Biological Reference Points for Spiny Dogfish: Revisiting Rago and Sosebee (2010)

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Abstract

We provide an update to the previously established biological reference point (B_{MSY}) developed by Rago and Sosebee (2010) for spiny dogfish of SSB_{MAX}: the spawning stock biomass index value that corresponds to the greatest resulting recruitment index value. The SSB_{MAX} is based on the principle that the stock-recruit relationship of spiny dogfish follows that of a Ricker function. Several attributes of this method were reviewed: an ad hoc retrospective analysis, environmentally explicit functions, and alternate stock-recruit models. The retrospective analysis indicated that the depensatory response of the Ricker model has weakened with recent years data added. While environmentally explicit Ricker models highlighted the impact of sex ratios, female fitness, and temperature on the stock-recruit relationships, these alternate models did not substantively improve the model fits. Lastly, it appears that both RIcker and Beverton-Holt models fit equally well. Based on the updated model fits, particularly the retrospective analyses and functional relationship evaluations, it has become less clear that the stock-recruit function of Atlantic spiny dogfish follows a Ricker model, and subsequently that SSB_{MAX} is an appropriate proxy reference point.

Introduction

As part of fisheries stock assessments, biological reference points are used to guide fisheries managers on appropriate target biomass levels and harvest rates that support sustainable fisheries. For data-rich species, such reference points are based on population model outputs and estimated parameters, often from those of the stock-recruit relationship. For data-limited species, alternative proxies for B_{MSY} and F_{MSY} are needed.

Such has been the case for Atlantic spiny dogfish (*Squalus acanthias*), a long-lived elasmobranch of the northwest Atlantic. The current stock assessment uses an index-based approach, which includes a swept-area bottom trawl survey index and landings, to estimate the stock size and fishing rate over time. Previous biomass reference points for spiny dogfish have been based on a Ricker stock-recruitment model using proxy spawner and recruit relative abundance indices derived from Northeast Fishery Science Center trawl survey data (Rago and Sosebee 2010). From this relationship, the spawning stock biomass index value that results in the maximum estimated recruitment, termed SSB_{MAX}, is used as the proxy for B_{MSY}. This approach is based on the understanding that the spiny dogfish stock-recruit model follows the Ricker model formulation. This model has also been extended with parameterization to incorporate additional considerations for the species that may impact the spawner-recruit relationship (e.g., average size of the recruits) to best estimate the productivity of the stock.

As found for many stocks, our inference on the stock-recruit dynamics often changes over time via the reassessment of these relationships with additional years' data. Such changes often occur as the drivers on the stock-recruit relationship change over time. Thus, the reanalysis as to whether previously accepted inferences on the stock-recruit dynamics, such as density-dependence and covariate contributions, is critical. In this working paper, we revisit the Rago and Sosebee (2010) approach for estimating the B_{MSY} proxy. We first looked to determine how additional years' data impact our understanding of $\mathrm{SSB}_{\mathrm{MAX}}$. We then revisited the incorporation of additional covariates into the stock-recruit model to see if the same variables were still important in predicting recruitment. Lastly, we reassessed our fundamental understanding of whether the stock-recruit dynamics for spiny dogfish still follows the theoretical Ricker model, or does the relationship at this point better reflect that of Beverton-Holt. In the absence of biological reference points produced from a length or age-based assessment model, we provide revised reference points for use in understanding whether the spiny dogfish stock is overfished or not.

The work aims to address multiple terms of reference (TORs) as part of the Spiny Dogfish Research Track Assessment:

> *TOR1: Identify relevant ecosystem and climate influences on the stock. Characterize the uncertainty in the relevant sources of data and their link to stock dynamics. Consider findings, as appropriate, in addressing other TORs. Report how the findings were considered under impacted TORs.*
>
> *TOR6: Update or redefine status determination criteria (SDC; point estimates or proxies for BMSY, BTHRESHOLD, FMSY and MSY reference points) and provide estimates of those criteria and their uncertainty, along with a description of the sources of uncertainty. If analytic model-based estimates are unavailable, consider recommending alternative measurable proxies for reference points. Compare estimates of current stock size and fishing mortality to existing, and any redefined, SDCs."*

Methods

Data for this analysis was used from the Northeast Fisheries Science Center (NEFSC) Bottom Trawl Survey (Table 1). The trawl survey is conducted in spring and fall annually within federal waters of the Northeast US Shelf (Cape Hatteras to the Gulf of Maine) using a random stratified sampling design. Annual indices for spiny dogfish were derived from the spring portion of the survey; it is believed that based on the species life history and design of the trawl survey, the fall portion of the survey does not adequately sample the population, and thus resulting indices represent trends of the stock. Available trawl survey data from 1980 to 2021 were used for this analysis. Annual mean spring bottom temperature was also derived from the NEFSC Bottom Trawl Survey, and the winter (December, January, February) North Atlantic Oscillation (NAO) index was derived from the National Center for Atmospheric Research (NCAR 2022). Trends and data were described and cross correlated to infer correspondence between variables.

For the stock-recruit analyses, recruits were defined as dogfish less than 36 cm total length (TL), and spawners were defined as females greater than 80 cm. This determination follows the approach set out by Rago and Sosebee (2010). A Ricker function has been used to describe the spawner-recruit relationship for US spiny dogfish since 1999, based on a joint meeting of the Science and Statistical Committees (SSCs) of the New England and Mid-Atlantic Fishery Management Councils (Rago and Sosebee 2010). As such, the Ricker model was used for the majority of the analyses presented herein. The Ricker model is expressed as:

$$R_t = a * S_t * e^{-b*St}$$

where R_t and S_t represent recruit and spawner annual indices in year t, respectively, and a and b are estimated parameters. Given the expected age of recruits less than 36 cm, no lag was applied to either recruit or spawner time series. The model was fit using data from several time periods: 1980-1996, 1980-2003, 1980-2009, and all years (1980-2021). The first three stanzas represent reproductions as put forth in Rago and Sosebee (2010) as a form of retrospective analysis to compare how the stock-recruit dynamics have changed over time and their sensitivity to the time series data.

For Ricker models with additional covariates included to inform recruitment predictions, additional parameterization was incorporated:

$$R_t = a * S_t * e^{-b*St} * e^{-c*Vt}$$

where V and c represent the time series of the environmental or biological covariate time series and the associated parameter, respectively. Three covariates were evaluated in the stock-recruit model to determine if incorporation of additional biological characteristics of the population improves model fit. The first variable assessed was an annual average female biomass per dogfish for individuals 80 cm and larger. The hypothesis tested with this variable was that the recruits per spawner will be greater with larger, better fit females. The second covariate evaluated was the sex (male:female) ratio, with the understanding that a population with a lower ratio (i.e., more females) increases the recruits per spawner. The third covariate assessed was spring bottom temperature to determine if certain thermal conditions allow for enhanced recruits per spawner.

To determine if the Ricker model was still most appropriate to describe the stock-recruit relationship for the population, the Berverton-Holt relationship was also evaluated with the same recruit and spawner data and similar parameter representation:

$$R_t = (a * S_t)/(1 + b * S_t)$$

All models were fit with maximum likelihood in the software R using package ‘bbmle’ (Bolker 2009), assuming a Gamma distributed error structure: R~Gamma(shape, mean/shape). The Gamma distribution was parameterized with shape parameter and scale parameter was set equal to the mean/shape. Model fit comparisons were done using Akaike information criterion (AIC).

The biological reference point proxy of SSB_{MAX} was defined as the spawning stock biomass per tow that results in the maximum recruitment produced (kg per tow). This value was then scaled to the trawl survey domain to calculate the stock's absolute spawning stock biomass:

$$SSB_{MAX}\ (mt) = SSB_{MAX}\ (kg\ per\ tow) * (1\ tow / 0.01\ nm^2) * 66{,}812\ nm^2 * (1\ kg / 0.001\ mt)$$

A tow from the trawl survey was assumed to have a swept area of 0.01 nm^2, and the maximum domain over the time series of 66,812 nm^2 was also used. Biological reference point estimates were calculated for the various time periods examined (described above) to provide an inference on how reference points may have changed over time, or how sensitive they are to the years of interest.

Results

Time Series Data

Spiny dogfish recruitment appeared to decline from variable estimates in the 1980s to time series lows in the late 1990s and early 2000s. Recruitment reached its time series peak in the early 2010s, but has since declined in more recent periods to levels comparable to the late 1990s and early 2000s (Figure 1; Table 1). Trends in mature female biomass indicate similar patterns, but more variable; in recent years, it appears female biomass has been declining, though substantive variability exists (Figure 1). The average weight per mature female was at its peak in the 1980s, but declined by up to a kilogram per individual between then and the late 1990s. The average weight per mature female has since been rather consistent (Figure 1). The ratio of mature male to female dogfish has always been skewed male but for select years during the 1980s. Additionally, the sex ratio has steadily increased over the time series, with exceptionally skewed male to female ratios in 1998, 2017, and 2021 (Figure 1). The log transformed recruits per spawner suggest indicated a decline from the 1980s to the early 2000s, but then increased and remained relatively stable over the time period (Figure 1). The spring bottom temperature suggests a warming on the NEUS from the 2010s onward, whereas the winter NAO indicated variable, somewhat stable conditions (Figure 2; Table 2). These time series do indicate some degree of coherence or correlation (Figure 3,4). Average mature female weight and length per individual were highly correlated; as such, thus only average weight is used in analyses. The sex ratio was negatively correlated to both average mature female weight and length per individual. Mature females per tow were positively correlated with ave individual size and length, and negatively with the sex ratio (Figure 3). Correlations with these variables and recruits were generally weaker, with the strongest one between recruits and mature females per tow (Figure 3). Recruits and log-transformed recruits per spawner were not significantly correlated to spring bottom temperature or the winter NAO index (Figure 4).

Stock-Recruit Modeling

The Ricker model fit to the entire time series showed a slight compensatory response at high mature female biomass (Figure 5). Retrospective analyses, or different time periods analyzed, influenced the shape of the curve. A compensatory response was greatest when only looking at data through 1996. The other time periods also have compensatory responses at high biomass, but much smaller compensatory responses (Figure 6). Model fitness was greatest for the model that only included data through 1996, and progressively worsened with additional years of data included (Table 3).

Incorporating average weight per mature female spiny dogfish into the Ricker model allowed for determining its impact on resulting recruitment predictions. Greater average weight per mature female allowed for higher recruits being predicted, with lower average weight per mature female having a similar effect, highlighting the positive correlation between the two variables (Figure 7). When looking at mean, minimum, and maximum values of the average weight per mature female time series, the mean value is closer to the minimum value (Figure 7). The male to female sex ratio had the inverse effect on the stock-recruit relationship; a lower ratio (skewed more female) resulted in greater recruits per spawner, whereas the higher ratio (skewed more males) equated to fewer recruits per spawner (Figure 8). The inclusion of spring temperature in an environmentally-explicit model indicated that warmer waters allowed for greater recruits per spawner (Figure 9). However, when comparing these three models to a base Ricker model, model fitness was nearly similar, as AIC values were all within 2 points of each other (Table 2).

Fitting both Ricker and Beverton-Holt models to the entire time series data highlighted their differing functional response (Figure 10). Despite the historical perspective of the Ricker model being more appropriate for modeling stock-recruit dynamics for spiny dogfish, little improved model fit was found in comparison to using a Beverton-Holt model (Table 3).

Biological Reference Points

Updating the biological reference points with data through 2021 indicated an approximate B_{MSY} proxy ($\mathrm{SSB}_{\mathrm{MAX}}$) of 445,349 mt (Table 4). This biomass is larger than any level estimated in Rago and Sosebee (2010). Differences appear to result in differing estimates of the mature female biomass per tow that result in the highest recruitment (i.e., greatest recruitment per mature female biomass).

Discussion

We present updated biological reference points for the Atlantic spiny dogfish using the methods proposed by Rago and Sosebee (2010).

Additional time series data for spiny dogfish highlighted a recent decline in both recruitment and the spawning stock, which is highlighted by a constant female weight per individual since 2000 and an increasing skewed male ratio (Figure 1). Few of the spiny dogfish time series data were correlated to the environment, which is also reflected in the fact that environmentally-explicit models did not improve model fitness compared to a base Ricker model. Exploratory change point analyses for log-transformed recruits per spawner suggest that no major shift has occurred for the stock's per capita recruitment (Figure 11).

Ricker model fits were sensitive to the extent of which time series data were included in the model (Figure 6; Table 3). It appears that data from the earliest time period best matched a theoretical Ricker model fit, with more recent periods reflecting less of a response, and ultimately greater SSB_{MAX} values (Table 4). When comparing the Ricker and Beverton-Holt models, little difference was observed in the AIC scores, suggesting that the Ricker model may not be a more suitable stock-recruit model formulation than the Beverton-Holt. If a stock-recruit function other than the Ricker model is assumed to be a better fit, then the reference point SSB_{MAX} is also no longer suitable, as its use is predicated on the belief that the Ricker model is most appropriate for spiny dogfish (Rago and Sosebee 2010).

Uncertainty in the SSB_{MAX} estimates can arise from the statistical framework used for the models. Maximum likelihood estimation (MLE) was used for this exercise, but other tools could be used in the future (e.g., Baeysian formulation). Ricker models using non-linear least squares (NLS) were also conducted to identify the uncertainty in the modeling (Table 5). While the MLE approach is the recommendation for use in providing insights here, the NLS method highlights model fitting uncertainty and how that can influence SSB_{MAX} estimates. While the swept area of the survey is a key component for estimating the final SSB_{MAX}, the values do not tend to vary much other than when the survey is cut short (Figure 12).

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Rago PJ and KA Sosebee. 2010. Biological Reference Points for Spiny Dogfish . Northeast Fish Sci Cent Ref Doc. 10-06; 52 p. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at: http://www.nefsc.noaa.gov/nefsc/publications/

Table 1. NEFSC Spring Bottom Trawl Survey indices for spiny dogfish used for the analyses presented herein.

Year	mean length all <= 35	all num <= 35	female KG >= 80 cm	female mean length >= 80	female mn wt >= 80 cm	num female >= 80	num male > = 60 cm	mat male/mat fem
1980	29.88	2.30	30.34	93.03	3.58	8.48	15.85	1.87
1981	30.96	12.46	53.13	94.50	3.76	14.13	12.33	0.87
1982	29.51	2.40	63.40	95.40	3.88	16.33	16.85	1.03
1983	30.75	12.60	11.42	94.32	3.76	3.04	12.19	4.02
1984	28.98	0.74	17.35	93.50	3.66	4.73	11.58	2.45
1985	29.29	19.24	45.06	92.68	3.58	12.57	63.82	5.08
1986	29.68	3.89	27.15	92.76	3.58	7.59	2.54	0.33
1987	30.85	12.46	30.97	93.35	3.65	8.49	24.22	2.85
1988	30.75	3.54	63.10	92.79	3.60	17.55	17.36	0.99
1989	29.85	5.28	23.91	88.41	3.07	7.78	18.98	2.44
1990	28.88	3.70	58.38	90.06	3.26	17.92	39.31	2.19
1991	30.45	4.38	32.76	89.99	3.25	10.08	22.04	2.19
1992	29.53	3.46	41.21	87.07	2.92	14.10	28.19	2.00
1993	27.99	2.94	33.79	89.29	3.17	10.67	23.99	2.25
1994	32.27	15.22	15.47	87.01	2.90	5.33	28.63	5.37
1995	30.00	1.12	15.54	85.44	2.73	5.69	21.27	3.74
1996	28.15	5.09	28.53	86.53	2.84	10.04	37.69	3.75
1997	26.99	0.27	12.62	83.79	2.56	4.94	26.07	5.28
1998	25.41	0.45	4.09	84.60	2.64	1.55	29.18	18.85
1999	26.32	0.15	9.39	83.98	2.57	3.65	31.82	8.73
2000	26.48	0.46	12.70	85.24	2.71	4.69	20.62	4.40

2001	27.58	0.20	8.34	85.94	2.78	3.00	19.28	6.43
2002	28.10	0.31	13.09	83.98	2.58	5.08	30.80	6.06
2003	26.83	0.80	10.07	84.13	2.59	3.89	30.56	7.86
2004	27.26	4.18	6.33	85.37	2.72	2.33	14.96	6.42
2005	27.14	1.88	8.33	84.85	2.67	3.12	35.20	11.26
2006	27.92	0.69	37.89	84.88	2.67	14.20	47.77	3.36
2007	27.06	1.54	24.96	85.23	2.70	9.23	26.33	2.85
2008	28.15	2.57	36.78	85.09	2.69	13.69	33.90	2.48
2009	30.19	12.03	21.58	85.05	2.68	8.05	32.06	3.98
2010	28.90	5.20	22.47	84.89	2.66	8.44	30.39	3.60
2011	29.31	6.62	30.08	85.47	2.72	11.05	42.06	3.81
2012	27.67	22.35	50.20	85.77	2.75	18.23	65.43	3.59
2013	32.21	19.75	19.48	85.92	2.77	7.04	40.04	5.69
2014								
2015	30.41	4.23	17.49	85.98	2.78	6.30	29.66	4.71
2016	28.41	7.51	26.82	86.56	2.83	9.46	45.82	4.84
2017	30.37	0.96	4.19	85.83	2.76	1.52	31.89	21.01
2018	30.69	2.63	14.04	86.31	2.81	5.00	33.64	6.73
2019	29.82	2.16	21.75	86.20	2.80	7.77	58.56	7.54
2020								
2021	28.91	2.88	11.75	85.28	2.70	4.35	82.35	18.95

Table 2. Environmental data used in the analyses: NEFSC Bottom Trawl spring bottom temperatures (Spring_Mean_Temp) and the Winter NAO Index (DJF).

Year	Spring_Mean_Temp	DJF
1980	7.1	0
1981	7.2	1.9
1982	6.8	-0.5
1983	7.4	1.9
1984	7.4	2.9
1985	7.9	-1.7
1986	8.2	-0.7
1987	7.8	-1.5

1988	7.1	-0.2
1989	6.4	3.4
1990	7.7	1.9
1991	8.3	1.2
1992	7.2	0.7
1993	6.4	1.9
1994	7.2	2
1995	7.8	2.8
1996	6.7	-2.1
1997	7.6	-0.8
1998	6.8	-0.2
1999	8.3	2.7
2000	8.4	2.6
2001	7.0	-1.3
2002	8.1	-0.5
2003	6.4	-0.2
2004	6.1	-1.1
2005	6.5	1.4
2006	7.9	-0.2
2007	7.0	1.4
2008	10.2	1.4
2009	8.3	1
2010	8.1	-5.2
2011	8.3	-2.1
2012	10.4	3.2
2013	9.4	0.4
2014	8.3	3.6

2015	8.3	4.6
2016	10.3	1.8
2017	8.7	0.9
2018	9.2	2.2
2019	9.2	0.2
2020	10.9	3.4
2021	9.6	NA

Table 3. Comparisons of model variants based on AIC. Model comparisons with dAIC are relative within a given comparison.

Model	dAIC
Retrospective	
Through 1996	0
Through 2003	19.3
Through 2009	49.0
Through 2021	107.3
Environmental Drivers	
No Driver	0
Avg Female Weight per Indiv.	0.5
Spring Bottom Temperature	0.8
Mean Sex Ratio	1.8
Model Formation	
Ricker	0
Beverton-Holt	0.2

Table 4. Estimated proxy biological reference points, SSB_{MAX}, using a Ricker model over various time periods of data (i.e., retrospective comparisons).

Retrospective Models	SSB_{MAX} (kg/tow)	SSB_{MAX} (mt)
Through 1996	27.3	182,089
Through 2003	73.6	491,709
Through 2009	48.7	325,314
Through 2021	66.6	445,349

Table 5. Estimated SSB_{MAX} (kg per tow) using maximum likelihood estimation with a gamma error distribution and a non-linear least squares model (NLS)

Retrospective Models	SSB_{MAX} (MLE)	SSB_{MAX} (NLS)
Through 1996	27.3	45.1
Through 2003	73.6	50.6
Through 2009	48.7	32.5
Through 2021	66.6	54.7

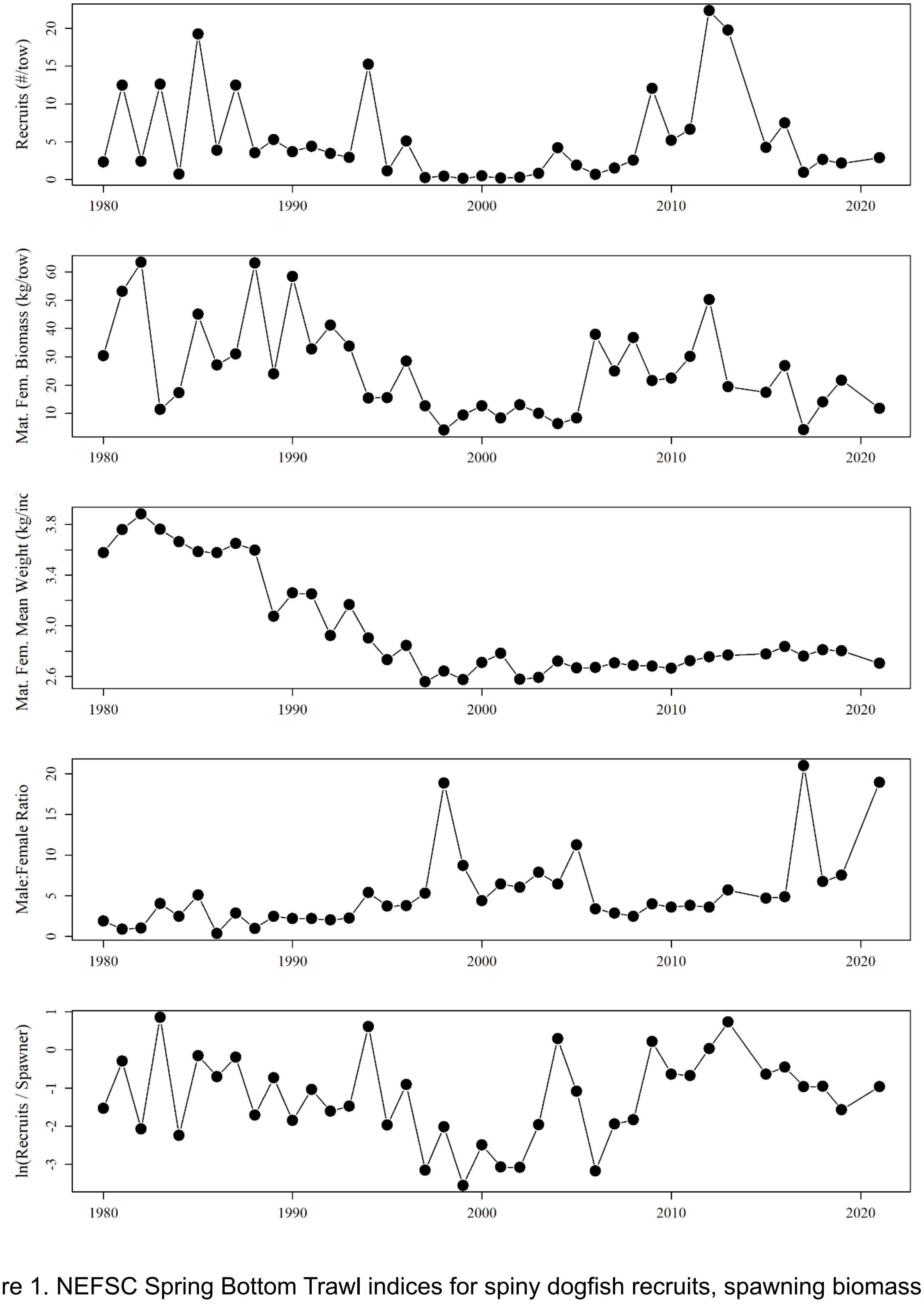


Figure 1. NEFSC Spring Bottom Trawl indices for spiny dogfish recruits, spawning biomass, female mean weight per individual, sex ratio, and natural-log transform recruts per spawner.

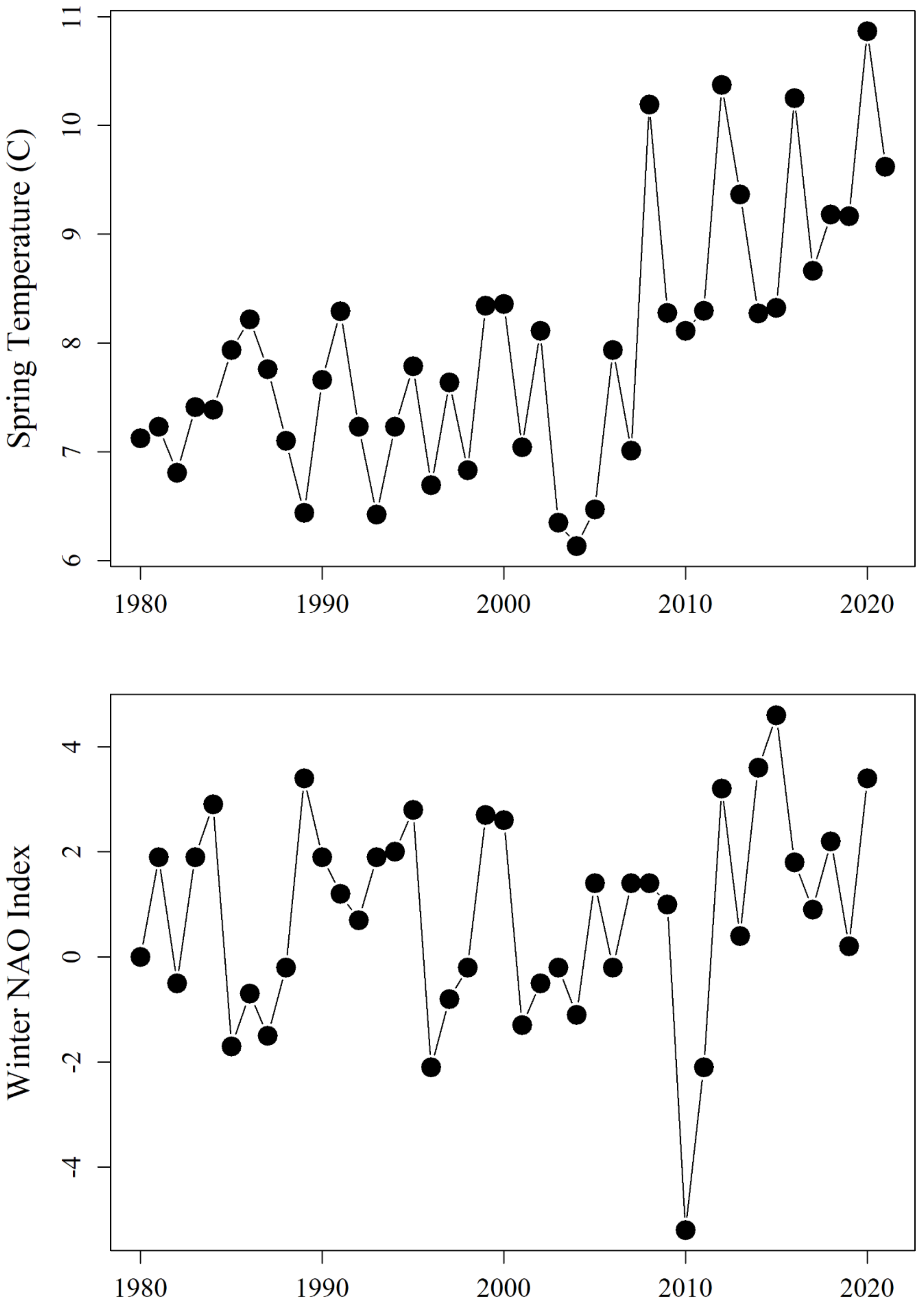


Figure 2. Environmental data used in analyses: NEFSC Spring Bottom Trawl mean spring bottom temperature and winter NAO index.

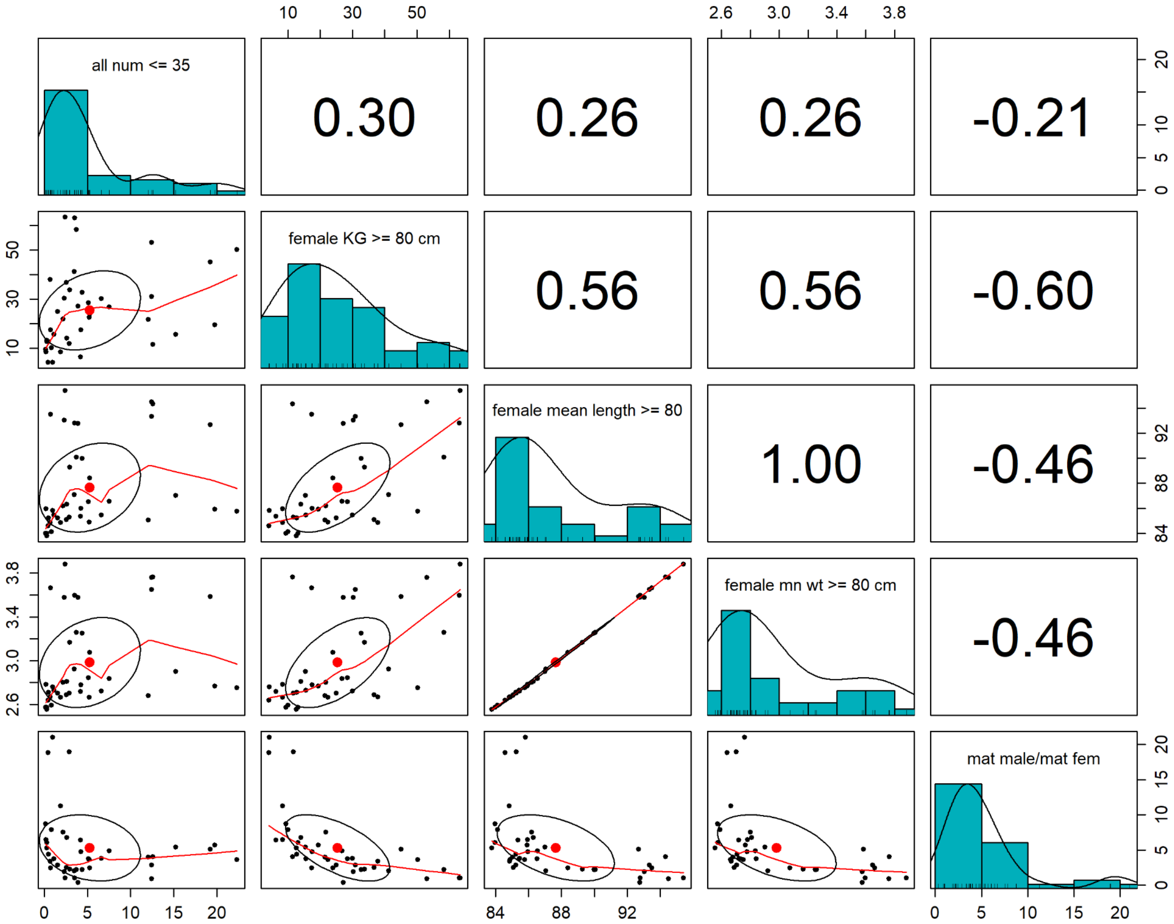


Figure 3. Cross correlations for spiny dogfish indices from the NEFSC Spring Bottom Trawl Survey.

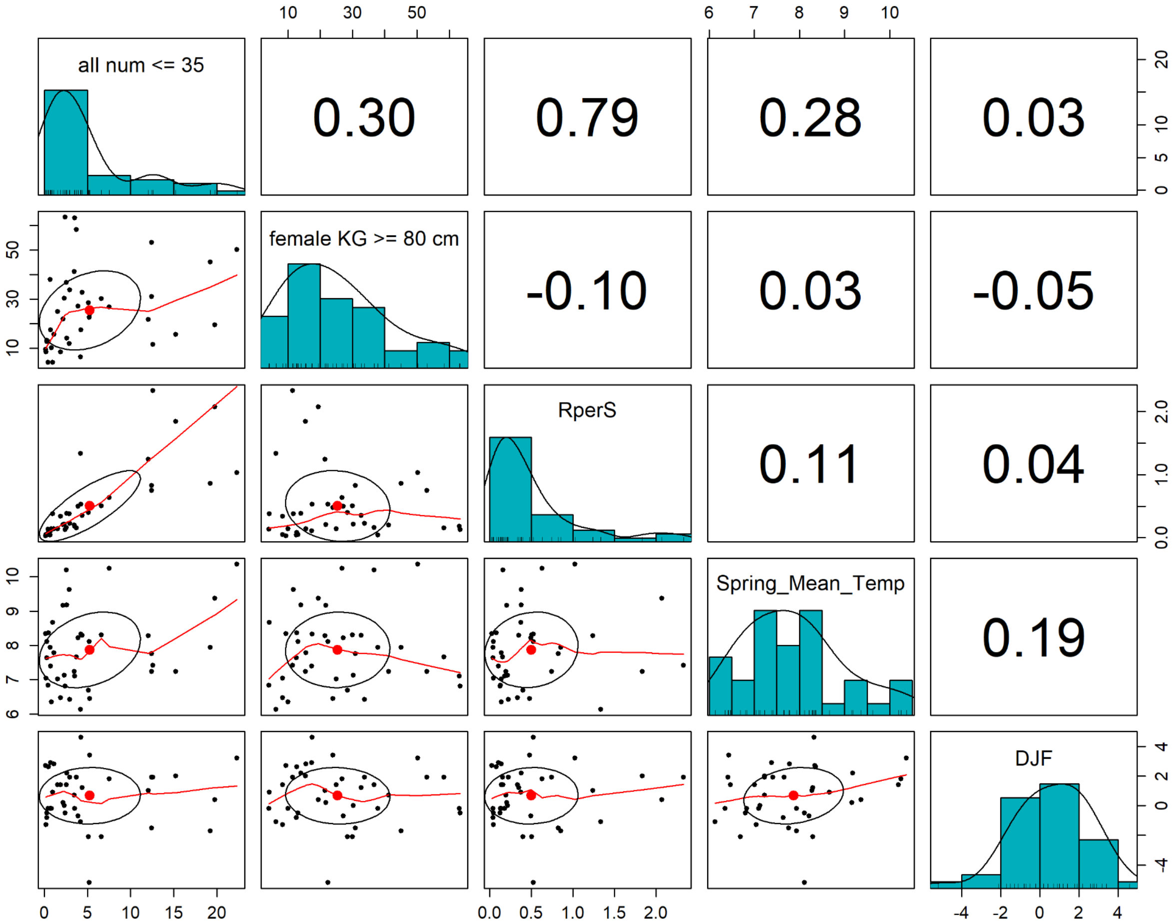


Figure 4. Cross correlations for spiny dogfish indices from the NEFSC Spring Bottom Trawl Survey and environmental variables.

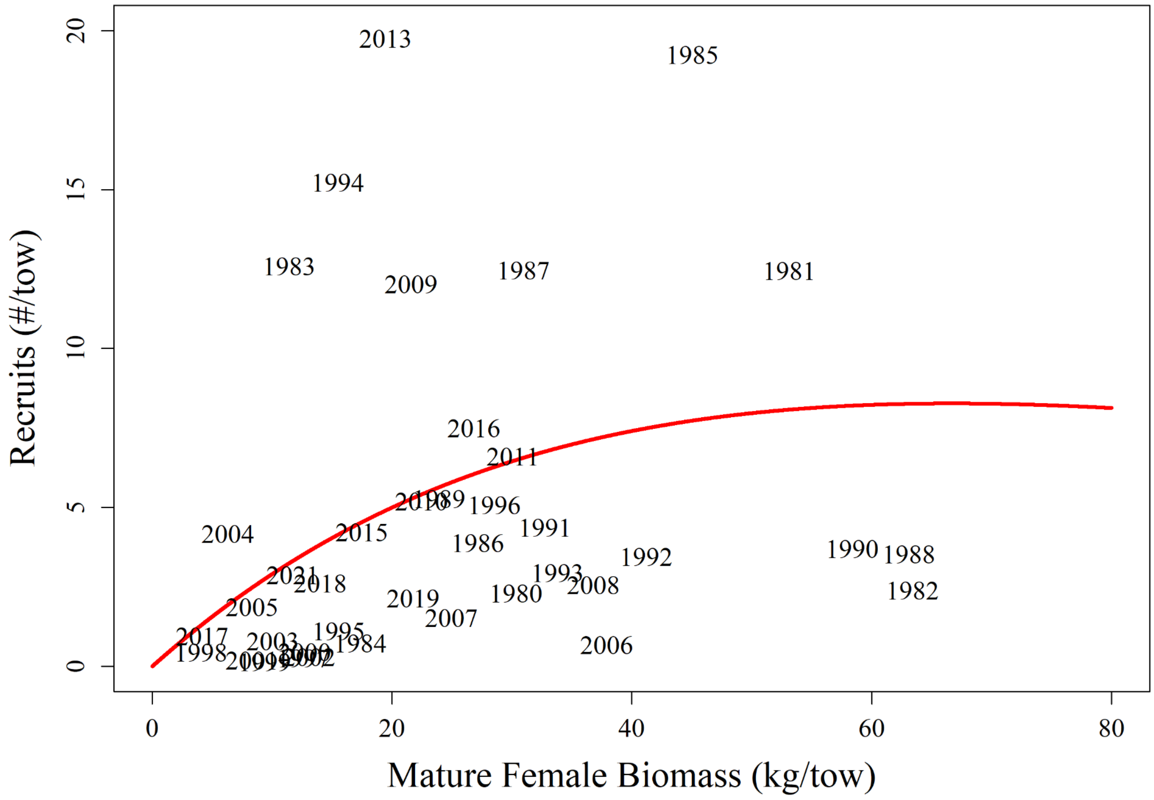


Figure 5. Ricker model fit to mature female and recruit dogfish indices from the NEFSC Spring Bottom Trawl Survey. All years' data are included in the model fit.

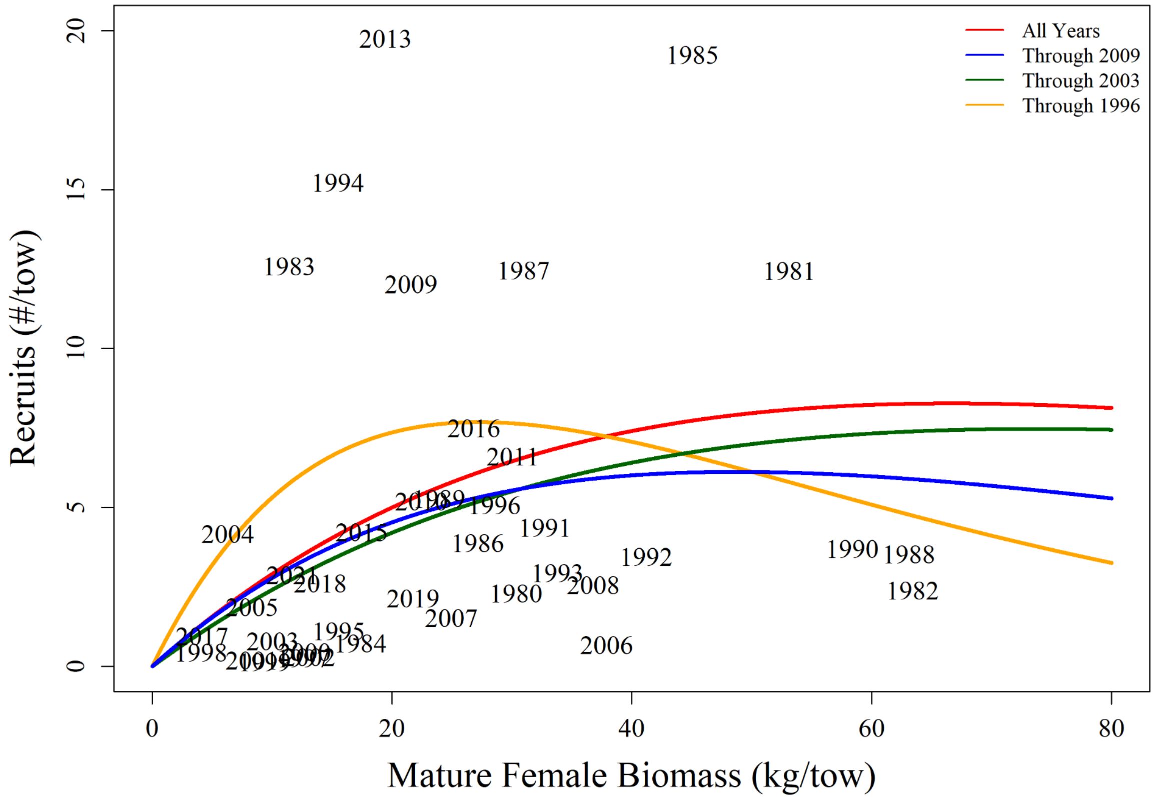


Figure 6. Ricker model fit to mature female and recruit indices from the NEFSC Spring Bottom Trawl Survey using various time series lengths.

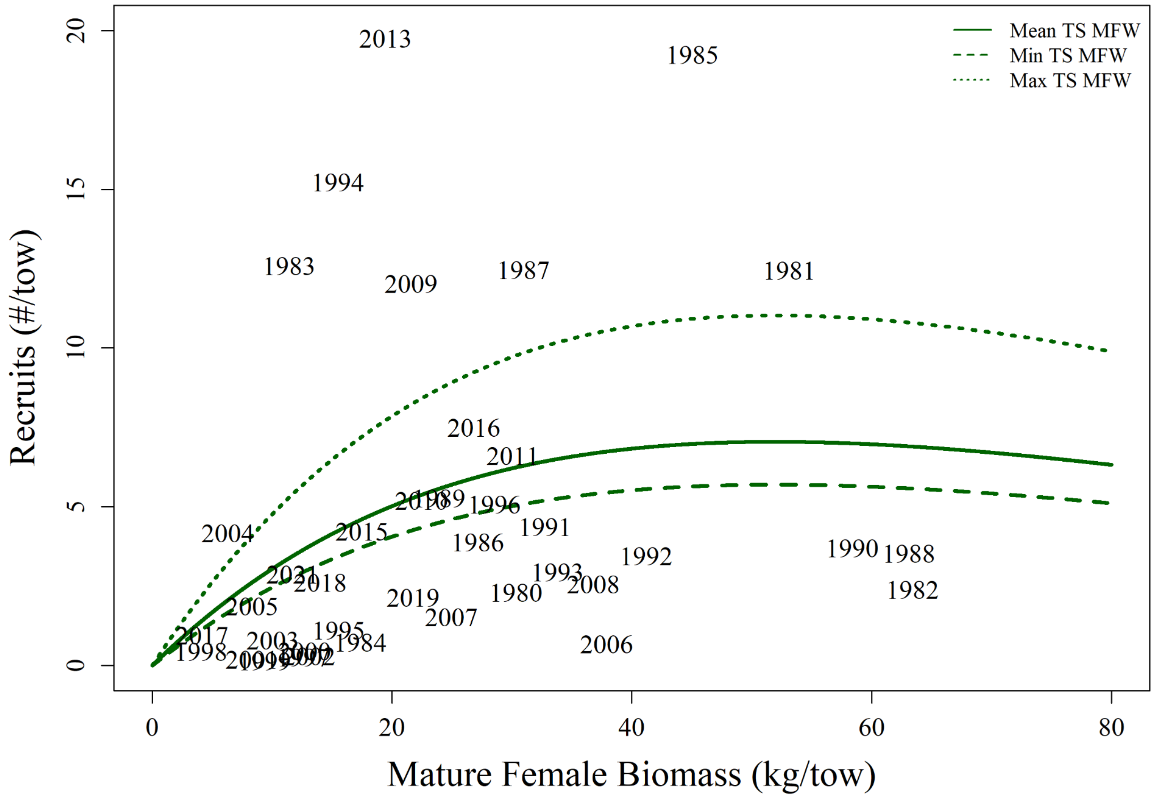


Figure 7. Ricker model fit to mature female and recruit indices from the NEFSC Spring Bottom Trawl Survey, with annual mean mature female weight (MFW) per individual as a covariate in the model. The solid line represents model predictions with the time series mean value for mature female weight per individual, whereas the dotted and dashed lines represent the maximum and minimum time series (TS) values, respectively.

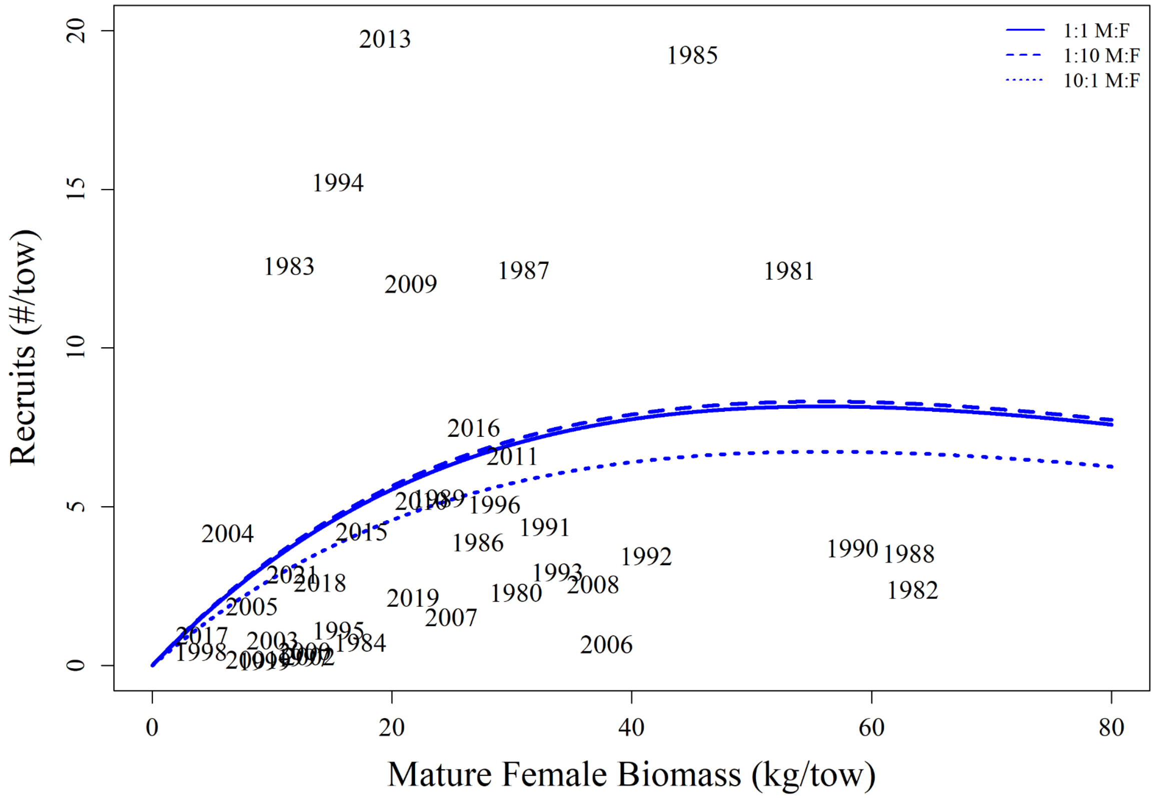


Figure 8. Ricker model fit to mature female and recruit indices from the NEFSC Spring Bottom Trawl Survey, with male to female sex ratio as a covariate in the model. The solid line represents model predictions with a sex ratio of one (equal males and females), whereas the dotted and dashed lines represent the examples of populations skewed male (10:1) and female (1:10), respectively.

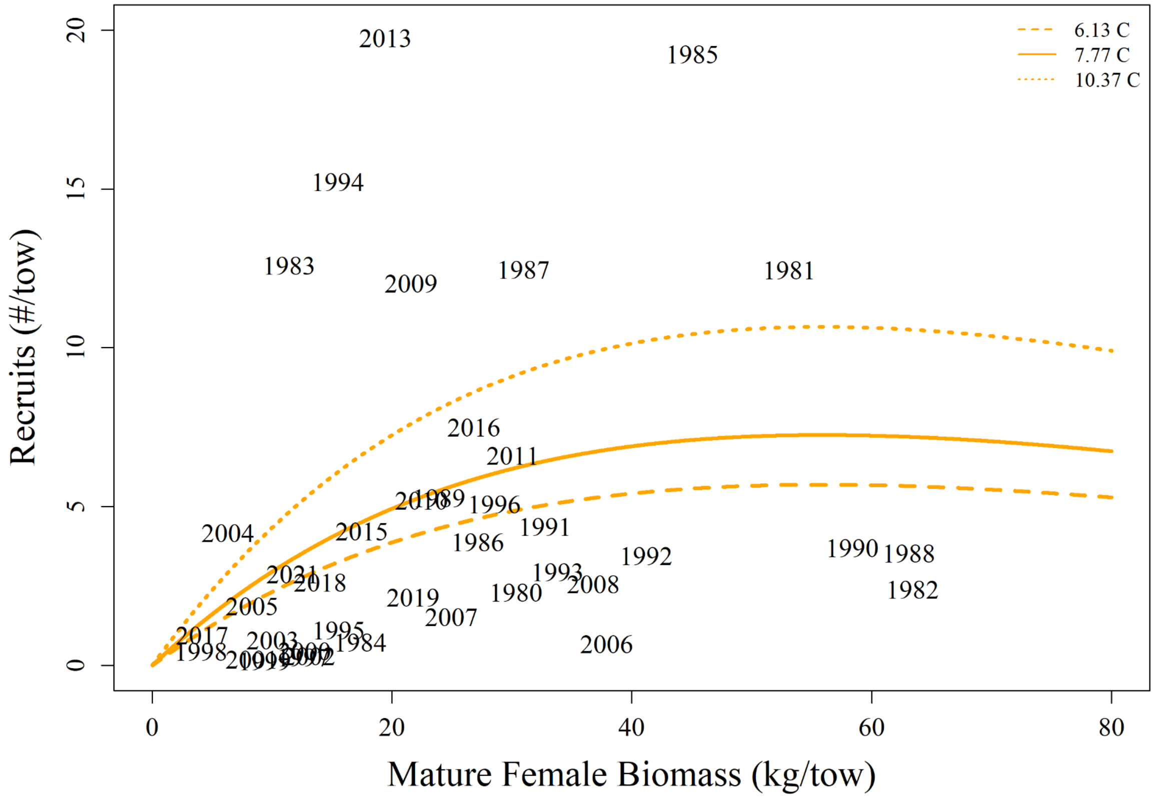


Figure 9. Ricker model fit to mature female and recruit indices from the NEFSC Spring Bottom Trawl Survey, with spring bottom temperature as a covariate in the model. The solid line represents model predictions using the 50th percentile of the spring bottom temperature time series, whereas the dotted and dashed lines represent the minimum and maximum time series values, respectively.

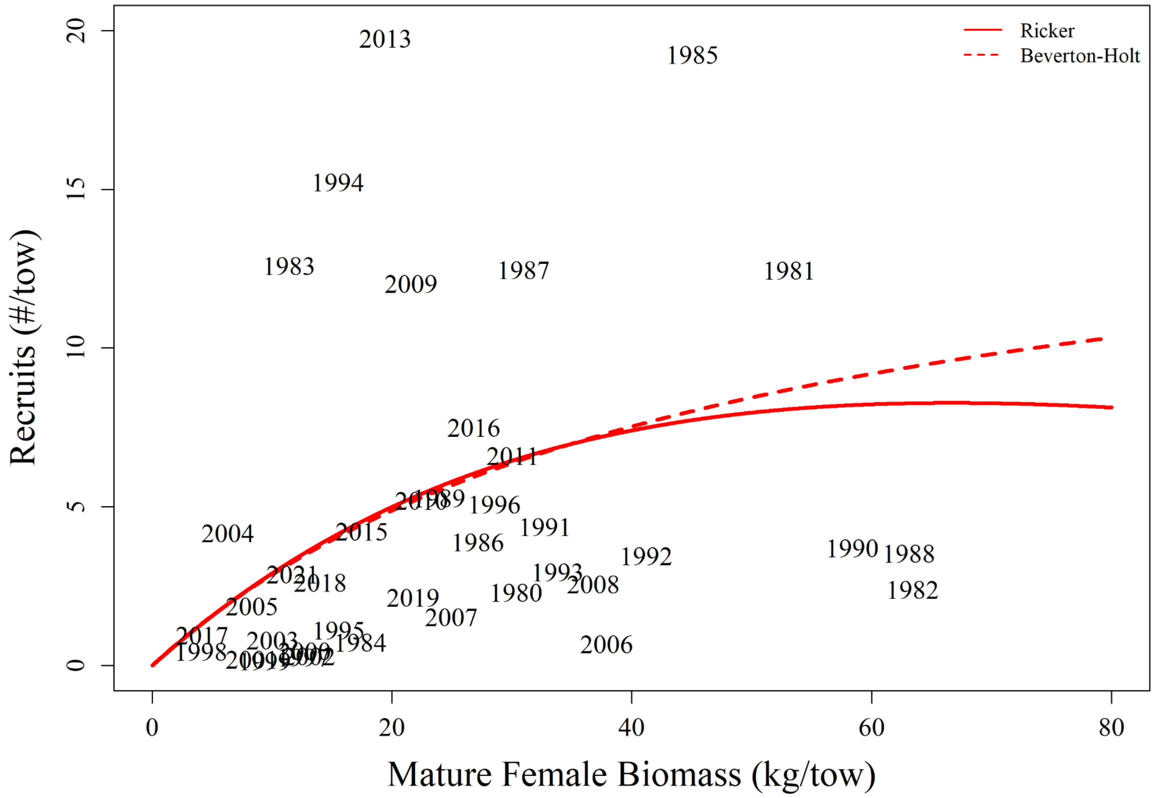


Figure 10. Ricker (solid line) and Beverton-Holt (dashed line) model fits to mature female and recruit indices from the NEFSC Spring Bottom Trawl Survey.

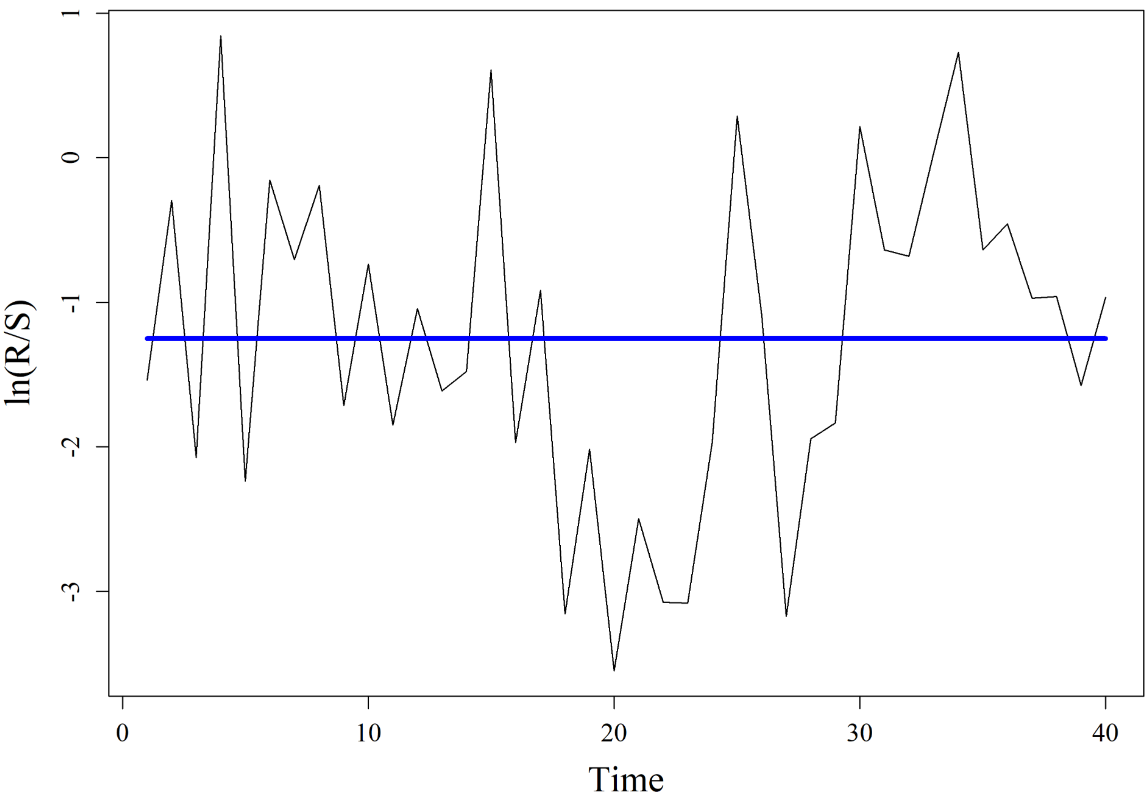
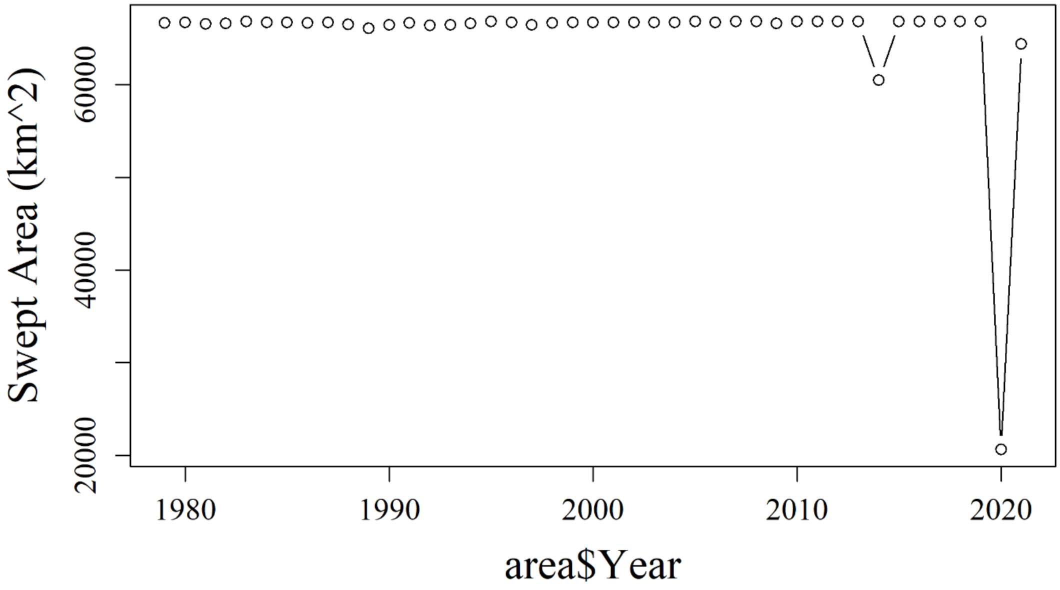


Figure 11. Changepoint analysis for log-transformed recruits per spawner (ln[R/S]). Search method used was the pruned exact linear time method (Killick and Eckley, 2014).



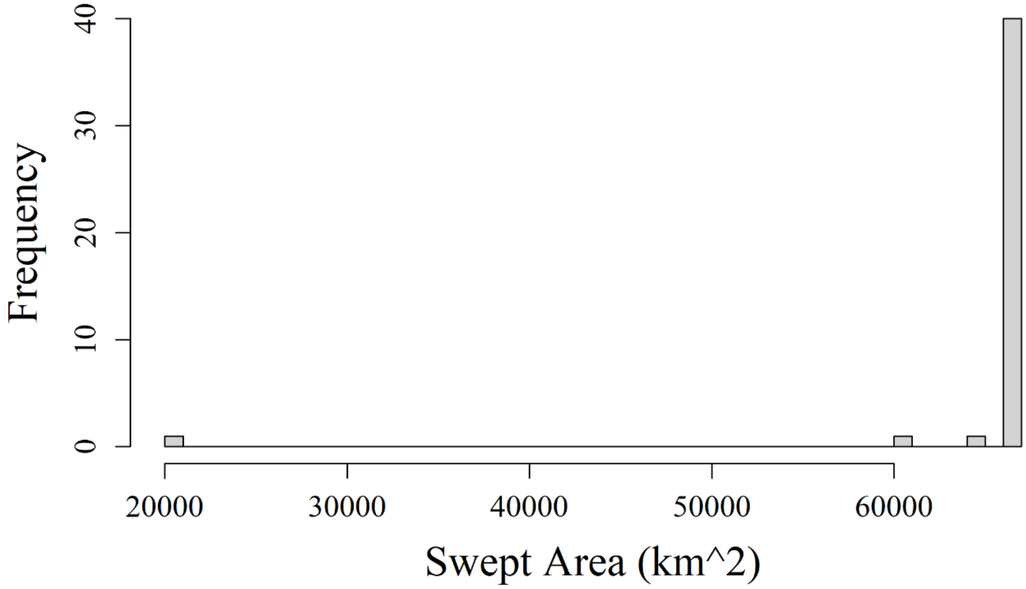


Figure 12. Annual swept area estimates for the NEFSC Spring Bottom Trawl Survey over time (top) and the distribution (bottom)