SEDAR

Southeast Data, Assessment, and Review

Update assessment to SEDAR 21

HMS Dusky Shark

July 2016

SEDAR
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1. INTRODUCTION

1.1. TERMS OF REFERENCE

1. Update the approved dusky shark base model and sensitivity runs reflective of plausible states of nature identified in SEDAR 21 with data through 2015.
2. Document any changes or corrections made to model and input datasets and provide updated input data tables.
3. Update model parameter estimates and their variances, model uncertainties, estimates of stock status and management benchmarks, and projections of future stock status as conducted in SEDAR 21.
4. Develop a stock assessment update report to address these TORs and fully document the input data and results of the stock assessment update.

NOTE: The intent of update assessments is to expedite appraisals of stock status by using only the methods and data sets used in the base model and approved during the preceding SEDAR assessment of that stock. Accordingly, it is not the intent of this update to resolve any outstanding issues identified in the initial SEDAR 21 assessment. However, because the SEDAR reviewers identified several scenarios, in addition to the base run, as plausible states of nature, we will not limit the updated analyses to the base scenario only.

2. DATA REVIEW

The SEDAR 21 CIE reviewers identified five scenarios, including the base run, as plausible states of nature. Therefore, we updated the analyses for all five scenarios reflective of plausible states of nature identified and approved in the preceding SEDAR 21 assessment. However, only two of the previously approved input data sets were updated: the indices of relative abundance (CPUE) and the relative effort series (sections 2.2 and 2.4 below). The remaining previously approved input data sets (sections 2.1 and 2.3 below) were unchanged from the previous assessment.

2.1. LENGTH COMPOSITIONS, AGE COMPOSITIONS, AND SELECTIVITIES

No changes were introduced to the data or methodology for length compositions, age compositions, or selectivity previously identified and approved for dusky sharks during the preceding SEDAR 21 assessment. Briefly, age composition data were not available and length composition data were not input directly into the model. However, length composition data were used to generate age-frequency distributions through an age-length key. The age-frequency distributions produced were then used to estimate selectivity curves externally to the stock assessment model. Two types of selectivity curve were identified and approved during the preceding SEDAR 21 assessment for the CPUE series:

1) A logistic curve:

$$s = \frac{1}{1+e^{-\left(\frac{a-a_{50}}{b}\right)}},$$

where a_{50} is the median selectivity age (inflection point) and b is slope.

2) A double logistic curve of the form:

$$s = \frac{\frac{1}{1+e^{-\left(\frac{a-a_{50}}{b}\right)}} \times \left(1-\frac{1}{1+e^{-\left(\frac{a-c_{50}}{d}\right)}}\right)}{s_{max}},$$

where a_{50} and c_{50} are the ascending and descending inflection points, b and d are the ascending and descending slopes, respectively, and s_{max} is the maximum selectivity.

The VIMS LL (Virginia Institute of Marine Science) was represented by the double logistic curve, with age at full selectivity of 1 followed by a quickly descending right limb to reflect the fact that mostly juveniles are caught.

The LPS (Large Pelagic Survey) was also represented by the double logistic curve with fully selected age at 4 and with an ascending portion of the curve prior to the inflection point covering the younger age classes. The reason for the dome shape was to reflect the fact that larger, older animals could escape by breaking the monofilament line.

The BLLOP (Bottom Longline Observer Program) was assumed to fully select all ages, thus s=1 for all ages.

The NELL (Northeast Longline) survey was assumed to follow a logistic curve with full selectivity age of 6.

The PLLOP (Pelagic Longline Observer Program) was also represented by the double logistic curve with fully selected age at 5 and the dome shape also to reflect the fact that larger, older animals could escape by breaking the monofilament leader.

The model also considered three fleets: pelagic longline, commercial bottom longline, and recreational, which were assigned the selectivity functions corresponding to the PLLOP, BLLOP, and LPS CPUE series, respectively. All selectivities used in the assessment are summarized in Table 2.1 and Figure 2.1.

2.2. INDICES OF RELATIVE ABUNDANCE

The five indices of relative abundance described above (VIMS LL, LPS, BLLOP, NELL, and PLLOP), which were identified and approved during the preceding SEDAR 21 assessment, were updated here (Table 2.2, Figure 2.2). The VIMS LL and NELL indices are fishery independent, whereas the BLLOP, PLLOP, and LPS are fishery dependent (the first two, commercial, and the last, recreational). The updated indices were standardized using the same GLM techniques identified and approved for each index during the preceding SEDAR 21 assessment, except that the data were updated here to 2015. The CVs associated with the updated indices are provided in Table 2.3. The updated indices and their CVs were used in the five scenarios reflective of plausible states of nature as described in section 3 of this report.

Figure 2.3 shows each updated index superimposed on the index used for SEDAR 21 (ending in 2009). The updated VIMS LL index tracked the old index fairly closely and showed a clearly declining trend since 2009. The updated LPS index showed an oscillating but generally flat trajectory since 2009. The updated standardized BLLOP index tracked the old index relatively closely, but the series had to be truncated to 2013 because of regulatory changes introduced in 2014. After 2009, the BLLOP index showed a very high peak in 2012 followed by a strong decrease until 2013, with an overall slightly negative tendency since 2009. The updated NELL index, which only had two additional data points since 2009, showed a strong linear increase since 2009. The updated PLLOP index tracked the old index very closely and displayed a generally negative tendency since 2009.

2.3. LIFE HISTORY INPUTS

No changes were introduced to the data or methodology for life history inputs previously identified and approved for dusky sharks during the preceding SEDAR 21 assessment. The life history inputs used in the SEDAR 21 base run and this update are presented in Table 2.4. These include age and growth, several parameters associated with reproduction, including sex ratio, reproductive frequency, fecundity at age, maturity at age, month of pupping, and natural mortality (M). The values of M are intended to represent a maximum compensatory response in the absence of fishing. For fecundity, since the Age-Structured Catch-Free Model (ASCFM; as described below in section 3 of this report) tracks only females, the number of pups per female

(7.13) is multiplied by 0.5 to account for a 50/50 sex ratio, and further multiplied by 0.33 to account for an agreed-upon triennial reproductive cycle. Since the proportion of females in maternal condition—a quantity that accounts for the time it takes for a female to become pregnant and produce offspring after it reaches maturity and which is more appropriate than using the proportion of mature females (Walker 2005) —was not available, we offset the maturity ogive by one year (the gestation period) as a proxy to using the maternity ogive.

The ASCFM uses most life history characteristics as constant inputs and others are estimated parameters, which are given priors and initial values, as described below in section 3 of this report.

2.4. RELATIVE EFFORT SERIES

The relative effort series for three fleets (bottom longline (BLL); recreational (REC); pelagic longline (PLL)), which were previously identified and approved during the preceding SEDAR 21 assessment, were updated here (Table 2.5, Figure 2.4). We followed the same rationale for deriving relative effort for the three fleets as described in section 3.5 of the preceding SEDAR 21 Data Workshop report, except that the effort data were updated here for the period 1960 – 2015. The updated effort series were used to determine a single annual weighted selectivity vector for modeling fishing mortality in the five scenarios reflective of plausible states of nature as described in section 3 of this report.

The derivation is as follows. First, the annual numbers of hooks from all pelagic longline fleets operating in the northwest Atlantic Ocean were obtained from the International Commission for the Conservation of Atlantic Tunas (ICCAT) Task II database up to 2014. Note that the updated effort series obtained from ICCAT differs from that used in SEDAR 21 because the effort estimation methodology has been improved and the new effort estimates are considered to be more reliable than those used for SEDAR 21 (Paul DeBruyn, International Commission for the Conservation of Atlantic Tunas, pers. comm.). A series of relative effort for 1960 – 2015 was then created by standardizing the annual effort to the 2014 value. The average relative effort for 2012 – 2014 was used to produce an estimate for 2015. Second, for both the REC and BLL fleets, it was thought that there was not much effort before 1980. The directed shark bottom longline fleet is known to have developed in the 1970s, while the recreational fishery did not develop until about the late 1970s, Therefore, from 1960 to 1980, effort for both the recreational and the bottom longline fishery was set to very low levels to reflect the fact these fisheries had not really developed yet. For the remaining years, relative effort trends for these two fisheries were derived by comparing available total removals (landings + dead discards) to removals from the PLL fleet (assuming that removals would be proportional to effort). Removals from the recreational sector were first available in 1981, in 1982 from the bottom longline fishery, and 1992 from the pelagic longline fishery, although their magnitude and reliability is questionable owing to identification and reporting issues (see section 3). Indeed, for the years where removals were available there were often large fluctuations, on the order of several orders of magnitude, among the removals from the three sources. This was not believed to be a reflection of drastic changes in effort, but rather be due possibly to misidentification, misreporting or expansion factors based on very small sample sizes. In SEDAR 21, an exploratory exercise was undertaken to identify the period when the magnitude of the removal ratios REC:PLL and BLL:PLL was lowest, resulting in the years 2002-2007. Those years were thus used to derive an average ratio of removals for REC:PLL and BLL:PLL. Third, these estimated ratios of removals were then used to obtain relative effort in 1990-2015 for REC and BLL by multiplying the annual PLL relative effort by each corresponding ratio of removals (0.89 for REC:PLL and 0.46 for BLL:PLL). Fourth, these estimated annual relative effort series were then projected back from 1990 to 1980 by assuming a linear decrease with a slope equal to the value in 1990 divided by 11 (number of years from 1970 to 1980). Although dusky sharks have been a prohibited species since 2000, there is incidental catch and discard and thus we did not eliminate effort after 2000. Table 2.5 lists the values and Figure 2.4 displays them graphically.

2.5. REFERENCES

Walker, T. I. 2005. Reproduction in fisheries science. In: Reproductive Biology and Phylogeny of Chondrichthyans: Sharks, Batoids, and Chimaeras (Ed. W.C. Hamlett) pp. 81-127. Science Publishers Inc., Enfield, NH, USA.

2.6 TABLES

Table 2.1. Selectivity curves for indices of relative abundance used in the assessment update. Parameters are ascending inflection point (a_{50}), ascending slope (b), descending inflection point (c_{50}), descending slope (d), and maximum selectivity (s_{max}).

Series	Selectivity	a_{50}	b	c_{50}	d	max(sel)
BLLOP	Fixed at 1					
VIMS	Double logistic	0	0.25	2	4.50	0.55
LPS	Double logistic	3.03	0.06	14.05	4.33	0.91
PLLOP	Double logistic	2.19	0.82	13.56	7.77	0.73
NELL	Logistic	3.10	0.28			

Table 2.2. Updated standardized indices of relative abundance used in the assessment update (scaled by the mean).

YEAR	VIMS LL	LPS	BLLOP	NELL	PLLOP
1961	-	-	-	-	-
1962	-	-	-	-	-
1963	-	-	-	-	-
1964	-	-	-	-	-
1965	-	-	-	-	-
1966	-	-	-	-	-
1967	-	-	-	-	-
1968	-	-	-	-	-
1969	-	-	-	-	-
1970	-	-	-	-	-
1971	-	-	-	-	-
1972	-	-	-	-	-
1973	-	-	-	-	-
1974	-	-	-	-	-
1975	2.904	-	-	-	-
1976	-	-	-	-	-
1977	0.440	-	-	-	-
1978	5.421	-	-	-	-
1979	-	-	-	-	-
1980	2.221	-	-	-	-
1981	1.195	-	-	-	-
1982	-	-	-	-	-
1983	-	-	-	-	-
1984	-	-	-	-	-
1985	-	-	-	-	-
1986	-	2.275	-	-	-
1987	0.458	2.353	-	-	-
1988	-	0.785	-	-	-
1989	0.193	1.680	-	-	-
1990	0.152	1.243	-	-	-
1991	0.209	1.290	-	-	-
1992	0.043	0.420	-	-	5.806
1993	0.403	3.040	-	-	2.442
1994	-	0.566	0.703	-	3.377
1995	0.227	0.883	1.291	-	1.398
1996	0.792	1.285	1.034	0.030	1.712
1997	-	0.882	1.280	-	0.626
1998	0.282	0.600	1.066	0.116	2.395
1999	1.062	0.453	1.331	-	0.438
2000	1.154	0.756	0.499	-	0.958
2001	0.608	0.343	0.692	0.134	0.389
2002	1.256	0.588	0.385	-	0.176
2003	0.529	0.420	0.453	-	0.127
2004	0.937	0.532	0.575	0.441	0.725
2005	1.945	0.577	0.756	-	0.601
2006	2.220	0.199	0.505	-	1.008
2007	0.507	1.007	0.555	0.717	0.389
2008	0.589	1.358	0.677	-	0.242
2009	2.091	0.878	0.789	1.714	0.251
2010	1.286	0.970	1.230	-	0.169
2011	0.410	0.789	0.886	-	0.221
2012	0.802	0.904	5.023	2.113	0.206
2013	0.423	1.162	0.271	-	0.174
2014	0.185	0.863	-	-	0.111
2015	0.057	0.902	-	2.736	0.061

Table 2.3. Updated coefficients of variation used in the assessment update for weighting the indices of relative abundance.

YEAR	VIMS LL	LPS	BLLOP	NELL	PLLOP
1961	1	1	1	1	1
1962	1	1	1	1	1
1963	1	1	1	1	1
1964	1	1	1	1	1
1965	1	1	1	1	1
1966	1	1	1	1	1
1967	1	1	1	1	1
1968	1	1	1	1	1
1969	1	1	1	1	1
1970	1	1	1	1	1
1971	1	1	1	1	1
1972	1	1	1	1	1
1973	1	1	1	1	1
1974	1	1	1	1	1
1975	0.477	1	1	1	1
1976	1	1	1	1	1
1977	0.610	1	1	1	1
1978	0.745	1	1	1	1
1979	1	1	1	1	1
1980	0.447	1	1	1	1
1981	0.328	1	1	1	1
1982	1	1	1	1	1
1983	1	1	1	1	1
1984	1	1	1	1	1
1985	1	1	1	1	1
1986	1	0.152	1	1	1
1987	0.373	0.135	1	1	1
1988	1	0.317	1	1	1
1989	0.903	0.180	1	1	1
1990	0.544	0.166	1	1	1
1991	0.814	0.165	1	1	1
1992	0.918	0.305	1	1	0.228
1993	0.499	0.245	1	1	0.174
1994	1	0.395	0.334	1	0.174
1995	0.863	0.328	0.291	1	0.214
1996	0.389	0.414	0.288	0.819	0.253
1997	1	0.406	0.291	1	0.318
1998	0.545	0.499	0.336	0.593	0.256
1999	0.459	0.685	0.359	1	0.349
2000	0.331	0.532	0.854	1	0.270
2001	0.438	0.686	0.455	0.546	0.337
2002	0.428	0.621	0.607	1	0.807
2003	1.097	0.386	0.427	1	0.593
2004	0.517	0.347	0.416	0.363	0.272
2005	0.316	0.358	0.568	1	0.261
2006	0.253	0.505	0.620	1	0.244
2007	0.501	0.248	0.760	0.476	0.287
2008	0.618	0.215	0.820	1	0.379
2009	0.501	0.268	0.477	0.366	0.257
2010	0.281	0.259	0.427	1	0.337
2011	0.388	0.279	0.445	1	0.313
2012	0.377	0.270	0.362	0.383	0.330
2013	0.647	0.276	0.661	1	0.334
2014	0.624	0.307	1	1	0.338
2015	1.014	0.264	1	0.283	0.455

Table 2.4. Life history inputs used in the assessment update (all these quantities are treated as constants in the model).

Age	Proportion mature	M
1	0.00	0.104
2	0.00	0.104
3	0.00	0.104
4	0.00	0.104
5	0.00	0.104
6	0.00	0.098
7	0.00	0.092
8	0.00	0.088
9	0.00	0.084
10	0.00	0.080
11	0.00	0.077
12	0.00	0.074
13	0.00	0.072
14	0.00	0.070
15	0.01	0.068
16	0.02	0.066
17	0.05	0.064
18	0.13	0.063
19	0.28	0.061
20	0.51	0.060
21	0.74	0.059
22	0.88	0.058
23	0.95	0.057
24	0.98	0.056
25	0.99	0.055
26	1.00	0.054
27	1.00	0.053
28	1.00	0.052
29	1.00	0.052
30	1.00	0.051
31	1.00	0.048
32	1.00	0.048
33	1.00	0.048
34	1.00	0.048
35	1.00	0.048
36	1.00	0.048
37	1.00	0.048
38	1.00	0.048
39	1.00	0.048
40	1.00	0.048

Sex ratio at birth:	1:1
Reproductive frequency:	3 yr
Pupping month:	June
Gestation period:	12 months
Fecundity:	7.13 pups
L_{inf}	350.3 cm FL
k	0.039
t_0	-7.04
Weight vs length relation:	$W=0.000032415L2^{.7862}$
maturity ogive:	a=-19.76, b=0.99

Table 2.5. Updated relative effort for three fleets used in the assessment update (BLL=commercial bottom-longline shark fishery; REC=recreational fishery; PLL=pelagic longline fishery).

Year	PLL	REC	BLL
1960	0.032	0.001	0.001
1961	0.020	0.001	0.001
1962	0.103	0.002	0.002
1963	0.248	0.002	0.002
1964	0.463	0.003	0.003
1965	0.447	0.003	0.003
1966	0.246	0.001	0.001
1967	0.217	0.001	0.001
1968	0.308	0.002	0.002
1969	0.243	0.002	0.002
1970	0.335	0.002	0.002
1971	0.509	0.002	0.002
1972	0.396	0.002	0.002
1973	0.466	0.002	0.002
1974	0.690	0.002	0.002
1975	0.626	0.002	0.002
1976	0.632	0.002	0.002
1977	0.660	0.002	0.002
1978	0.612	0.002	0.002
1979	0.877	0.002	0.002
1980	0.721	0.056	0.029
1981	0.714	0.111	0.057
1982	0.706	0.167	0.086
1983	0.599	0.222	0.115
1984	0.859	0.278	0.144
1985	0.984	0.333	0.172
1986	1.162	0.389	0.201
1987	0.843	0.444	0.230
1988	0.853	0.500	0.258
1989	0.793	0.555	0.287
1990	0.686	0.611	0.316
1991	0.789	0.702	0.363
1992	0.906	0.806	0.417
1993	0.905	0.806	0.416
1994	1.144	1.018	0.526
1995	1.232	1.096	0.567
1996	1.056	0.940	0.486
1997	1.053	0.937	0.484
1998	1.001	0.891	0.461
1999	1.112	0.990	0.512
2000	1.147	1.021	0.528
2001	0.855	0.761	0.393
2002	1.288	1.147	0.593
2003	1.401	1.247	0.645
2004	2.028	1.805	0.933
2005	1.033	0.919	0.475
2006	1.236	1.100	0.568
2007	1.071	0.953	0.493
2008	1.073	0.955	0.494
2009	1.281	1.140	0.589
2010	1.167	1.038	0.537
2011	1.487	1.324	0.684
2012	1.686	1.501	0.776
2013	1.534	1.365	0.706
2014	1.000	0.890	0.460
2015	1.407	1.252	0.647

2.6. FIGURES

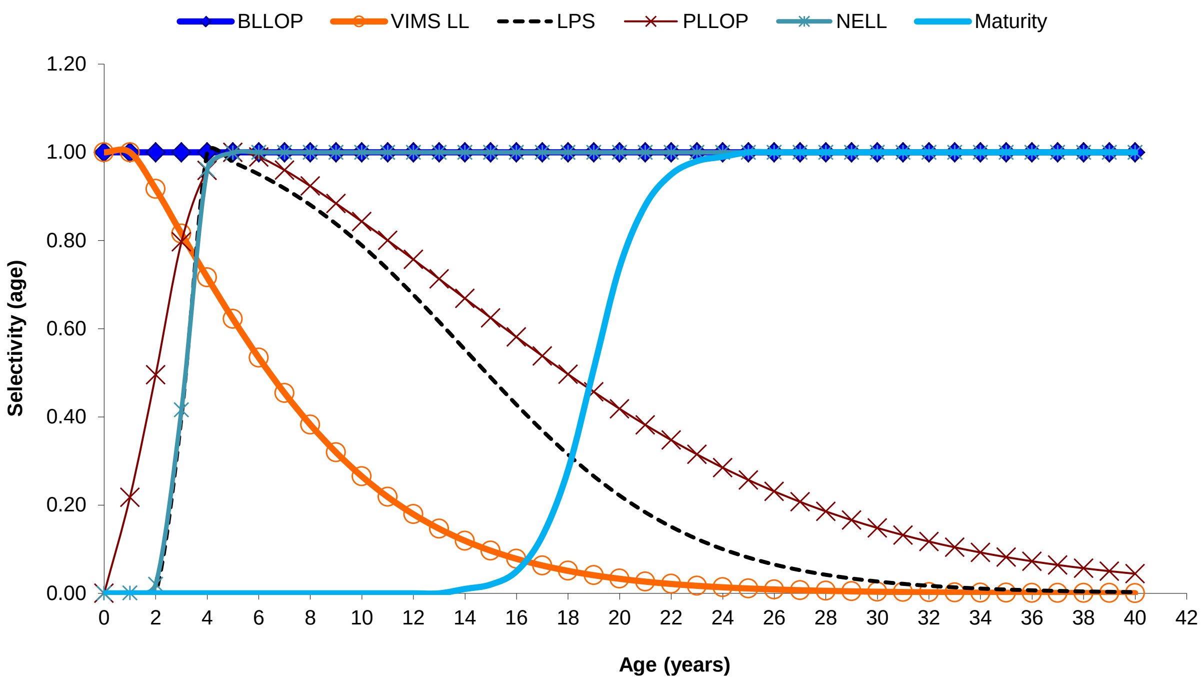


Figure 2.1. Selectivity curves for indices of relative abundance used in the assessment update. The maturity ogive for dusky shark has been added for reference.

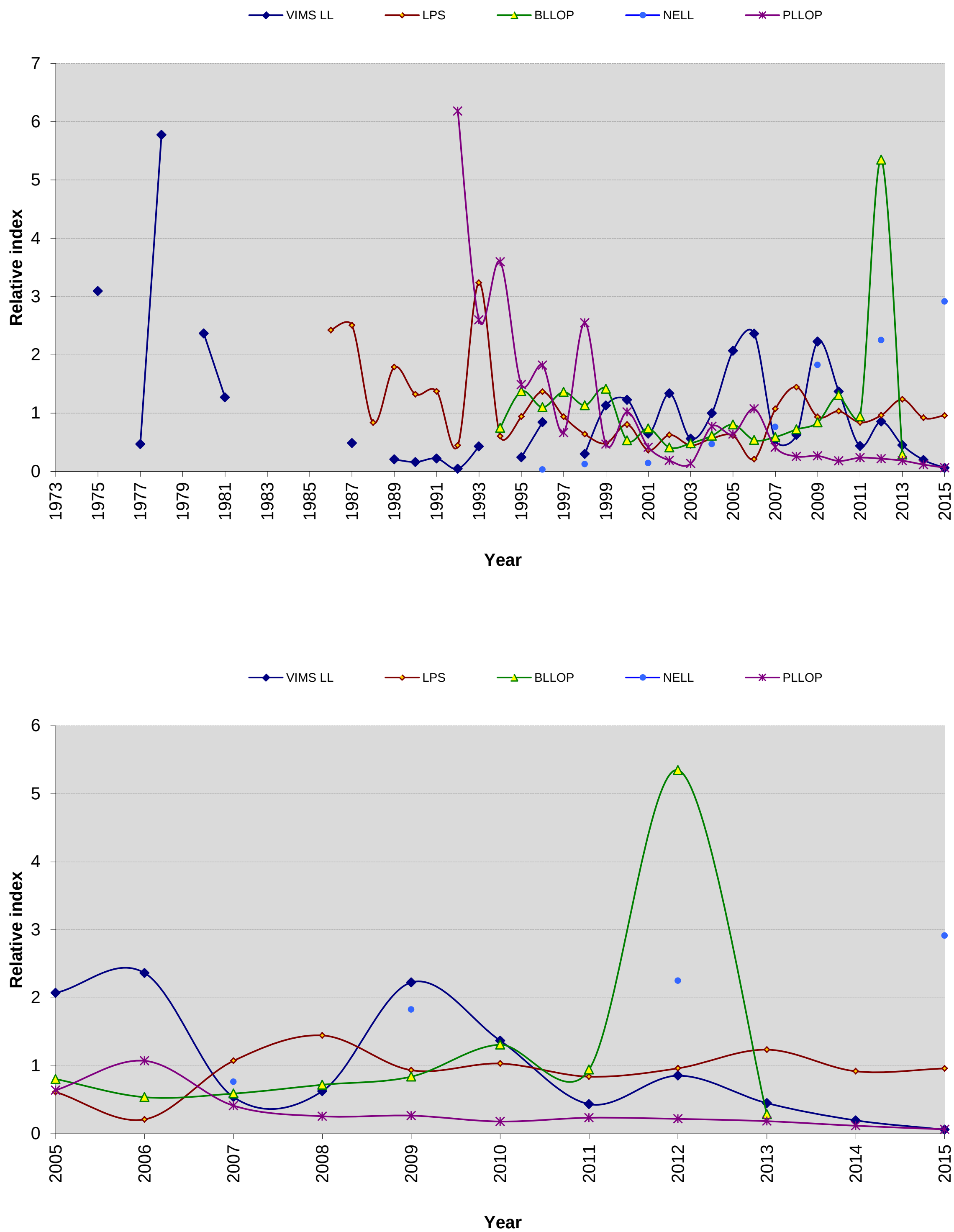


Figure 2.2. Updated indices of relative abundance for dusky shark (VIMS LL, LPS, BLLOP, NELL, and PLLOP) used in the assessment update. Top panel: complete time period; bottom panel: past decade. All indices are statistically standardized and scaled (divided by their respective mean and a global mean for overlapping years).

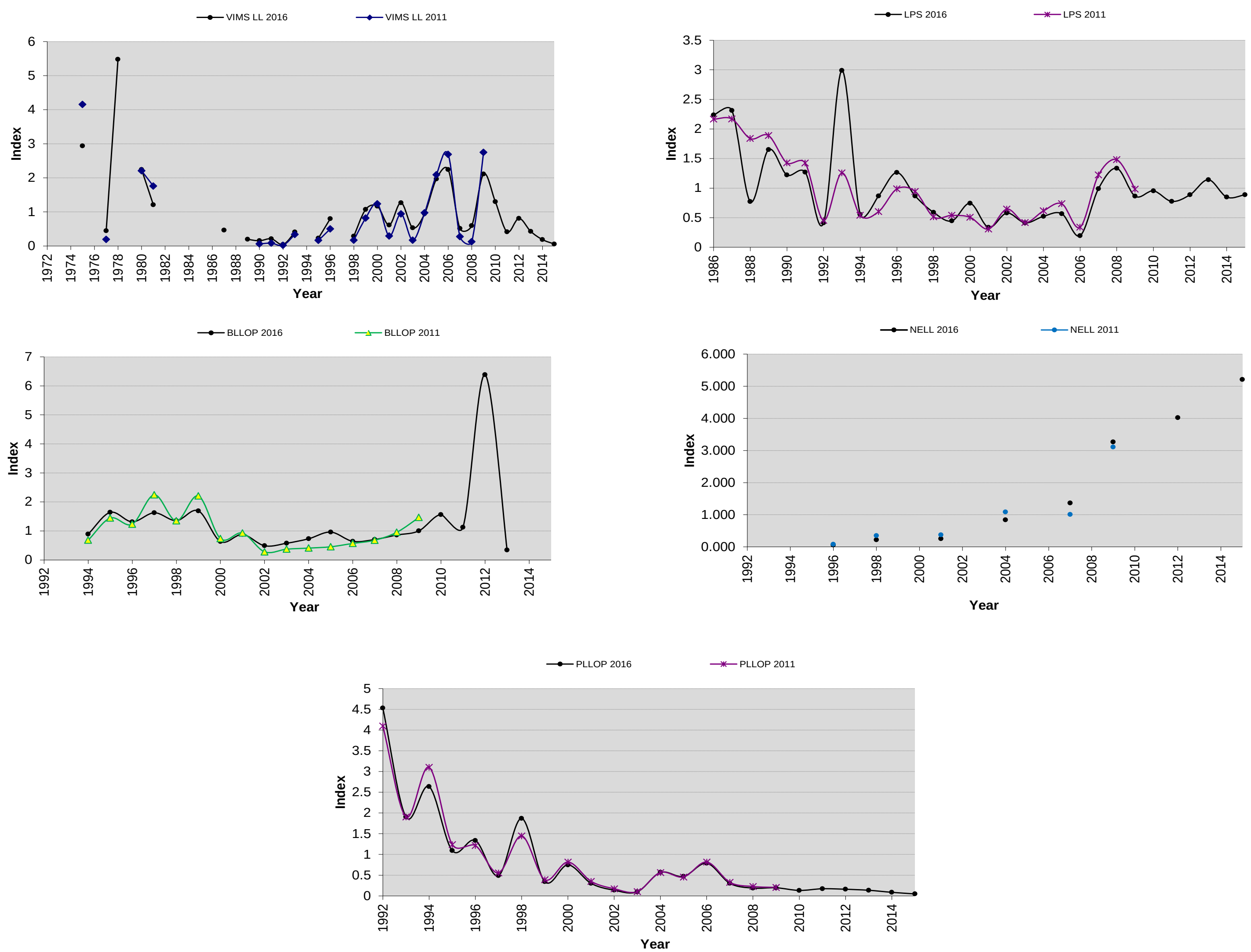


Figure 2.3. Indices of relative abundance for dusky shark used in the preceding SEDAR 21 assessment (2011) vs. those used in this assessment update (2016). From top to bottom and left to right: VIMS LL, LPS, BLLOP, NELL, and PLLOP. All indices are scaled (divided by the mean of overlapping years).

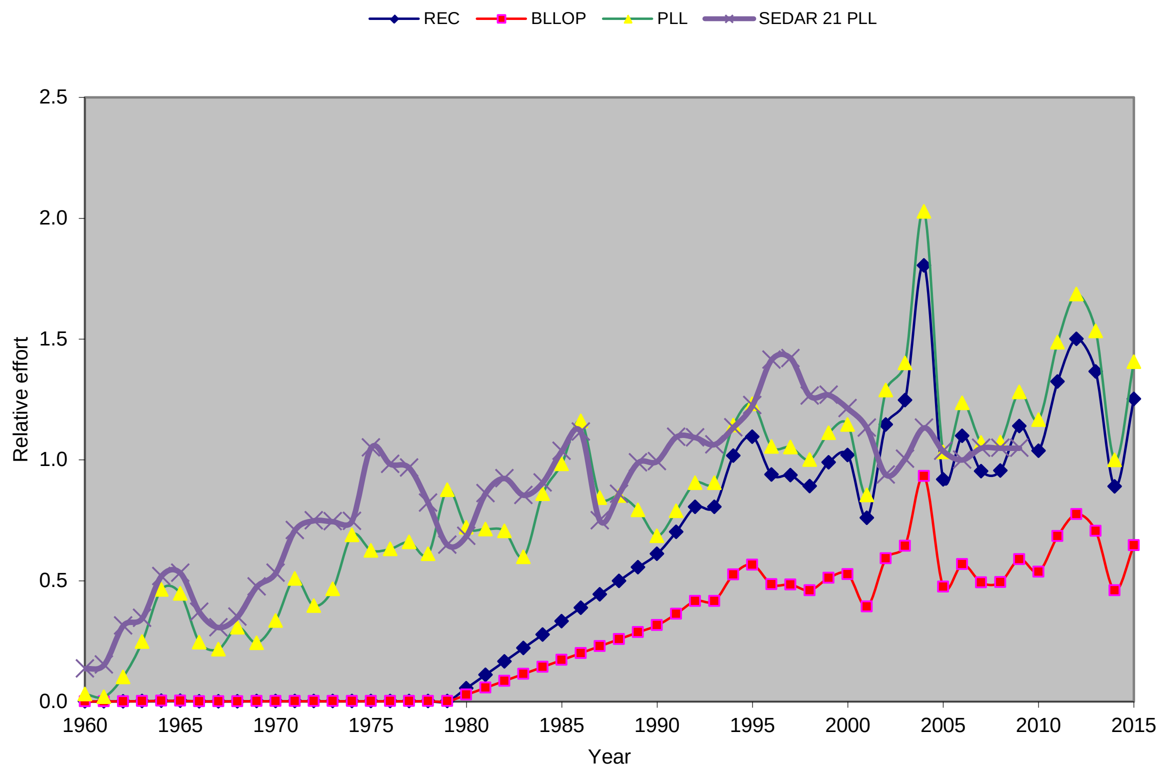


Figure 2.4. Updated relative effort for three fleets (BLL=commercial bottom-longline shark fishery; REC=recreational fishery; PLL=pelagic longline fishery).The PLL effort series used in the preceding SEDAR 21 assessment (SEDAR 21 PLL) is shown for reference.

3. STOCK ASSESSMENT MODEL AND RESULTS

3.1. ASSESSMENT METHODS

3.1.1. Age-Structured Catch-Free Model (ASCFM) Description

In fisheries where there is a high degree of uncertainty in reported catches, or catches are not reported at all, stock assessment models that rely on catch data may not be appropriate. For numerous shark species there is uncertainty about the magnitude of commercial and recreational catches, in part due to identification problems. The level of reported discards is especially uncertain and may be underestimated because sharks are often not brought aboard for positive identification and may therefore go unreported. Without accurate knowledge of the magnitude of total catches and discards, it is not possible to estimate absolute abundance levels for the population. An alternative modeling methodology appropriate to these situations is to re-scale the model population dynamics as proportional to virgin (unexploited) conditions. If estimates of effort are available for the time series of exploitation, this information can be incorporated to guide model estimates of annual fishing mortality. Information about population declines relative to virgin can also be incorporated if there is expert opinion or data to suggest possible estimates of depletion. If catch and effort information are available from sampled trips or observer programs, then standardized catch rates can be developed and incorporated into the model.

In the present application, dusky shark landings are first available in the early 1980s at very low levels. Commercial landings during this time period are two to three orders of magnitude lower than those from the recreational fishery. It is not believed that this is a real trend in landings, but rather that it reflects underreporting and poor species identification. Indeed, dusky sharks—especially immature individuals—are easy to confuse with some other similar-looking species, in particular silky sharks. This has likely led to identification problems in the past in the commercial fisheries, but is most problematic in the recreational fisheries, where anglers unfamiliar with shark identification may incorrectly identify dusky sharks, leading to over- or under-representation of the expanded recreational catches. Underreporting (or mis-reporting as other species) is also likely to have occurred in the commercial fisheries because take of the species was prohibited in 1999. Dead discard estimates of dusky shark from the pelagic longline fishery are first available in 1992 as a result of the observer program that placed observers on a fraction of the vessels to estimate both discards and landings. With such high uncertainty in the series of reported catch and discard, the catch-free methodology was selected as an appropriate application for SEDAR 21. The ASCFM was initially developed by Porch et al. (2006) for use in a goliath grouper assessment for which only life history information and relative abundance (CPUE) indices were available.

3.1.2. Data Sources

The ASCFM was fit to life history data and the five abundance indices included in the SEDAR 21 base run and four alternative states of nature (see section 2 for a description of these data sources).

3.1.3. Model Configuration and Equations

The ASCFM used in this update assessment builds upon the methodology first described by Porch et al. (2006) as used by Cortés et al. (2006) in a previous assessment of dusky sharks, and as used in the preceding SEDAR 21 assessment. A first step in applying the catch-free methodology is to determine a year in which the population can be considered to be at virgin conditions. From that year forward, information on fishing effort and/or prior information about possible levels of depletion allow the model to estimate the relative number at age for the year that data (e.g., catch rates) are first available. The period from virgin conditions just prior to availability of fishery data is referred to as the *historic* period. In the present incarnation of the ASCFM, the time period spanning the first year with fishery data through the end of 1999 is referred to as the *first modern* period. The time period from 2000 to the end of the assessment period (2015) is referred to as the *second modern* period (landings for dusky shark were prohibited during the second modern period).

The underlying equations are simply a re-scaled age-structured production model. The stock-recruitment relationship is defined in terms of the spawning stock in year y and the resultant recruits in year $y+r$, and the first model age is a_r. Assuming that all survival beyond recruitment is density independent, then at virgin conditions the population age structure beyond a_r can be calculated from the expected survival at age from natural mortality:

$$N_{a,1} = \begin{cases} 1 & a = a_r \\ N_{a-1,1} \exp^{(-M_{a-1})} & a_r < a < A \\ N_{a-1,1} \dfrac{\exp^{(-M_{A-1})}}{1-\exp^{(-M_{A-1})}} & a = A \end{cases} , \quad (3.1)$$

where A is the age of the plus-group (assumed to be 40 years in the present assessment).

Subsequent annual relative recruitment, r_y, is modeled as following a Beverton-Holt function (with recruitment deviations set to zero). This function can be parameterized in terms of $\hat{\alpha}$, the maximum number of recruits produced by each spawner over its lifetime (Myers et al. 1999). The parameter $\hat{\alpha}$ is equivalent to the slope of the spawner-recruit curve at the origin multiplied by φ_0 (unexploited number of pups per recruit). The slope of the stock-recruit curve at the origin is equivalent to density-independent survival of pups (e^{-M_0} ; see section 3.1.4). The Beverton-Holt function is given by:

$$r_y = \frac{e^{-M_0}\varphi_0 S_{y-a_r}}{1+(e^{-M_0}\varphi_0 - 1)S_{y-a_r}}. \quad (3.2)$$

In (3.2), S_{y-a_r} is a measure of relative spawning stock fecundity, which is calculated as:

$$S_y = \frac{\sum_{a=a_r}^{A} E_a N_{a,y} \exp^{(-(F_{a,y}+M_a)t_s)}}{\sum_{a=a_r}^{A} E_a N_{a,1} \exp^{(-M_a t_s)}} . \quad (3.3)$$

In (3.3), E_a is per-capita eggs by age class (the product of fecundity and maturity at age was used as a proxy for eggs in the present application), $F_{a,y}$ is total fishing mortality on age *a* in year *y*, and t_s is the fraction of the year elapsed at the time of spawning. Since this assessment employs a constant fec_{age} value (i.e., fecundity does not vary by age), fecundity cancels out of (3.3); in fact (3.3) may be interpreted as either relative mature spawning stock biomass, or relative spawning stock fecundity.

The parameter φ_0 in (eq. 3.2) is calculated as:

$$\varphi_0 = \sum_{a=1}^{A-1} fec_a \times mat_a \prod_{j=1}^{a-1} \exp(-M_j) + fec_A \times mat_A \frac{\exp(-M_{A-1})}{1-\exp(-M_{A-1})} \prod_{j=1}^{A-2} \exp(-M_j) , \quad (3.4)$$

where fec_a is fecundity at age and mat_a is maturity at age (Goodyear 1993).

This implementation of the catch-free model can incorporate multiple fleets that may be exploiting the resource. Annual, fleet-specific apical fishing mortality can potentially be estimated from fleet-specific effort series, if available ("apical" in this context refers to the fishing mortality that would be experienced by an age class that is fully vulnerable). However, effort series for the two other fleets considered (i.e., bottom longline and recreational) were missing, and initial efforts to incorporate effort series derived using proportionality constants (section 2.4) resulted in collinearity when attempting to estimate fleet-specific parameters. As such, total age-specific fishing mortality was modeled as follows:

$$F_{a,y} = Fapical_y \bar{v}_{a,y} , \quad (3.5)$$

where $\bar{v}_{a,y}$ gives mean vulnerability (selectivity) at age in year *y* across all fleets:

$$\bar{v}_{a,y} = \frac{\sum_{fleet} v_{fleet,a} Effort_{fleet,y}}{\sum_{fleet} Effort_{fleet,y}} \tag{3.6}$$

(see sections 2.1 and 2.4 for fleet specific vulnerability schedules ($v_{fleet,a}$) and derivation of effort series, respectively). Since the pelagic long line (PLL) fleet dominated the fishery early in the time series, we modeled apical fishing mortality as proportional to PLL effort the first 20 years of the assessment model, and as a correlated random walk thereafter:

$$Fapical_y = \begin{cases} \beta_1 \times Effort_{PLL,y} & y < 1980 \\ Fapical_{y-1} \exp(\delta_y) & 1980 \le y \le 2015 \end{cases} . \tag{3.7}$$

An advantage of estimating total fishing mortality in this manner is that it implicitly includes both discard mortality as well as mortality of those animals retained in the catch. The correlated random walk structure was induced by setting

$$\delta_y = \begin{cases} \varepsilon_y & y = 1980 \\ \rho\delta_{y-1} + \varepsilon_y & 1981 \le y \le 1999 \\ \tau & y = 2000 \\ \rho\delta_{y-1} + \varepsilon_y & 2001 \le y \le 2015 \end{cases} , \tag{3.8}$$

where ρ is a correlation coefficient and ε_y is sampling error (assumed to be normally distributed).

A break in the correlated walk series was implemented in 2000 to allow for the possibility of reduced fishing mortality following prohibition of dusky landings in late 1999. The correlation coefficient ρ was fixed to 0.5 in all runs; see section 3.1.4 for description of prior distributions on ε_y and τ.

Given recruitment (i.e., it is assumed that $N_{1,y} = r_y$ from Eq. 3.2, with a_r=1), and fishing and natural morality at age, abundance is propagated forward in the usual fashion:

$$N_{a,y} = \begin{cases} N_{a-1,y-1} \exp^{(-(M_{a-1}+F_{a-1,y-1}))} & 2 < a < A \\ N_{A-1,y-1} \exp^{(-(M_{a-1}+F_{a-1,y-1}))} + N_{A,y-1} \exp^{(-(M_A+F_{A,y-1}))} & a = A \end{cases} \quad (3.9)$$

When fitting to indices of abundance and catch rates, the model predicts values for index *j* in year *y* as:

$$\tilde{U}_{j,y} = \frac{q_j v_{j,0} N_{1,y+1}}{\theta_y^{1-t_j}} + q_j \sum_{a=1}^{A} v_{j,a} N_{a,y} \exp^{(-(M_a+F_{a,y})t_j)} \quad . \quad (3.10)$$

(all indices were measured in numbers). Here, q_j is the catchability coefficient, $v_{j,a}$ is age-specific vulnerability for index *j* (see section 2.1 for fleet specific vulnerability schedules), and t_j is the fraction of the year that has elapsed prior to the timing of index *j* (assumed to be 0.5 for all indices). The first term in the expression is an attempt to account for indices that catch pups; since recruitment is assumed to occur at age 1, the number of pups alive when the index was collected in the previous year is back predicted using the year-specific value of pup survival, computed as

$$\theta_y = \frac{N_{1,y+1}}{\sum_a N_{a,y} \, fec_a mat_a} \quad . \quad (3.11)$$

3.1.4. Parameter Estimation

Parameters were estimated by minimizing an objective function (the negative log joint posterior density function) using AD Model Builder software (Otter Research, Ltd. 2004). The (log) joint posterior distribution was specified up to a proportionality constant and included log likelihood components for observed data (Λ_1), process error components (Λ_2), prior distribution components (Λ_3), and several penalties intended to keep parameter values within plausible ranges during estimation (Λ_4). The total objective function was then given by $\Lambda = \Lambda_1 + \Lambda_2 + \Lambda_3 + \Lambda_4$, with each component as described below.

Observed data log likelihood—The observed data log likelihood was specified as lognormal, but included a number of variance terms that could be estimated or fixed to allow for a wide range of choices for how to fit the data. The overall contribution is provided by

$$\Lambda_1 = 0.5\sum_i \sum_y \frac{(\log(U_{i,y}) - \log(\tilde{U}_{i,y}))^2}{\sigma^2_{i,y}} + \log(\sigma^2_{i,y}), \qquad (3.12)$$

where $U_{i,y}$ and $\tilde{U}_{i,y}$ give observed and predicted indices, respectively, and

$$\sigma^2_{i,y} = \log(1 + \mathrm{CV}^2_{\mathrm{i,y}}) + \sigma^2_i + \sigma^2_{\mathrm{overall}}. \qquad (3.13)$$

Here, $\sigma^2_{\mathrm{overall}}$ gives an (estimated) baseline level of variance which is applied to all indices, $\mathrm{CV}_{i,y}$ gives the observed CV reported along with index *i* in year *y* (for example, as a byproduct of the CPUE standardization process), and σ^2_i gives an estimated "additional" level of process variance for index *i* that is unaccounted for in observed CVs. Typically, it will not be possible to estimate $\sigma^2_{\mathrm{overall}}$ and σ^2_i in the same model run.

Process errors—Process errors for *F* were included as part of the random walk model for *F* (described in section 3.1.3). The objective function contribution for these deviations was given by

$$\Lambda_2 = 0.5 \sum_{1976 \le y \le 1999,\, 2001 \le y \le 2015} \frac{(\varepsilon_y - \rho\varepsilon_{y-1})^2}{0.1} + \log(0.1). \qquad (3.14)$$

Prior distributions—The following set of prior distributions was implemented:

- Historical *F*-effort relationship (see Equation 3.7): $p(\beta_1)$: Uniform(0,0.7)
- Pup survival at low biomass: $p(\exp(-M_0))$: Lognormal(median = 0.814, CV = 0.3)
- Catchability: $p(q_i)$: Uniform(0.0001, 100)
- Additional variance: $p(\sigma^2)$: Uniform(0, 2.0)
- Depletion in 1975: $p(B_{1975})$: Lognormal(median = 0.83, CV = 0.2).

The total contribution for prior distributions to the objective function was then

$$\Lambda_3 = \log(p(\beta_1)) + \log(p(\exp(-M_0))) + \sum_i \log(p(q_i)) + \sum_i \log(p(\sigma^2_i)) + \log(p(\beta_{1975})) \qquad (3.15)$$

Penalties and constraints—The following set of penalties was implemented:

- Penalty for $F_{2000} > F_{1999}$. A penalty was implemented to mirror the a priori notion that fishing mortality rates should decrease following prohibition of dusky landings: $P_1 = I_{F_{2000} > F_{1999}} (F_{2000} - F_{1999})^2 \times 1000$
- Penalty for apical F exceeding 1.0: $P_2 = \sum_y I_{Fapical_y > 1.0} (Fapical_y - 1.0)^2 \times 1000$

The total contribution for penalties was then $\Lambda_4 = P_1 + P_2$. The additional constraint $F_{2015} = (F_{2014} + F_{2013} + F_{2012}) / 3$ was also made, since retrospective runs suggested the terminal fishing mortality estimate was subject to substantial negative bias.

The model started in 1960 and ended in 2015, with the historic period covering 1960-1974, the first modern period spanning 1975-1999, and the second modern period spanning 2000-2015. Estimated model parameters were pup (age-0) survival, catchability coefficients associated with indices, a parameter representing the slope of the relationship between PLL effort and fishing mortality for the period 1960-1979, additional variance parameters for each index, relative depletion in 1975, and fishing mortality in the modern periods. Fishing mortality starting in 1980 was modeled using a correlated random walk and so are not 'full' parameters. Pup survival (see above) was given an informative lognormal prior with median=0.81 (mean=0.85, mode=0.77), a CV of 0.3, and was bounded between 0.50 and 0.99.

A list of estimated model parameters is presented in Table 3.1 (other parameters were held constant and thus not estimated, see section 3.2). The table includes predicted parameter values and their associated SDs from ASCFM, initial parameter values, minimum and maximum values a parameter could take, and prior densities assigned to parameters.

3.1.5. Uncertainty and Measures of Precision

Initial model runs were made by maximizing the joint posterior (minimizing the negative of the objective function) using AD Model Builder software (Otter Research Ltd. 2004). Subsequent runs attempted to better quantify uncertainty by estimating marginal posterior distributions for key assessment parameters. We used the "likelihood profiling" procedure in AD Model Builder, which attempts to directly integrate the joint likelihood function. This procedure was used to quantify uncertainty in terminal stock status, terminal fishing mortality, and productivity parameters for the base run and the four plausible alternative states of nature referred to in the TORs for this update.

More specifically, the SEDAR 21 CIE review identified five scenarios, including the base run, as plausible states of nature (see the SEDAR 21 HMS Dusky Shark Assessment Report, their section V Table 7 and their section VI Table 6.3). Consequently, for this update, uncertainty in data inputs and model configuration was examined through the updated analysis of the five scenarios reflective of plausible states of nature previously identified and approved in the preceding SEDAR 21 assessment: (1) the base scenario; (2) a high natural mortality scenario; (3) a U-shaped natural mortality curve allowing senescence; (4) a high productivity scenario; and (5) a low productivity scenario. These sensitivities consisted of the following:

1. Base scenario—The base scenario as described above.

2. High natural mortality scenario—The base run used a "maximum survival" approach to derive natural mortality estimates to ensure producing a positive population growth rate in the absence of fishing. However, model runs using this natural mortality vector tended to result in estimates of productivity that were a little higher than expected for typical long-lived shark species (steepness estimates were typically in the 0.45-0.55 range in contrast to expected levels in the 0.25-0.35 range; see e.g. Brooks et al. 2010). It thus seemed plausible that the assumed natural mortality values were too low. As an alternative, we solved for a constant c such that cM_a resulted in a virgin spawners-per-recruit value of 2.0 (which would impose a lower bound on e^{-M_0} of 0.5). For this sensitivity run, the base natural mortality vector was multiplied by the resulting estimate of c = 1.342.

3. U-shaped natural mortality scenario—Plots of abundance by age revealed a relatively large proportion of sharks that were forty years old or larger, which raised concerns that the results of the assessment might be unduly influenced by the presence of such a large cryptic biomass of mature, older individuals. Since older individuals are rarely encountered (likely due to a number of processes such as dome-shaped selectivity), it is difficult to assess the validity of the presence of such a cryptic biomass via standard survey methods. As one way of examining the importance of older classes in estimates of stock status, we conducted a sensitivity run with elevated rates of natural mortality for older age classes (representing senescence; Table 3.2).

4. High productivity scenario—Whereas the base run used a triennial reproductive cycle, 7.1 pups per reproductive female, and median pup survival of 0.81, this scenario assumed a more productive stock characterized by a biennial cycle, 10 pups per female, and median pup survival of 0.97.

5. Low productivity scenario—In contrast to scenario (4), this scenario assumed a less productive stock characterized by a triennial reproductive cycle, 4 pups per reproductive female, and median pup survival of 0.51.

3.1.6. Benchmark Calculations

Since reliable catch data are not available, the model is unable to scale to absolute levels of population biomass, and therefore cannot calculate an absolute level of MSY or SSF_{MSY}. Rather, it is possible to estimate MSY and SSF_{MSY} relative to the unexploited level of recruitment (R_0). This is done as follows.

First, the vector of vulnerability used for equilibrium calculations is derived from the vector of total age-specific fishing mortality in the final year of the model:

$$\dot{v}_a = \frac{F_{a,y}}{\max\{F_{a,y}\}} \tag{3.16}$$

Next, the value of fishing mortality ($\tilde{F}_{MSY}$) that generates the maximum sustainable relative yield (MSY/R_0) is found by solving

$$\frac{MSY}{R_0} = \max_F \left\{ \frac{\dot{R}_F}{R_0} \sum_a w_a F \dot{v}_a \frac{1-\mathrm{e}^{(-M_a - F\dot{v}_a)}}{M_a + F\dot{v}_a} \mathrm{e}^{(-\sum_{i=0}^{a-1}(M_i + F\dot{v}_i))} \right\} \tag{3.17}$$

In the above expression, the term to the right of the summation is simply the calculation of yield per recruit for a given fishing mortality, *F*; this then gets scaled by the relative equilibrium recruitment that results from that *F*, R_F. Relative equilibrium recruitment can be calculated from

$$\frac{\dot{R}_F}{R_0} = \tilde{r}_F = \frac{\tilde{s}_F}{SPR_F} \tag{3.18}$$

where SPR_F is simply the ratio of pups per recruit with fishing mortality *F* to pups per recruit with $F = 0$ (eq. 3.4), i.e.

$$SPR_F = \frac{\sum_{age} fec_{age} \cdot mat_{age} \prod_{j=1}^{age-1} \mathrm{e}^{(-M_j - Fv_j)}}{\sum_{age} fec_{age} \cdot mat_{age} \prod_{j=1}^{age-1} \mathrm{e}^{(-M_j)}} = \frac{\varphi_F}{\varphi_0} \tag{3.19}$$

Finally, in (3.18), the equilibrium number of relative spawners at fishing mortality *F* ($\tilde{s}_F$) can be calculated by dividing eq. (3.2) by *r* and then solving for *s*:

$$\tilde{s}_F = \frac{e^{-M_0}\varphi_0 SPR_F - 1}{e^{-M_0}\varphi_0 - 1} \tag{3.20}$$

Replacing the term for relative recruitment in (3.17) with $\tilde{s}_F$ /SPR_F and solving for the *F* that maximizes the expression, results in the equilibrium estimate of relative MSY.

The minimum spawning stock threshold (MSST) is typically calculated as (1-*M*)*SSF_{MSY} when absolute spawning stock fecundity is estimable. Although only relative estimates are possible here (i.e., SSF_{2015}/SSF_{MSY}), it is still possible to calculate SSF_{2015}/SSF_{MSST} as described above. Since natural mortality was assumed to be age-specific in this assessment, we calculated an age-independent *M* as $\overline{M}_a$ for ages 1-40. This procedure results in the same cumulative survivorship up to the plus group (age *A*=40) for the two approaches (age specific vs. age independent). Specifically, we used a value of *M*=0.066 for all MSST calculations.

3.1.7. Projection Methods

Projections were conducted for the updated analysis of the five scenarios reflective of plausible states of nature previously identified and approved in the preceding SEDAR 21 assessment, (see section 3.1.5 of this report). 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 time series (that is, in 2015) as well as in underlying productivity. Projections were run using Monte Carlo bootstrap simulation, where initial biomass (B_{2015}^{boot}), fishing mortality (F_{2015}^{boot}), and pup survival at low biomass ($\exp(-M_0)_{2015}^{boot}$) were sampled from a multivariate normal distribution with expectations equivalent to posterior modes from the updated analysis of the five scenarios reflective of plausible states of nature, and standard deviations set to the posterior standard deviation (obtained numerically by rejection sampling of the "profile likelihood" posterior approximation). Covariance values were obtained from the Hessian approximation of the variance-covariance matrix at the posterior mode. The multivariate normal approximation was chosen because it reduces the probability of selecting values of the different parameters that are unlikely to have generated the data (for instance, high fishing mortality and low pup survival).

Since the ASCFM is on an arbitrary scale, it at first appears difficult to provide any advice on landings, annual biological catch, or catch limits. However, managers often need such information to set quotas. As in SEDAR 21, we thus scaled the ASCFM estimates of abundance to levels that would best explain observed removals in years where managers had the most confidence in reported catch using the same techniques previously identified and approved during the preceding SEDAR 21 assessment. In particular, we estimated a scaling parameter ψ to match observed removal data from 1993 to 1998. These years were chosen because they were after catch reporting was mandatory, but before landings of dusky sharks were prohibited (after which, removals were purportedly negatively biased). To do this, total removals in dressed weight (including both landings and discards) were input into the ASCFM, and a value of ψ was estimated that minimized

$$\Lambda_5 = 0.5\sum_i \sum_y \frac{(\log(C_{i,y}) - \log(\tilde{C}_{i,y}))^2}{\sigma_C^2} + \log(\sigma_C^2) \ , \qquad (3.21)$$

where $C_{i,y}$ and $\tilde{C}_{i,y}$ were observed and predicted catches, respectively. The variance term σ_C^2 was set to a large value (2,000,000) so that the catch data did not affect estimation of any parameter but ψ. Catches were predicted using the Baranov catch equation:

$$\tilde{C}_{i,y} = \psi \sum_a N_{a,y} \frac{F_{a,y}}{Z_{a,y}} (1 - \exp^{-Z_{a,y}}) w_a, \tag{3.22}$$

where w_a is dressed weight at age. A comparison of observed to predicted catch data (Fig 3.1) shows the ASCFM predicted catches throughout the entire time series when scaled in this manner for the base model configuration. Using this formulation, ψ was estimated at 5705.9 for the base model configuration. For each scenario, a scalar parameter ψ was estimated as in Equations 3.21 and 3.22 to scale up abundance to the level of absolute removals.

Projections were started in 2015 and used 10,000 Monte Carlo bootstrap simulations with initial values drawn from a multivariate normal distribution (described above). Moments of the bootstrap runs were summarized using quantiles, with median used for the central tendency, and the 30th percentile used as the criterion for whether a projection had a 70% chance of rebuilding by the rebuilding year.

Projections were conducted for the five scenarios reflective of plausible states of nature in order to examine the utility of different rebuilding strategies under each scenario and to characterize uncertainty as to these underlying "states of nature" and encapsulate the range of possible underlying productivity, mortality, and states of the stock in the terminal year of the assessment. For each scenario, we estimated the following:

(1) The year in which $F = 0$ would result in a 70% chance of recovery (Year$F$=0_{p70})

(2) The target rebuilding year, which was calculated as $\text{Year}_{\text{rebuild}}$ = (Year$F$=0_{p70})+40 (generation time is estimated at 40 years, as described below)

(3) The fixed annual fishing mortality rate (apical F) that would allow recovery of the stock with a probability of 0.5 by $\text{Year}_{\text{rebuild}}$ (F-$\text{Year}_{\text{rebuild}}$ P50)

(4) The fixed annual fishing mortality rate (apical F) that would allow recovery of the stock with a probability of 0.7 by $\text{Year}_{\text{rebuild}}$ (F-$\text{Year}_{\text{rebuild}}$ P70)

(5) The fixed annual level of total removals in lb dressed weight (total allowable catch) that would allow recovery of the stock with a probability of 0.5 by $\text{Year}_{\text{rebuild}}$ (TAC-$\text{Year}_{\text{rebuild}}$ P50)

(6) The fixed annual level of total removals in lb dressed weight (total allowable catch) that would allow recovery of the stock with a probability of 0.7 by $\text{Year}_{\text{rebuild}}$ (TAC-$\text{Year}_{\text{rebuild}}$ P70)

All projections assumed the selectivity function for 2015; projections thus assume that the current allocation of effort within the fishery (between fleets) stays the same. They also assumed that any change in management would not take effect until 2019 (estimated 2015 fishing levels were thus assumed for 2015-2018).

Generation time is often needed for certain calculations regarding possible rebuilding times, and was calculated using the formula:

$$\frac{\sum_x l(x)b(x)x}{\sum_x l(x)b(x)}, \qquad (3.23)$$

where *l(x)* is cumulative survival to age *x*, and *b(x)* is female pup production per female by age (cf., Gotelli 2001). Using this method, generation time was calculated as 40.5 in the SEDAR 21 assessment, which is considerably larger than the value obtained from an earlier 2006 assessment (for which generation time was computed as 30 years). This difference is largely a result of accounting for a large number of age classes in the SEDAR 21 assessment calculation. If generation time is instead calculated with a maximum age of 40, generation time is 29, and more along the lines of the 2006 assessment.

3.2. RESULTS

3.2.1. Measures of Overall Model Fit

Estimates of additional variance were negligible for the LPS index and relatively small for the BLLOP index, indicating lower levels of process error (Table 3.1). As a result, the assessment model tended to ‘key in’ on these indices and fit them better (Figure 3.2). In contrast, additional variance was estimated to be considerably larger for the PLLOP and VIMS indices, and especially for the NELL survey, indicating substantial process error not accounted for in input CVs. As such, fits to these indices were quite poor (Figure 3.2).

In general, the ASCFM was unable to fit any of the indices perfectly. The reproductive constraints of the species (i.e., low fecundity) limits the stock’s capability to dramatically increase in abundance from year to year, making it difficult to match some of the observed index patterns (e.g., large interannual fluctuations in some time series).

3.2.2. Parameter Estimates and Associated Measures of Uncertainty

A list of model parameters is presented in Table 3.1. The table includes predicted parameter values with associated SDs, initial parameter values, minimum and maximum allowed values, and prior density functions assigned to parameters. Priors designated as constant were estimated as such; parameters that were held fixed (not estimated) are described elsewhere (e.g., see section 2 of this report) and are not included in this table.

3.2.3. Stock Abundance and Recruitment

Predicted stock abundance at age relative to unfished equilibrium (virgin) numbers at age (relative abundance) is presented in Table 3.3 and Figure 3.3. Recruitment is assumed to occur at age 1, and predicted recruitment relative to virgin conditions (relative recruitment) is presented in Table 3.3. Recruitment is predicted to have remained at roughly virgin levels until the late 1980s, after which it progressively declined; by 2015, depletion in relative recruitment is estimated to be around 50% (only 50% of the virgin recruitment levels) and depletion in numbers ca. 65%. Declines in spawning stock fecundity (discussed below) are estimated to be partially compensated for by increases in pup survival (i.e., density dependent recruitment; Figure 3.4).

3.2.4. Total Stock Biomass and Spawning Stock Fecundity

Predicted total stock biomass relative to virgin conditions (relative biomass), and predicted spawning stock fecundity relative to virgin conditions (relative spawning stock fecundity; S_y in Equation 3.3) are presented in Table 3.3. All trajectories in Table 3.3 show relatively little depletion until the late 1980s; however, by 2015, depletion in relative spawning stock fecundity is estimated to be around 81% (only 19% of the virgin stock remaining) and depletion in relative biomass ca. 73%.

3.2.5. Fishery Selectivity

As explained in section 2.1 and shown in Table 2.1 and Figure 2.2, selectivities are estimated externally to the model and a functional form inputted for each fleet and index. In Figure 2.2 one can see that most indices fully select for immature animals.

3.2.6. Fishing Mortality

Predicted apical fishing mortality rates are presented in Table 3.4 and Figure 3.5. Fishing mortality was low from 1960 through the early 1980s, and then is estimated to have ramped up to unsustainably high levels in the l990s (see section 3.2.9), and to have declined following prohibition of dusky landings in 2000. The moratorium on dusky shark catch appears to have been an effective management tool in this regard, although terminal estimates of fishing mortality still indicate the stock is undergoing overfishing (see section 3.2.9).

3.2.7. Stock-Recruitment Parameters

The estimated maximum theoretical pup (age-0) survival (i.e., that would occur as biomass approaches zero) obtained from the base run of the updated dusky shark ASCFM was 0.88 (Tables 3.1 and 3.6; Figure 3.6). The corresponding Beverton-Holt steepness value (h= $\hat{\alpha}$ / (4+ $\hat{\alpha}$)); see section 3.1.3) was 0.51 (Table 3.5), which is substantially higher than the ca. 0.25-0.35 range that has been reported for several long-lived elasmobranchs (see, e.g., Brooks et al. 2010;

Cortés et al. 2015). See section 3.2.3 above and the next section for further discussion on pup survival.

3.2.8. Evaluation of Uncertainty

Estimates of asymptotic standard errors for all model parameters are presented in Table 3.1. Posterior distributions for several model parameters of interest were obtained through likelihood profiling as implemented in AD Model Builder. Prior and posterior distributions for pup survival are shown in Figure 3.6. There appeared to be information in the data since the posterior is different from the prior. The mode for the posterior of pup survival was estimated at a higher value than the prior mode.

Posterior distributions were also obtained for several benchmarks (Figure 3.7). The distribution for relative spawning stock fecundity (SSF_{2015}/SSF_0) is fairly wide, but most of the density is concentrated between 0.05 and 0.40, indicating substantial depletion (i.e. 60 – 95%) for such a long-lived species. In contrast, posterior distributions for spawning stock fecundity relative to MSY and MSST levels (SSF_{2015}/SSF_{MSY} and SSF_{2015}/SSF_{MSST}, respectively) were much tighter, and indicated that relative spawning stock fecundity in 2015 was between 45 and 60% of MSY levels. The posterior for apical fishing mortality relative to MSY levels (F_{2015}/F_{MSY}) indicated considerable uncertainty in terminal estimates of fishing mortality relative to MSY levels (Figure 3.7).

Results of the five plausible states of nature are summarized in Table 3.5. Estimates of spawning stock fecundity relative to unfished equilibrium (SSF_{2015}/SSF_0) ranged from 0.14 (High Productivity scenario) to 0.32 (Low Productivity scenario). Estimates of spawning stock fecundity at MSY relative to unfished equilibrium (SSF_{MSY}/SSF_0) ranged from 0.28 to 0.47. Estimates of biomass-related benchmarks, defined here as spawning stock fecundity relative to MSY and MSST, ranged from 0.49 to 0.68 for SSF_{2015}/SSF_{MSY}, and 0.52 to 0.73 for SSF_{2015}/SSF_{MSST}. All five scenarios thus resulted in the same conclusion that the stock was overfished, providing evidence that stock status determination based on biomass-related point estimates is robust to changes in natural mortality and productivity.

Estimates of F_{MSY} ranged from 0.007 to 0.054. Stock productivity, expressed as steepness, ranged from 0.25 to 0.71. The High *M*, U-shaped *M*, and low productivity scenarios resulted in lower estimates of productivity, with steepness values ranging from 0.25 to 0.32. This level of productivity is more typical of levels expected a priori given the life history of the species (as described in section 3.1.5). In all, with the exception of the U-shaped *M* scenario, all scenarios found that the stock was still undergoing overfishing, although the estimates were imprecise (CVs>1).

We also performed “likelihood profiling” for the four alternative states of nature. Posterior probability distributions for SSF_{2015}/SSF_{MSST} were tight and indicated that spawning stock fecundity ranged from 0.45 to 0.80 of MSST levels overall. Posterior distributions for F_{2015}/F_{MSY} were also tight, with the exception of the low productivity scenario, and indicated that fishing mortality in 2015 was well above that corresponding to MSY levels, with mass well above 1.0 (Figure 3.8).

Examination of retrospective plots (Figures 3.9 and 3.10) suggested that there was relatively little retrospective pattern in estimates of relative spawning stock fecundity trajectories, although removal of one to five years of data resulted in larger terminal relative SSF than in the base run and the trajectories only coincided with that of the base run around 1980. There was more retrospective pattern in estimates of terminal apical fishing mortality rate, with removal of one, two, or three years of data predicting a lower terminal *F* than in the base run, but removal of four or five years greatly reducing the discrepancy

3.2.9. Benchmarks/Reference Points

Benchmarks and MSY reference points for the five plausible states of nature scenarios are summarized in Table 3.5 and detailed information is presented for the base run in Tables 3.6 and 3.7 and presented visually in Figures 3.11 and 3.12. As noted above, all runs clearly indicated an overfished stock (most of the density in the histograms indicated that $SSF_{2015} < SSF_{\mathrm{MSST}}$; Table 3.5 and Figures 3.7, 3.8). The estimates of current (2015) apical fishing mortality relative to MSY ($F_{2015}/F_{\mathrm{MSY}}$) in all the runs were very uncertain (CV = 0.83 – 1.51; Table 3.5), but, as discussed above, posterior distributions for the five runs all indicated that overfishing was still occurring (most of the density in the histograms indicated that $F_{2015} > F_{\mathrm{MSY}}$; Table 3.5 and Figures 3.7, 3.8).

The base model estimated that overfishing started occurring in 1984 ($F_{1984} > F_{\mathrm{MSY}}$) and has occurred ever since (Table 3.7 and Figure 3.12). The base run also indicated that the stock first became overfished in 2003 ($SSF_{2003} < SSF_{\mathrm{MSST}}$; Table 3.7 and Figure 3.11) All runs estimated that the stock is currently overfished ($SSF_{2015} < SSF_{\mathrm{MSST}}$) and, perhaps with the exception of the U-shape *M* run, that overfishing is still occurring (Table 3.5; Figures 3.13 and 3.14). These conclusions thus generally agree with those from SEDAR 21 (2011) and the preliminary 2006 assessment (Cortés et al. 2006).

3.2.10. Projections

Results of projections are summarized in Table 3.8 and Figures 3.15 – 3.19. The target year for rebuilding ($\mathrm{Year}_{\mathrm{rebuild}}$) ranged from 2086 to 2200 depending on the plausible state of nature for the projection scenario (Base, High *M*, U-shaped *M*, High Productivity, and Low Productivity). Projections under all scenarios suggested that fishing mortality would need to be reduced in order to meet rebuilding targets. Since removals are generally not known for this stock, this would most likely need to be accomplished using effort reductions. For example, projections for the low productivity scenario were the most extreme, indicating that the annual effort level would need to be reduced to about 9% of its current value to result in a 70% chance of stock recovery by $\mathrm{Year}_{\mathrm{rebuild}}$ =2200 (i.e., a reduction in apical *F* from 0.023 to around 0.002; Table 3.8 and Figure 3.19). In contrast, projections for the U-shaped natural mortality scenario suggested that a reduction of fishing mortality to about 55% percent of its current value would be required to rebuild the stock by $\mathrm{Year}_{\mathrm{rebuild}}$ = 2096 (i.e., a reduction in apical *F* from 0.019 to around 0.010; Table 3.8 and Figure 3.17). If catches predicted in the fixed removal scenarios using the scaling parameter ψ (see equation 3.22) are believed to be true, there would be a 70% probability that total catches ranging from ca. 3,200 to ca. 37,200 lb dw would allow stock recovery by the rebuilding year.

3.3. DISCUSSION

As was the case for the previously completed SEDAR 21 dusky shark assessment, an issue of concern regarding the indices of relative abundance, is that many of them show interannual variability that does not seem to be compatible with the life history of the species, suggesting that the GLMs used to standardize the indices did not include all factors to help track relative abundance, that the spatial scope of sampling is too limited to yield precise inference about stock-wide trends, and that the indices are tracking a particular segment of the population only. The poor fit to some of the indices is likely the result of the model attempting to reconcile different signals provided by different indices and fitting a more central tendency. The ASCFM estimated additional variance for each index, which helped to alleviate, but not solve, this problem.

The ASCFM for the five plausible states of nature indicated that dusky sharks are currently overfished and, except for one model run, that overfishing has been occurring since the mid-1980s. These conclusions largely mirror results from the previous assessments (SEDAR 21 and Cortés et al. 2006). While fishing mortality is estimated to have declined dramatically since the 1990s, fishing mortality in the six additional years of data available since SEDAR 21 took place did not continue to decline, but instead slightly increased. This was a consequence of the trends displayed by the updated indices of abundance (section 2.2), which showed a stable (LPS), slightly declining (BLLOP, PLLOP), and strongly declining (VIMS LL) trends since 2009, with only the NELL index, which consisted of two points only (2012 and 2014; Figure 2.3), showing a strongly increasing trend.

Estimates of biomass-based stock status were robust in all cases to changes in life history parameters determining productivity. Estimates of fishing mortality-based status were also robust to these changes, with the exception of the U-shaped *M* scenario, which predicted that the stock was only on the verge of undergoing overfishing. This is notable because the estimates of steepness obtained ranged from 0.25 for the low productivity scenario to 0.71 for the high productivity scenario, with values for the low productivity, high *M*, and U-shaped *M* scenarios ranging from 0.25 to 0.32, which are likely more representative of long-lived shark species such as the dusky shark (Brooks et al. 2010; Cortés et al. 2015).

The combination of some life-history parameters and the vulnerability of dusky sharks to the various gears long before they become mature suggest a population that cannot support much exploitation. However, the prohibition on catches in recent years appears to have reduced, but apparently not ended, overfishing. With the present allocation of effort among fishing sectors, projection results indicate that the stock appears to be capable of rebuilding by the end of the current rebuilding time period (2086-2200, depending on the scenario), and that it could sustain a small amount of fishing-related mortality during this period. Current estimates are that fishing mortality would have to be reduced to 0.002–0.042, which would take a 47–91% reduction in total effort (i.e., corresponding to a 47–91% approximate reduction in fishing mortality to achieve rebuilding with a 70% probability by $Year_{rebuild}$ for the five scenarios reflective of plausible states of nature; Table 3.8) These results are consistent with those from the previously completed SEDAR 21 assessment for dusky shark (see section VI: Addenda and post-review updates), which indicated reductions in *F* ranging from 47% to 97% were needed to achieve rebuilding with a 70% probability. How this could be achieved is not entirely clear, as most of the mortality now comes from commercial discards and possibly from recreational fisheries too.

We also provided an estimate of the total weight of removals associated with different reductions in total *F*, but caution that these are estimates only, and subject to considerable uncertainty because the data used to scale up to absolute abundance were themselves uncertain. If catches predicted in the fixed removal scenarios are believed to be true, there would be a 70% probability that total catches ranging from ca. 3,200 to ca. 37,200 lb dw would allow stock recovery by the rebuilding year (Table 3.8).

3.4. REFERENCES

Brooks, E. N., J. E. Powers, and E. Cortés. 2010. Analytical reference points for age-structured models: application to data-poor fisheries. ICES J. Mar. Sci. 67:165–175.

Cortés, E., E. Brooks, P. Apostolaki, and C. Brown. 2006. Stock Assessment of Dusky Shark in the U.S. Atlantic and Gulf of Mexico. NMFS/SEFSC Sustainable Fisheries Division Contribution SFD-2006-014, Miami, FL.

Cortés E, E. N. Brooks, and K. W. Shertzer. 2015. Risk assessment of cartilaginous fish populations. ICES J. Mar. Sci. 72:1057–1068.

Goodyear, C. P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. In: Smith, S. J, Hunt, J. J. and Rivard, D. (Eds.), Risk Descriptive Evaluation and Biological Reference Points for Fisheries Management. Canadian Special Publication in Fisheries and Aquatic Sciences No. 120, National Research Council of Canada, Ottawa, pp. 67–81.

Gotelli, N. J. 2001. A Primer of Ecology. Sinauer, Sunderland, MA.

Myers, R. A., K. G. Bowen, and N. J. Barrowman. 1999. Maximum reproductive rate of fish at low population sizes. Can. J. Fish. Aquat. Sci. 56:2404–2419.

Otter Research Ltd. 2004. An introduction to AD MODEL BUILDER Version 7.1.1. Box 2040, Sidney, B. C. V8L 3S3, Canada.

Porch, C.E., A-M. Eklund, and G.P. Scott. 2006. A catch-free stock assessment model with application to goliath grouper (*Epinephelus itajara*) off southern Florida. Fish. Bull. 104:89–101.

SEDAR 21. Stock assessment report— Sandbar, dusky and Gulf of Mexico blacknose shark. NMFS, North Charleston, SC.

Siegfried, K. I. 2006. Fishery management in data-limited situations: applications to stock assessment, marine reserve design and fish bycatch policy. PhD dissertation. U.C. Santa Cruz, CA.

3.5. TABLES

Table 3.1. List of parameters estimated in the base run of the updated dusky shark ASCFM. The list includes predicted parameter values with associated SDs, initial parameter values, minimum and maximum allowed values, and prior density functions assigned to parameters. Priors designated as constant were estimated as such; parameters that were held fixed (not estimated) are not included in this table. Fishing mortality was modeled as an auto-correlated random walk so they are not 'full' parameters and thus not presented here. All SD estimates are based on a Hessian approximation to the numerically maximized posterior surface.

	Predicted					Prior pdf		
Parameter/Input name	Value	SD	Initial	Min	Max	Type	Value	SD(CV)
Pup (age-0) survival	8.81E-01	2.54E-01	8.14E-01	5.00E-01	9.90E-01	lognormal	0.814	(0.3)
Catchability coefficient LPS index	3.78E-01	1.16E-01	2.20E-02	1.00E-04	1.00E+01	constant	0	1
Catchability coefficient BLLOP index	1.61E-01	5.59E-02	3.20E-02	1.00E-04	1.00E+01	constant	0	1
Catchability coefficient VIMS LL index	1.56E-01	4.40E-02	7.41E-02	1.00E-04	1.00E+01	constant	0	1
Catchability coefficient NELL index	1.03E-01	6.75E-02	1.20E-02	1.00E-04	1.00E+01	constant	0	1
Catchability coefficient PLLOP index	1.81E-01	6.79E-02	1.70E+00	1.00E-04	2.00E+01	constant	0	1
Historic effort/F relationship	1.87E-02	2.23E-02	0.1	1.00E-13	0.7	constant	0	(0.5)
Additional variance LPS index	3.06E-08	4.33E-05	4.00E-01	0	2	constant	0	0.1
Additional variance BLLOP index	1.15E-02	1.14E-01	4.00E-01	0	2	constant	0	0.1
Additional variance VIMS LL index	6.95E-01	3.00E-01	4.00E-01	0	2	constant	0	0.1
Additional variance NELL index	2.00E+00	3.13E-03	4.00E-01	0	2	constant	0	0.1
Additional variance PLLOP index	8.23E-01	3.41E-01	4.00E-01	0	2	constant	0	0.1
Depletion in 1975	9.73E-01	3.19E-02	0.83	0	∞	lognormal	0.83	(0.202)

Table 3.2. Values of natural mortality (*M*, instantaneous natural mortality rate) at age used in the U-shaped *M* scenario (senescence).

Age	U-shaped M
1	0.137
2	0.124
3	0.114
4	0.106
5	0.099
6	0.093
7	0.088
8	0.083
9	0.079
10	0.076
11	0.073
12	0.070
13	0.068
14	0.066
15	0.064
16	0.062
17	0.061
18	0.059
19	0.058
20	0.057
21	0.069
22	0.081
23	0.093
24	0.104
25	0.115
26	0.125
27	0.134
28	0.144
29	0.152
30	0.160
31	0.168
32	0.175
33	0.182
34	0.188
35	0.193
36	0.198
37	0.203
38	0.207
39	0.211
40	0.214

Table 3.3. Predicted recruitment (Rec/Rec_0), abundance (N/N_0), total stock biomass (B/B_0), and spawning stock fecundity (SSF/SSF_0) obtained from the base run of the updated dusky shark ASCFM. Because the ASCFM is on a relative scale, model estimates of recruitment (in numbers; Equation 3.2), abundance (in numbers; Equation 3.9), total biomass (in kg; abundance multiplied by weight at age), and spawning stock fecundity (in numbers; Equation 3.3) are calculated relative to unfished equilibrium (virgin) levels.

Year	*Rec/Rec₀*	*N/N₀*	*B/B₀*	*SSF/SSF₀*
1960	1	1	1	1
1961	1.00	1.00	1.00	1.00
1962	1.00	1.00	1.00	1.00
1963	1.00	1.00	1.00	1.00
1964	1.00	1.00	1.00	1.00
1965	1.00	0.99	1.00	1.00
1966	1.00	0.99	0.99	1.00
1967	1.00	0.99	0.99	0.99
1968	1.00	0.99	0.99	0.99
1969	1.00	0.98	0.99	0.99
1970	1.00	0.98	0.99	0.99
1971	1.00	0.98	0.98	0.99
1972	1.00	0.98	0.98	0.99
1973	1.00	0.98	0.98	0.98
1974	1.00	0.97	0.98	0.98
1975	0.99	0.97	0.97	0.98
1976	0.99	0.96	0.97	0.97
1977	0.99	0.96	0.97	0.97
1978	0.99	0.96	0.96	0.96
1979	0.99	0.95	0.96	0.96
1980	0.99	0.95	0.95	0.95
1981	0.99	0.94	0.95	0.95
1982	0.99	0.94	0.94	0.94
1983	0.99	0.93	0.93	0.93
1984	0.98	0.92	0.92	0.92
1985	0.98	0.91	0.91	0.91
1986	0.98	0.89	0.90	0.90
1987	0.97	0.87	0.88	0.88
1988	0.97	0.85	0.86	0.86
1989	0.96	0.82	0.83	0.83
1990	0.95	0.79	0.80	0.80
1991	0.94	0.76	0.77	0.77
1992	0.93	0.73	0.74	0.74
1993	0.92	0.69	0.71	0.71
1994	0.91	0.66	0.67	0.67
1995	0.89	0.63	0.64	0.63
1996	0.88	0.59	0.60	0.59
1997	0.86	0.56	0.56	0.55
1998	0.84	0.52	0.52	0.51
1999	0.81	0.48	0.47	0.46
2000	0.78	0.44	0.43	0.42
2001	0.75	0.40	0.39	0.38
2002	0.72	0.38	0.36	0.35
2003	0.69	0.37	0.34	0.33
2004	0.67	0.36	0.33	0.31
2005	0.65	0.36	0.31	0.29
2006	0.63	0.36	0.31	0.28
2007	0.61	0.37	0.30	0.26
2008	0.60	0.37	0.30	0.25
2009	0.58	0.37	0.29	0.24
2010	0.57	0.37	0.29	0.23
2011	0.56	0.37	0.29	0.22
2012	0.54	0.37	0.28	0.21
2013	0.53	0.36	0.28	0.21
2014	0.52	0.36	0.27	0.20
2015	0.50	0.35	0.27	0.19

Table 3.4. Apical instantaneous fishing mortality rates (apical *F*) by year obtained from the base run of the updated dusky shark ASCFM.

Year	F
1960	0.001
1961	0.000
1962	0.002
1963	0.005
1964	0.009
1965	0.008
1966	0.005
1967	0.004
1968	0.006
1969	0.005
1970	0.006
1971	0.010
1972	0.007
1973	0.009
1974	0.013
1975	0.012
1976	0.012
1977	0.012
1978	0.011
1979	0.016
1980	0.018
1981	0.021
1982	0.024
1983	0.029
1984	0.036
1985	0.044
1986	0.056
1987	0.069
1988	0.084
1989	0.097
1990	0.107
1991	0.116
1992	0.124
1993	0.135
1994	0.151
1995	0.171
1996	0.196
1997	0.226
1998	0.256
1999	0.280
2000	0.280
2001	0.247
2002	0.195
2003	0.145
2004	0.107
2005	0.082
2006	0.066
2007	0.057
2008	0.053
2009	0.053
2010	0.055
2011	0.059
2012	0.065
2013	0.071
2014	0.075
2015	0.070

Table 3.5. Summary of stock status results obtained from the updated dusky shark ASCFM for the five scenarios reflective of plausible states of nature (Base, High *M*, U-Shaped *M*, High Productivity, and Low Productivity; see section 3.1.5 of this report for definitions of each scenario). Measures of relative spawning stock fecundity (SSF_{2015}/SSF_0 and SSF_{MSY}/SSF_0) are defined as in Equations 3.3 and 3.20, respectively. The minimum spawning stock threshold (SSF_{MSST}) is defined in section 3.1.6. The Beverton-Holt steepness value corresponding to the estimated maximum theoretical pup (age-0) survival (i.e., that would occur as biomass approaches zero) is also provided (see section 3.2.7). All estimates of CV are based on the numerical Hessian evaluated at the posterior mode.

	Base		High *M*		U-shaped *M*		High productivity		Low productivity	
	Est	CV	Est	CV	Est	CV	Est	CV	Est	CV
F_{MSY}	0.035	0.062	0.017	0.062	0.019	0.061	0.054	0.052	0.007	0.062
SSF_{MSY}/SSF_0	0.35	0.19	0.43	0.45	0.43	0.45	0.28	0.08	0.47	0.06
SSF_{2015}/SSF_0	0.19	0.53	0.26	0.36	0.29	0.36	0.14	0.65	0.32	0.37
SSF_{2015}/SSF_{MSST}	0.58	0.61	0.66	0.69	0.72	0.69	0.52	0.66	0.73	0.37
SSF_{2015}/SSF_{MSY}	0.54	0.61	0.61	0.69	0.67	0.69	0.49	0.66	0.68	0.37
F_{2015}/F_{MSY}	2.02	1.23	1.44	1.48	0.99	1.51	2.48	0.83	3.04	1.49
Pup survival	0.88	0.29	0.93	0.29	0.94	0.29	0.97	NA	0.51	NA
Steepness	0.51	0.14	0.32	0.20	0.32	0.20	0.71	NA	0.25	NA

Table 3.6. Summary of MSY quantities and management benchmarks obtained from the base run of the updated dusky shark ASCFM. All estimates of CV are based on the numerical Hessian evaluated at the posterior mode.

Quantity	Est	CV
SSF_{2015}/SSF_{MSY}	0.54	0.61
SSF_{2015}/SSF_{MSST}	0.58	0.61
F_{2015}/F_{MSY}	2.02	1.23
SPR_{MSY}	0.51	0.04
F_{MSY}	0.035	0.06
SSF_{MSY}/SSF_0	0.35	0.19
SSF_{MSST}/SSF_0	0.33	0.19
F_{2015}	0.070	1.23
N_{2015}/N_0	0.35	0.38
SSF_{2015}/SSF_0	0.19	0.53
B_{2015}/B_0	0.27	0.44
Pup survival	0.88	0.29
Alpha	4.14	0.29
$F_{20\%}$	0.085	0.07
$F_{30\%}$	0.063	0.06
$F_{40\%}$	0.048	0.06
$F_{50\%}$	0.036	0.07
$F_{60\%}$	0.026	0.07
SPR_0	4.70	NA

Table 3.7. Estimated temporal trends in stock status obtained from the base run of the updated dusky shark ASCFM for apical fishing mortality relative to MSY levels (F/F_{MSY}) and spawning stock fecundity relative to MSY and MSST levels (SSF/SSF_{MSY} and SSF/SSF_{MSST}, respectively).

Year	F/F_{MSY}	SSF/SSF_{MSY}	SSF/SSF_{MSST}
1960	0.02	2.83	3.03
1961	0.01	2.83	3.03
1962	0.06	2.83	3.03
1963	0.13	2.83	3.03
1964	0.25	2.83	3.03
1965	0.24	2.82	3.02
1966	0.13	2.82	3.02
1967	0.12	2.81	3.02
1968	0.17	2.81	3.01
1969	0.13	2.81	3.01
1970	0.18	2.80	3.00
1971	0.27	2.80	3.00
1972	0.21	2.79	2.99
1973	0.25	2.78	2.98
1974	0.37	2.77	2.97
1975	0.34	2.76	2.96
1976	0.34	2.75	2.95
1977	0.35	2.74	2.94
1978	0.33	2.73	2.93
1979	0.47	2.72	2.91
1980	0.51	2.70	2.90
1981	0.59	2.69	2.88
1982	0.70	2.67	2.86
1983	0.84	2.64	2.83
1984	1.03	2.61	2.80
1985	1.28	2.58	2.76
1986	1.60	2.54	2.72
1987	1.99	2.49	2.67
1988	2.41	2.43	2.60
1989	2.79	2.36	2.53
1990	3.09	2.28	2.44
1991	3.32	2.19	2.35
1992	3.56	2.10	2.25
1993	3.89	2.00	2.15
1994	4.35	1.90	2.04
1995	4.93	1.80	1.92
1996	5.65	1.68	1.80
1997	6.51	1.56	1.68
1998	7.37	1.44	1.54
1999	8.05	1.31	1.41
2000	8.05	1.19	1.28
2001	7.10	1.09	1.16
2002	5.62	1.00	1.07
2003	4.18	0.93	0.99
2004	3.08	0.87	0.93
2005	2.35	0.83	0.88
2006	1.90	0.79	0.84
2007	1.65	0.75	0.80
2008	1.53	0.72	0.77
2009	1.52	0.69	0.74
2010	1.59	0.66	0.71
2011	1.71	0.63	0.68
2012	1.87	0.61	0.65
2013	2.03	0.58	0.62
2014	2.15	0.56	0.60
2015	2.02	0.54	0.58

Table 3.8. Summary of projection results obtained for the updated dusky shark ASCFM for the five scenarios reflective of plausible states of nature (Base, High *M*, U-Shaped *M*, High Productivity, and Low Productivity; see section 3.1.5 of this report for definitions of each scenario).See section 3.1.7 of this report for definitions of YearF=0p70, $Year_{rebuild}$, *F*-$Year_{rebuild}$, and TAC-$Year_{rebuild}$. Total allowable catch (TAC) is total annual removals in lb dressed weight.

	Terminal conditions					*F*-$Year_{rebuild}$		TAC-$Year_{rebuild}$ (lb dressed weight)	
Scenario	F_{2015}	F_{2015}/F_{MSY}	SSF_{2015}/SSF_{MSY}	YearF=0p70	$Year_{rebuild}$	P50	P70	P50	P70
Base	0.070	2.02	0.54	2058	2098	0.027	0.023	33149	23802
High M	0.024	1.44	0.61	2087	2127	0.011	0.007	18772	10512
U-shaped M	0.019	0.99	0.67	2056	2096	0.014	0.010	29459	20349
Hi Prod	0.134	2.48	0.49	2046	2086	0.047	0.042	49533	37226
Low Prod	0.023	3.04	0.68	2160	2200	0.004	0.002	6944	3227

3.6. FIGURES

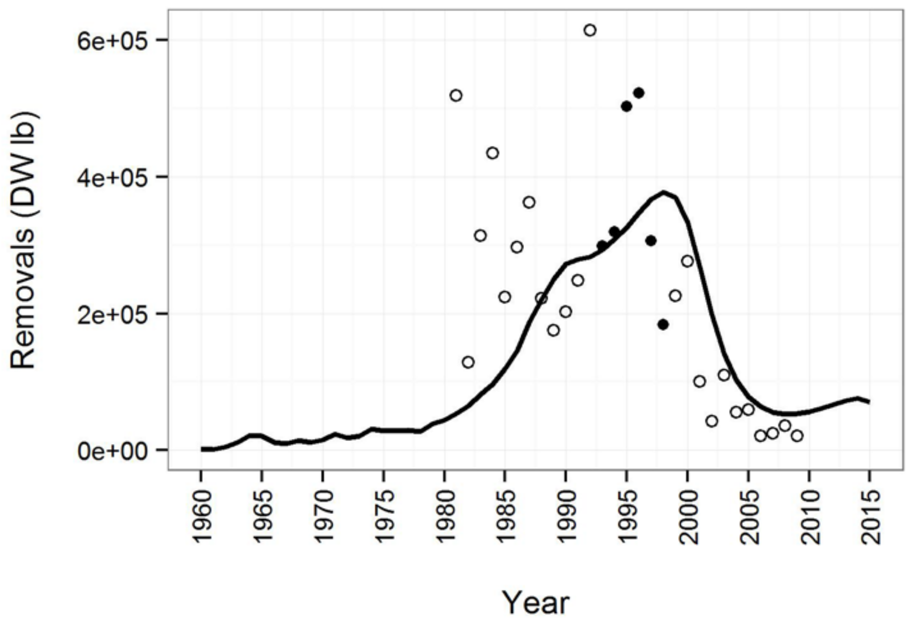
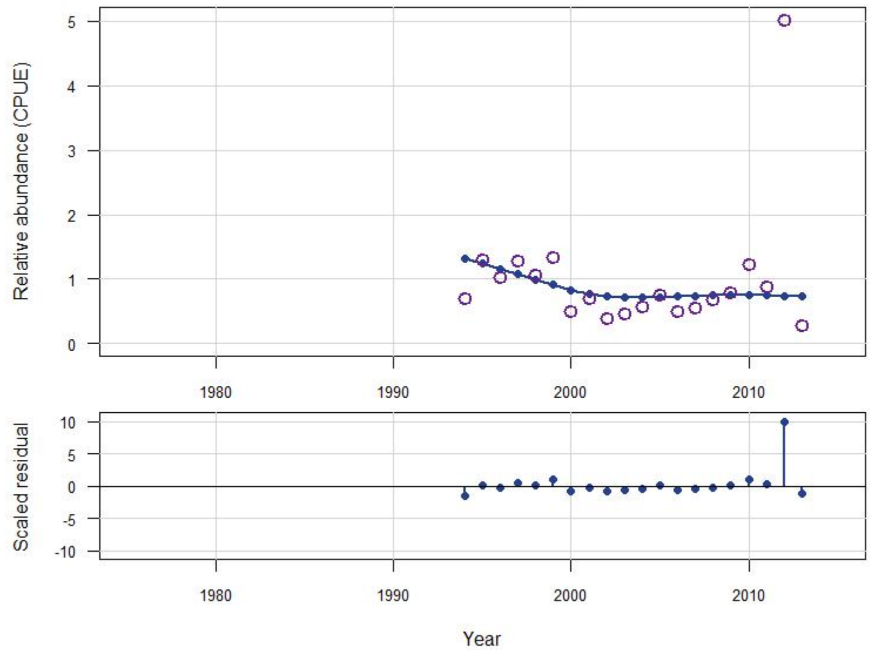


Figure 3.1. Predicted catches (total removals; black line) obtained from the base run of the updated dusky shark ASCFM when observed removals during 1993-1998 (solid points) are used to scale abundance levels up to the absolute scale. Open circles represent observed catches in other years. The estimated scaling factor is used to generate predicted removals for stock projections. Note that observed removals were thought to be unreliable in SEDAR 21, and thus not recommended for use in fitting stock assessment models. All values are in dressed weight (lb).

A. BLLOP



B. PLLOP

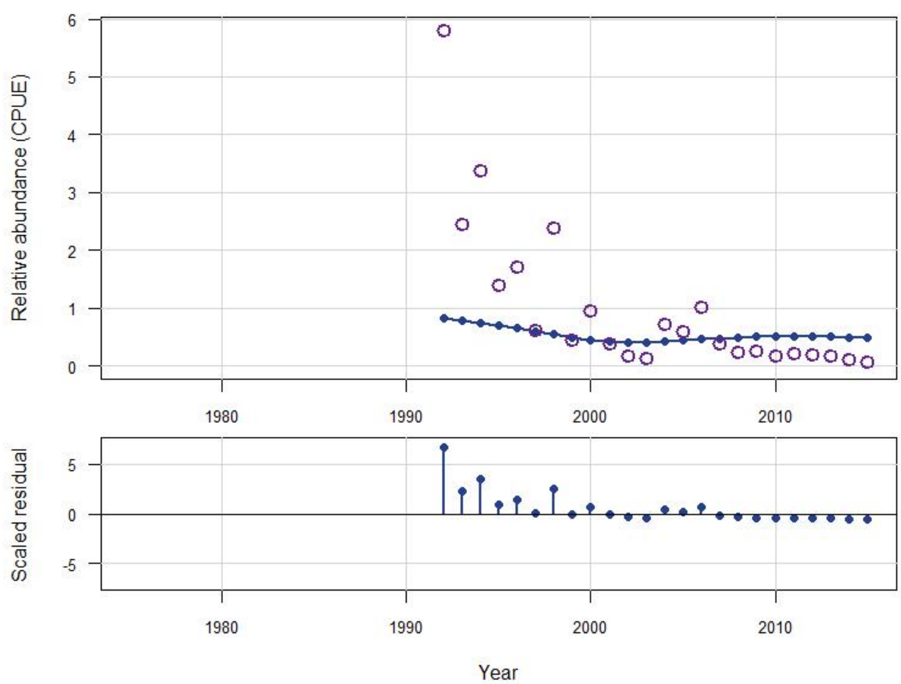
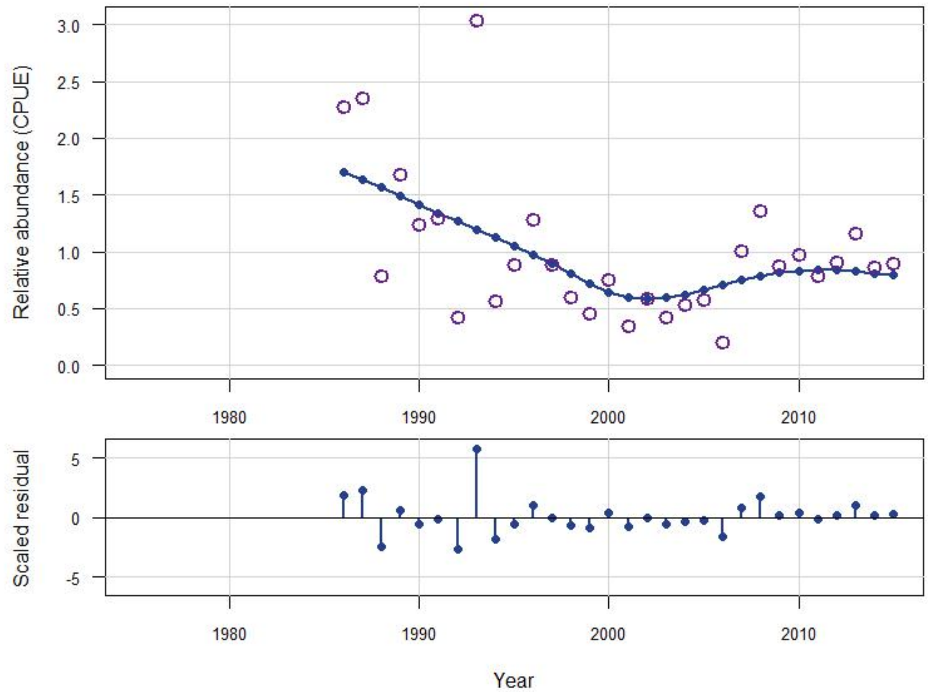


Figure 3.2. Fits to indices obtained from the base run of the updated dusky shark ASCFM. The line with solid circles denotes ASCFM predictions, while open circles denote observed values. Bottom panels give scaled residuals.

C. LPS



D. VIMS LL

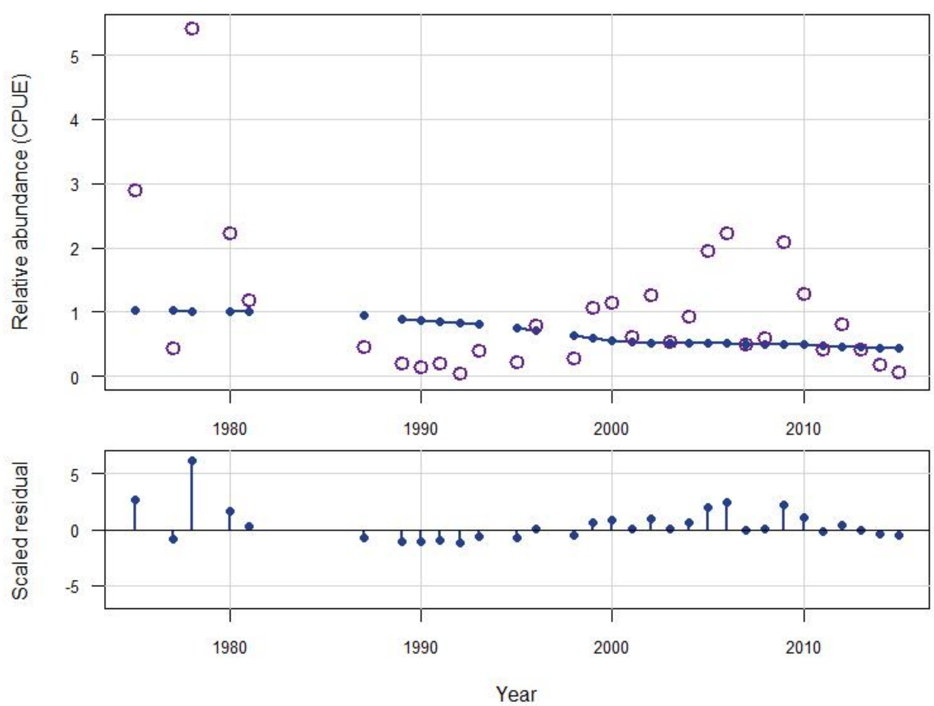


Figure 3.2. Fits to indices for the base run (continued).

E. NELL

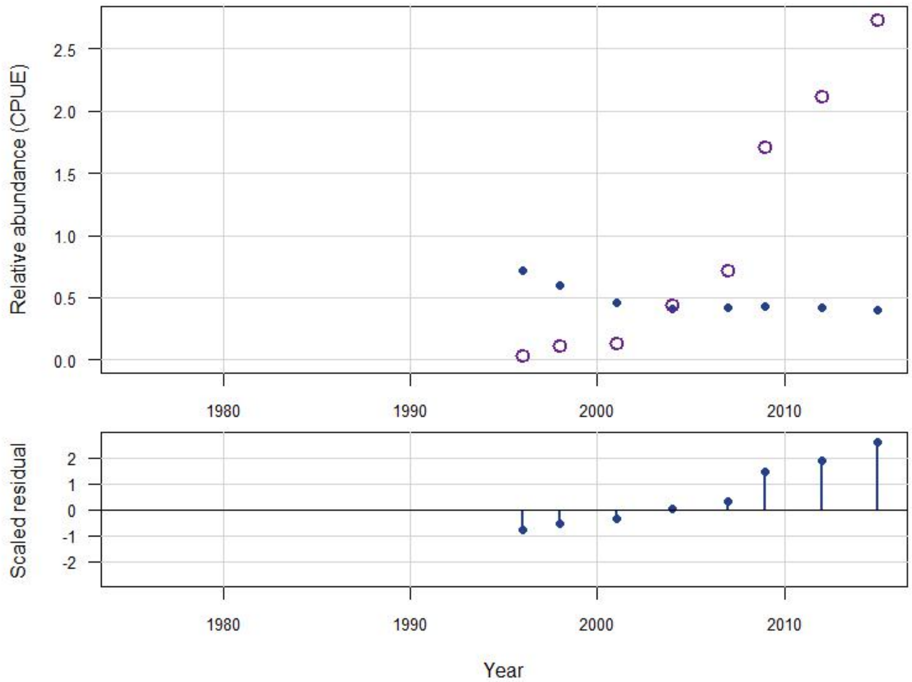


Figure 3.2. Fits to indices for the base run (continued).

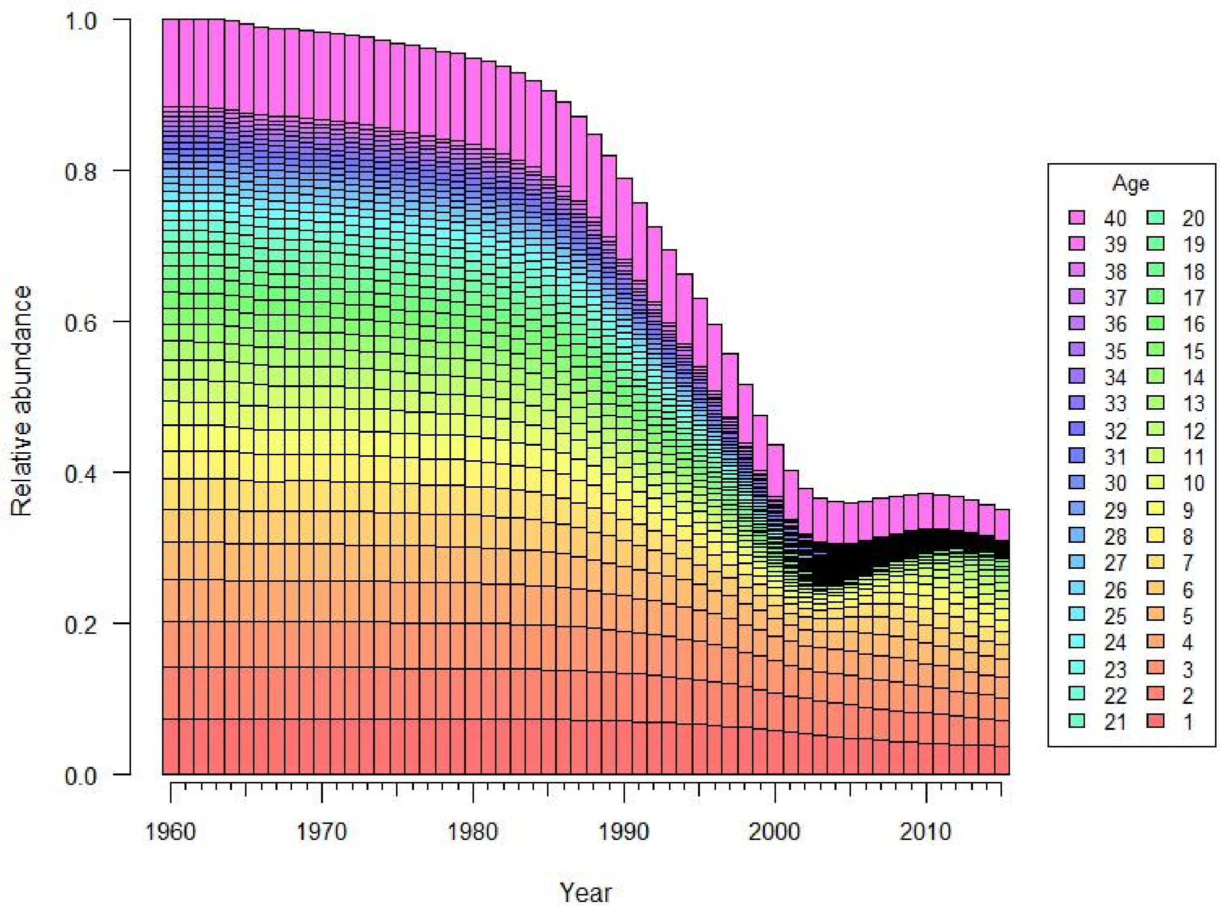


Figure 3.3. Predicted stock abundance at age relative to the unfished equilibrium (virgin) numbers at age (relative abundance) obtained from the base run of the updated dusky shark ASCFM, 1960 – 2015.

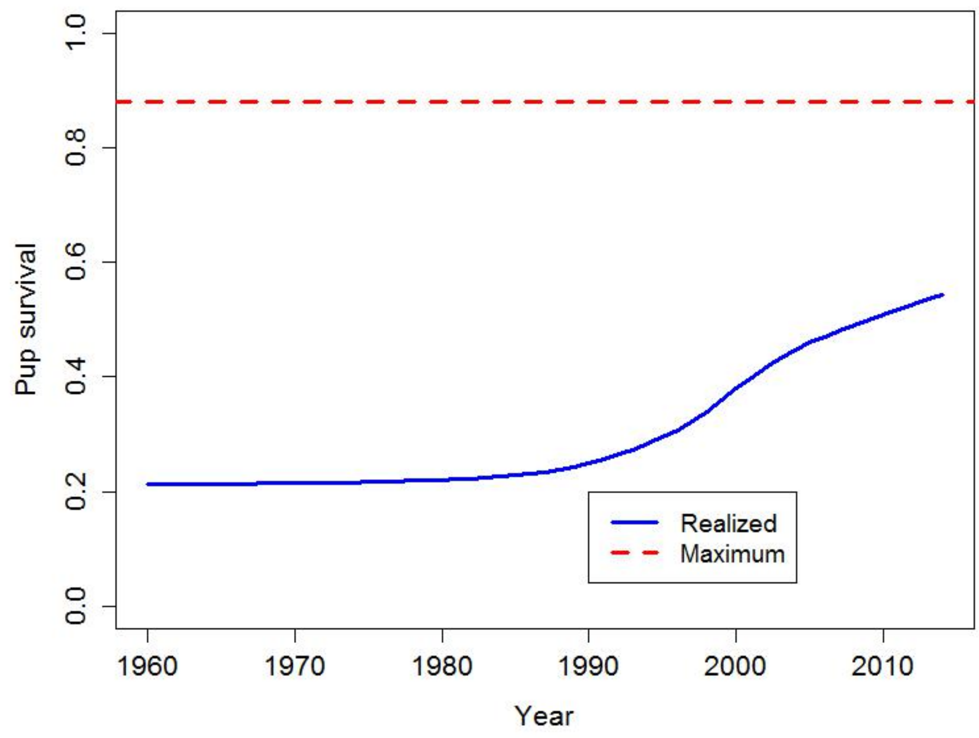


Figure 3.4. Realized pup survival for 1960 – 2014 predicted from the base run of the updated dusky shark ASCFM (Equation 3.11). Pup survival is assumed to be density dependent, with an estimated maximum theoretical value of 0.88 in the base run (Tables 3.1 and 3.6).

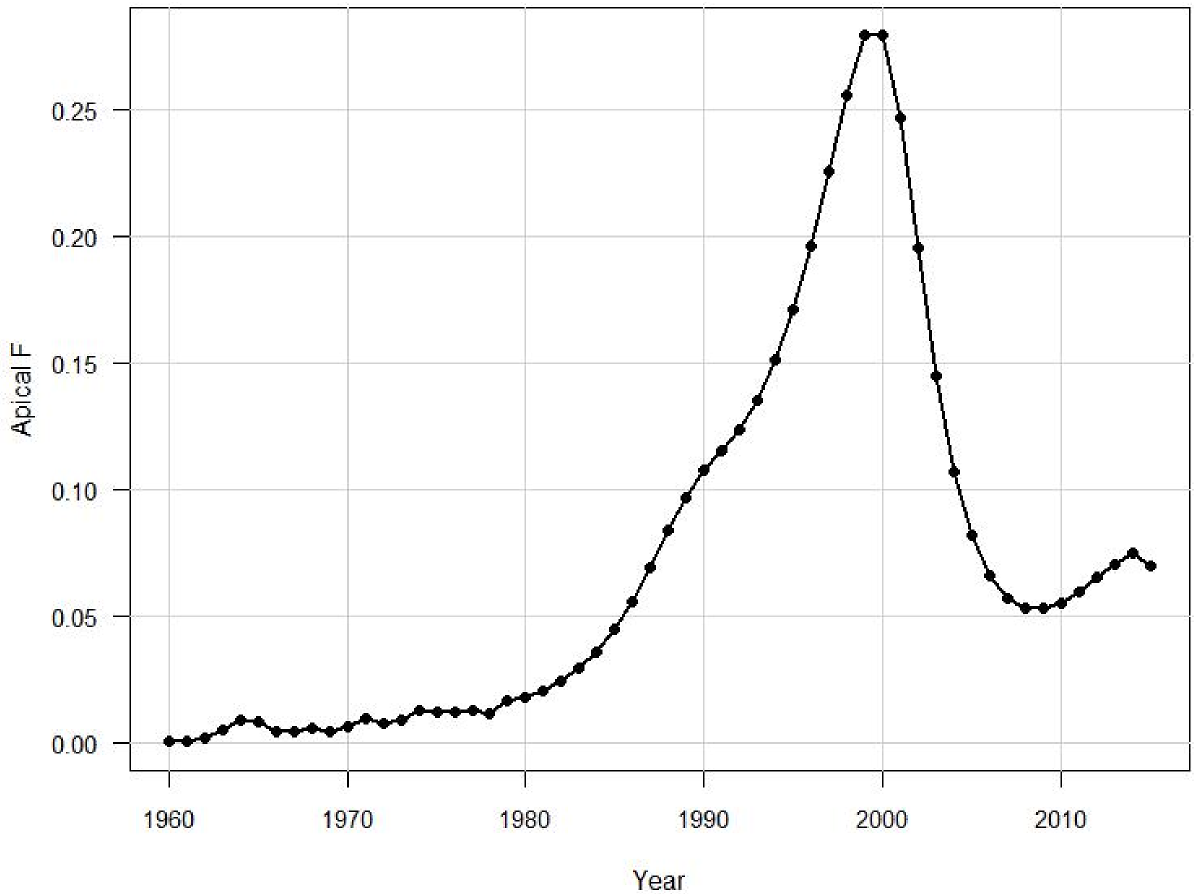


Figure 3.5. Apical instantaneous fishing mortality rate (apical *F*) by year obtained from the base run of the updated dusky shark ASCFM.

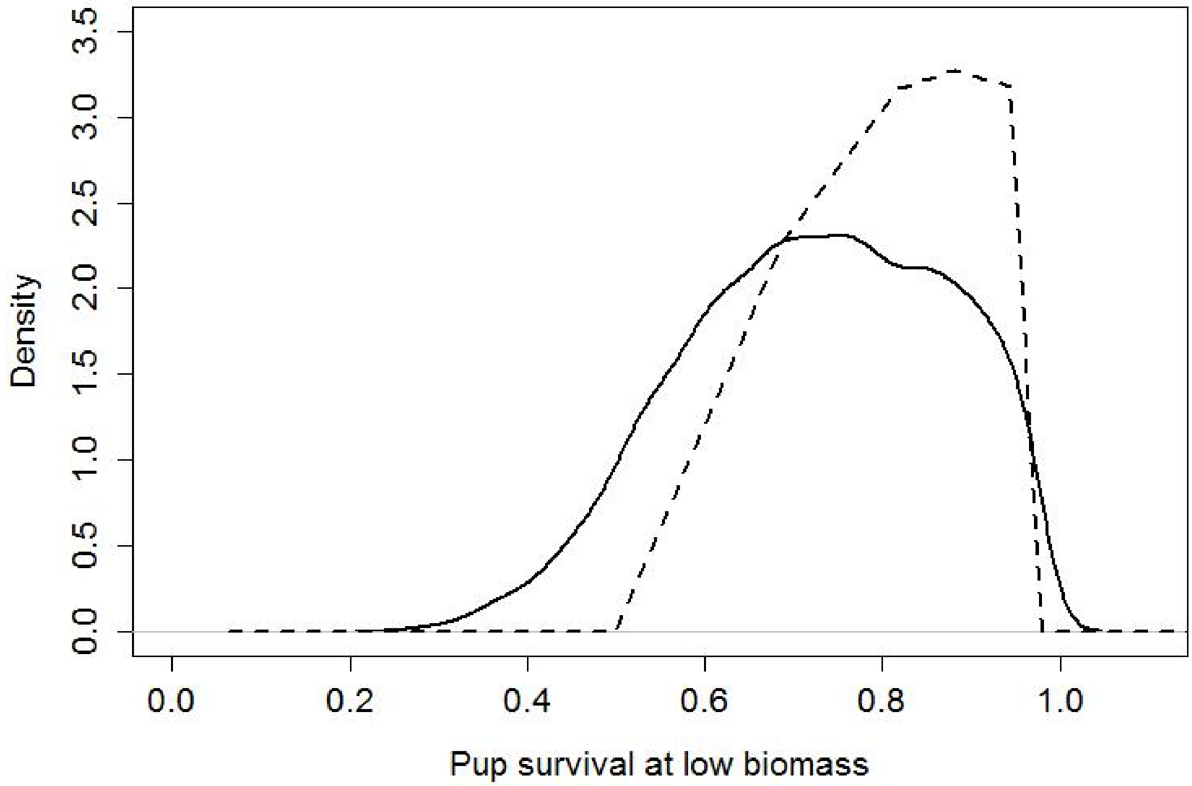


Figure 3.6. Prior (solid line) and estimated posterior distribution (dashed line) for pup survival at low stock size obtained from the base run of the updated dusky shark ASCFM. Pup survival at low stock size was constrained to be between 0.5 and 0.98.

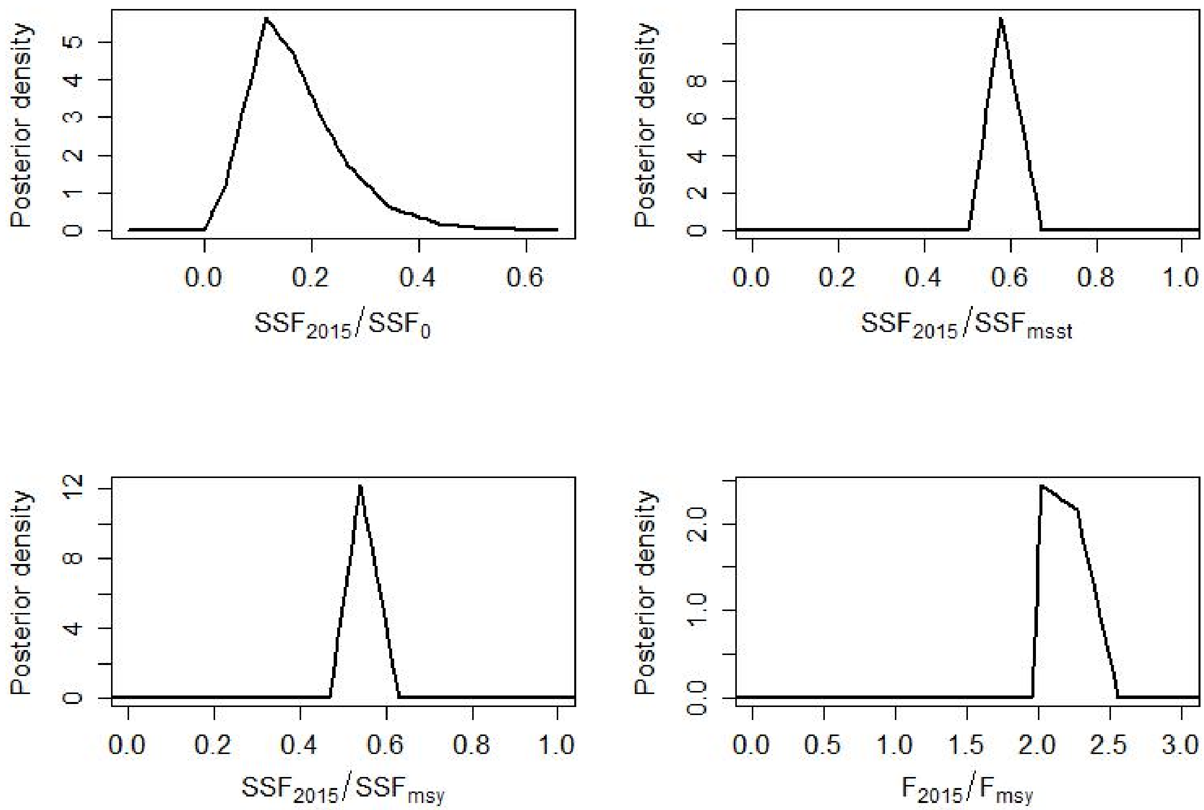


Figure 3.7. Estimated posterior distributions for stock status relative to management benchmarks obtained from the base run of the updated dusky shark ASCFM. Relative spawning stock fecundity (SSF_{2015}/SSF_0) is calculated as in Equation 3.3.

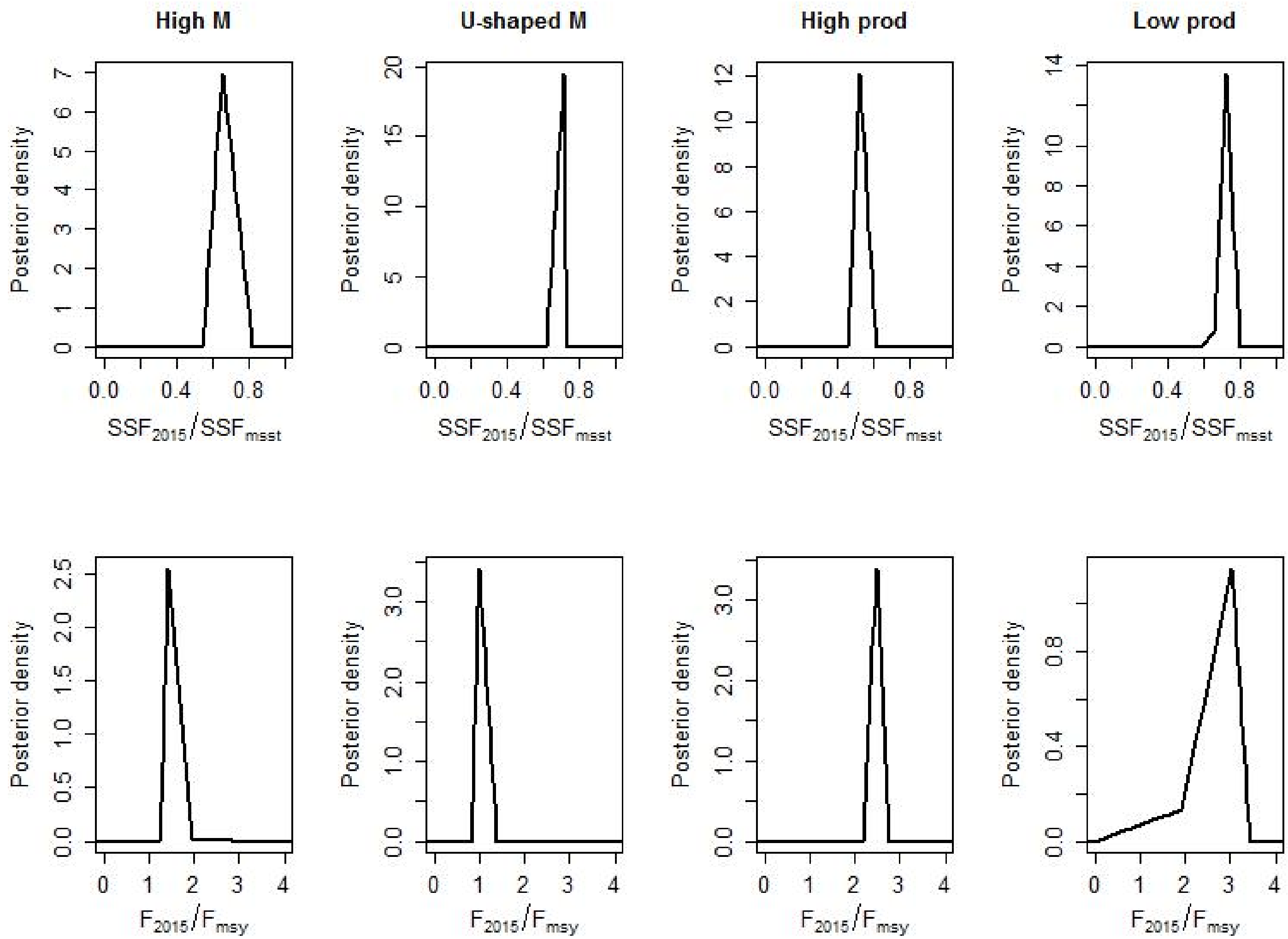


Figure 3.8. Estimated posterior distributions for stock status relative to management benchmarks (top panels: SSF_{2015}/SSF_{MSST}; lower panels: F_{2015}/F_{MSY}) obtained from the updated dusky shark ASCFM for four additional scenarios reflective of plausible states of nature (High *M*, U-Shaped *M*, High Productivity, and Low Productivity; see section 3.1.5 of this report for definitions of each scenario).

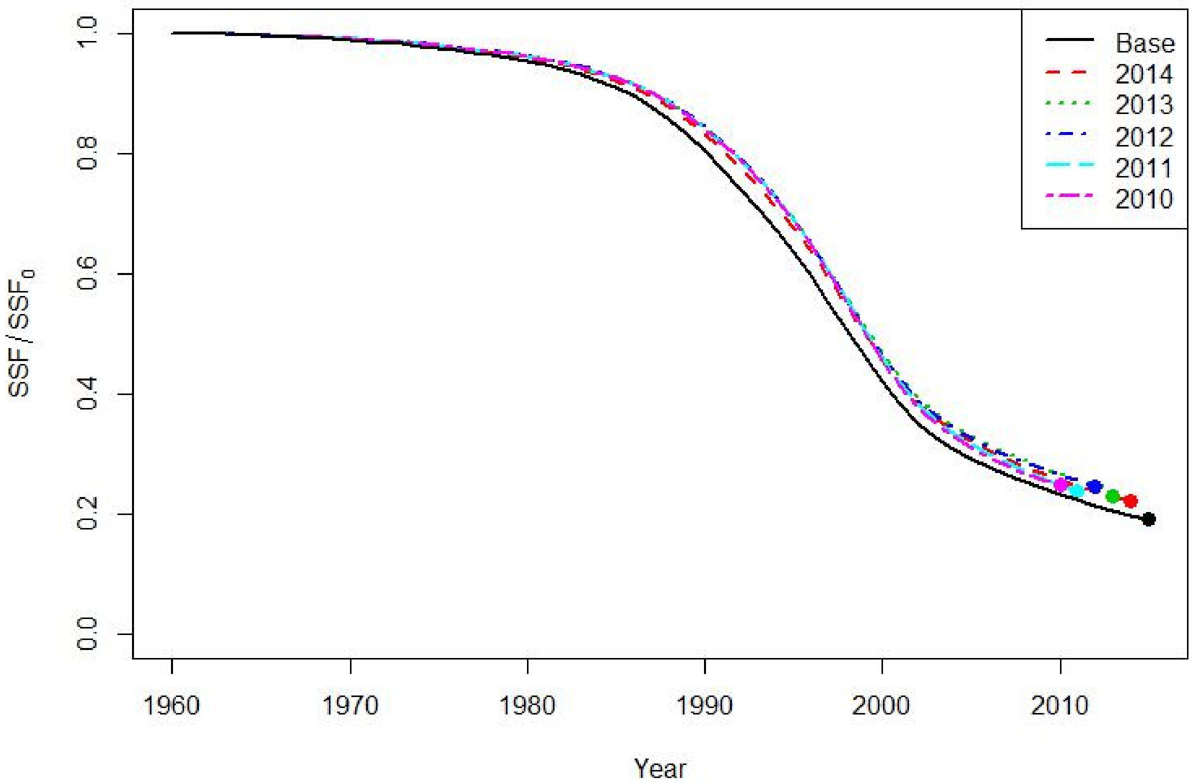


Figure 3.9. Retrospective pattern in spawning stock fecundity (SSF) relative to unfished equilibrium levels (SSF_0) obtained from the base run of the updated dusky shark ASCFM as a function of the last year included in the ASCFM. The base model ended in 2015. Relative spawning stock fecundity (SSF/SSF_0) is calculated as in Equation 3.3.

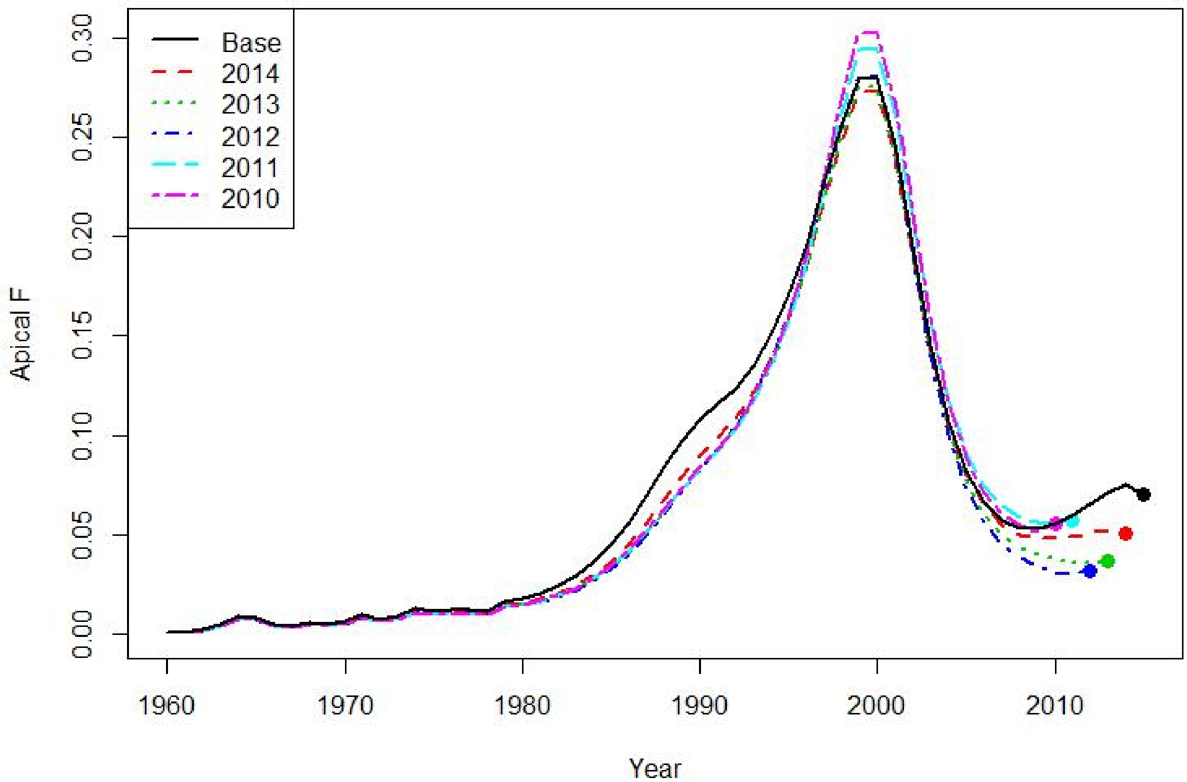


Figure 3.10. Retrospective pattern in estimated terminal year fishing mortality rate (apical *F*) obtained from the base run of the updated dusky shark ASCFM as a function of the last year included in the ASCFM. The base model ended in 2015.

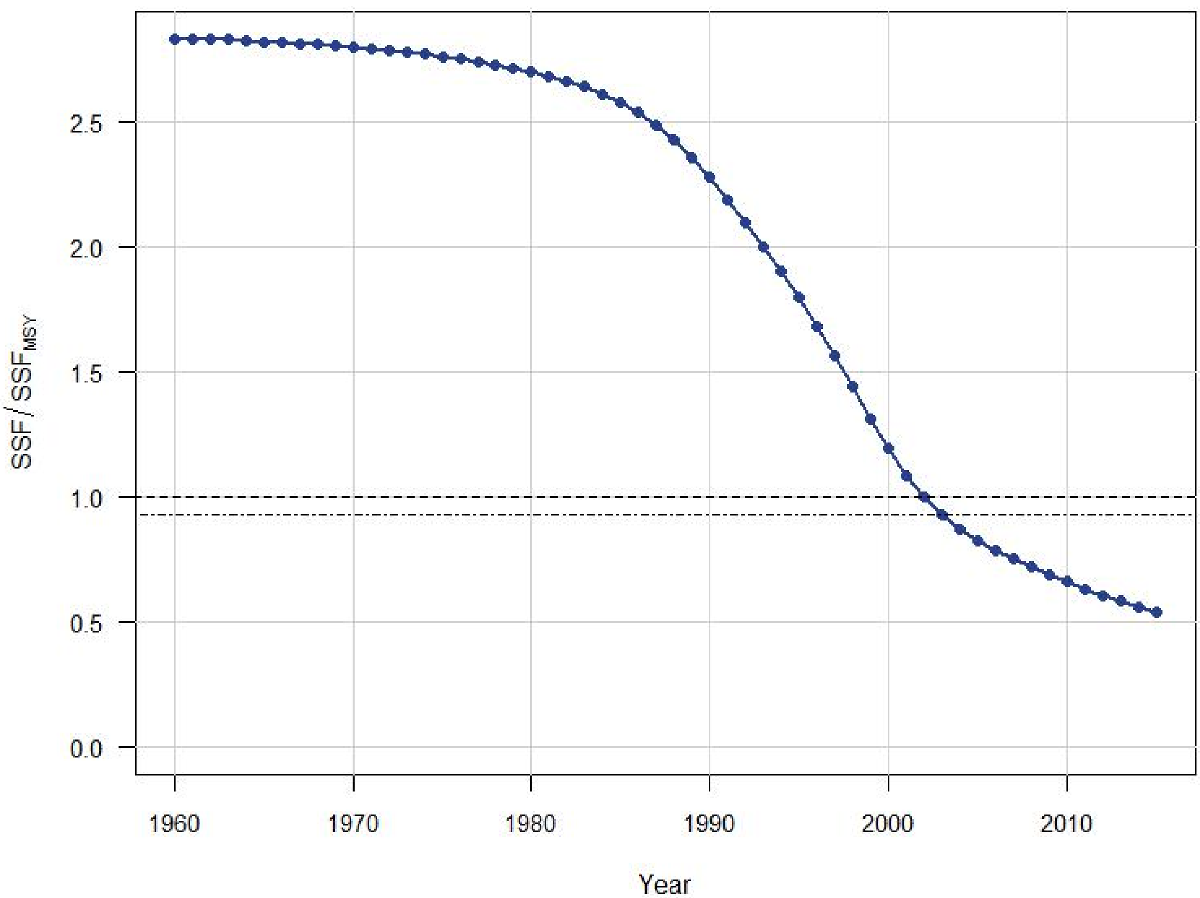


Figure 3.11. Spawning stock fecundity relative to MSY levels (horizontal dashed line) over time obtained from the base run of the updated dusky shark ASCFM. The lower horizontal dot-dash line indicates the MSST level.

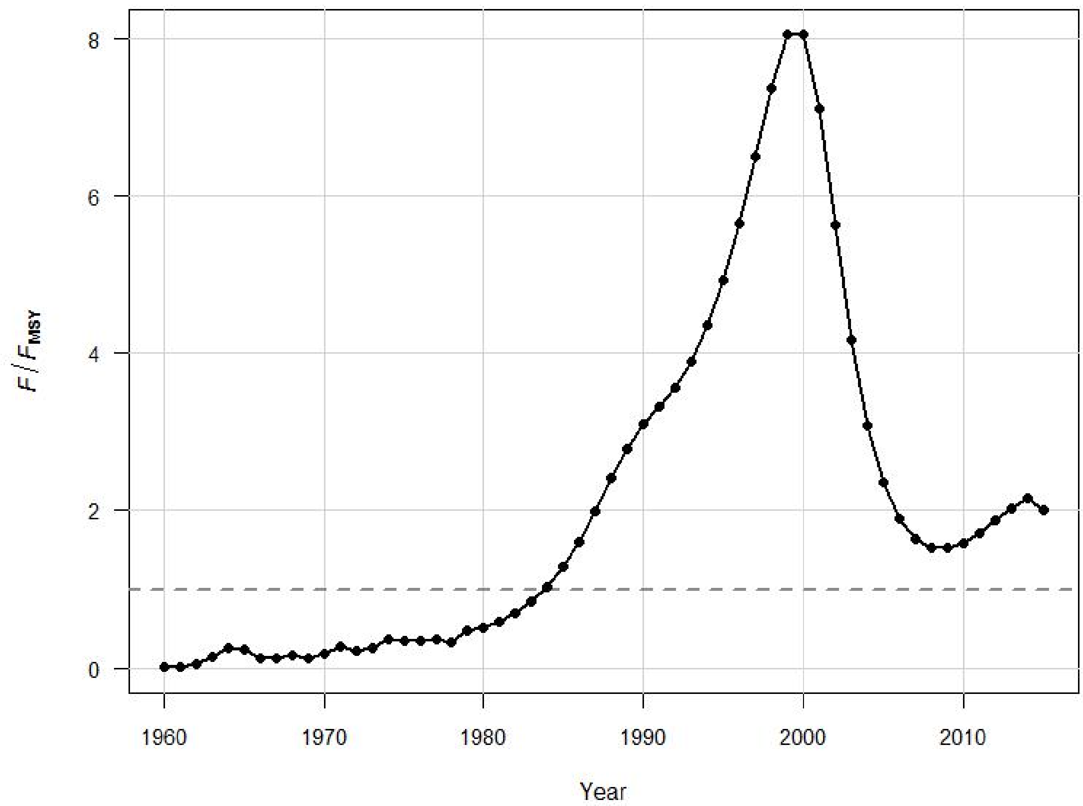


Figure 3.12. Apical fishing mortality relative to MSY levels obtained from the base run of the updated dusky shark ASCFM, 1960 – 2015, indicating that overfishing has been occurring since 1984.

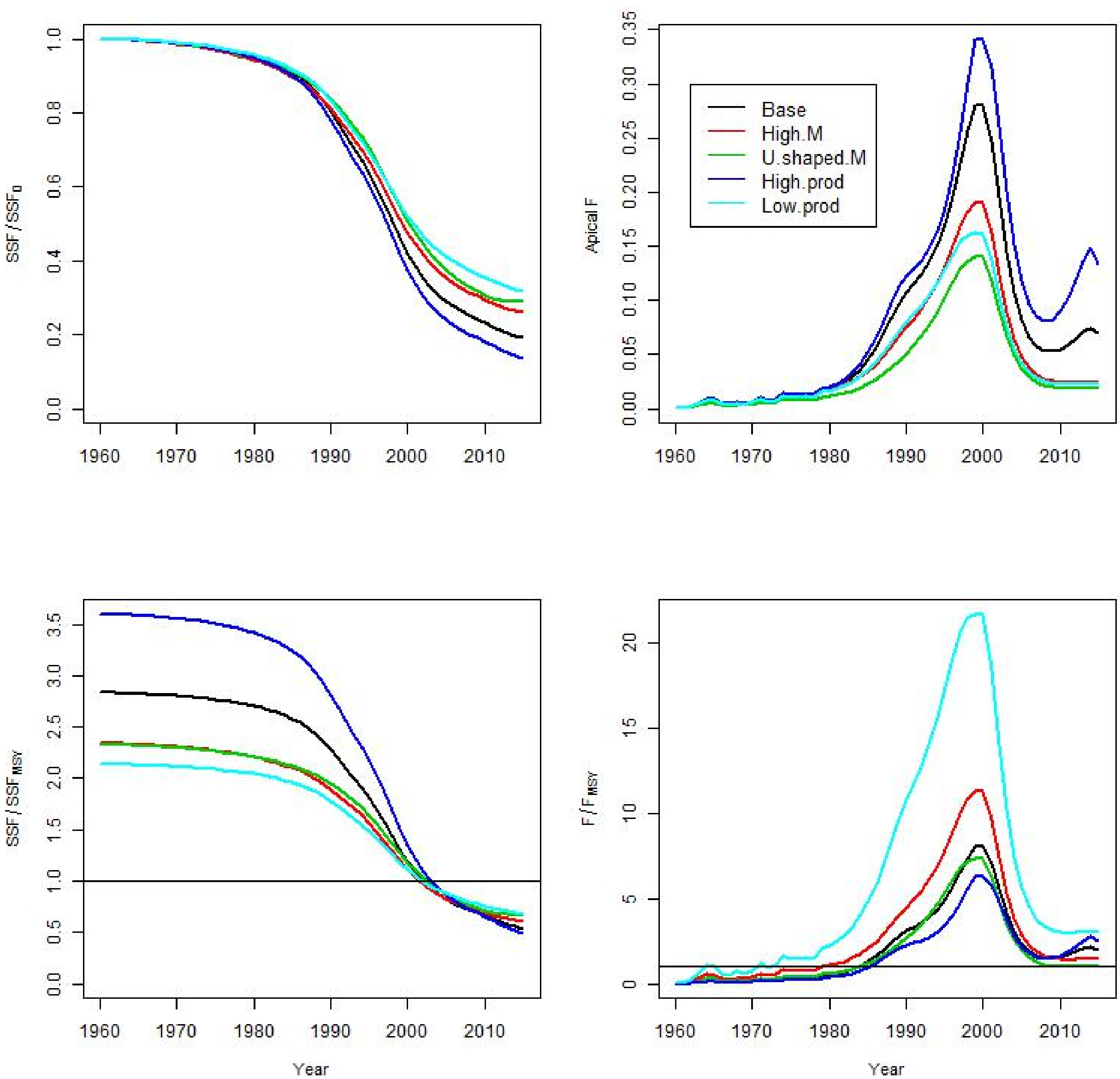


Figure 3.13. Estimated time series of relative spawning stock fecundity, apical fishing mortality rates, spawning stock fecundity in relation to MSY levels, and fishing mortality rates in relation to MSY levels obtained from the updated dusky shark ASCFM for the five scenarios reflective of plausible states of nature (Base, High *M*, U-Shaped *M*, High Productivity, and Low Productivity; see section 3.1.5 of this report for definitions of each scenario)

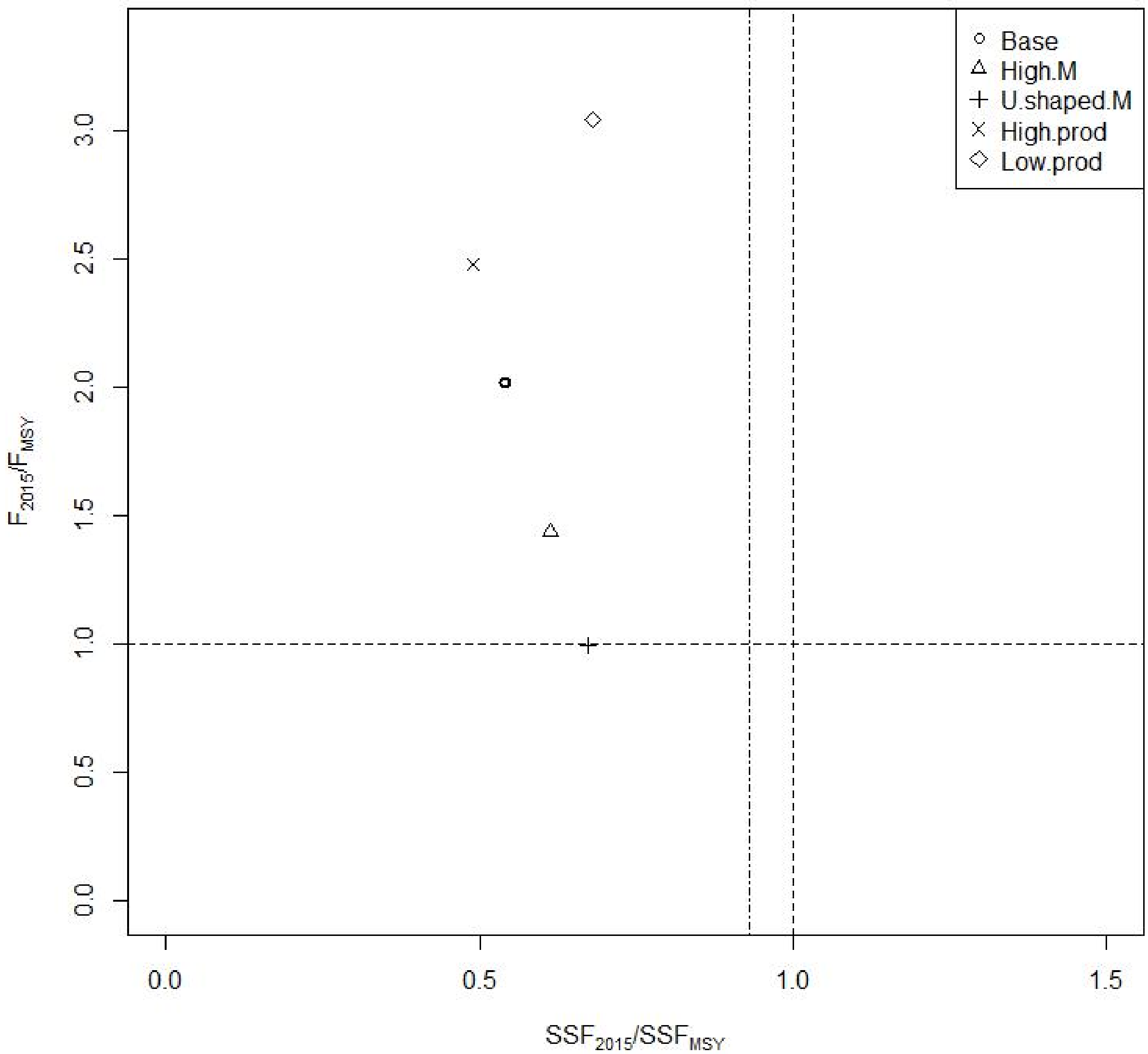


Figure 3.14. A phase plot summarizing stock status of dusky sharks in the terminal year (2015) obtained from the updated ASCFM for the five scenarios reflective of plausible states of nature (Base, High *M*, U-Shaped *M*, High Productivity, and Low Productivity; see section 3.1.5 of this report for definitions of each scenario). For clarity we only show the overfished reference point (relative to SSF_{MSST}) for the updated base run (vertical dot-dashed line), with points to the left of the line indicating the stock was estimated to be overfished ($SSF_{2015} < SSF_{MSST}$). Points above the horizontal black line indicate overfishing is estimated to have occurred ($F_{2015} > F_{MSY}$).

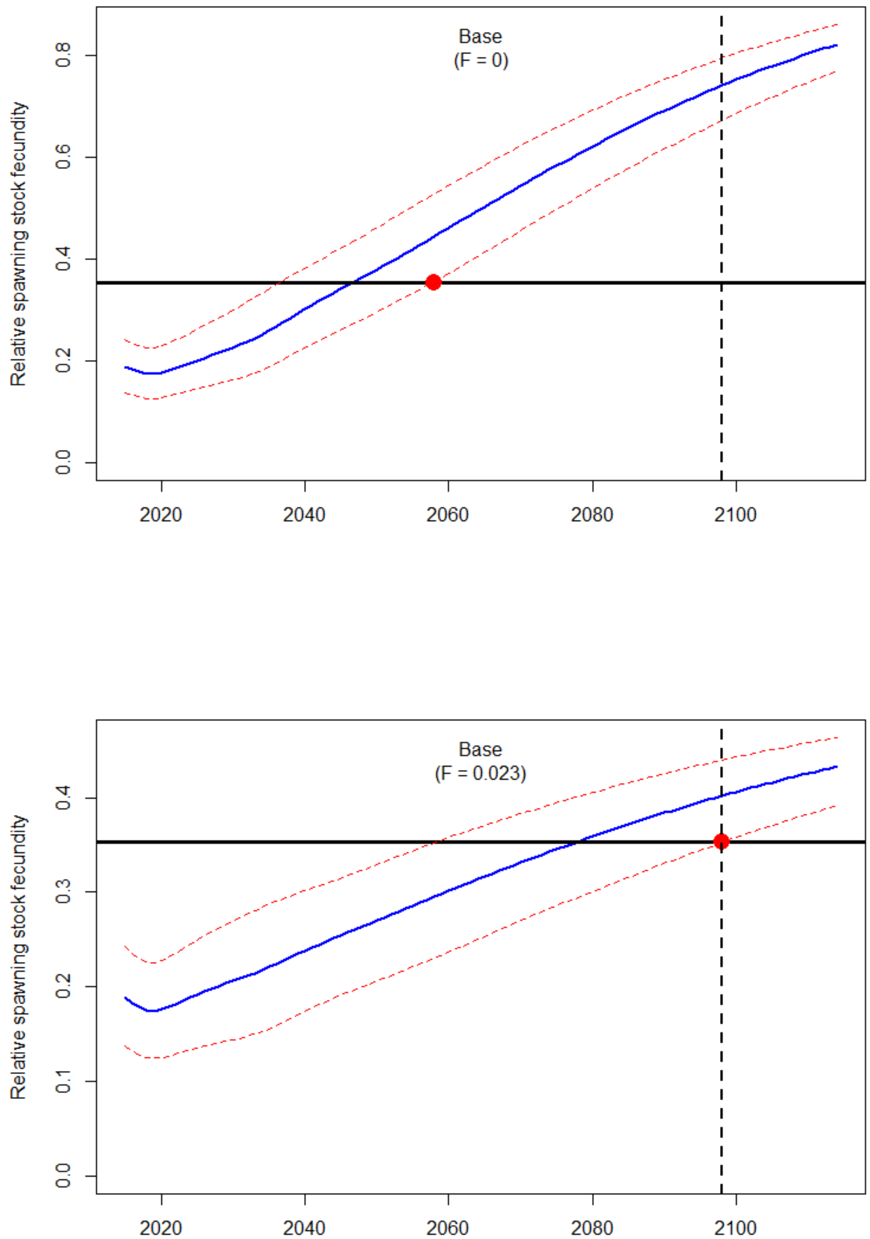


Figure 3.15. Projections for the base scenario; Median (blue line), 30th, and 70th percentiles (red dashed lines) of relative spawning stock fecundity (SSF_t/SSF_0) obtained from 10,000 bootstrap replicates. Rebuilding to relative SSF_{MSY} (SSF_{MSY}/SSF_0; horizontal solid black line) under zero fishing mortality (*F* = 0) is achieved with 70% probability in year 2058 ($YearF{=}0_{p70}$, solid red circle in upper panel). Rebuilding with 70% probability by 2098 ($Year_{rebuild} = YearF{=}0_{p70} + 40$; vertical dashed black line) is achieved with a constant fishing mortality *F* = 0.023 (solid red circle in lower panel).

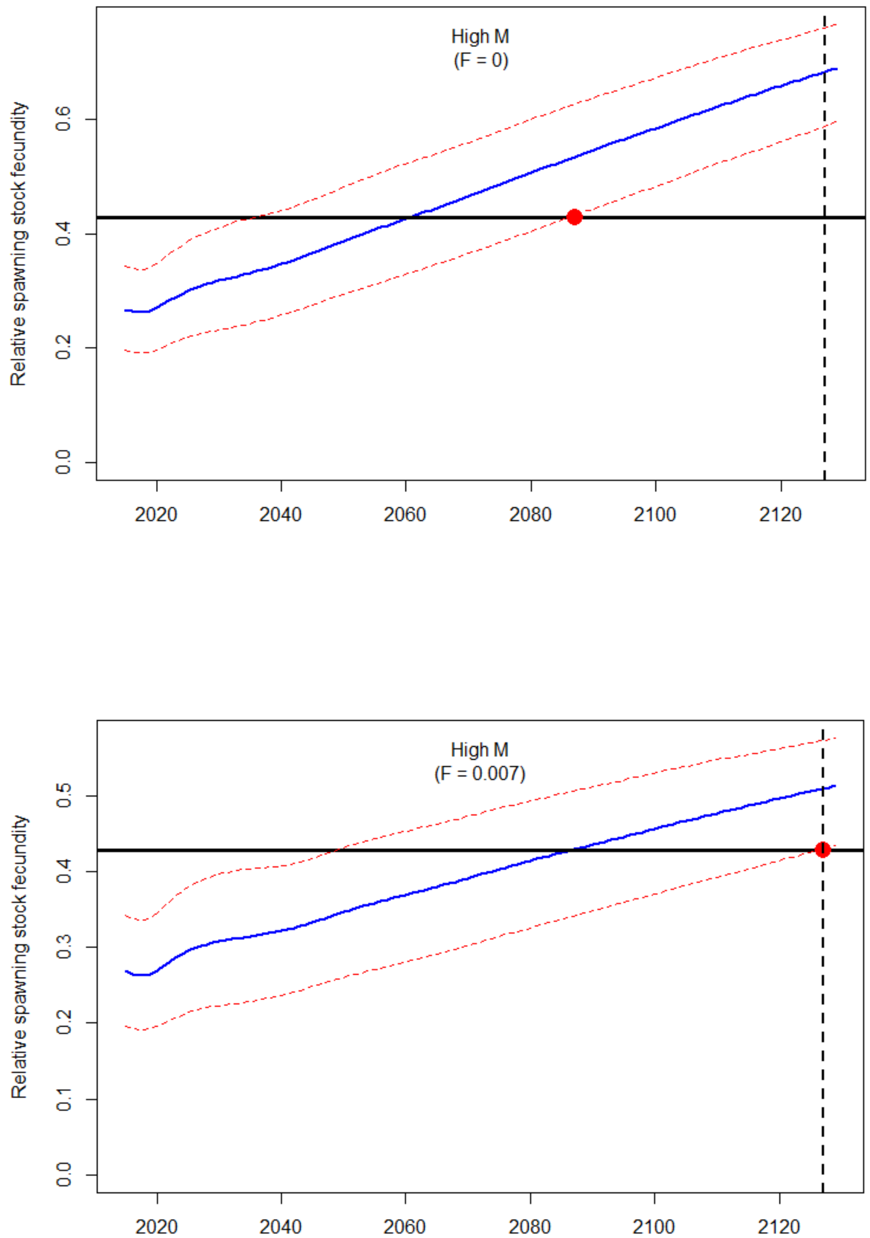


Figure 3.16. Projections for the high natural mortality (High *M*) scenario; Median (blue line), 30th, and 70th percentiles (red dashed lines) of relative spawning stock fecundity (SSF_t/SSF_0) obtained from 10,000 bootstrap replicates. Rebuilding to SSF_{MSY}/SSF_0 (horizontal solid black line) under zero fishing mortality (F = 0) is achieved with 70% probability in year 2087 ($YearF{=}0_{p70}$, solid red circle in upper panel). Rebuilding with 70% probability by 2127 ($Year_{rebuild} = YearF{=}0_{p70} + 40$; vertical dashed black line) is achieved with a constant fishing mortality F = 0.007 (solid red circle in lower panel).

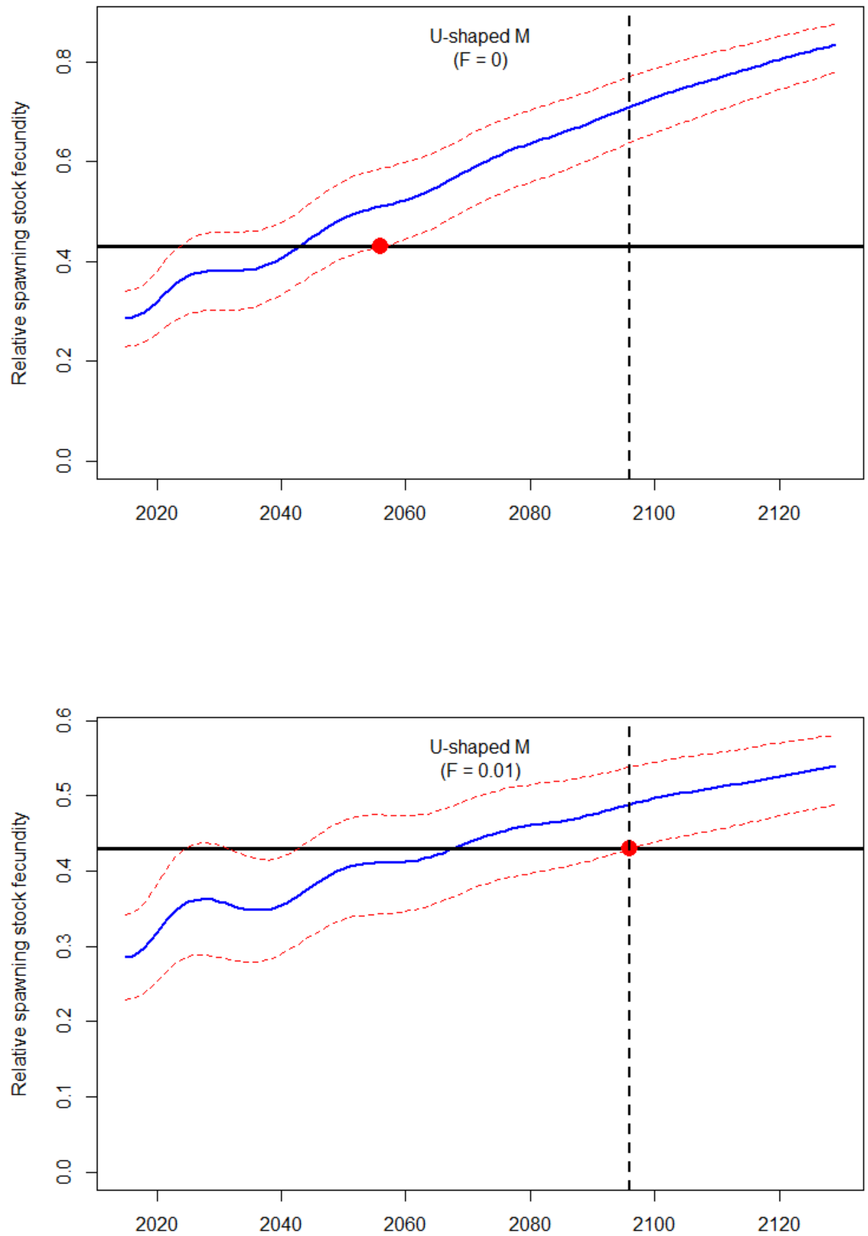


Figure 3.17. Projections for the U-shaped natural mortality (U-shaped *M*) scenario; Median (blue line), 30th, and 70th percentiles (red dashed lines) of relative spawning stock fecundity (SSF_t/SSF_0) obtained from 10,000 bootstrap replicates. Rebuilding to SSF_{MSY}/SSF_0 (horizontal solid black line) under zero fishing mortality ($F = 0$) is achieved with 70% probability in year 2056 ($YearF{=}0_{p70}$, solid red circle in upper panel). Rebuilding with 70% probability by 2096 ($Year_{rebuild} = YearF{=}0_{p70} + 40$; vertical dashed black line) is achieved with a constant fishing mortality $F = 0.010$ (solid red circle in lower panel).

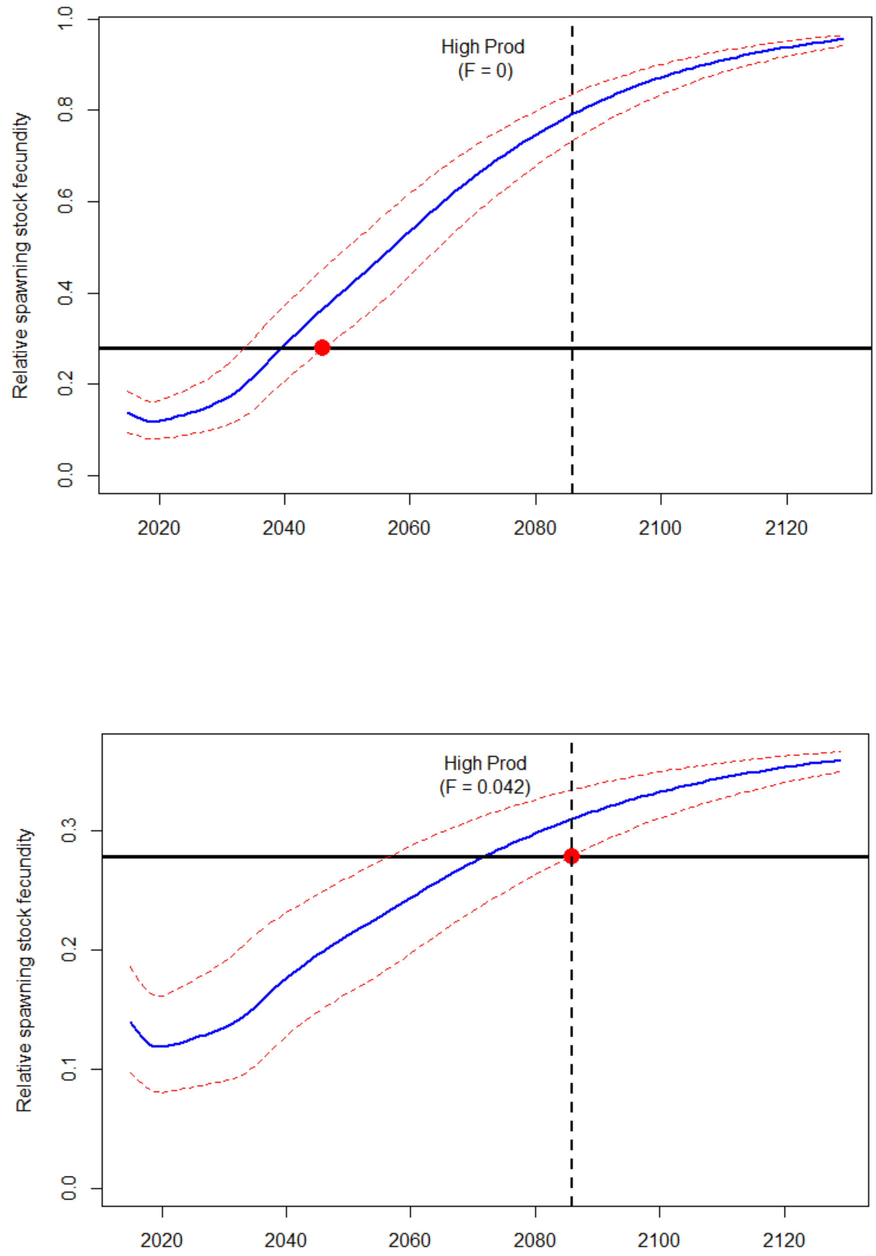


Figure 3.18. Projections for the high productivity (High Prod) scenario; Median (blue line), 30th, and 70th percentiles (red dashed lines) of relative spawning stock fecundity (SSF_t/SSF_0) obtained from 10,000 bootstrap replicates. Rebuilding to SSF_{MSY}/SSF_0 (horizontal solid black line) under zero fishing mortality (F = 0) is achieved with 70% probability in year 2046 ($YearF{=}0_{p70}$, solid red circle in upper panel). Rebuilding with 70% probability by 2086 ($Year_{rebuild} = YearF{=}0_{p70} + 40$; vertical dashed black line) is achieved with a constant fishing mortality F = 0.042 (solid red circle in lower panel).

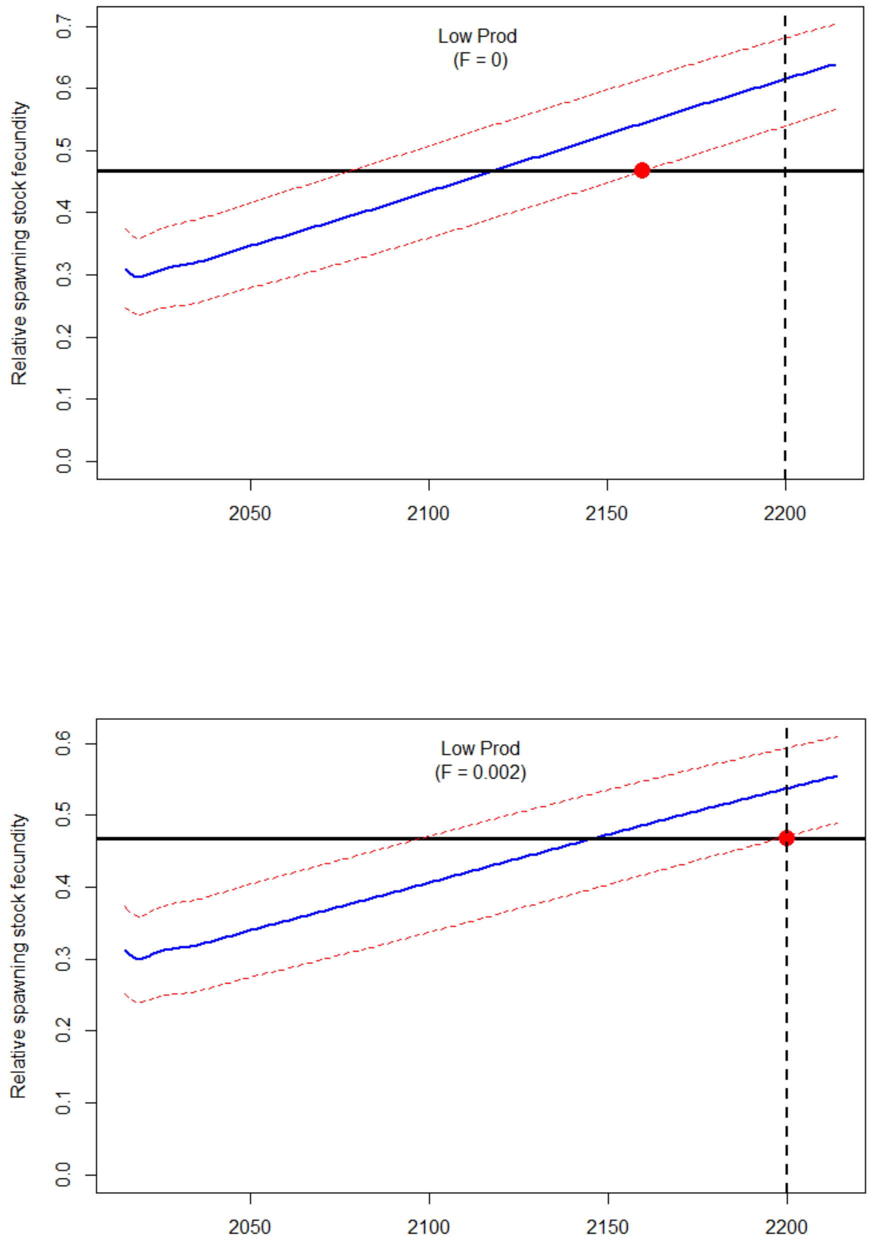


Figure 3.19. Projections for the low productivity (Low Prod) scenario; Median (blue line), 30th, and 70th percentiles (red dashed lines) of relative spawning stock fecundity (SSF_t/SSF_0) obtained from 10,000 bootstrap replicates. Rebuilding to SSF_{MSY}/SSF_0 (horizontal solid black line) under zero fishing mortality (F = 0) is achieved with 70% probability in year 2160 ($YearF{=}0_{p70}$, solid red circle in upper panel). Rebuilding with 70% probability by 2200 ($Year_{rebuild} = YearF{=}0_{p70} + 40$; vertical dashed black line) is achieved with a constant fishing mortality F = 0.002 (solid red circle in lower panel).