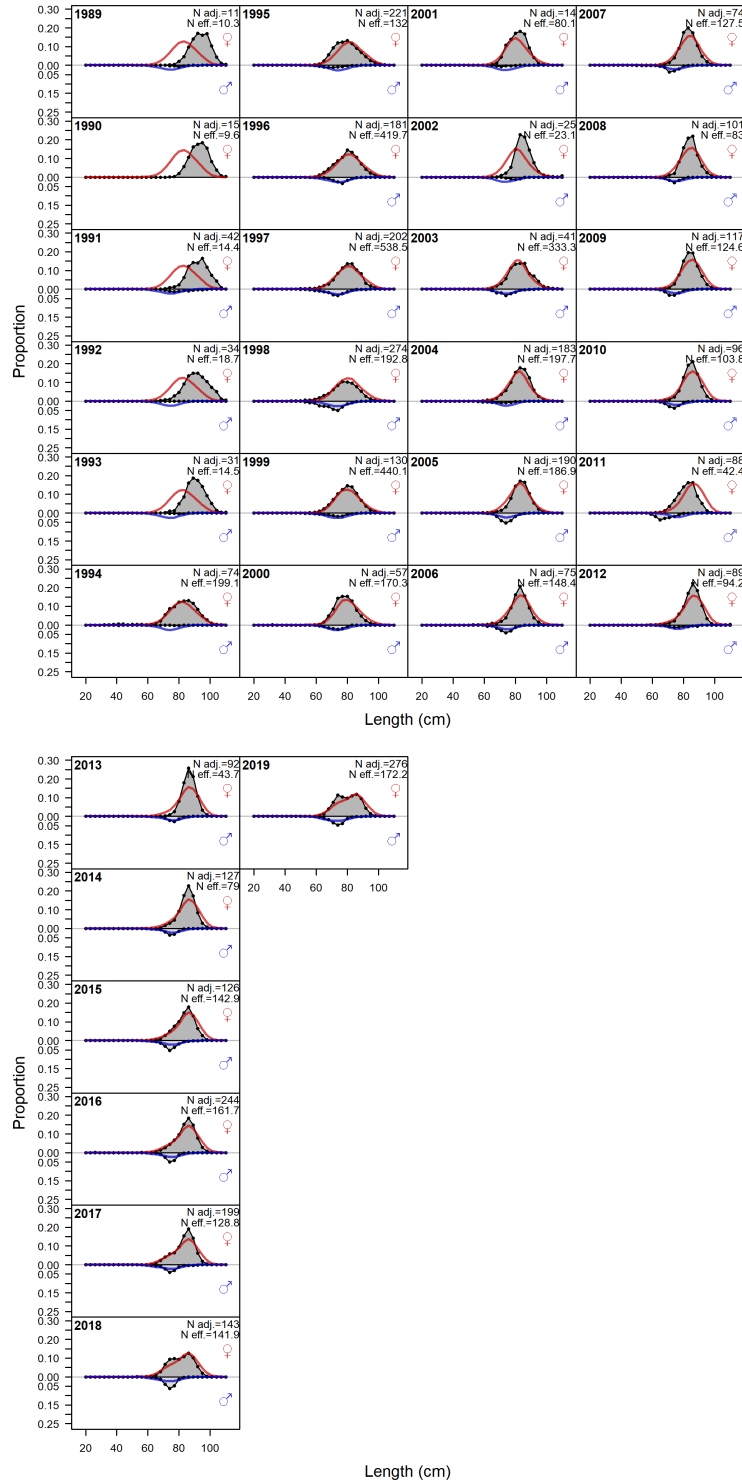


Figure 21: Fit to length compositions by year and sex for fleet 1: Landings_SGN_Rec_Others.

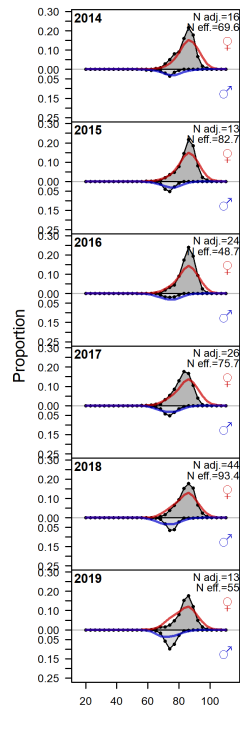
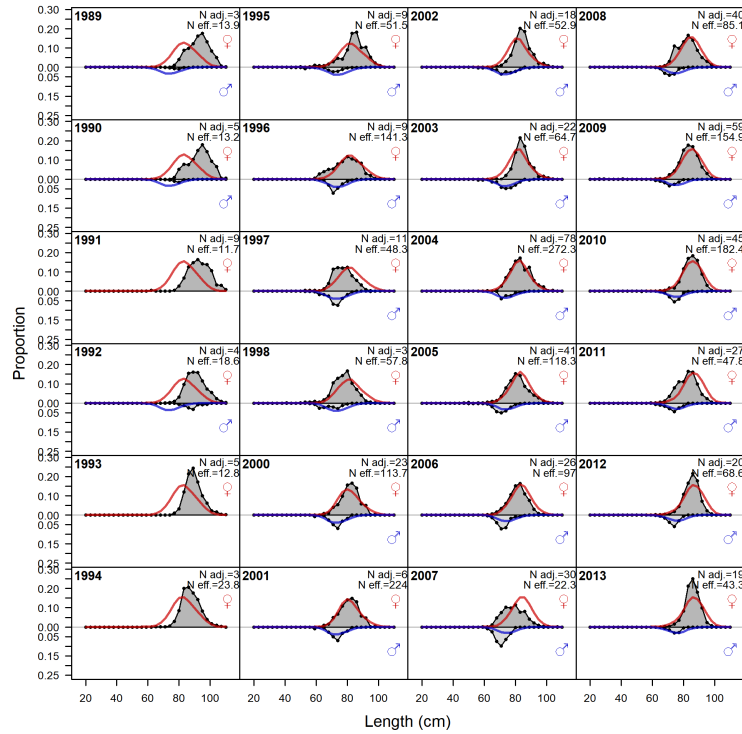


Figure 22: Fit to length compositions by year and sex for fleet 2: Landings_LL_OT_Foreign.

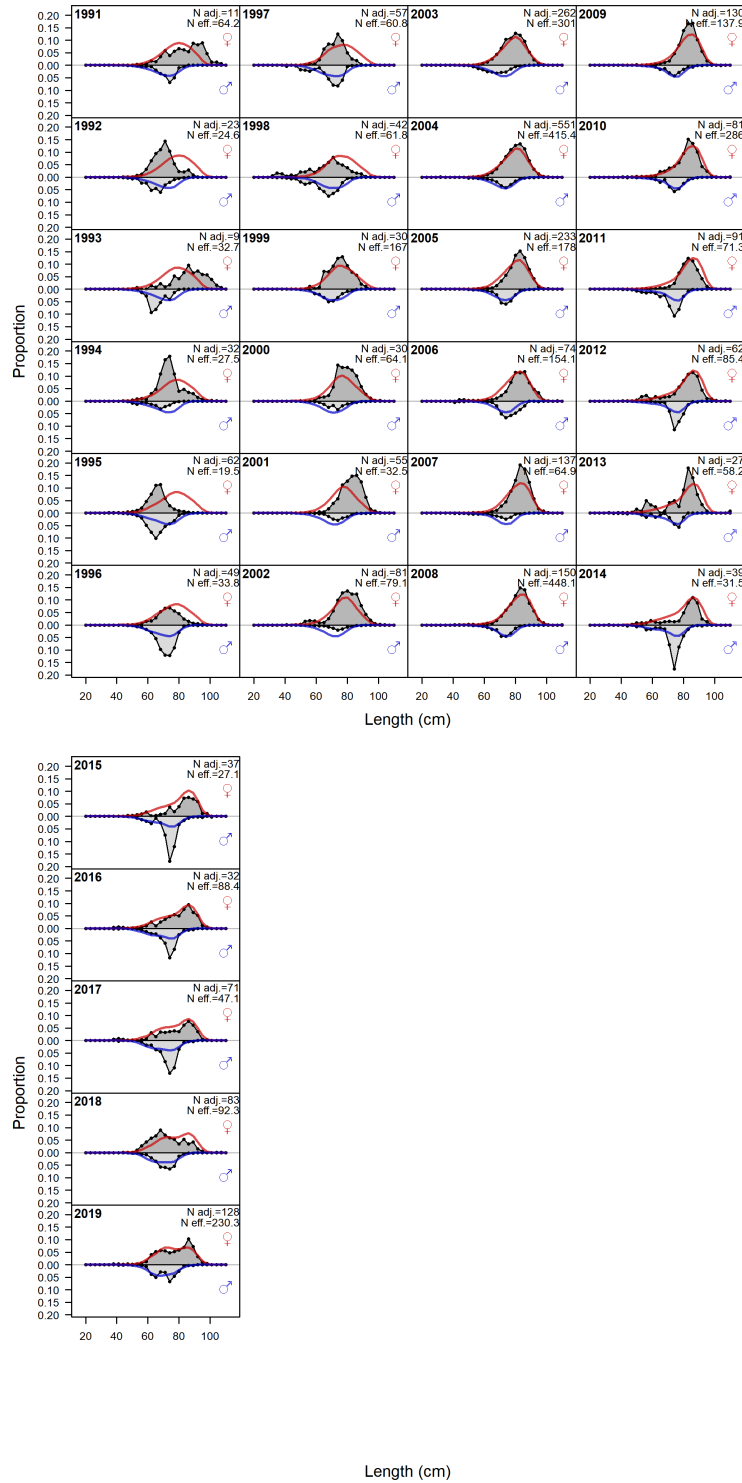


Figure 23: Fit to length compositions by year and sex for fleet 3: Discard_SGN_SD.

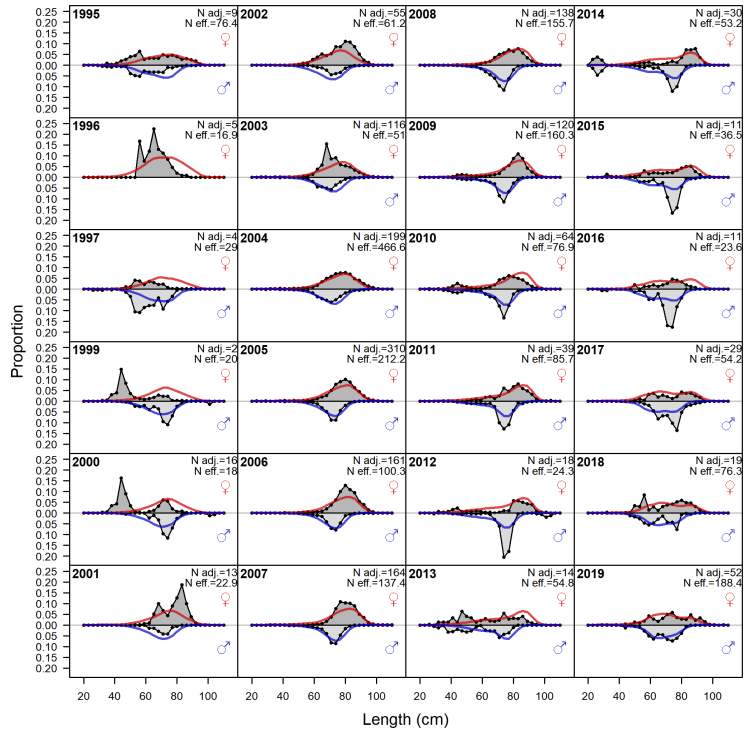
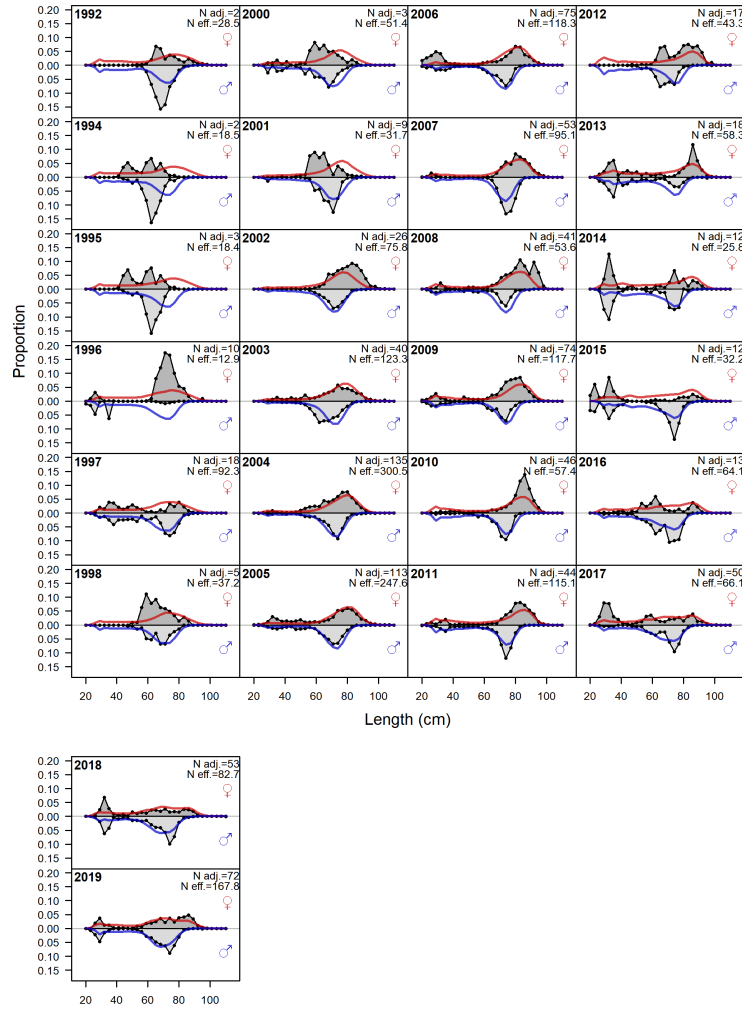


Figure 24: Fit to length compositions by year and sex for fleet 4: Discard_LMOT_LL_Rec.



Proportion

Length (cm)

Figure 25: Fit to length compositions by year and sex for fleet 5: Discard_SMOT.

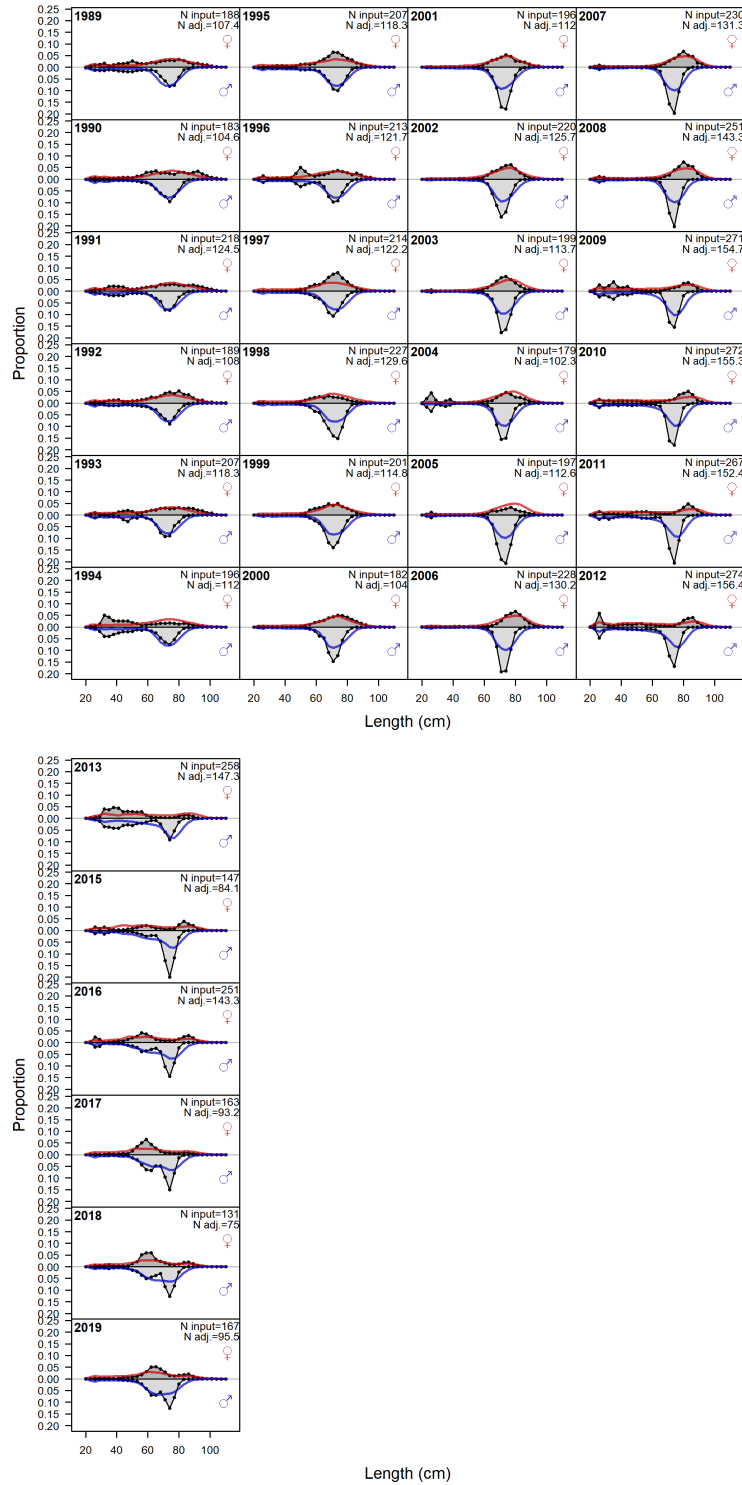


Figure 26: Fit to length compositions by year and sex for NEFSC spring bottom trawl survey.

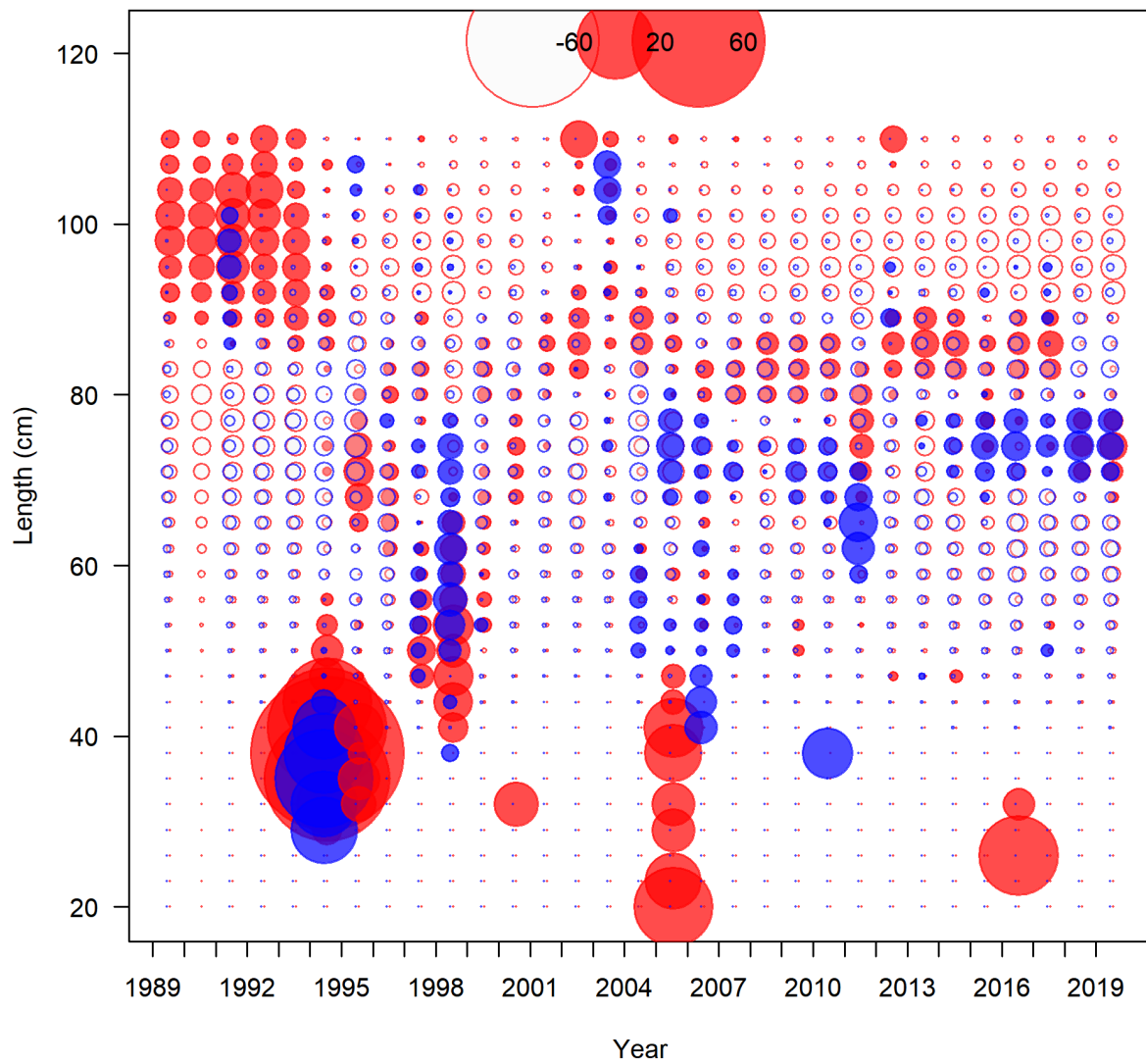


Figure 27: Pearson residuals for the fit to length compositions by year and sex for fleet 1: Landings_SGN_Rec_Others. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

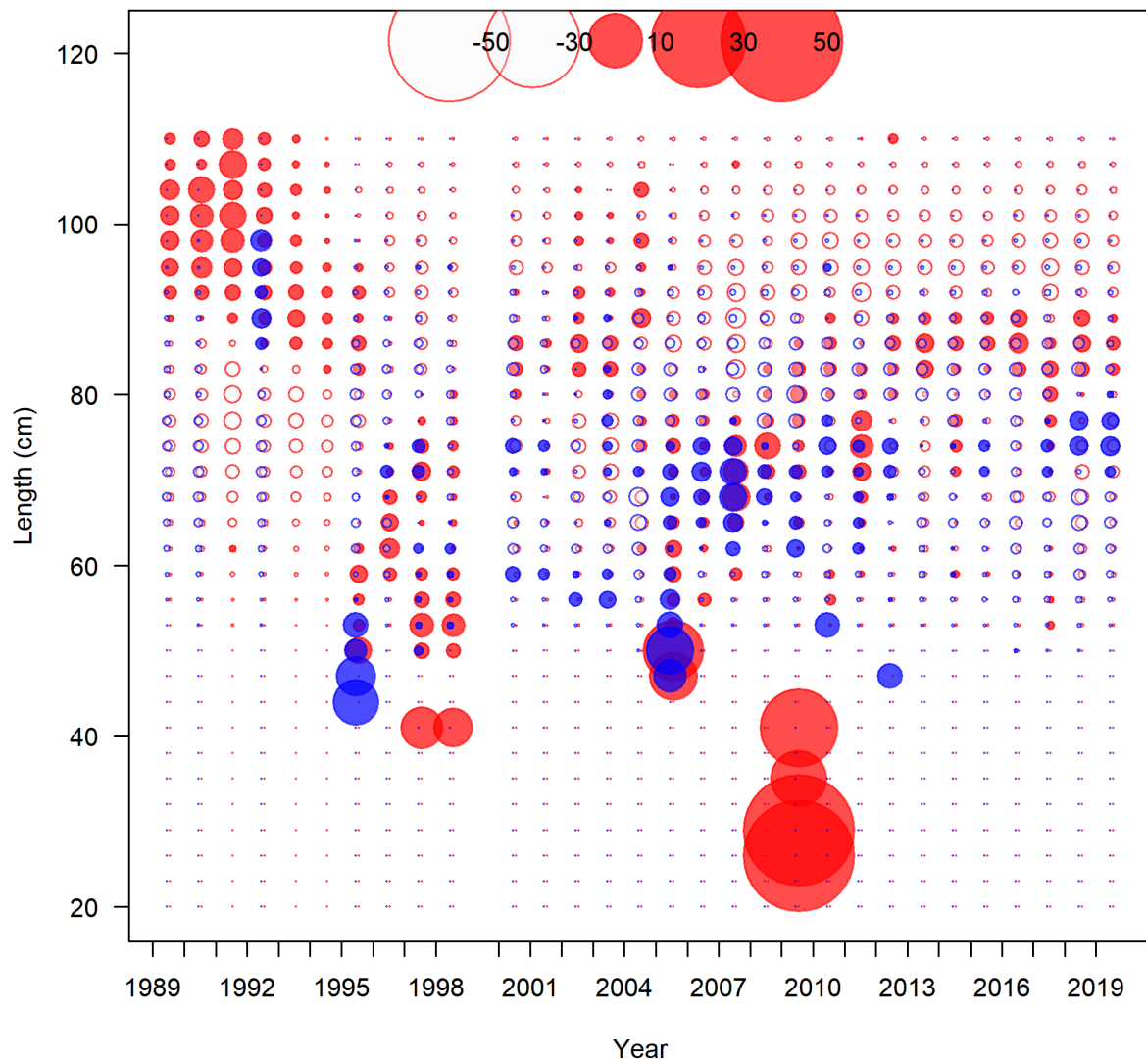


Figure 28: Pearson residuals for the fit to length compositions by year and sex for fleet 2: Landings_LL_OT_Foreign. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

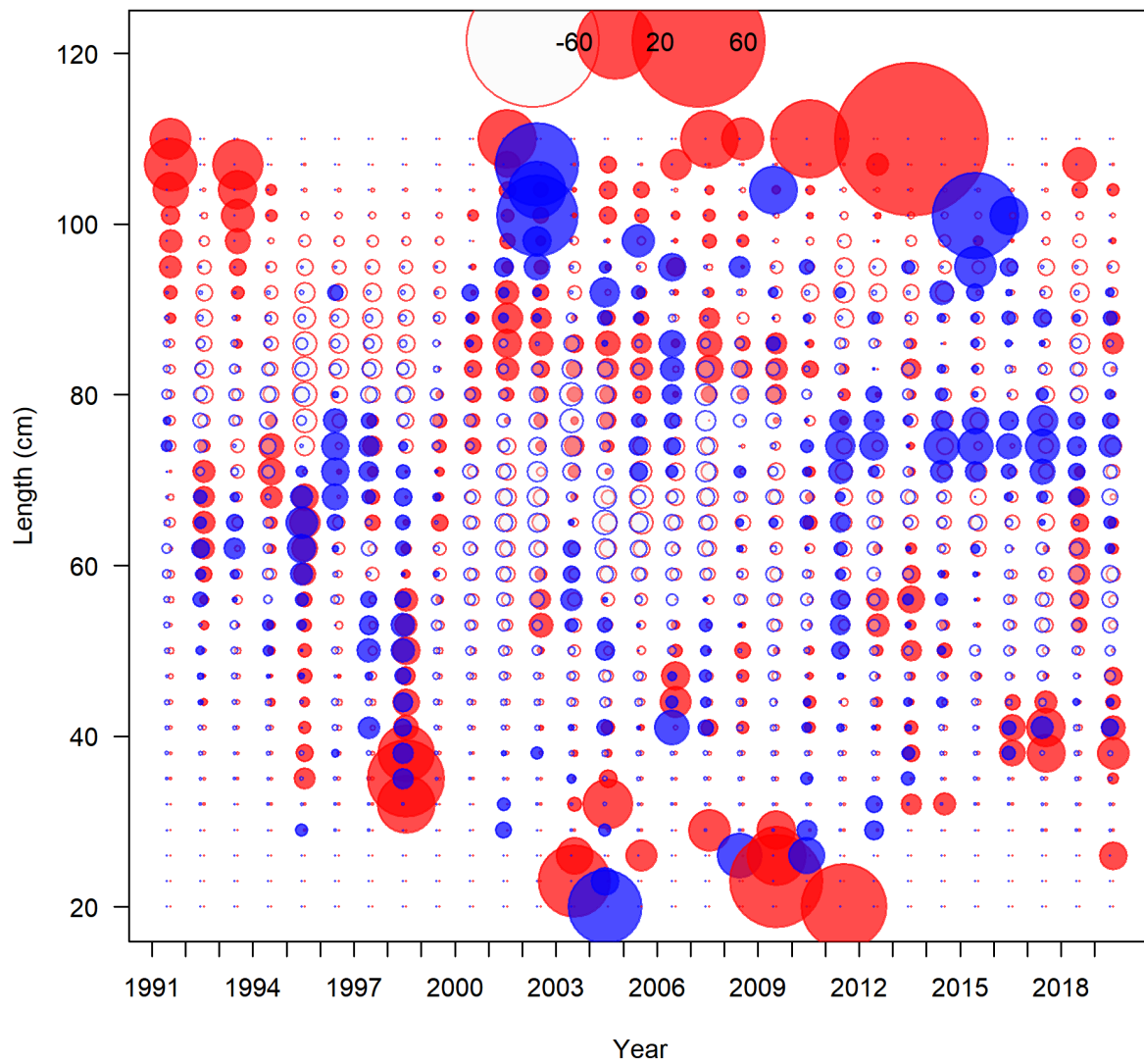


Figure 29: Pearson residuals for the fit to length compositions by year and sex for fleet 3: Discard_SGN_SD. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

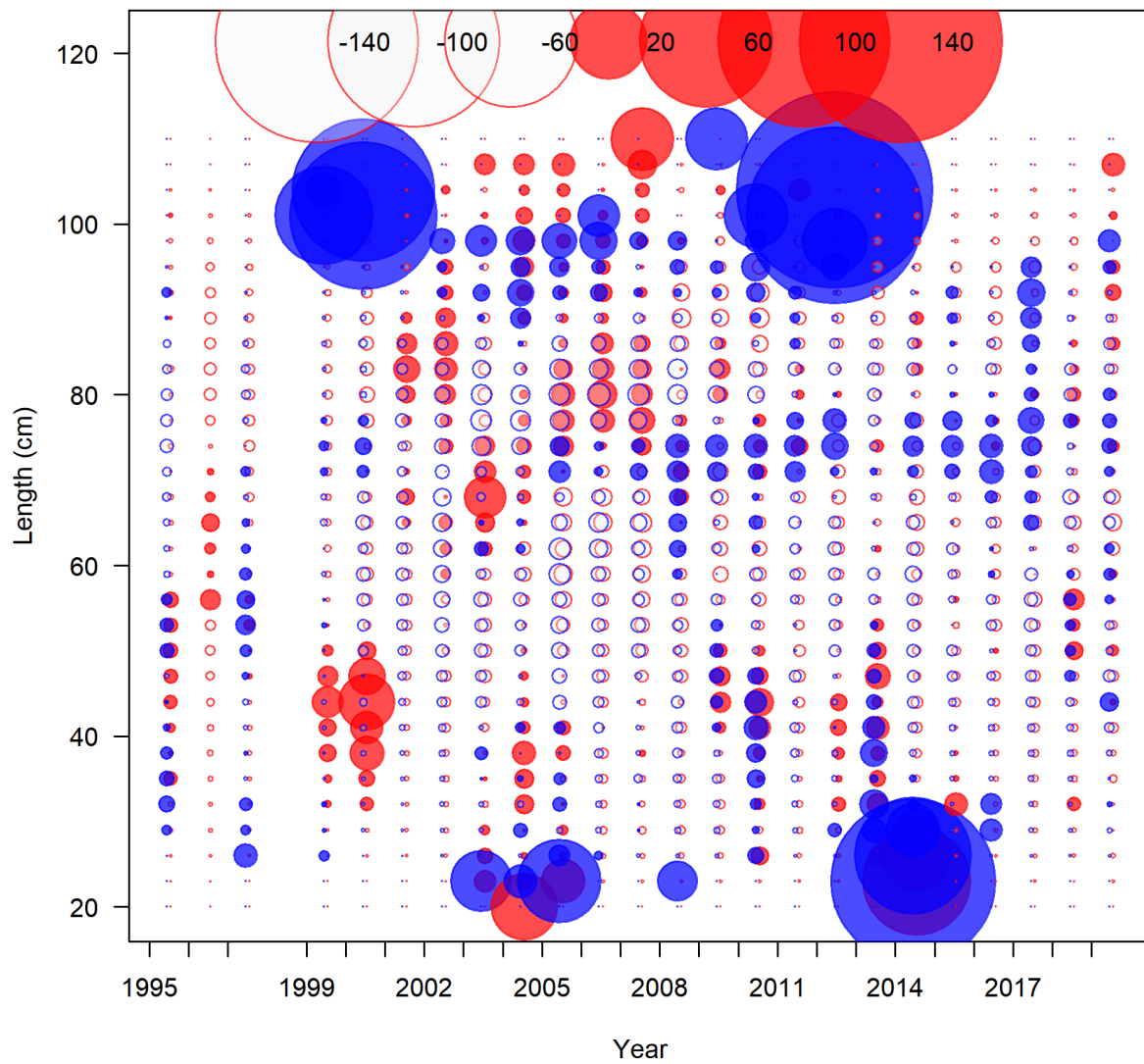


Figure 30: Pearson residuals for the fit to length compositions by year and sex for fleet 4: Discard_LMOT_LL_Rec. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

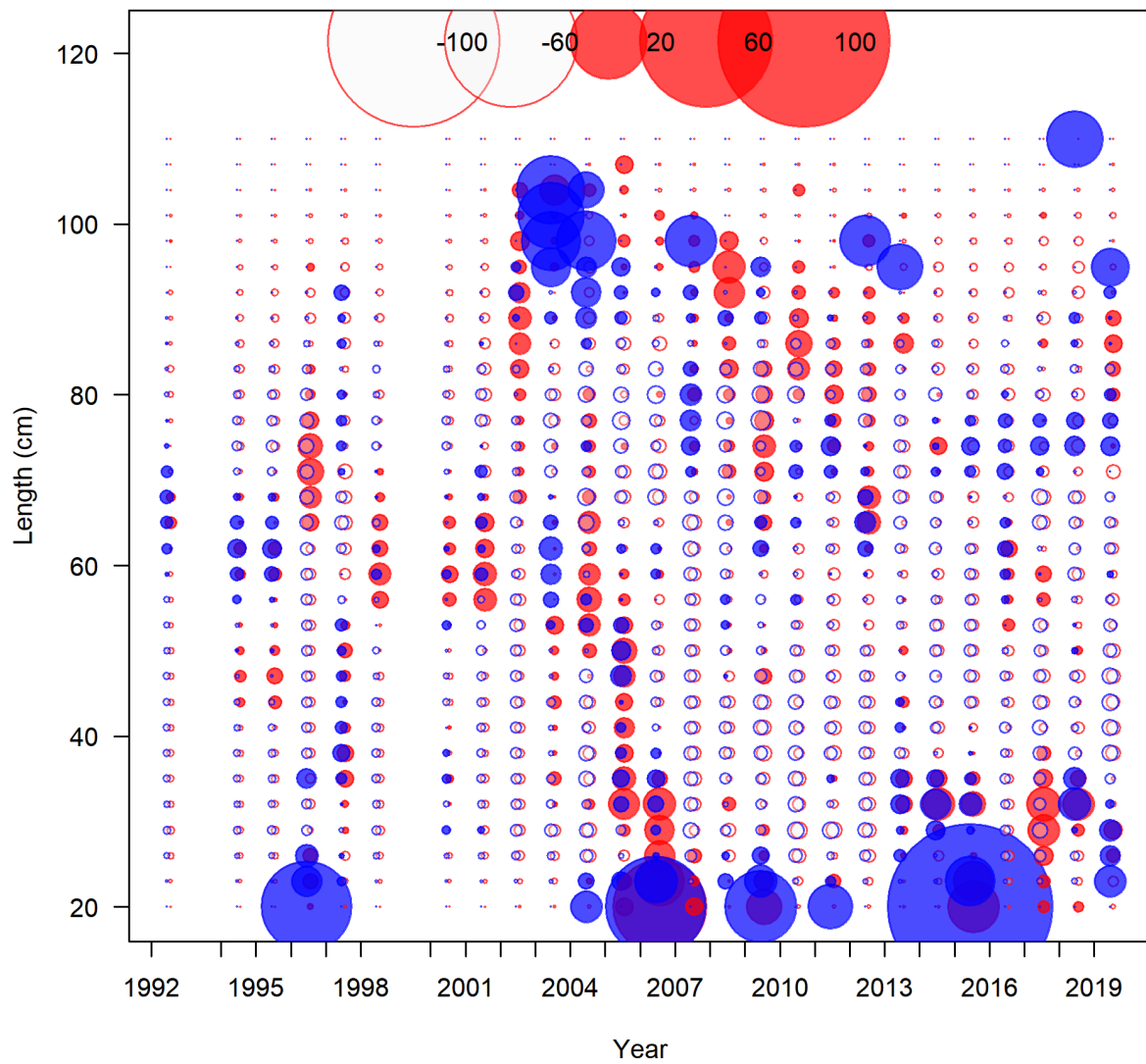


Figure 31: Pearson residuals for the fit to length compositions by year and sex for fleet 5: Discard_SMOT. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

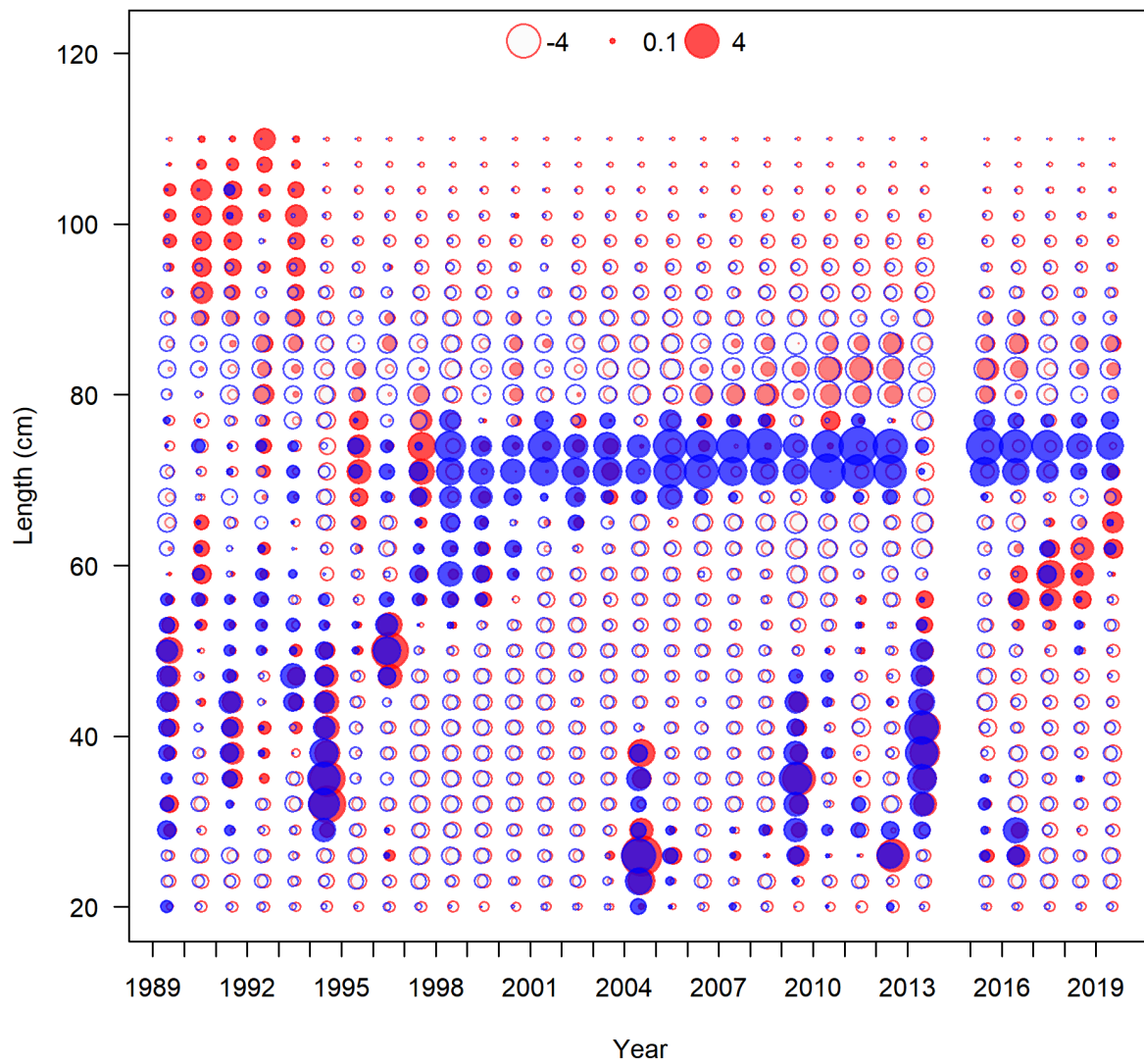


Figure 32: Pearson residuals for the fit to length compositions by year and sex for NEFSC spring bottom trawl survey. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

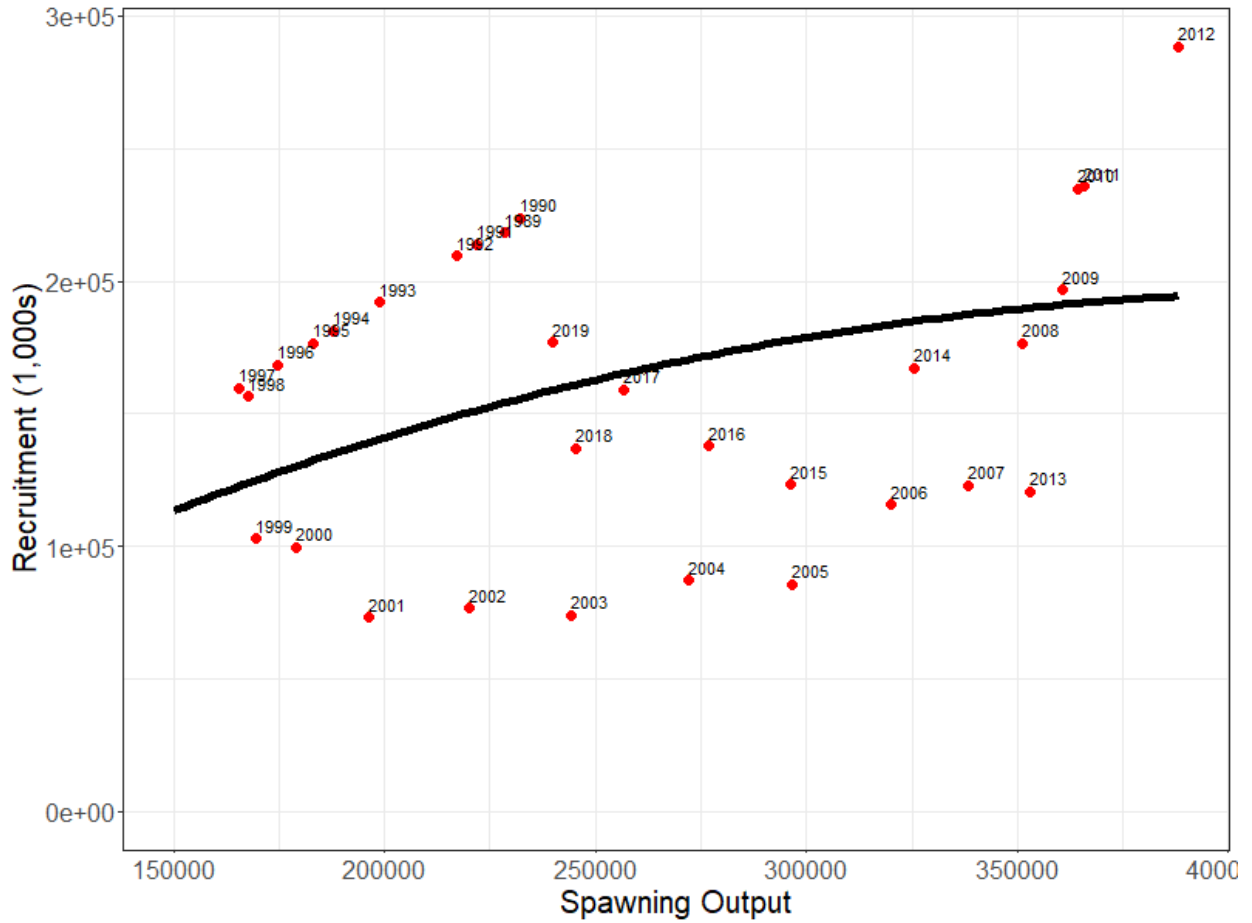


Figure 33: Fixed survivorship spawner-recruitment relationship, estimated age-0 recruitment (1,000s), and estimated spawner output by year for Atlantic spiny dogfish.

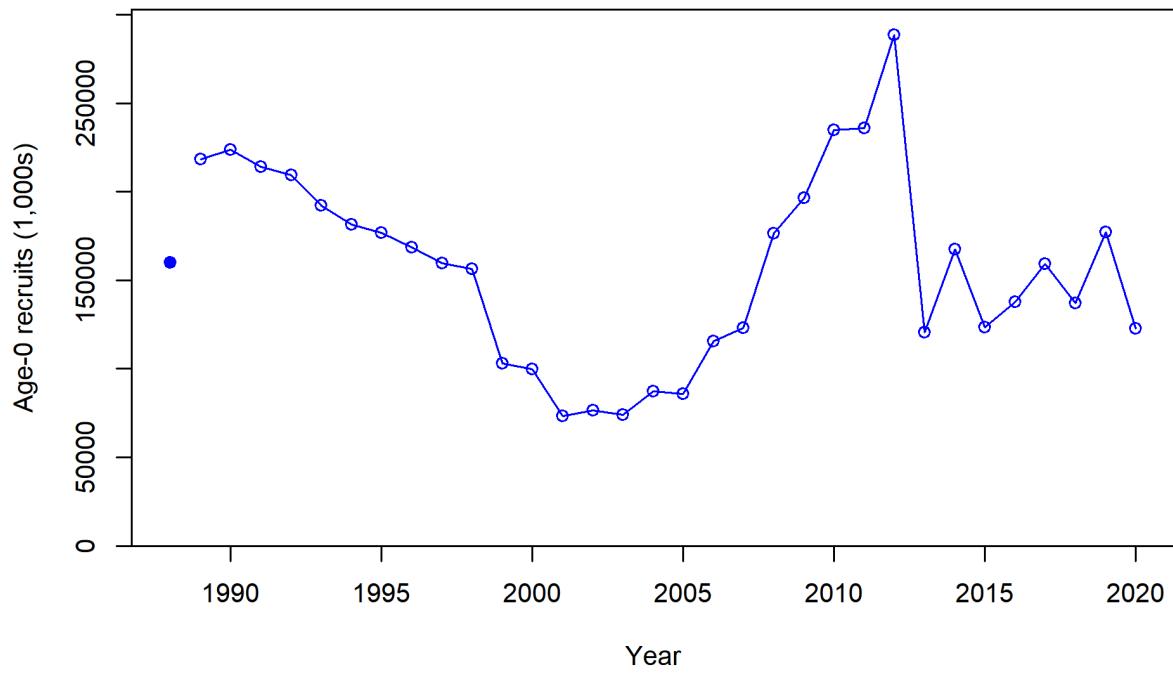


Figure 34: Estimated age-0 recruitment (1,000) by year for Atlantic spiny dogfish.

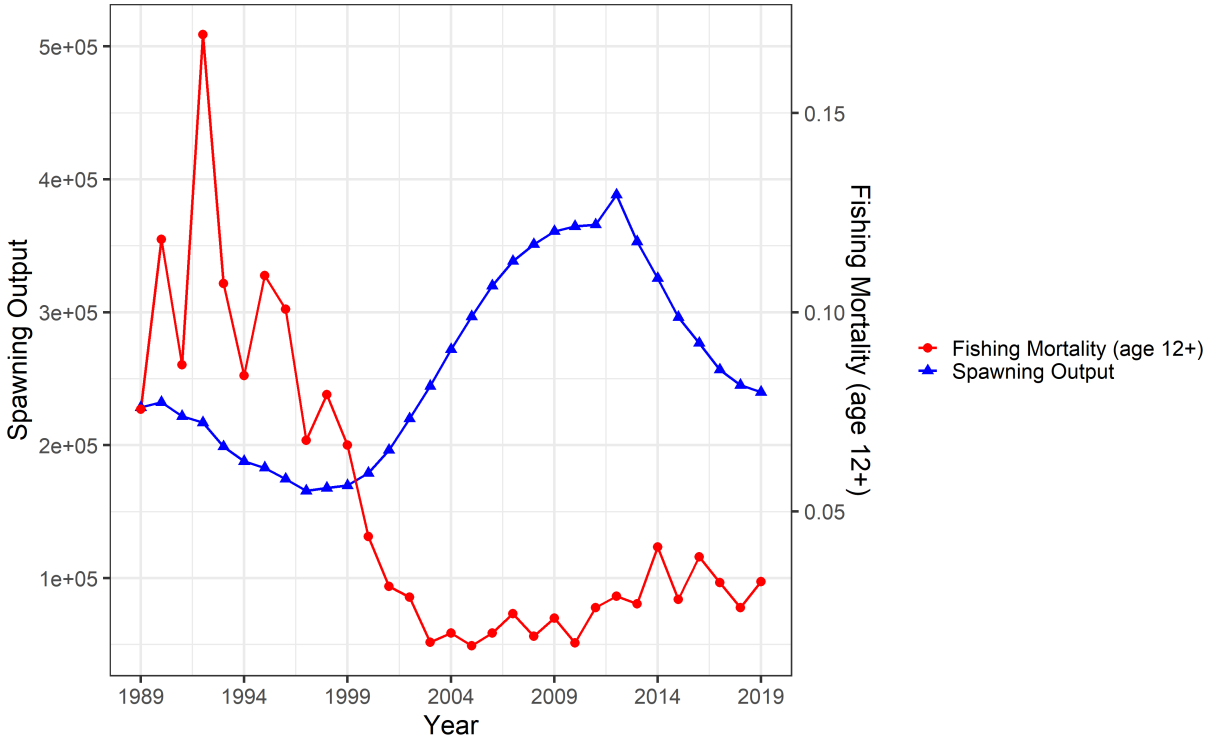


Figure 35: Estimated spawning output and fishing mortality (age 12+) by year for Atlantic spiny dogfish.

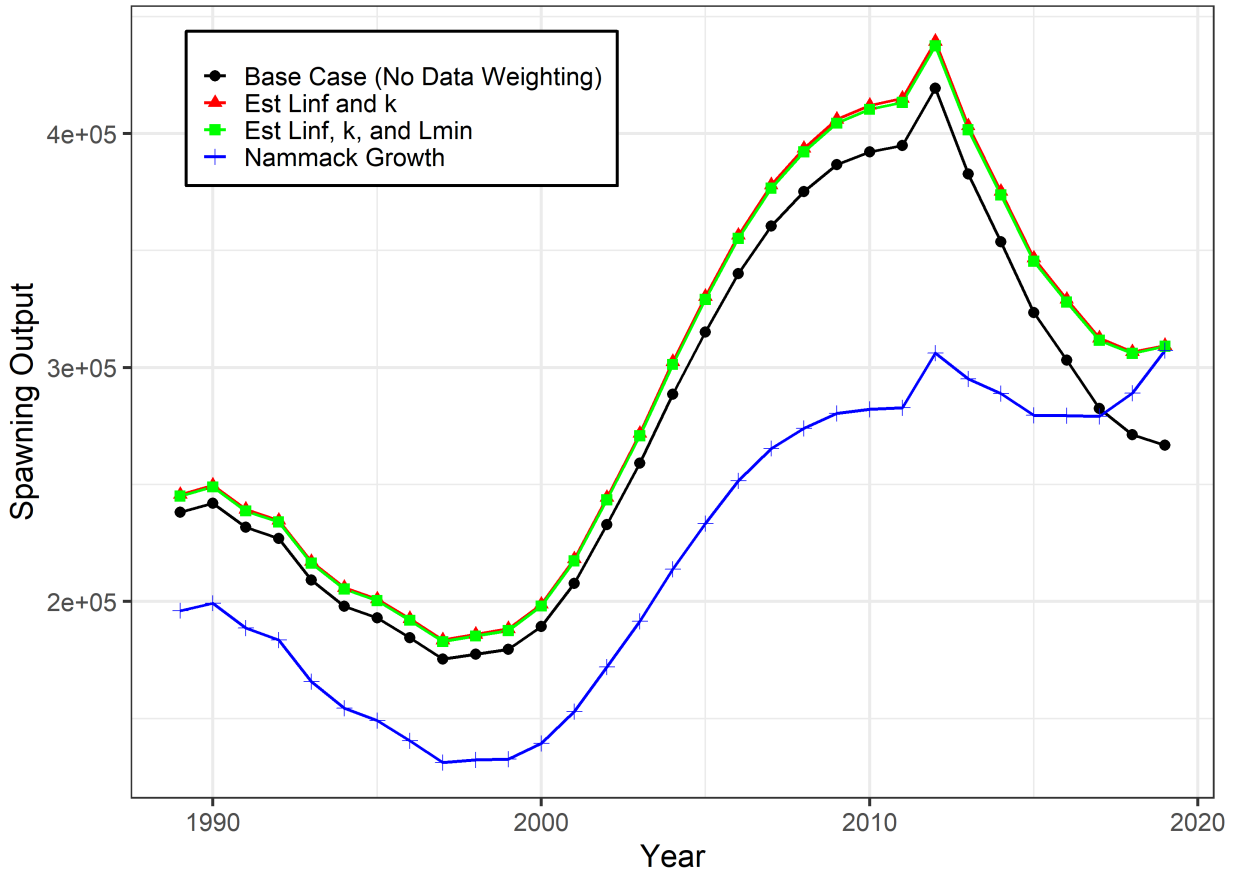


Figure 36: Spawning output estimated using different growth assumptions.

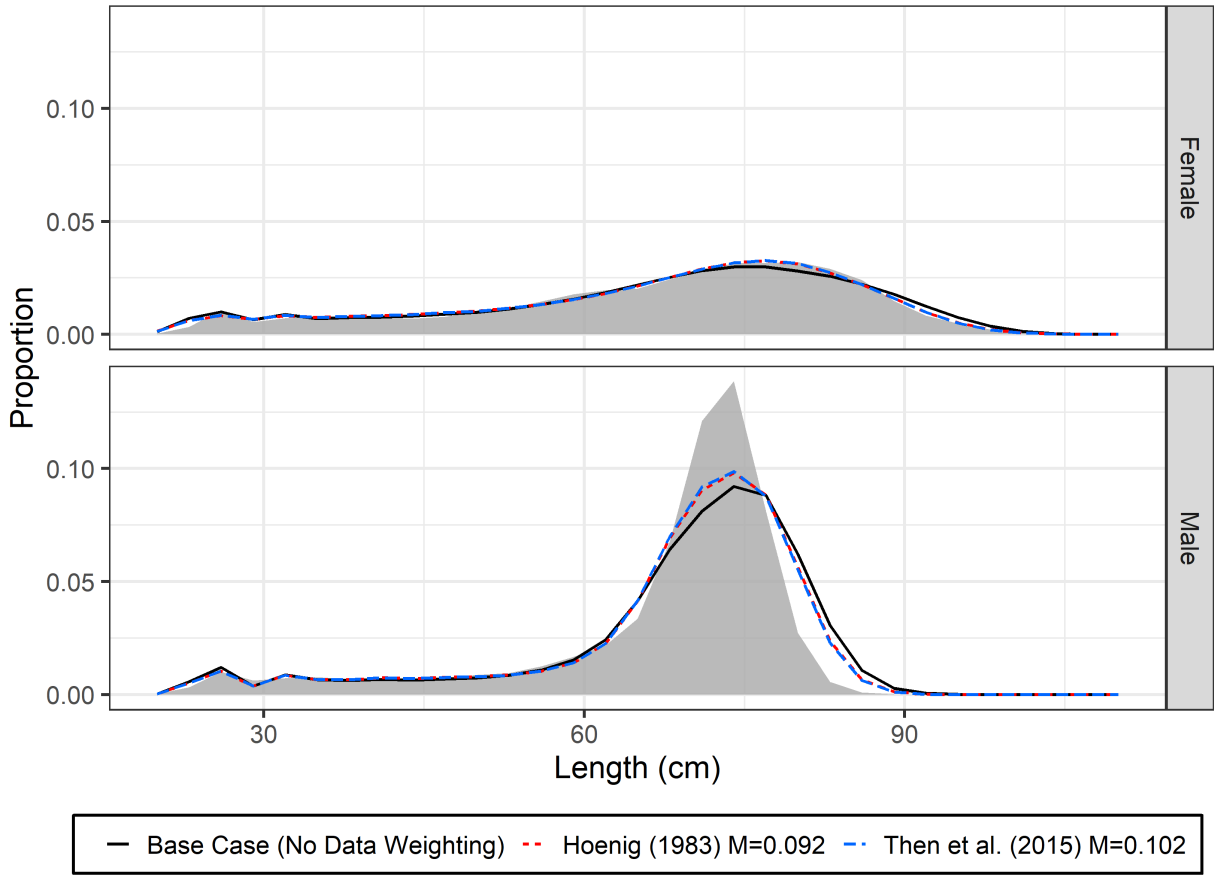


Figure 37: Observed (shaded) and model-predicted (line) length compositions by sex and natural mortality assumptions, aggregated across time.

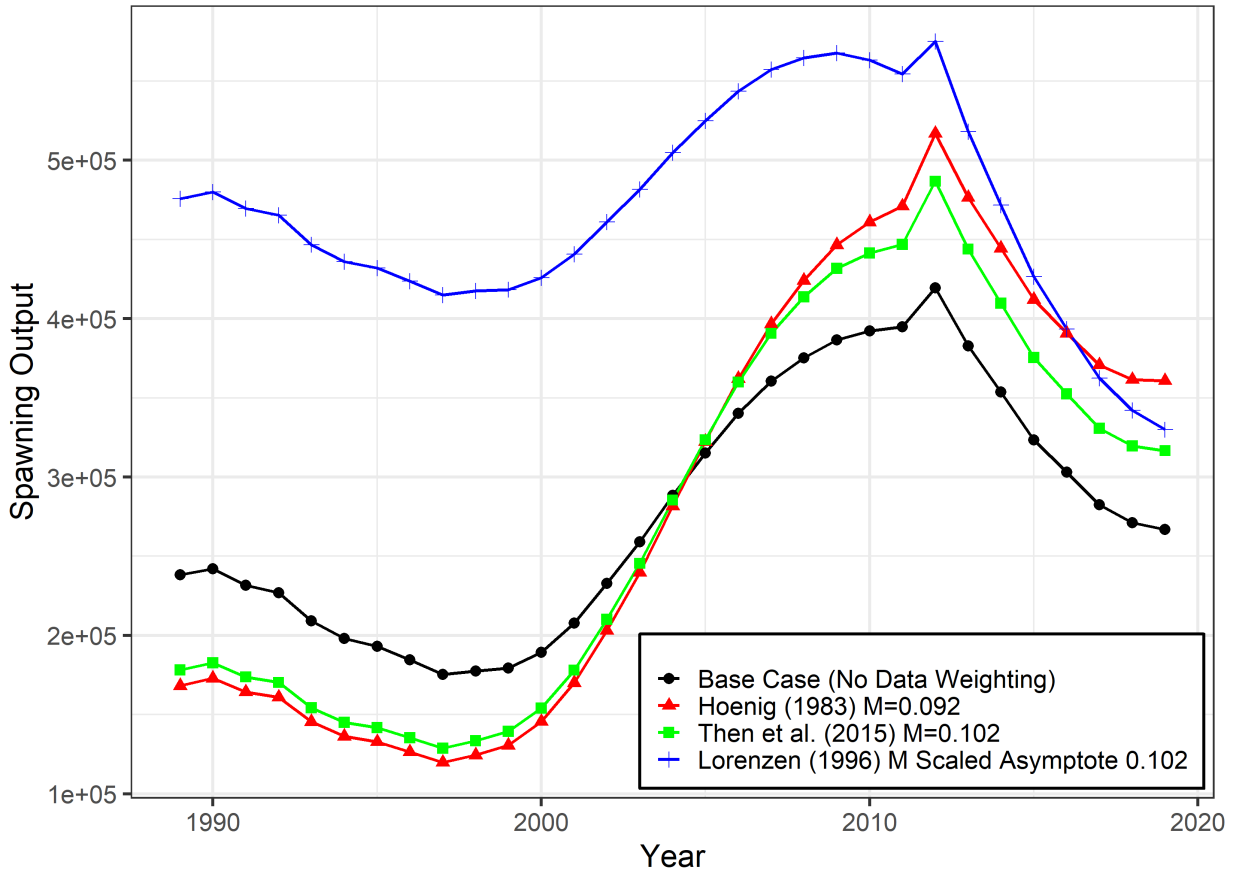


Figure 38: Spawning output estimated using different natural mortality assumptions.

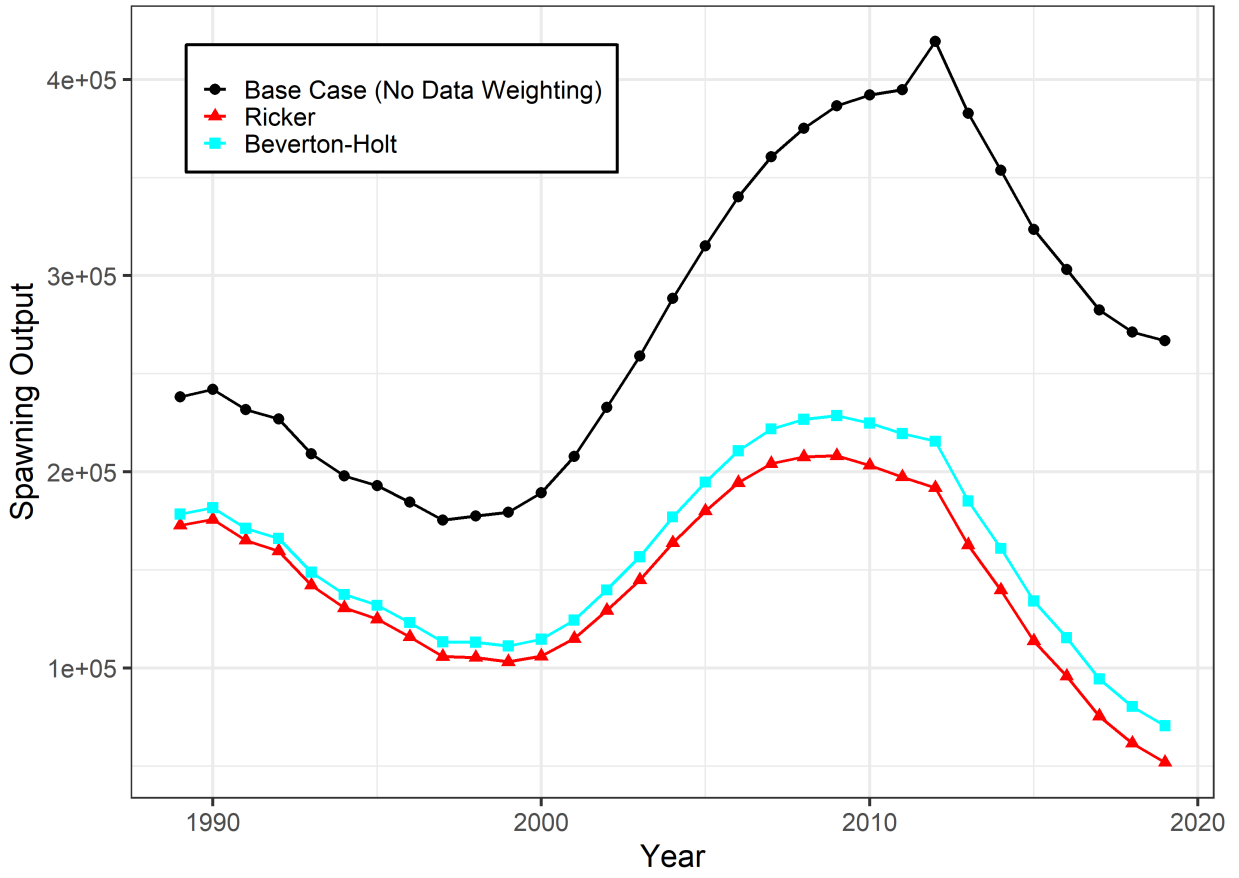


Figure 39: Spawning output estimated using different spawner-recruitment relationship assumptions.

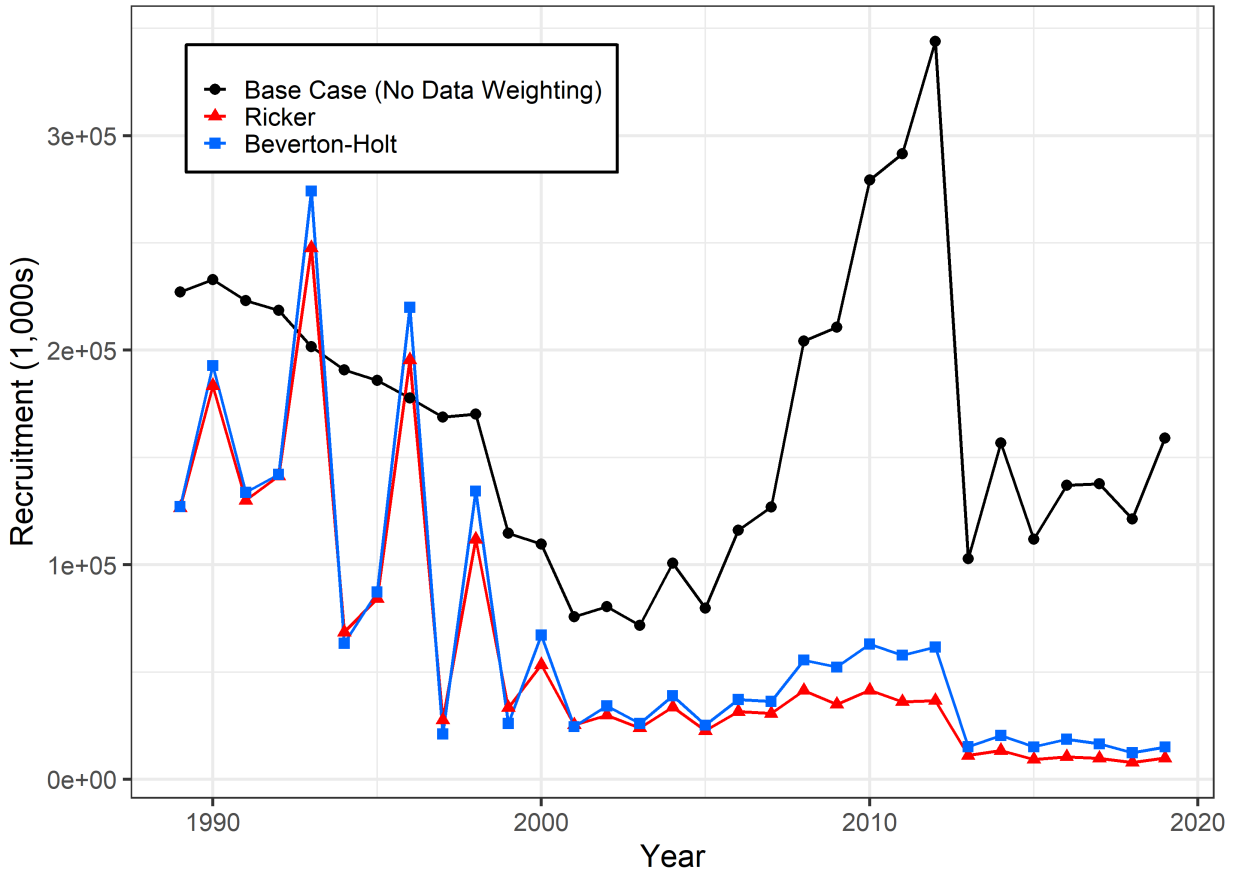


Figure 40: Recruitment (1,000) estimated using different spawner-recruitment relationship assumptions.

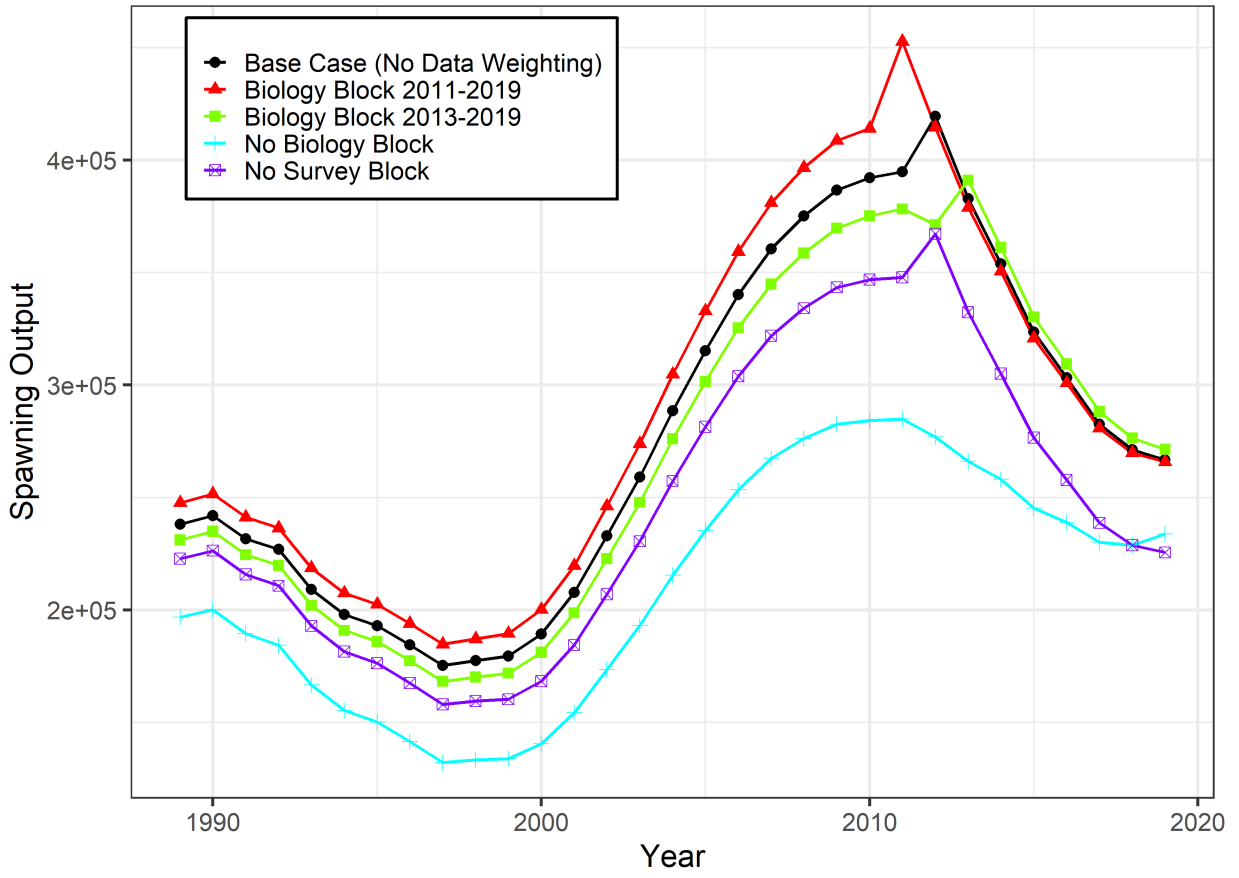


Figure 41: Spawning output estimated using different time block assumptions.

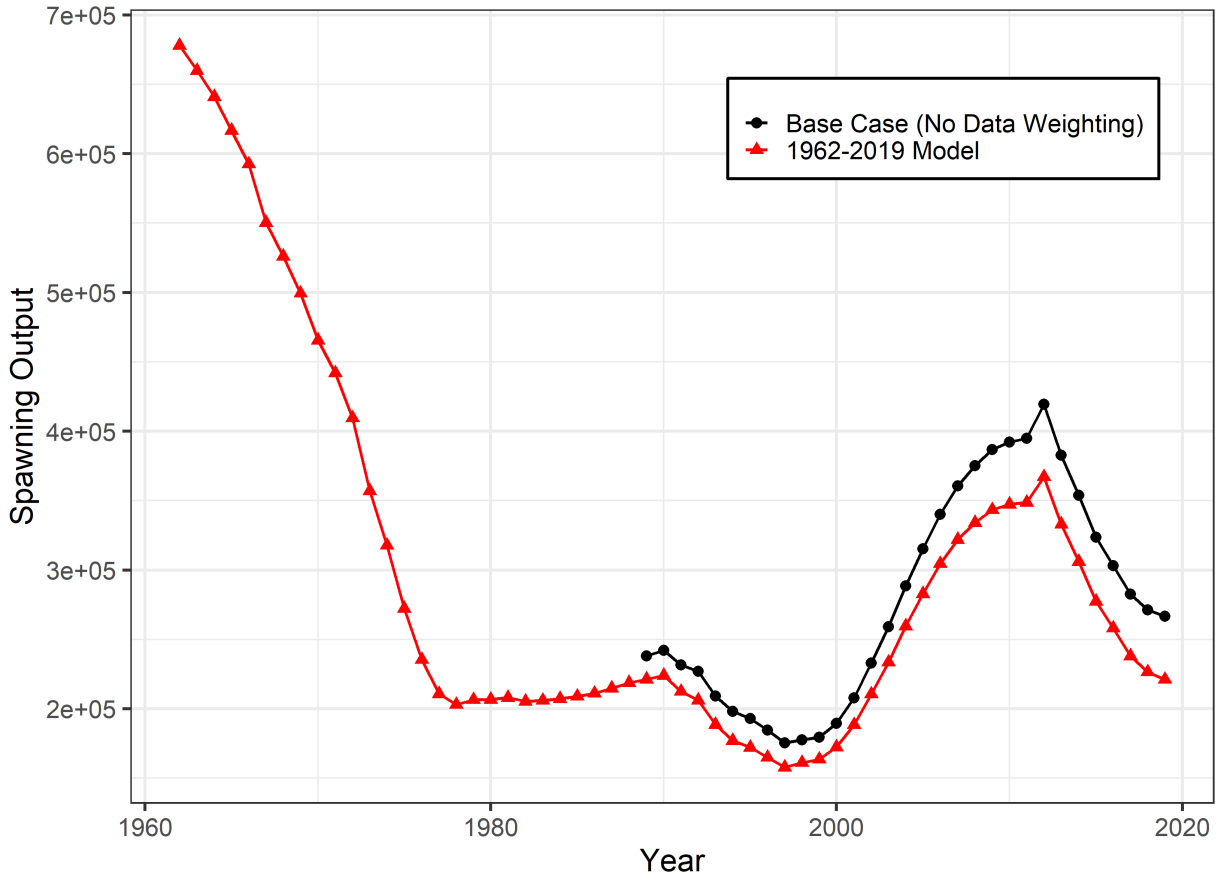


Figure 42: Spawning output estimated using different starting year assumptions.

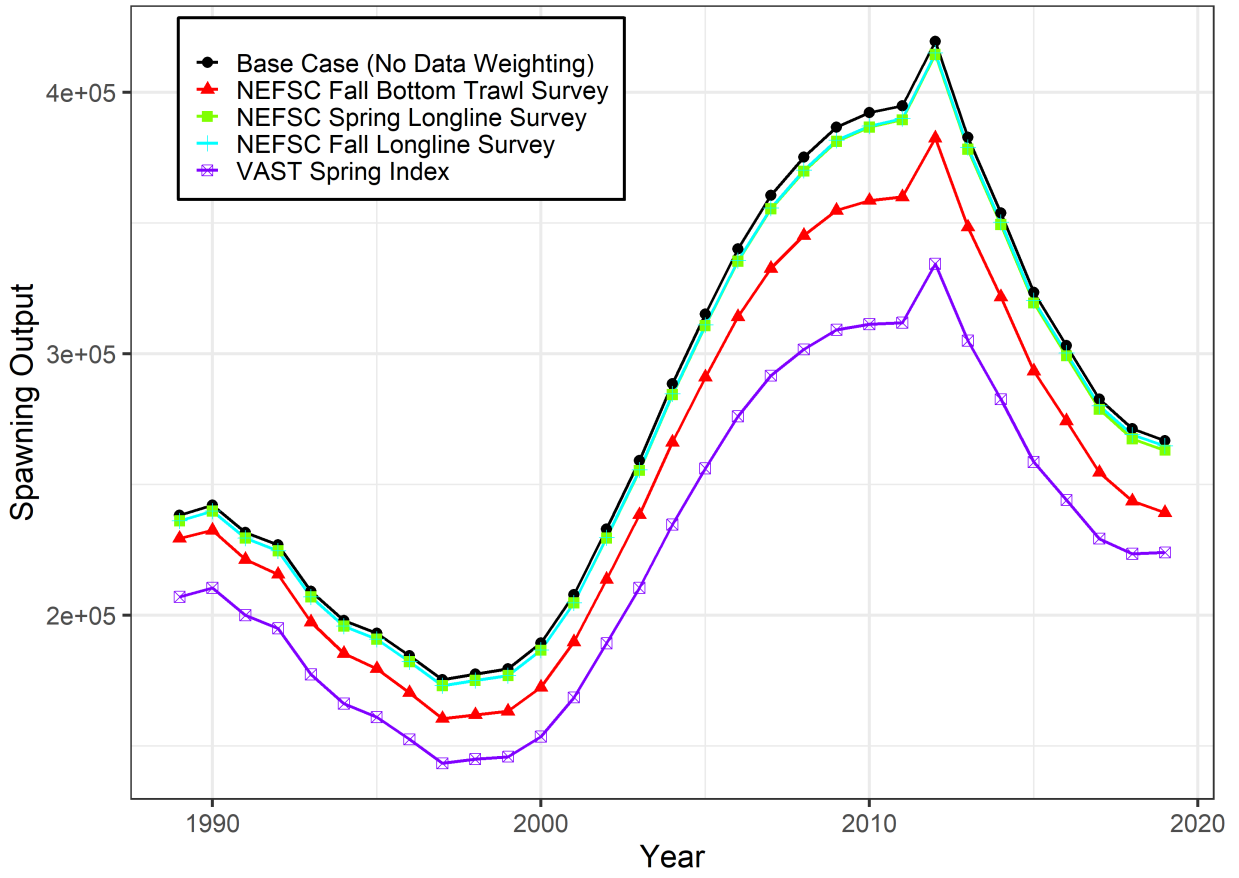


Figure 43: Spawning output estimated using different survey data.

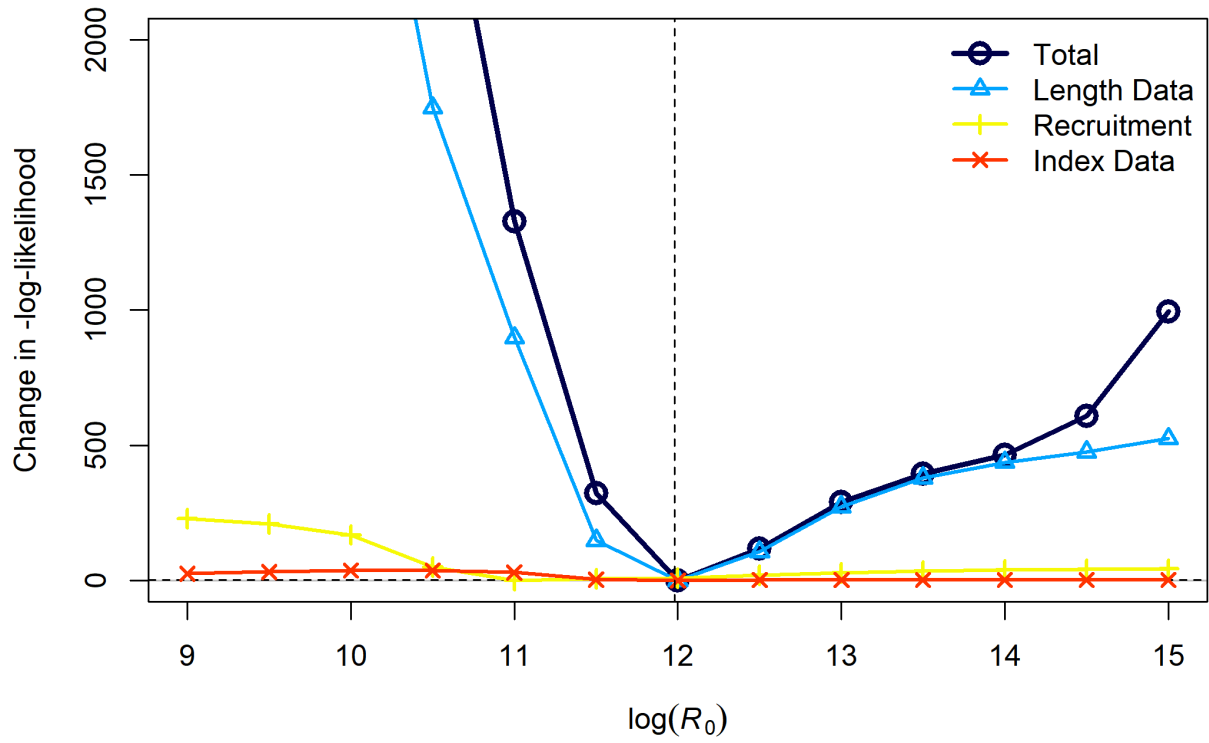


Figure 44: Log-likelihood profiles for R_0 for various data components.

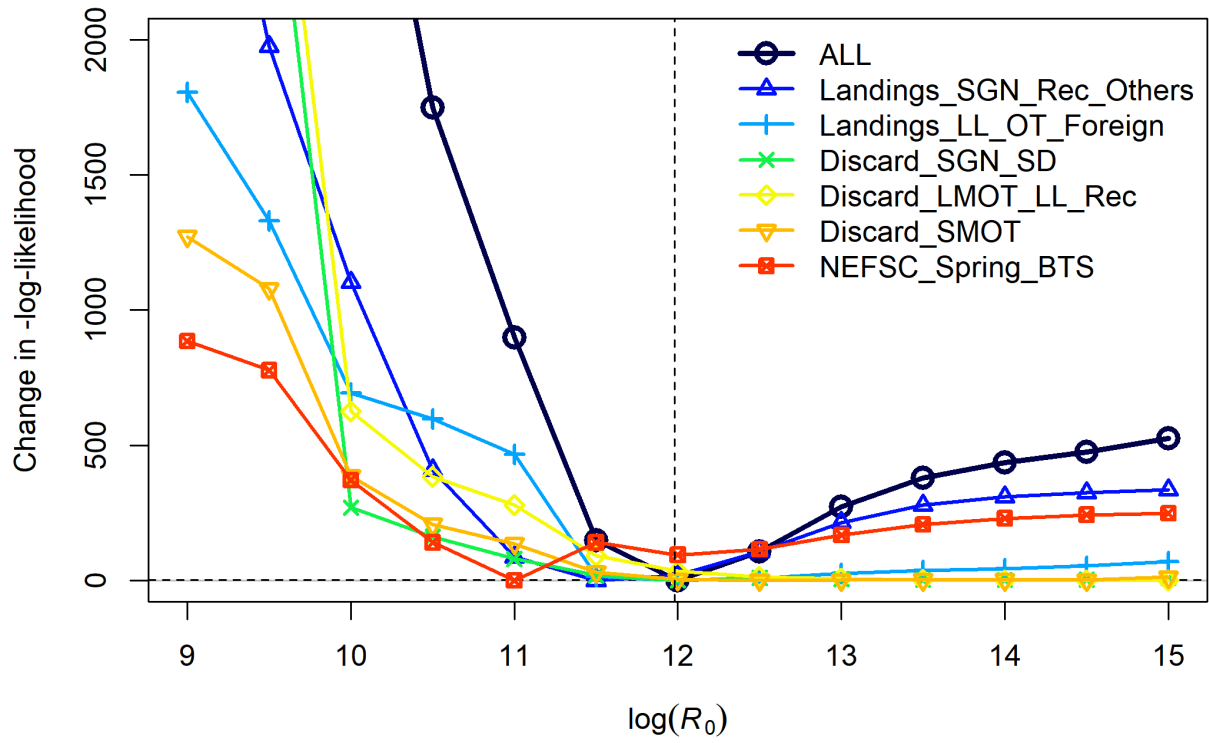


Figure 45: Log-likelihood profiles for R_0 for various source of length composition data.

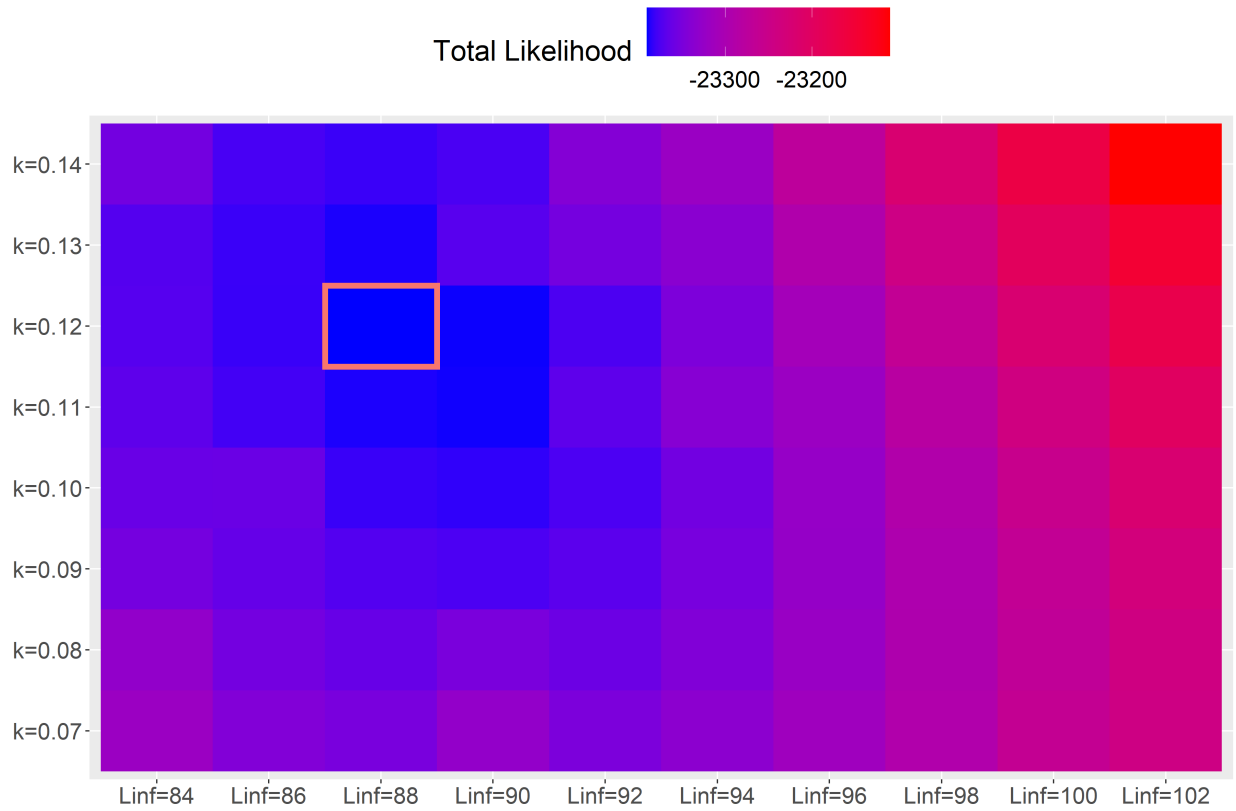


Figure 46: Total log-likelihood surface from profiling female L_{∞} and k von Bertalanffy growth parameters. The box indicated the run with the smallest total likelihood.

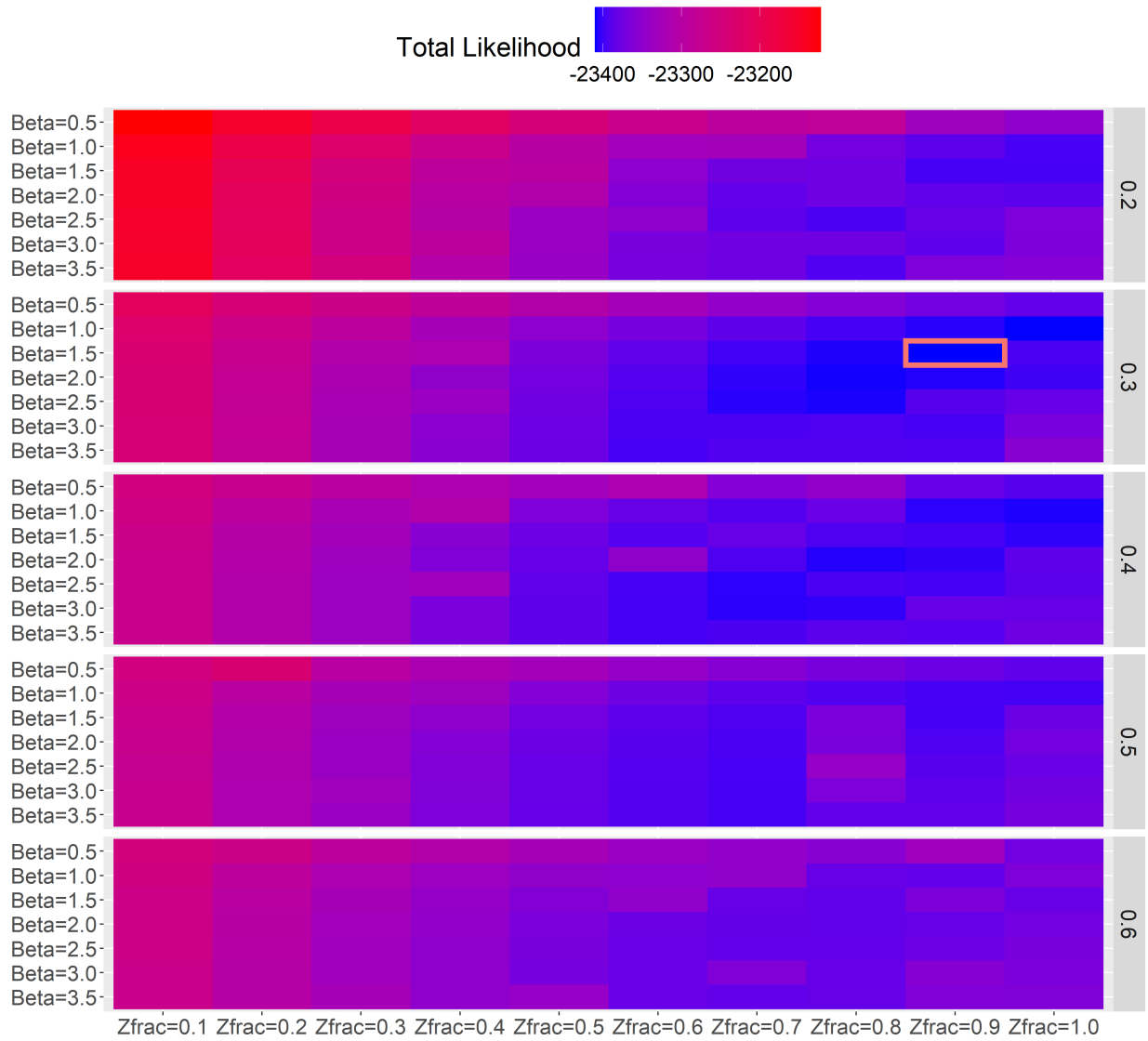


Figure 47: Total log-likelihood surface from profiling survivorship spawner-recruitment parameters Z_{frac} , β , and σ_R . The box indicated the run with the smallest total likelihood.

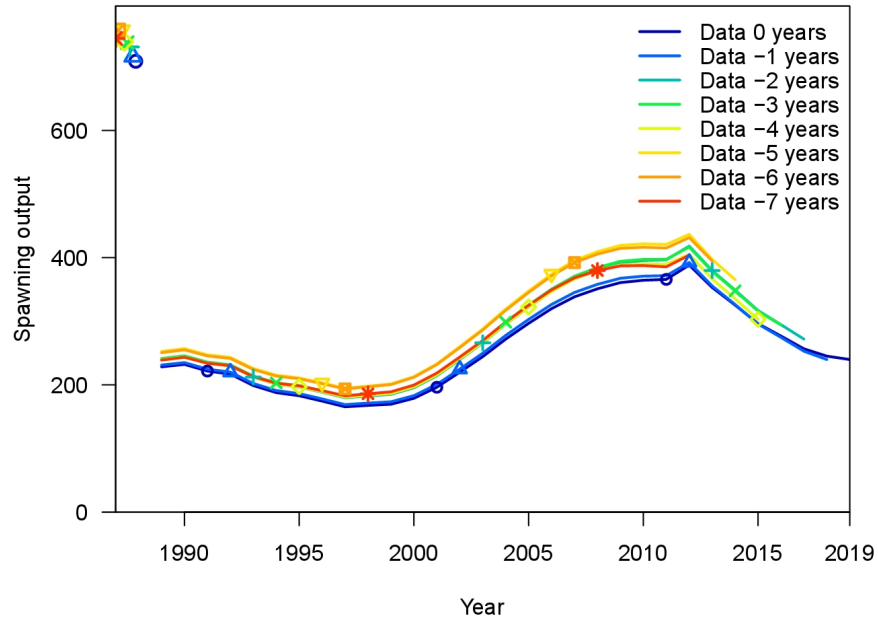


Figure 48: Retrospective plot for spawning output.

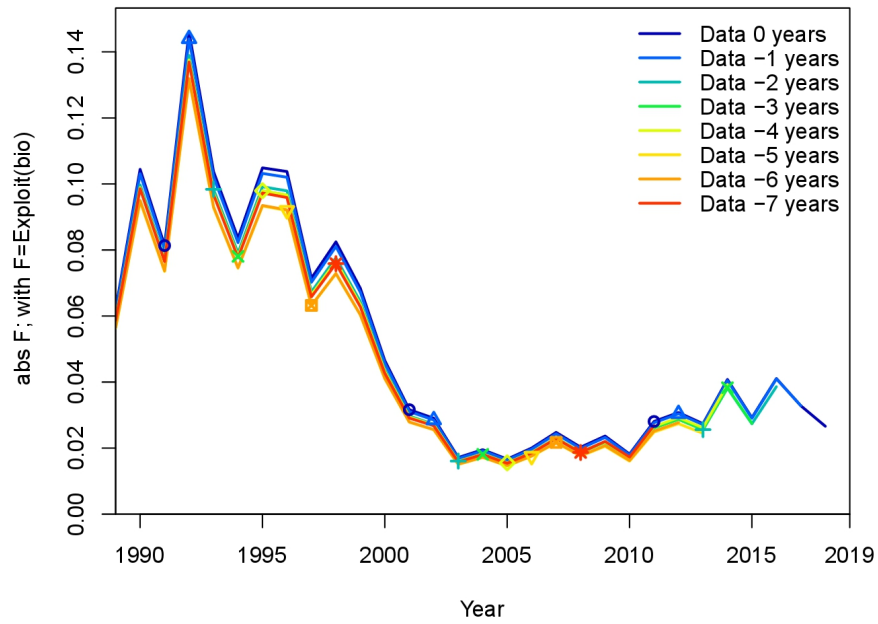


Figure 49: Retrospective plot for fishing mortality (age 12+).