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Projections for the SEDAR 39 Atlantic Smooth Dogfish (*Mustelus canis*) Stock Assessment Report Base Model Configuration

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SUMMARY

Projection results are provided here for the SEDAR 39 Atlantic smooth dogfish (*Mustelus canis*) Stock Assessment Report base model configuration, which utilized a dome-shaped functional form of selectivity (Sel-2; modeled with a double logistic function at length) for the main targeted fishery (fleet F1 – NE Gillnet Kept). Projections utilized 10,000 Monte Carlo simulations drawn from a bivariate normal distribution for unexploited equilibrium recruitment ($\hat{R}_0^{SS3}$) and the terminal fishing mortality ($\hat{F}_{2012}^{SS3}$) obtained from the SS3 assessment model and then projected for 10 years (t = 2013 – 2022) with lognormal variability in the Beverton-Holt stock-recruitment relationship based on the standard deviation of recruitment (in log space) (σ_R) obtained from the SS3 assessment model. Simulations were conducted for 21 alternative fixed levels of total annual removals due to fishing (1000s of sharks) ranging from zero to 1,000 in increments of 50 (**Table 1**). Projection results from 10,000 Monte Carlo simulations over the range of fixed removals levels evaluated here (**Table 1**) indicated that levels of fixed removals less than or equal to 550 (1000s of sharks) resulted in at least a 70% probability of maintaining $SSF_{t,}$ above SSF_{MSY} during the years 2013 – 2022 (**Table 2 and Figure 1**). The short term projections with Monte Carlo simulation are provided here in response to the SEDAR 39 Atlantic smooth dogfish Term of Reference 9: Project Future Stock Conditions, as a proxy to a

typical P* approach based on a pre-specified acceptable probability of overfishing (e.g., P^* = 0.3; < 0.5).

INTRODUCTION

The SEDAR 39 Assessment Panel recommended the alternative model configuration with a dome-shaped functional form (Sel-2; modeled with a double logistic function at length) for the main targeted fishery (fleet F1 – NE Gillnet Kept) as the base model configuration for the assessment (see the SEDAR 39 Atlantic smooth dogfish Stock Assessment Report). Consequently, projection results are provided here for the SEDAR 39 Atlantic smooth dogfish base model configuration with a dome-shaped functional form (Sel-2).

Projection methods followed those developed during previous HMS shark stock assessments conducted within SEDAR (NMFS 2011; NMFS 2012a, 2012b; NMFS 2013a, 2013b; e.g., Courtney et al. 2014), except as described below. Projections were governed with the same set of population dynamics equations as the original assessment model, but allowed for uncertainty in initial conditions at the beginning of the projection time series as well as in annual recruitment variability. Projections were implemented in R statistical software (R 2013). Projection data were obtained from Stock Synthesis output (SS3 v. 3.21d) (Methot 2011; e.g., Methot and Wetzel 2013) with either the program r4ss (Taylor et al. 2014) or with Excel. Projections utilized Monte Carlo simulation with uncertainty in parameter estimates obtained from the asymptotic standard errors and parameter correlations estimated in the SS3 assessment model (e.g., SEDAR 39 Atlantic Assessment Report **Table 4.2.b)**, which in turn were based on the inverted Hessian matrix at the converged solution (Fournier et al. 2012).

PROJECTION MODEL

The projection model was initialized in the terminal year of the SS3 assessment model (t = p.styr = h.endyr = 2012). The ending year of the projection period (t = p.endyr) was the projection period plus the initialization year (e.g., for a 10 year projection period, p.endyr = p.styr +10 = 2022). Projections were limited to 10 years based in part on previous CIE reviews that suggested limiting the projection period to a decade because the probabilities and stock trajectories associated with long term projections, for example longer than a decade, are probably unreliable (e.g, Courtney et al. 2014). The maximum age for all projections ($a_{\max}$) was set equal to the maximum age from the SS3 assessment model (18 years).

Terminal assessment year fishing mortality rate at age.—In order to be consistent with the SS3 output reported in the SEDAR 39 Atlantic Assessment Report, fishing mortality at age from the terminal year of the stock assessment model ($\hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a}$) was obtained from SS3 output as the total exploitation rate (in numbers) at each age.

Terminal assessment year selectivity at age.—In the projection model, the terminal assessment year selectivity at age *a* ($\mathrm{sel}_{t=\mathrm{h.endyr},a}$) was then calculated from $\hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a}$ as follows:

(Eq. 1) $$\mathrm{sel}_{t=\mathrm{h.endyr},a} = \hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a} \Big/ \max\left(\hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a}\right),$$

where: (1) the parameter estimate $\hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a}$ was assumed to be separable into the terminal assessment year selectivity at age, $\mathrm{sel}_{t=\mathrm{h.endyr},a}$, and the terminal assessment year annual fishing mortality rate ($F_{t=\mathrm{h.endyr}}$) as follows: $\hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a} = \mathrm{sel}_{t=\mathrm{h.endyr},a} F_{t=\mathrm{h.endyr}}$; (2) the maximum selectivity at age was assumed to be equal to one; and (3) $F_{t=\mathrm{h.endyr}}$ was calculated from $\hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a}$ as: $F_{t=\mathrm{h.endyr}} = \max\left(\hat{F}^{\mathrm{SS3}}_{t=\mathrm{h.endyr},a}\right)$.

By scaling the maximum selectivity at age equal to one, selectivity at age was interpreted as the probability of capturing an animal of a given age relative to the probability of capturing an animal at the age at which the probability of capture is highest (i.e., equal to one). Within this context, the projection model calculation of selectivity at age included both the concepts of gear selectivity (probability of capture once contact with the gear was made) as well as availability to the gear, which is consistent with the interpretation of selectivity at age in SS3 (e.g., Punt et al. 2014).

In order to account for inter-annual variability in the number of sharks captured among fleets during the years 2010, 2011, and 2012 (see SEDAR 39 Atlantic Assessment Report

Section 4.6 Stock Biomass and Fishing Mortality), selectivity at age *a* (sel_a^p) for the projections was calculated as the average selectivity at age obtained with the methods described above for the years 2010, 2011, and 2102 scaled to a maximum of one. Selectivity at age was assumed to be constant over the projection interval.

Monte Carlo simulation.—Projections used 10,000 parametric Monte Carlo simulations with initial values drawn from a bivariate normal distribution with expectations equivalent to posterior modes obtained from the SS3 assessment model output (SEDAR 39 Atlantic smooth dogfish Stock Assessment Report **Table 4.2.b)**.

Parametric random draws of unexploited equilibrium recruitment ($\hat{R}_0^{\mathrm{SS3}}$) and terminal assessment year (h.endyr) fishing mortality rate ($\hat{F}_{t=\mathrm{h.endyr}}^{\mathrm{SS3}}$) were obtained from the SS3 assessment model with a bivariate normal distribution. A parametric random draw (R_0^{boot}, $F_{t=\mathrm{h.endyr}}^{\mathrm{boot}}$) was rejected if any value was less than zero or if $F_{t=\mathrm{h.endyr}}^{\mathrm{boot}}$ was greater than one.

The bivariate normal distribution was developed from the parameter estimates, their standard deviations, and their correlation coefficients (*r*) using the R statistical software (R 2013) function *mvrnorm* obtained from the R library *MASS* (Crawley 2007 p. 237). For example, for the parameters *x* and *y*, the function *mvrnorm* was implemented from the matrix of standard deviations (SD_x and SD_y) and covariance, $\begin{bmatrix} \mathrm{SD}_x^2 & \mathrm{cov}(x,y) \\ \mathrm{cov}(y,x) & \mathrm{SD}_y^2 \end{bmatrix}$, where the covariance of *x* and *y* was calculated from correlation coefficient and standard deviations of *x* and *y* as follows: $\mathrm{cov}(x,y) = \mathrm{cov}(y,x) = r\sqrt{\mathrm{SD}_x^2\mathrm{SD}_y^2}$.

Projection period numbers at age.— In the projection model, numbers at age were calculated from recruitment at the beginning of each projection year and from the numbers at age at the beginning of the previous year multiplied by the annual survival rate during the previous year. For the projection period, population numbers at age *a* at the beginning of each projection year, *t*, were calculated as follows:

(Eq. 2)

$$N_{t,a}^{p} = \begin{cases} \left\{ \hat{N}_{t=\text{p.styr},a}^{SS3} \right\} & \text{if } t = \text{p.styr} \\ \left. \begin{cases} R_t^p & \text{if } a = 1 \\ N_{t\text{-}1,a\text{-}1}^{p} e^{-Z_{t-1,a-1}^{p}} & \text{if } 1 < a < a_{\max} \\ N_{t\text{-}1,a\text{-}1}^{p} e^{-Z_{t-1,a-1}^{p}} + N_{t\text{-}1,a}^{p} e^{-Z_{t-1,a}^{p}} & \text{if } a = a_{\max} \end{cases} \right\} & \text{if p.styr} < t \le \text{p.endyr} \end{cases}$$

where, for the first projection period (t = p.styr), population numbers at the beginning of the year were set equal to the SS3 assessment model terminal year, t = h.endyr, estimates of population numbers at age (for both sexes combined) ($\hat{N}_{t=\text{p.styr},a}^{\text{SS3}} = \hat{N}_{t=\text{h.endyr},a}^{\text{SS3}}$).

Projection period annual fishing mortality rate.—Projections were implemented with the terminal assessment year (h.endyr) fishing mortality rate ($\hat{F}_{t=\text{h.endyr}}^{\text{SS3}}$) obtained from the SS3 assessment model for the first three full projection years (2013, 2014, 2015), and then with fixed harvest levels during the remaining projection years (2016 – 2022). For projection years with fixed harvest levels, the annual fishing mortality rate (F_t^p) was obtained numerically each year as the fishing mortality rate that minimized the squared difference $\left(C_{\text{trial}}^{p} - \sum_{a=1}^{a_{\max}} \left(C_{t,a}^{p}\right)\right)^2$, where C_{trial}^{p} was the trial value of total annual removals (in 1000s of sharks) evaluated for the projection scenario (**Table 1**) and $C_{t,a}^{p}$ was the catch at age corresponding to F_t^p obtained from the Baranov catch equation in projection year t, as described below.

Projection period total mortality rate at age.— In the projection model, the total mortality rate was calculated from the fishing mortality rate plus the natural mortality rate at an annual time step. For the projection period, the total mortality rate at age a in year t ($Z_{t,a}^{p}$) was calculated from F_t^p and sel_a^p, obtained as described above, and from the natural mortality rate at age a obtained from the SS3 assessment model output (M_a^{SS3}) as follows:

(Eq. 3) $$Z_{t,a}^{p} = \text{sel}_a^p F_t^p + M_a^{\text{SS3}}.$$

Projection period annual spawning stock size.—In the projection model, the annual spawning stock size was calculated from the annual numbers at age (for females and males combined) and from the net fecundity at age. For the projection period, the annual spawning stock size in year *t* (S_t^p), defined as spawning stock fecundity (SSF) in the SS3 assessment model, was calculated from the annual numbers at age, $N_{t,a}^p$ (for both sexes combined), the annual total mortality rate at age, $Z_{t,a}^p$, and the net (per capita) fecundity at age *a* (f_a) as follows:

(Eq. 4) $$S_t^p = \sum_{a=1}^{a_{\max}} f_a N_{t,a}^p e^{-\tau_M Z_{t,a}^p},$$

where f_a was obtained from SS3 as described below, τ_M was the fraction of year from the beginning of the calendar year (January 1) to the beginning of the pupping season used in the SS3 assessment model, and $e^{-\tau_M Z_{t,a}^h}$ was the expected survival rate at age *a* from the beginning of calendar year *t* to the beginning of the pupping season. For these projections, the parameter τ_M was set equal to zero in order to be consistent with the calculation of SSF in the SS3 assessment model.

Spawning Stock Fecundity.—Previous HMS shark assessments conducted with a State Space Age Structured Production Model (SSAPM) utilized spawning stock fecundity, SSF, calculated as the sum of numbers at age times pup production at age, as the measure of spawning output in the stock-recruitment relationship (NMFS 2012a, 2013a, 2013b). Consequently, the same approach was implemented in the SS3 assessment model. The life history data recommended in the SEDAR 39 Data Workshop report for female *Mustelus canis* in the Atlantic Ocean were used to compute the average annual number of pups (male and female) produced by each female at age (SEDAR 39 Atlantic Assessment Report Section 2; **Table 2.9**). The resulting age specific vector of fecundity was input in the projection and multiplied by the assumed fraction female (fixed at 0.5) to produce the net (per capita) fecundity at age *a*, f_a (Eq. 4). The resulting measure of spawning output in the stock-recruitment relationship for projections, S_t^p

(Eq. 4), was the spawning stock fecundity, SSF, and had the same interpretation as that used in the SS3 assessment model.

Stock-Recruitment.—The annual number of sharks recruiting to the population at the start of year $t + a_r$ (R_{t+a_r}) was related to spawning stock size in year t (S_t) using a Beverton–Holt spawner-recruit curve, (Quinn and Deriso 1999 their Eq. 3.6; e.g., Brooks et al. 2010 their Eq. 1), and was calculated here (e.g., Courtney In Prep) as:

(Eq. 5) $$R_{t+a_r} = \frac{\alpha S_t}{1+\beta S_t} e^{\left(\varepsilon_t - 0.5\sigma_R^2\right)}; \quad \varepsilon_t \sim N\left(0;\sigma_R^2\right).$$

The parameter α controlled productivity, and β controlled the level of density dependence (Quinn and Deriso 1999 their Eq. 3.6). The parameterization $e^{\left(\varepsilon_t\right)}$ was the assumed log-normally distributed error in annual recruitment for year t, σ_R was the standard deviation of recruitment in log space. The parameterization $e^{\left(\varepsilon_t - 0.5\sigma_R^2\right)}$ (e.g., Wetzel and Punt 2011, their Eq. A.7) was a bias correction to simulate the mean recruitment deviation (on the natural scale) from log-normally distributed recruitment error.

The Beverton–Holt stock recruitment relationship (Eq. 5) was re-parameterized in terms of the steepness parameter (h) defined as the proportion of recruitment relative to the recruitment at equilibrium with no fishing when the spawner abundance or biomass is reduced to 20% of the virgin level (Mace and Doonan 1998; Hilborn and Walters 1992; Myers et al. 1999; Brooks et al. 2010, their equation 7; *e.g.,* Haddon 2011, their Appendix 10.3), and was modeled here (e.g., Courtney In Prep) as:

(Eq. 6) $$hR_0 = \frac{\alpha 0.2 S_0}{1+\beta 0.2 S_0},$$

(Eq. 7) $$\alpha = \frac{4hR_0^{\text{boot}}}{S_0'\left(1-h\right)}, \text{ and}$$

(Eq. 8) $$\beta = \frac{5h-1}{S_0'(1-h)}.$$

Assuming that the virgin population had a stable age distribution, and given the values for R_0 and S_0 obtained from the SS3 assessment model output, the corresponding value for the unexploited spawners produced per recruit (SPR_0) (e.g., which can be found analytically as described in Brooks et al. 2010 their Eq. 2) was obtained here as $\mathrm{SPR}_0 \equiv \mathrm{S}_0/R_0$. For each Monte Carlo simulation replicate obtained for R_0^{boot}, the corresponding equilibrium spawning stock size (S_0') was then obtained here as $\mathrm{S}_0' = \mathrm{SPR}_0 R_0^{boot}$. Given the specified value for the Beverton–Holt stock recruitment steepness parameter*,* h (Eq. 6), the corresponding values for parameters α and β of the Beverton–Holt stock recruitment relationship (Eq. 5) were then found analytically for each Monte Carlo simulation replicate from Eq. (7) and Eq. (8).

In order to be consistent with our interpretation of the recruitment dynamics within SS3, simulated recruitment for age-0 sharks in the projection model occurred on January 1st of the year following birth ($a_r = 1$).

Projection period annual catch at age in numbers.—For the projection period, the annual catch at age a in year t, $C_{t,a}^p$ in numbers, was calculated from $N_{t,a}^p$, $F_{t,a}^p$, and $Z_{t,a}^p$ using the Baranov catch equation (e.g., Quinn and Deriso 1999 equation 1.22) as follows:

(Eq. 9) $$C_{t,a}^p = \frac{F_{t,a}^p}{Z_{t,a}^p}\left(1-e^{-Z_{t,a}^p}\right)N_{t,a}^p,$$

where, $F_{t,a}^p$ was calculated as: $F_{t,a}^p = \mathrm{sel}_a^p F_t^p$, and sel_a^p, F_t^p, $N_{t,a}^p$, and $Z_{t,a}^p$ were obtained as described above.

PROJECTION RESULTS

Projection results from 10,000 Monte Carlo simulations were reported as the proportion of times that spawning stock fecundity in projection year t (SSF_t) was above spawning stock fecundity at maximum sustainable yield (SSF_{MSY}), $Pr(SSF_t > SSF_{MSY})$, for a given fixed level of total annual removals due to fishing (1,000s of sharks) (**Tables 1 and 2**). The $Pr(SSF_t > SSF_{MSY})$ was color coded to represent $Pr \geq 0.70$ (green), $0.50 \leq Pr < 0.70$ (yellow), and $Pr < 0.50$ (red) (**Table 2**). The largest fixed level of total annual removals due to fishing that resulted in $Pr \geq 0.70$ (green) for all projection years was 550 (1,000s of sharks) (**Tables 1 and 2**), and provides an example of a fixed harvest level for which at least a 70% of simulations resulted in SSF_t exceeding SSF_{MSY} ($SSF_t > SSF_{MSY}$) for all projection years.

For example, the 30th percentile of $SSF_{t,boot}$/ SSF_{MSY} represents the 70% probability of maintaining $SSF_{t,}$ above SSF_{MSY} from 10,000 Monte Carlo simulations for a given level of fixed removals (in 1000s) and a given year (2013 – 2022) (**Figure 1**). Projection results from 10,000 Monte Carlo simulations over the range of fixed removals levels evaluated here (**Table 1**) indicated levels of fixed removals less than or equal to 550 (1000s of sharks) resulted in at least a 70% probability of maintaining $SSF_{t,}$ above SSF_{MSY} (**Table 2 and Figure 1**).

Frequency distributions obtained for projections from 10,000 Monte Carlo simulations (random draws) from the bivariate normal distribution for equilibrium recruitment (R_0^{boot}) and fishing mortality ($F_{t=\text{h.endyr}}^{\text{boot}}$) evaluated at the fixed harvest level of 550 (1000s of sharks) are provided in **Figure 2**.

DISCUSSION

Short term projections with Monte Carlo simulation are provided here as a proxy to a typical P* approach based on a pre-specified acceptable probability of overfishing (e.g., $P^* = 0.3$; < 0.5) in response to the SEDAR 39 Atlantic smooth dogfish Term of Reference 9: Project Future Stock Conditions. The short-term (~5 to 10 year) projections at fixed harvest levels presented here are similar to those used by the International Commission for the Conservation of Atlantic Tunas (ICCAT) Standing Committee on Research and Statistics (SCRS) in their Kobe II tables and plots (e.g., SCRS BFT Stock Assessment Meeting Report 2012; their Tables 16-18, and their figures 36-38). Within the context of application to the existing HMS domestic shark age structured stock assessment model, probabilistic projections at fixed harvest levels may provide a useful proxy to a typical P* approach (e.g., Courtney et al. 2014).

However, a difference is that Kobe II tables and plots are calculated based on bootstrap resampling, while the probabilistic projections presented here are based on parametric Monte Carlo simulation. Another difference is that Kobe II tables and plots also present apical fishing mortality rates relative to fishing mortality at MSY (e.g., SCRS BFT Stock Assessment Meeting Report 2012; Courtney et al. 2014). However, annual fishing mortality rate estimates obtained with the SEDAR 39 Atlantic smooth dogfish SS3 assessment model were reported as exploitation rate in numbers, and preliminary projections with apical fishing mortality rates were not comparable to the fishing mortality rates reported as exploitation rate in numbers.

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Table 1. Simulations were conducted for 21 alternative fixed levels of total annual removals due to fishing (1000s of sharks) ranging from zero to 1,000 in increments of 50.

Fixed level of total annual removals due to fishing (1000s of sharks)	Alternative
0	1
50	2
100	3
150	4
200	5
250	6
300	7
350	8
400	9
450	10
500	11
550	12
600	13
650	14
700	15
750	16
800	17
850	18
900	19
950	20
1000	21

Table 2. Projection results from 10,000 Monte Carlo simulations for the SEDAR 39 Atlantic smooth dogfish base model configuration, which utilized a dome-shaped functional form of selectivity (Sel-2) for the main targeted fishery, evaluated under a range of fixed annual removals due to fishing (1000s of sharks). Projection results were reported as the proportion of times that spawning stock fecundity in projection year *t* (SSF_t) was above spawning stock fecundity at maximum sustainable yield (SSF_{MSY}), $Pr(SSF_t > SSF_{MSY})$, for a given fixed level of total annual removals due to fishing (1,000s of sharks). The $Pr(SSF_t > SSF_{MSY})$ was color coded to represent $Pr \geq 0.70$ (green), $0.50 \leq Pr < 0.70$ (yellow), and $Pr < 0.50$ (red).

Alternative	Fixed level of total annual removals due to fishing (1000s of sharks)	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3	100	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4	150	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	200	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	250	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7	300	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	350	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99
9	400	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.96
10	450	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.95	0.91
11	500	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.90	0.84
12	550	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.83	0.74
13	600	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.88	0.75	0.63
14	650	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.81	0.65	0.51
15	700	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.72	0.54	0.38
16	750	1.00	1.00	1.00	1.00	1.00	1.00	0.90	0.64	0.43	0.28
17	800	1.00	1.00	1.00	1.00	1.00	1.00	0.84	0.54	0.34	0.18
18	850	1.00	1.00	1.00	1.00	1.00	1.00	0.77	0.46	0.24	0.10
19	900	1.00	1.00	1.00	1.00	1.00	0.99	0.70	0.37	0.17	0.05
20	950	1.00	1.00	1.00	1.00	1.00	0.98	0.62	0.29	0.10	0.02
21	1000	1.00	1.00	1.00	1.00	1.00	0.96	0.53	0.21	0.06	0.01

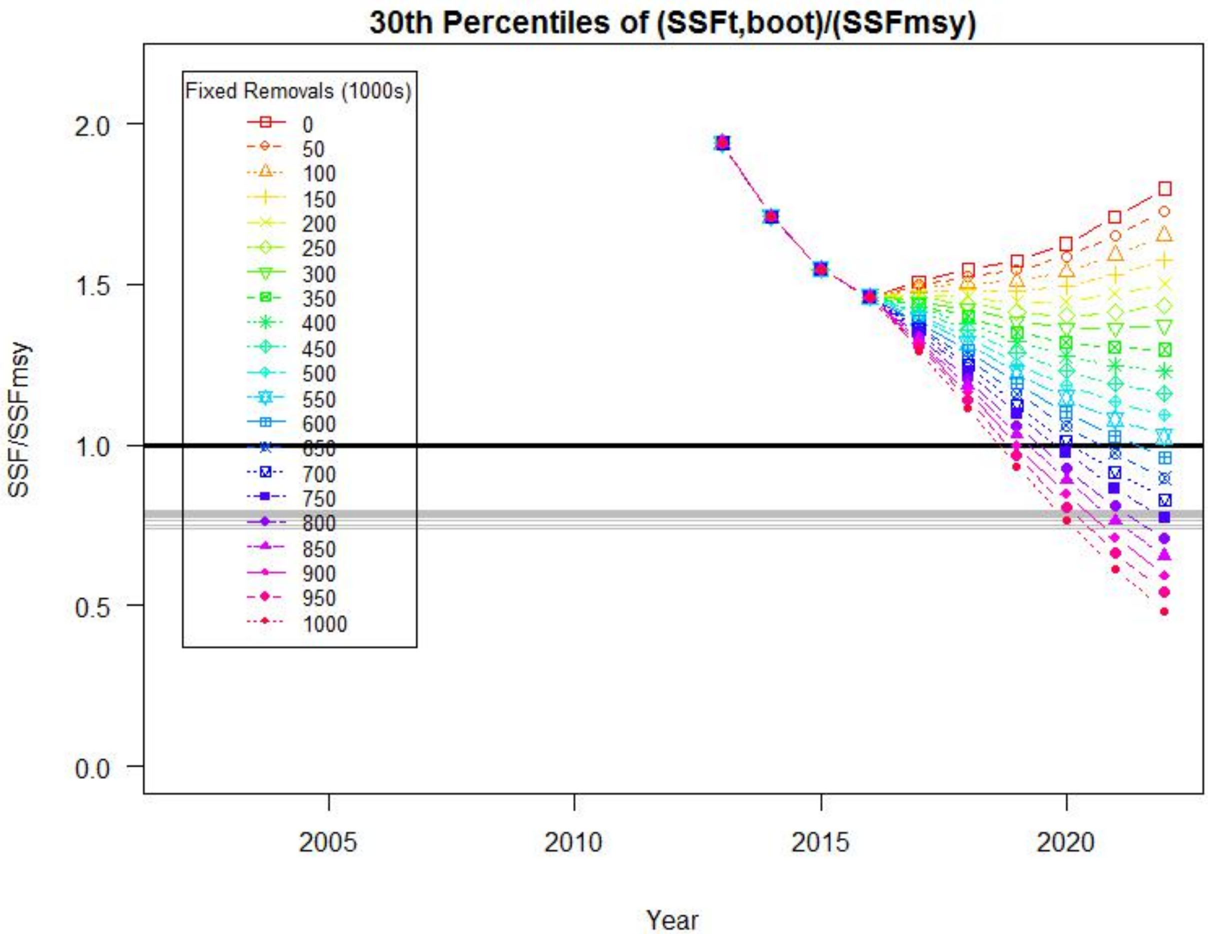

Figure 1. Projection results from 10,000 Monte Carlo simulations for the SEDAR 39 Atlantic smooth dogfish base model configuration, which utilized a dome-shaped functional form of selectivity (Sel-2) for the main targeted fishery, under a range of fixed annual removals due to fishing (1000s of sharks). Projection results were summarized as the 30[th] percentile of $SSF_{t,boot}$/ SSF_{MSY}, which represents the 70% probability of maintaining $SSF_{t,}$ above SSF_{MSY} from 10,000 Monte Carlo simulations for a given level of fixed removals (in 1000s) (**Tables 1 and 2**) and a given year (2013 – 2022). The shaded thick set of horizontal lines is the approximate location of the minimum stock size threshold (MSST) = $(1-\bar{M}_a)\times SSF_{MSY}$, where $(1-\bar{M}_a)$ is 1 - average natural mortality at age (SEDAR 39 Atlantic smooth dogfish Stock Assessment Report **Table 4.13)**.

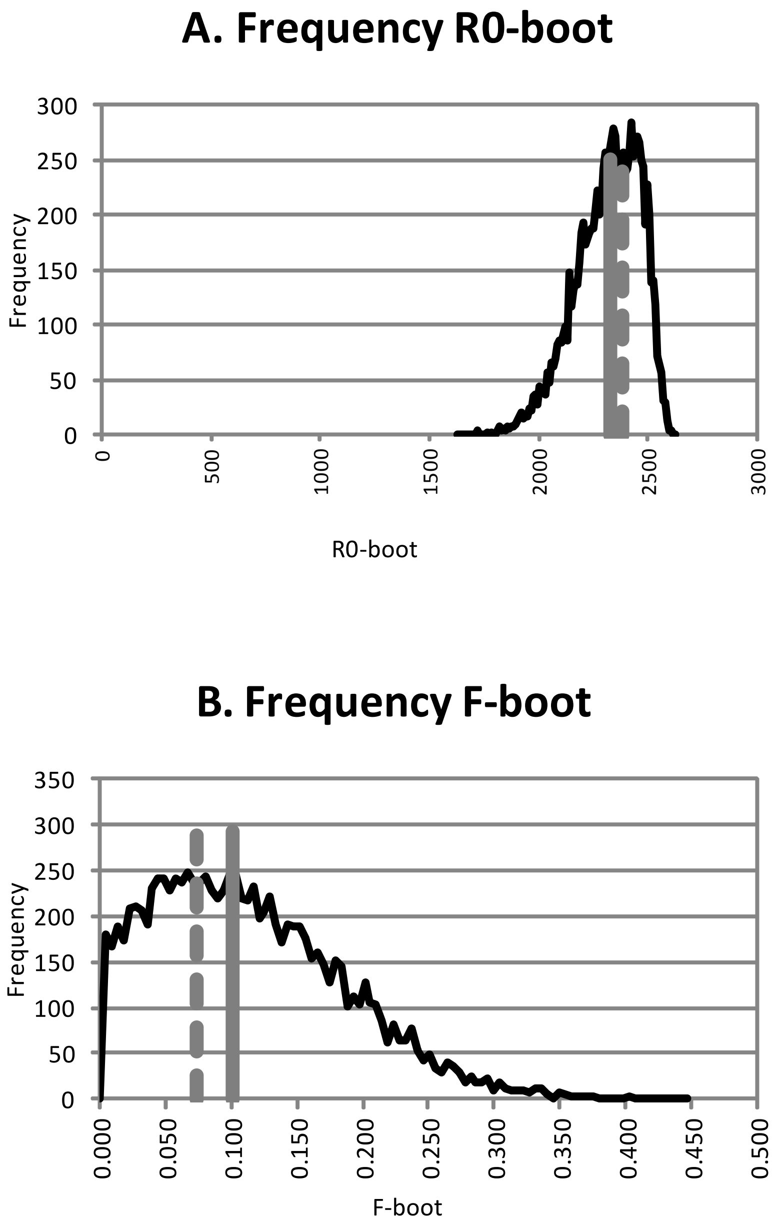

Figure 2. Frequency distributions obtained from 10,000 Monte Carlo simulations (random draws) from the bivariate normal distribution for equilibrium recruitment (R_0^{boot}) and fishing mortality ($F_{t=\text{h.endyr}}^{\text{boot}}$) evaluated at the fixed harvest level of 550 (1000s of sharks) along with the original parameter estimate (dashed line) and median (solid line) of the frequency distribution for the SEDAR 39 Atlantic smooth dogfish base model configuration, which utilized a dome-shaped functional form of selectivity (Sel-2) for the main targeted fishery.