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STATUS OF COMMON THRESHER SHARKS, *ALOPIUS VULPINUS*, ALONG THE WEST COAST OF NORTH AMERICA: UPDATED STOCK ASSESSMENT BASED ON ALTERNATIVE LIFE HISTORY

Steven L. H. Teo, Emiliano Garcia Rodriguez,
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Southwest Fisheries Science Center

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Status of Common Thresher Sharks, *Alopias vulpinus*, Along the West Coast of North America: Updated Stock Assessment Based on Alternative Life History

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Contents

ACRONYMS

AIC	Akaike's Information Criteria
AL	Alternate length
β	Shape parameter in the low fecundity stock recruitment function
B	Biomass
B_0	Unfished biomass
B_{MSY}	Biomass at MSY
C_{2014}	Catch in 2014
CALCOM	California Commercial Fishery Data
CCGS	California Cooperative Groundfish Survey
CDFW	California Department of Fish and Wildlife
CI	Confidence interval
CIE	Center of Independent Experts
CONAPESCA	Comision Nacional de Acuacultura y Pesca
CPFV	Commercial Passenger Fishing Vessel
CPUE	Catch per unit effort
CV	Coefficient of variation
DGN	Drift gillnet
EEZ	Exclusive Economic Zone
ENSO	El Nino-Southern Oscillation
FAO	Food and Agricultural Organization of the United Nations
F	Instantaneous rate of fishing mortality
F_{MSY}	F at MSY
$F_{current}$	F during current period
FL	Fork length in cm
FMP	Fishery management plan
GLM	Generalized Linear Model
H	Steepness of stock-recruitment relationship
HMS	Highly migratory species
INAPESCA	Instituto Nacional de Pesca
K	Growth rate coefficient
L_∞	Asymptotic fork length in cm
$L_{50\%}$	Fork length at which 50% of the females are mature
LL	Longline
LMSY	Local maximum sustainable yield
M	Instantaneous rate of natural mortality
MFMT	Maximum fishing mortality threshold
MPA	Marine protected area
MSST	Minimum stock size threshold

MSY	Maximum sustainable yield
MX	Mexico
MXDGN	Mexico drift gillnet fishery
MXART	Mexico artisanal fishery
N	Sample size
N_{input}	Input sample size
N_{eff}	Effective sample size
NOAA	National Oceanic and Atmospheric Administration
nm	Nautical mile
OY	Optimum yield
PacFIN	Pacific Fisheries Information Network
PFMC	Pacific Fishery Management Council
PGR	Population growth rate
q	Catchability
Q	Quarter of the year
R_0	Unfished recruitment
RecFIN	Recreational Fisheries Information Network
RMSE	Root mean square error
S	Spawning abundance in number of mature females
S_0	Unfished spawning abundance
S_{2014}	Spawning abundance in 2014
S_{MSY}	Spawning abundance at MSY (proxy for B_{MSY})
SCB	Southern California Bight
SDC	Status determination criteria
SN	Nearshore set gillnets and small-mesh drift gillnet
SPR	Spawning potential ratio
$1\text{-}SPR_{MSY}$	Fishing intensity at MSY (proxy for F_{MSY})
$1\text{-}SPR_{1214}$	Average fishing intensity from 2012 to 2014
SS	Stock Synthesis
SWFSC	Southwest Fisheries Science Center
t_0	Theoretical age at 0 cm in the von Bertalanffy growth function
US or USA	United States of America
USDGN	USA swordfish/shark drift gillnet fishery
USSN	USA nearshore set gillnets and small-mesh drift gillnet fishery
USREC	USA recreational fishery
z_{frac}	Fractional reduction in pre-recruitment mortality of the low fecundity stock-recruitment function as depletion approaches 0

EXECUTIVE SUMMARY

Stock

Common thresher sharks (*Alopias vulpinus*) along the west coast of North America are seasonally distributed in coastal waters from British Columbia, Canada to central Baja California, Mexico. Juvenile common thresher sharks tend to remain in shallow, nearshore areas over the continental shelf, especially within the Southern California Bight (SCB), which is an important nursery area. The horizontal distributions of common and bigeye thresher sharks are thought to overlap partially, with bigeye thresher sharks generally exploiting deeper waters. In contrast, there is relatively little overlap in the distributions of common and pelagic thresher sharks, except for years with large El Nino-Southern Oscillation (ENSO) events, when the distribution of pelagic thresher sharks shift northwards.

In this assessment, common thresher sharks along the west coast of North America are assumed to be a single, well-mixed stock. This assumption is supported by their genetics, tagging data, and seasonal movements. The mitochondrial genetic sequences of common thresher sharks from California waters are not significantly different from Oregon-Washington waters but both are significantly different from other sampling locations, noting that there have not been any published comparisons with samples from Mexico. There is also no evidence of pupping and nursery grounds outside of the SCB. Tags from common thresher sharks tagged in the SCB have been returned from California, USA, and Baja California, Mexico. There is also unlikely to be substantial interchange of individuals between this stock and other common thresher shark stocks because, geographically, the closest stock is likely to be along the west coast of Chile.

Fisheries

The history of fisheries for this stock of common thresher sharks in USA waters is not well known prior to the 1970s but small amounts of catch were recorded by a variety of USA commercial and recreational fisheries. The most important USA commercial fishery for common thresher sharks is the swordfish/shark drift gillnet (USDGN) fishery, which started in 1977 - 1978. Although the primary targets were initially common thresher and shortfin mako sharks, fishermen soon switched to primarily targeting swordfish because of substantially higher ex-vessel prices. Fishing operations of the USDGN fishery have been heavily regulated to reduce adverse interactions with other fisheries, fishing mortality of common thresher sharks, and incidental bycatch of marine mammals and sea turtles. Secondarily, nearshore set gillnets and small-mesh drift gillnets (USSN) occasionally catch young-of-year and juvenile common thresher sharks as bycatch. There is also a small USA recreational fishery in Southern California (USREC) that targets adult common thresher sharks but catches are usually relatively low.

The historically most important fishery for common thresher sharks in Mexico waters was the Mexico drift gillnet (MXDGN) fishery, which started in 1986. The fishing gear and operations of this fishery were similar to the USDGN fishery, with swordfish and pelagic sharks as the primary targets. The number of MXDGN vessels began to decline in the mid-1990s as vessels began converting to longline gear. The MXDGN fishery has been prohibited since 2010 by Mexico federal regulations. The Mexico artisanal (MXART) fishery operates from small boats called pangas, using various nearshore gears that are set and hauled by hand, along the entire Pacific coast of Mexico. The history of this fishery is poorly known but it has likely existed since the early 20th century. Only a small portion of pangas are allowed to fish for sharks. For example, there were 50 shark permits for this fishery in Baja California in 1998, representing about 180 out of more than 2000 pangas in total.

There are no historical nor current fisheries along the west coast of Canada that target common thresher sharks and bycatch appears to be rare. There are also no known historical nor current fisheries that target this stock of common thresher sharks in international waters and bycatch is expected to be minimal, given the largely coastal distribution of this population.

Fishery Removals

Fishery removals by eight fishing fleets based on country, fishing gear, and season were included in this assessment (Table ES.1). These included five USA fleets (F1: USDGN, F2: USDGNs2, F3: USSN, F4: USREC, and F5: USRECs2) and three Mexico fleets (F6: MXDGNLL, F7: MXDGNLLs2, and F8: MXART). The annual estimated removals for the eight fleets are shown in Fig. ES.1.

Estimates of USA commercial landings of common thresher sharks by gear during 1969 – 1980 and 1981 – 2014 were obtained from the CALCOM (http://calcomfish.ucsc.edu) and PacFIN (http://pacfin.psmfc.org) databases respectively. Several types of net gears in the databases could not be clearly separated into DGN and SN gears. The catch from these unidentified net gears were aggregated and then subdivided into DGN and SN gears based on the seasonal proportion of catch for DGN versus SN gears during representative periods. Some of the commercial landings for common thresher sharks were also likely recorded as unspecified sharks. A correction to the estimated removals by USA fisheries for this misreporting of species was performed by estimating the proportion of unspecified shark landings that was likely to be common thresher sharks. The proportion of common thresher sharks that were discarded at sea as dead fish was also estimated from observer records of the USDGN and USSN fisheries and used to expand the removals of the USDGN, USDGNs2, and USSN fleets.

Until recently, shark landings in Mexico were not reported by species. Therefore, the fishery removals for Mexico fisheries were estimated from annual reports of state-specific aggregated shark (tiburon) landings from the Instituto Nacional de Pesca (INAPESCA) that were available from 1976 through 2013. Subsequently, the proportion of common thresher sharks in the aggregated shark catch of the Pacific coast of Baja California was estimated for specific periods since 1976. The estimated common thresher shark catches were then separated into seasonal catches by the MXDGN, MXLL, and MXART fisheries. The estimated removals from 1976 – 2013 for each fleet were extrapolated to the 1969 – 1975 period and 2014 in order to match the

1969-2014 assessment period. All common thresher sharks caught were assumed to be retained by the Mexico fisheries.

Table ES.1. Description of fleets and abundance indices in the base case model.

Fleet ID	Short name	Fleet description
		Fleets with removals
F1	USDGN	USA swordfish/shark pelagic drift gillnet fishery for seasons 1, 3, and 4. Removals from USA miscellaneous fisheries for these seasons were included into this fleet.
F2	USDGNs2	USA swordfish/shark pelagic drift gillnet fishery for season 2. Removals from USA miscellaneous fisheries for season 2 were included into this fleet.
F3	USSN	USA nearshore set gillnet and small-mesh drift gillnet fishery for all 4 seasons.
F4	USREC	USA recreational fishery for seasons 1, 3, and 4. Catch units in number of fish.
F5	USRECs2	USA recreational fishery for season 2. Catch units in number of fish.
F6	MXDGNLL	Mexico swordfish/shark pelagic drift gillnet fishery for seasons 1, 3, and 4. Removals from the Mexico pelagic longline fishery for these seasons were included in this fleet.
F7	MXDGNLLs2	Mexico swordfish/shark pelagic drift gillnet fishery for season 2. Removals from the Mexico pelagic longline fishery for this season were included in this fleet.
F8	MXART	Mexico coastal artisanal fishery with mixed gillnet and longline gears. Also known as the panga fishery.
		Abundance indices input as surveys
S1	USDGN8284	Standardized annual index of relative abundance of sub-adult/adult common thresher sharks based on logbooks from the USA swordfish/shark pelagic drift gillnet fishery during 1982 – 1984.
S2	USDGN9200	Standardized annual index of relative abundance of sub-adult/adult common thresher sharks based on logbooks from the USA swordfish/shark pelagic drift gillnet fishery during 1992 – 2000.
S3	USDGN0113	Standardized annual index of relative abundance of sub-adult/adult common thresher sharks based on logbooks from the USA swordfish/shark pelagic drift gillnet fishery during 2001 – 2013.
S4	USSN8593	Standardized annual index of relative abundance of primarily age-0 common thresher sharks based on logbooks from the USA nearshore set gillnet and small-mesh drift gillnet fishery during 1985 – 1993.
S5	USSN9414	Standardized annual index of relative abundance of primarily age-0 common thresher sharks based on logbooks from the USA nearshore set gillnet and small-mesh drift gillnet fishery during 1994 – 2014.
S6	USJUV0614	Standardized annual index of relative abundance of juvenile common thresher sharks from a coastal longline survey conducted by the Southwest Fishery Science Center during 2006 – 2014.

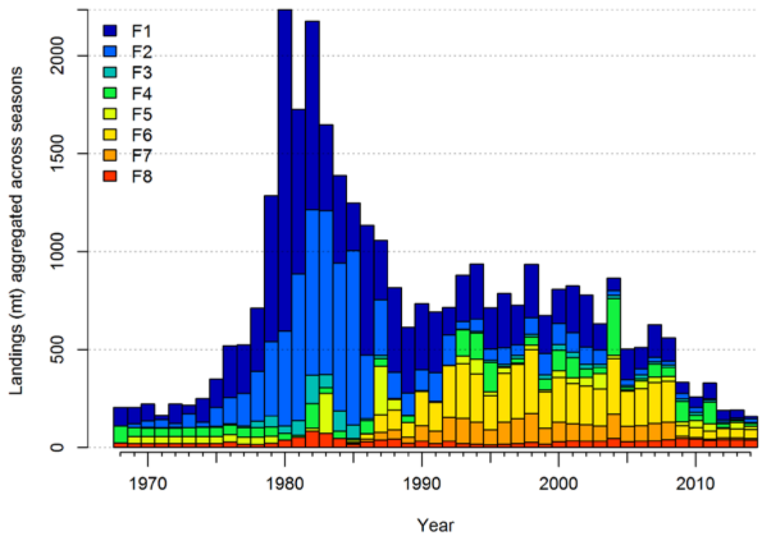

Figure ES.1. Estimated annual fishery removals by fleet. See Table ES.1 for a description of the fleets.

Data and Assessment

The Stock Synthesis modeling platform (v3.24U) was used to conduct the analysis and estimate management quantities. The base case model began in 1969, assuming that the stock was at equilibrium prior to 1969 in a near unfished state, and ended in 2014, which was the last year that data were available. Each fishing year was divided into 4 seasons (1: Feb-Apr; 2: May-Jul; 3: Aug-Oct; and 4: Nov-Jan). The assessment model was sex-specific due to differences in biology between genders and assumed that the sex ratio at birth was 1:1. Sex-specific growth was estimated within the model. A low fecundity stock-recruitment relationship was used in the model because common thresher sharks produce only a few pups per litter, with relatively little variability in litter size, and pups are born at a relatively large size, which suggested that common thresher sharks have lower potential productivity and a more direct connection between stock size and recruitment than for teleosts. The shape parameter, β, of the stock-recruitment relationship was also estimated within the model.

The model included eight fishing fleets that operated in USA and Mexico waters (see above in Fishery Removals and Table ES.1). Five abundance indices from fishery-dependent fisheries and one abundance index from a fishery-independent survey were available (Table ES.1). However, the survey abundance index (USJUV0614) was not fit in the base case model. Length composition data were available for the majority of the fleets and were fit in the base case model, with the exception of the MXDGNLL fleet. Conditional age-at-length data from two USA fleets (USDGN and USSN) were also fit in the base case model.

A large number of alternative model configurations were investigated to develop the base case model, which provided a realistic but parsimonious description of common thresher shark population dynamics based on the best available scientific information. The base case model reflected the best aspects of these exploratory models. Overall, the base case model appeared to have converged to a global minimum; while fitting the observed data well, with plausible model processes and parameters that were within reasonable bounds.

Major changes from the 2016 assessment

The first stock assessment of common thresher sharks along the west coast of North America that incorporated information from all fisheries exploiting the population throughout its distribution was conducted in 2016. This study is an update of the 2016 assessment, in response to the recommendations from a Center of Independent Experts (CIE) review panel. Major changes to the reproductive biology, natural mortality (*M*), and stock-recruitment parameters resulted in a stock with substantially lower productivity. It may be useful to think of these two assessments as bracketing the possible population dynamics of the stock, with the 2016 and this study representing a moderately productive and a highly unproductive shark stock respectively.

The reproductive biology of this stock was a major axis of uncertainty in the 2016 assessment. The 2016 assessment used the reproductive biology parameters from a previous study on this stock that reported an age of maturity of 5 y and an annual reproductive cycle with four pups per cycle. However, the reproductive biology of this stock was re-evaluated and the conclusions of the previous reproductive biology study were considered to be uncertain due to: 1) potential mis-identification of pelagic thresher sharks as common thresher sharks, and 2) inconsistency between observers' records on the presence of egg capsules or fetuses, and subsequent examination of the same specimens. Therefore, the CIE panel recommended that the 2016 assessment be updated to use the reproductive biology of the northwest Atlantic stock, with a length at 50% maturity of 215.1 cm FL (~age-13) for female sharks and a biennial reproductive cycle with four pups per cycle (i.e., 2 pups y^{-1}).

The change in reproductive biology parameters interacted strongly with the *M* and stock-recruitment parameters. After closely examining a suite of alternative models, and based on the recommendations of the CIE panel, the base case model used an *M* of 0.04 y^{-1}; and a low fecundity stock-recruitment function with z_{frac} fixed at 0.5 and an estimated β. There was concern that the *M* was unreasonably low but given the reproductive biology, a very low *M* and a z_{frac} of around 0.5 were required to obtain a converged model with reasonable model fit and diagnostics. Data and model structure of this assessment were considered reasonable by the CIE panel and were otherwise identical to the 2016 assessment.

Reproductive Capacity and Output

In this assessment, the reproductive capacity of the population was calculated as the number of mature female sharks (i.e., spawning abundance) rather than spawning biomass, because the size of mature female sharks did not appear to affect the number of pups produced (i.e., larger female sharks did not produce more pups). The reproductive output of the stock (i.e., the number of pups produced by the stock) in the base case model was calculated using two pups produced per year per mature female shark.

In the base case model, the estimated number of mature female common thresher sharks under unfished conditions was 220,000 sharks (95% CI: 125,600 – 314,300 sharks) with a reproductive output of 439,900 pups (95% CI: 251,300 – 628,600 pups) (Fig. ES.2). The start of targeted commercial fishing in 1977 – 1978 was quickly followed by a large increase in fishery removals, peaking in the early 1980s (Fig. ES.1). These relatively large removals resulted in the number of mature female sharks declining steadily over the next 3 decades. Although management actions to reduce fishing mortality on this stock began soon after the start of targeted commercial fishing, the effect of these actions on the adult population took a long time to show up because of the very low natural mortality and age structure assumed in the base case model. The historical low estimate occurred in 2006, with 116,900 mature female sharks (95% CI: 39,200 – 194,600 sharks). After 2006, the reproductive capacity gradually increased over the most recent decade. In 2014, the terminal year of the assessment model, the estimated number of mature female sharks reached 136,800 sharks (95% CI: 32,000 – 241,600 sharks) with a reproductive output of 273,600 pups (95% CI: 64,000 – 483,300 pups) (Table ES.2).

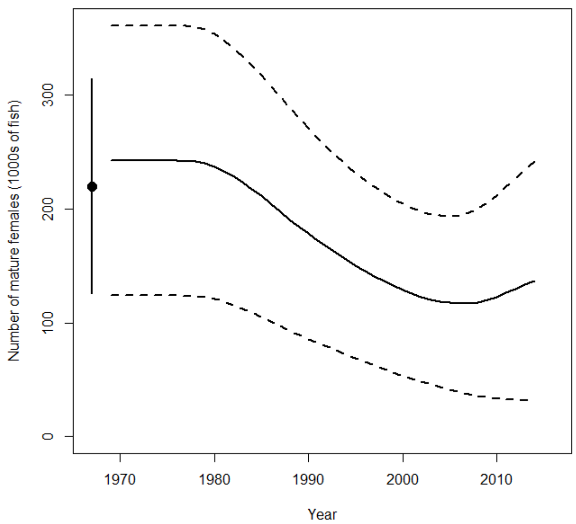

Figure ES.2. Estimated number of mature female sharks in Q2 (Feb – Apr). Dashed lines indicate 95% confidence intervals; and closed circle and error bar indicate estimated quantities and 95% confidence intervals under unfished conditions, respectively.

Depletion of the stock was estimated as the number of mature females in the second quarter (*S*) for a specific year divided by the number of mature females under unfished conditions (S_0) because the reproductive output of the stock (i.e., number of pups produced) was dependent on

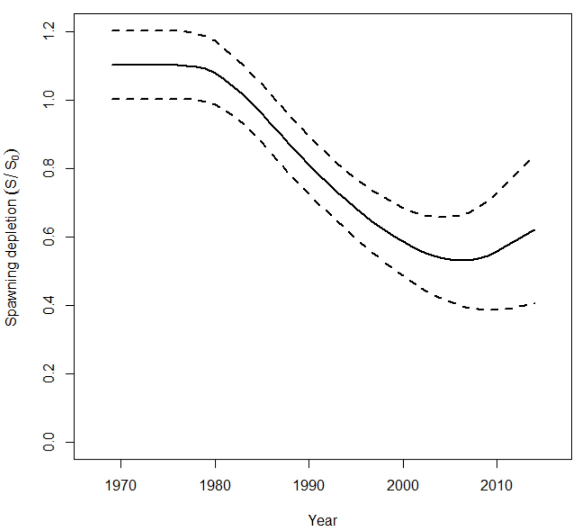

Figure ES.3. Estimated depletion of the stock (S/S_0). Dashed lines indicate 95% confidence intervals.

the number of mature females and not on the biomass of the female sharks. Therefore, the estimated depletion followed the same trajectory as the number of mature female sharks, albeit scaled to S_0 (Fig. ES.3).

Table ES.2. Recent estimates of total biomass (Q1, age-1+), biomass and number of mature female sharks in Q2, depletion (S/S_0), recruitment, and fishing intensity (1-SPR) estimated in the base case model. Reproductive output in number of pups was 2 * number of mature females.

Year	Total biomass age-1+ (t)	Biomass of mature female sharks (t)	Number of mature female sharks (1000s)	Depletion (S/S_0)	Number of recruits (1000s)	Fishing intensity (1-SPR)
2005	62027	21866	117.4	0.53	28.8	0.28
2006	62755	21681	116.9	0.53	88.0	0.27
2007	64337	21627	117.1	0.53	72.7	0.30
2008	66009	21711	118.2	0.54	50.9	0.28
2009	67732	21945	120.1	0.55	66.1	0.18
2010	70057	22324	122.8	0.56	69.1	0.14
2011	72737	22818	126.1	0.57	50.1	0.15
2012	75277	23382	129.7	0.59	73.7	0.10
2013	78378	23968	133.3	0.61	27.2	0.10
2014	80961	24566	136.8	0.62	52.6	0.09

Recruitment

The estimated recruitment and stock-recruitment relationship were generally consistent with the biology of the stock and assumptions in the base case model. Note that the recruitment is not equivalent to the reproductive output (number of pups produced) of the stock because the pups were assumed to experience density-dependent pre-recruit survival processes before recruiting to the stock.

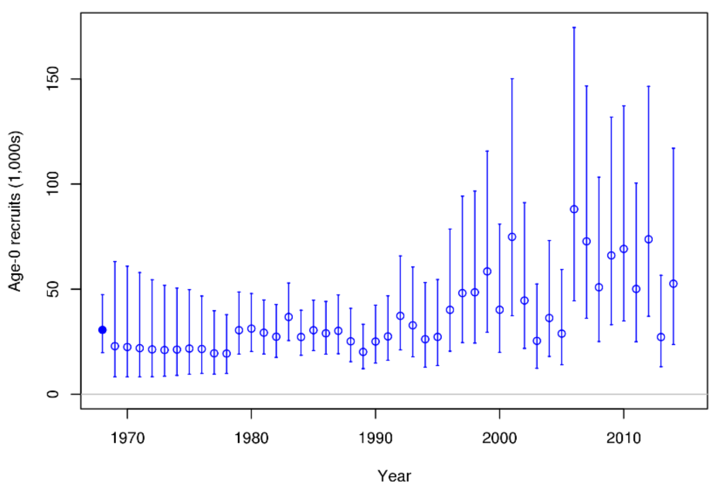

Figure ES.4. Estimated recruitment time series in the base case model. Error bars indicate 95% confidence intervals; and closed circle indicates recruitment under unfished conditions, respectively.

Unfished recruitment was estimated to be 30,600 sharks ($\log(R_0)$ = 3.421). The estimated recruitment fluctuated substantially during the assessment period (1969 – 2014), ranging from a low of 19,400 sharks (95% CI: 6,000 – 32,800 fish) in 1978 to a high of 88,000 sharks (95% CI:

25,900 – 150,200 fish) in 2006 (Fig. ES.4). Overall average recruitment during the assessment period was approximately 37,000 sharks but there appeared to be a period of relatively low recruitment during 1985 – 1995, with average recruitment at 28,300 sharks. In contrast, a more recent period during 2006 – 2012 had substantially higher recruitment, averaging approximately 67,200 sharks.

Reference Points

The current USA fishery management plan for USA West Coast fisheries associated with highly migratory species uses status determination criteria (SDC) for common thresher sharks that are based on maximum sustainable yield (MSY). Overfishing is declared to be occurring if the estimated current fishing mortality or a reasonable proxy exceeds the maximum fishing mortality threshold (MFMT) defined as F_{MSY} or reasonable proxy. The stock is declared in an overfished condition if current spawning biomass is less than the minimum stock size threshold (MSST), which is defined as $(1-M)*B_{MSY}$ or appropriate proxy, when $M \leq 0.5$ and M is the instantaneous rate of natural mortality. Based on an unpublished assessment of the USA portion of the stock, a harvest guideline of 340 t was established using the alternative optimum yield (OY) control rule for vulnerable species (i.e., 0.75*MSY).

Table ES.3. Estimated reference points for the base case model.

	Estimate (95% CI)	**Units**
Unfished conditions		
Number of mature female sharks (spawning abundance) (S_0)	220.0 (125.6 – 314.3)	1000s of sharks
Reproductive output	439.9 (251.3 – 628.6)	1000s of pups
Summary biomass at age-1+ (B_0)	103.5 (58.5 – 148.5)	Metric tons
Recruitment at age-0 (R_0)	30.6 (17.1 – 44.1)	1000s of sharks
MSY-based reference points		
MSY	717.7 (354.9 – 1080.4)	Metric tons
Number of mature female sharks at MSY (spawning abundance) (S_{MSY})	101.5 (58.5 – 148.5)	1000s of sharks
Minimum stock size threshold (MSST) $(1-M)*S_{MSY}$	97.5 (50.7 – 144.2)	1000s of sharks
Reproductive output at MSY	203.0 (105.7 – 300.4)	1000s of pups
Fishing intensity at MSY ($1-SPR_{MSY}$)	0.45 (0.42 – 0.49)	NA

For the base case model of this assessment, the estimated MSY for this stock was 717.7 t (95% CI: 354.9 – 1080.4 t), and the number of mature female sharks at MSY was estimated to be 101,500 sharks (95% CI: 58,500 – 148,500 sharks), with a reproductive output of 203,000 pups (95% CI: 105,700 – 300,400 pups) (Table ES.3). The fishing intensity (1-SPR; where SPR is the spawning potential ratio) corresponding to MSY was estimated at 0.45 (95% CI: 0.42 – 0.49). Based on these estimates, the MFMT was 0.45 (using $1 - SPR_{MSY}$ as a proxy for F_{MSY}) and the MSST was 95,500 mature female sharks (using S_{MSY}, the number of mature female sharks at MSY, as a proxy for B_{MSY}).

Status of the Stock

The estimated fishing intensity (1-SPR) on common thresher sharks off the west coast of North America is currently relatively low at 0.097 (average of 2012 – 2014) and substantially below the estimated overfishing threshold (MFMT), with (1-SPR_{1214})/(1-SPR_{MSY}) at 0.21 (Table ES.4 and Fig. ES.5). Similarly, the estimated number of mature female sharks in 2014 (S_{2014}) for this stock is at 62% of its unexploited level and is substantially larger than the estimated MSST, with S_{2014}/MSST at 1.40 (Table ES.4 and Fig. ES.5). Thus, this stock of common thresher sharks is unlikely to be in an overfished condition nor experiencing overfishing.

The stock began declining soon after the onset of the USA swordfish/shark drift gillnet fishery in the late 1970s. The stock was relatively slow to respond to management measures because of slow maturity and very low natural morality. Spawning depletion reached a minimum of 0.53 in 2006. However, the population has begun to recover slowly but steadily since 2006.

Uncertainty

This assessment explicitly estimated the model uncertainty due to parameter uncertainty, which was reported as confidence intervals for key parameters and management quantities. In addition, a suite of sensitivity runs was used to explore the uncertainty associated with alternative model specifications and examine the sensitivity of important model outputs to different model assumptions. These included alternative assumptions about fishery removals, initial conditions, stock-recruitment, life history like *M*, growth, maturity, and fecundity; as well as alternative data sources and weightings. The most important sources of uncertainty were related to the reproductive biology and stock-recruitment relationship of the stock.

Besides the base case model, the status of the stock was also examined under three alternative states of nature, based on alternative life history assumptions recommended by the CIE review panel. These alternative states of nature addressed the most important sources of uncertainty identified in the sensitivity analysis. The estimated management quantities from models assuming these alternative states of nature all indicated that this stock of common thresher sharks is unlikely to be in an overfished condition nor experiencing overfishing (Table ES.4 and Fig. ES.6).

Decision Table

Given the recommendations of the CIE review panel and large uncertainties in the reproductive biology, *M*, and stock-recruitment parameters of this stock, we did not perform quantitative stock projections. Therefore, this stock assessment of common thresher sharks along the west coast of North America does not include future projections of the base case model, and a decision table is not provided. However, the current low catch coupled with the estimated current status and population dynamics for the base case model and alternative states of nature suggest that the adult population is expected to continue increasing and stock depletion is expected to continue improving over the next several years, if future catch remain around current low levels.

Research and Data Needs

In this stock assessment, several critical assumptions were made based on limited supporting data and research. There are several research and data needs that if satisfied could improve future assessments, including:

1. Further research on the reproductive biology of this stock of common thresher sharks.
2. Further research into the use of the low fecundity stock recruitment relationship.
3. Re-examination and improvements in the survey design and protocols of the USA juvenile thresher shark survey.
4. Improved catch and catch-at-size estimates from USA fisheries, especially the USA recreational fishery.
5. Improved catch and catch-at-size estimates from Mexico fisheries.

Table ES.4. Summary of reference points and management quantities for the base case and three alternative states of nature. C_{2014} is the estimated fishery removals in metric tons in 2014. 1-SPR_{1214} is the average of the estimated fishing intensity (1-SPR) from 2012 through 2014. Key management quantities for the USA fishery management plan are in bold. Under the current USA fishery management plan, this stock is considered to be in an overfished state if S_{2014}/MSST is <1. Overfishing is considered to be occurring if (1-SPR_{1214})/(1-SPR_{MSY}) is >1.

	Base case (Biennial reproductive cycle; M = 0.04 y^{-1}; z_{frac} = 0.5)	**Alternative life history (Biennial reproductive cycle; M = 0.08 y^{-1}; z_{frac} = 0.5)**	**Alternative life history (Annual reproductive cycle; M = 0.08 y^{-1}; z_{frac} = 0.5)**	**Alternative life history (Annual reproductive cycle; M = 0.10 y^{-1}; z_{frac} = 0.5)**
MSY (t)	717.7	911.9	726.5	893.1
Number of mature female sharks at MSY (S_{MSY}) (1000s of sharks)	101.5	92.7	48.2	53.3
Number of mature female sharks under virgin conditions (SB_0) (1000s of sharks)	220.0	169.5	98.8	100.8
Minimum stock size threshold (MSST) (1-M)*S_{MSY}	97.5	85.2	44.4	47.9
Fishing intensity at MSY (1-SPR_{MSY})	0.453	0.351	0.411	0.368
C_{2014}/MSY	0.224	0.176	0.221	0.180
S_{2014}/S_{MSY}	1.348	1.411	1.323	1.476
S_{2014}/S_0	0.622	0.771	0.646	0.780
S_{2014}/MSST	1.404	1.534	1.438	1.640
(1-SPR_{1214})/(1-SPR_{MSY})	0.214	0.153	0.216	0.164

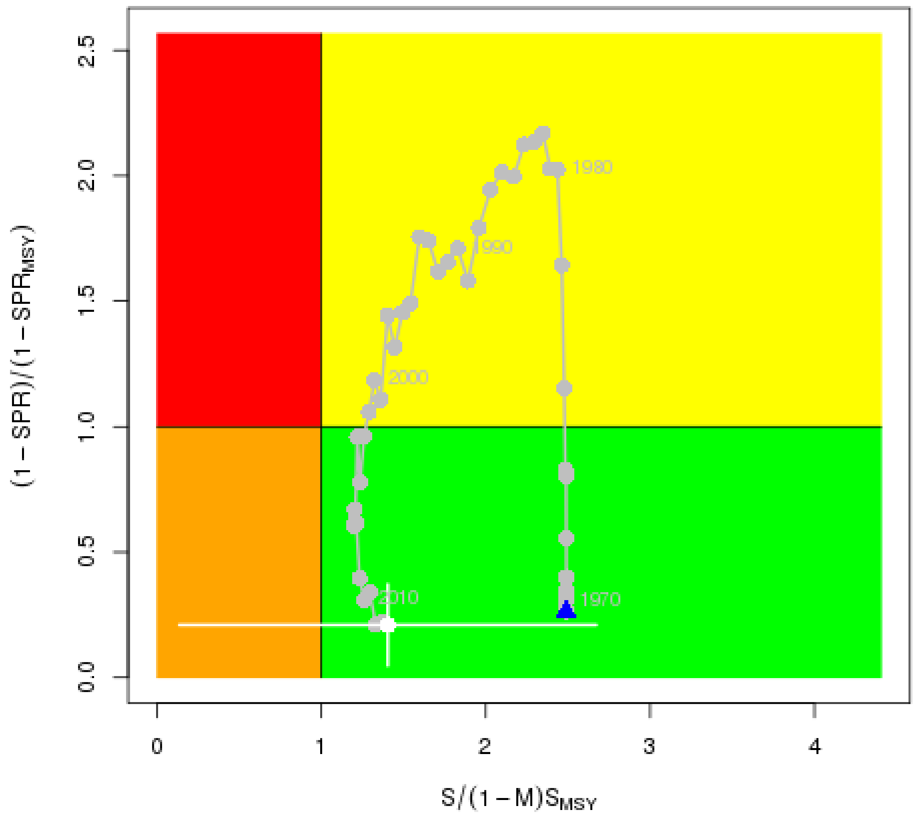

Figure ES.5. Kobe time series plot of the ratio of spawning abundance (S; number of mature female sharks) relative to the minimum stock size threshold reference point (MSST; (1-M)*S_{MSY}) and ratio of the fishing intensity (1-SPR) relative to the maximum fishing mortality threshold (MFMT; 1-SPR_{MSY}) for the base case model. Values for the start (1969) and end (2014) years are indicated by blue triangle and white circle, respectively. White lines indicate the 95% confidence intervals. Grey numbers indicate selected years.

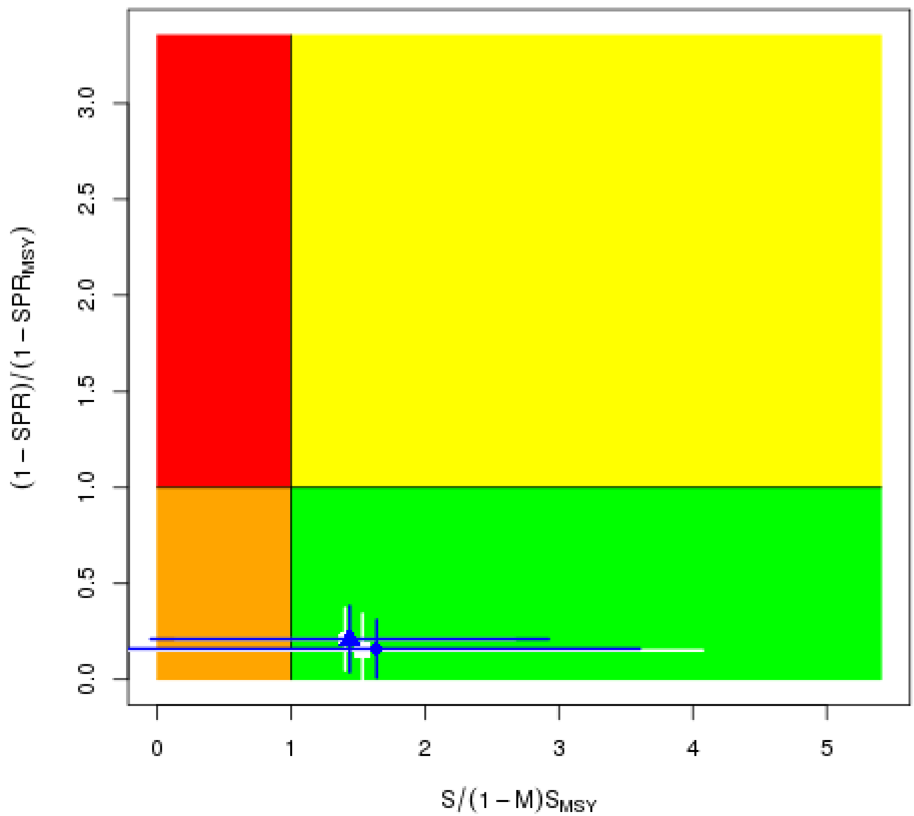

Figure ES.6. Kobe plot of the ratio of spawning abundance (S; number of mature female sharks) relative to the minimum stock size threshold reference point (MSST; (1-M)*S_{MSY}) and ratio of the fishing intensity (1-SPR) relative to the maximum fishing mortality threshold (MFMT; 1-SPR_{MSY}) for the end year (2014) of the base case model (white circle) and three alternative states of nature: 1) biennial reproductive cycle (i.e. 2 pups y^{-1}), natural mortality of 0.08 y^{-1}, and z_{frac} of 0.5 (white square); 2) annual reproductive cycle (i.e. 4 pups y^{-1}), natural mortality of 0.08 y^{-1}, and z_{frac} of 0.5 (blue triangle); and 3) annual reproductive cycle, natural mortality of 0.10 y^{-1}, and z_{frac} of 0.5 (blue diamond). White and blue lines indicate the respective 95% confidence intervals.

1. Introduction

There are three recognized species of thresher sharks around the world's oceans: 1) common (*Alopias vulpinus*); 2) bigeye (*A. superciliosus*); and 3) pelagic (*A. pelagicus*) thresher sharks. These three species are distinguished by the highly elongated dorsal lobe of their caudal fins, which approaches their body length (Compagno 1984). Thresher sharks typically feed on schooling fishes and squids (Preti et al. 2012), using their long caudal fin as a whip to stun and kill prey (Aalbers et al. 2010). All three species are caught by various international and USA fisheries, and are highly regarded for human consumption.

Common thresher sharks can be easily distinguished from bigeye thresher sharks but pelagic thresher sharks have been misidentified as common thresher sharks (Smith et al. 2008a; Romanov 2015). Bigeye thresher sharks are distinguished by very large eyes that have orbits that expand onto the dorsal surface of the head, and a deep horizontal groove on the side of the head (Compagno 1984). Common thresher sharks are distinguished by labial folds around the mouth, and a difference in skin color above the base of the pectoral fin (Compagno 1984).

All three species of thresher sharks are large pelagic sharks but exhibit differences in distribution, and are thought to have different ecological niches (Smith et al. 2008a). Common and bigeye thresher sharks are distributed circumglobally in the Atlantic, Indian, and Pacific Oceans and the Mediterranean Sea, while pelagic thresher sharks are restricted to the Indian and Pacific Oceans (Gruber and Compagno 1981; Compagno 1984). Compared to bigeye and pelagic thresher sharks, common thresher sharks are relatively coastal, occurring primarily within 40-75 miles of land, over continental and insular shelves and slopes, and occupy cooler, more temperate waters (Compango 1984; Smith et al. 2008a). Pelagic thresher sharks are distributed primarily in warmer, oceanic waters but misidentification of pelagic thresher sharks as common thresher sharks have resulted in less reliable habitat distribution information (Smith et al. 2008a; Romanov 2015). Bigeye thresher sharks are thought to exploit deeper waters in warm temperate and tropical areas, making forays into mesopelagic depths to at least 500 m (Smith et al. 2008a).

A harvest guideline of 340 t is currently in place for common thresher sharks in USA waters, based on an unpublished population growth rate (PGR) analysis using only data from USA fisheries (PFMC 2003). The PGR analysis resulted in an estimated local maximum sustainable yield (LMSY) of 450 t, which was in turn converted into an optimum yield (OY) for vulnerable species (defined as 0.75*MSY or reasonable proxy) (PFMC 2003). However, the LMSY was considered to be a minimal estimate because the analysis did not include any information from Mexico fisheries exploiting the same population (PFMC 2003). The PGR analysis was dependent on estimates of the intrinsic rate of increase for common thresher sharks, which indicated that common thresher sharks were likely to be moderately productive with productivity similar to blue and shortfin mako sharks (Smith et al. 2008b). The PGR analysis also assumed that the population was at an unfished state in 1981 (start of the CPUE series) even though the largest commercial fishery for this stock of common thresher shark began in 1977 – 1978 (Hanan et al. 1993). Given the drawbacks of the PGR analysis, a collaboration was initiated between scientists from the USA and Mexico to conduct a stock assessment of this common thresher shark population throughout its entire distribution along the west coast of North America.

Teo et al. (2016) conducted the first stock assessment of common thresher sharks along the west coast of North America that incorporated information from all fisheries exploiting the population throughout its distribution. This study is an update of that assessment, in response to recommendations from a Center of Independent Experts (CIE) review panel (Appendix A). Teo et al. (2016) identified the reproductive biology of this stock as a major axis of uncertainty, with Smith et al. (2008b) reporting an age of maturity of 5 y and an annual reproductive cycle with four pups per litter. In preparation for the review, Aryafar et al. (2017; Appendix B) re-evaluated the reproductive biology of this stock and concluded that the conclusions of Smith et al. (2008b) were uncertain due to: 1) potential misidentification of pelagic thresher sharks as common thresher sharks; and 2) inconsistency between observers' records on the presence of egg capsules or fetuses, and subsequent examination of the same specimens. In addition, the CIE review panel provided a recent working paper (Romanov 2015) from the Food and Agricultural Organization of the United Nations (FAO) that suggested pelagic thresher sharks were also commonly misidentified as common thresher sharks in the tropical Indian Ocean. Therefore, the CIE panel recommended that the 2016 assessment be updated, using the reproductive biology reported by Natanson and Gervelis (2013) for the northwest Atlantic stock, with a length at 50% maturity ($L_{50\%}$) of 215.1 cm FL (~13 y) and a longer reproductive cycle (biennial or triennial) with four pups per cycle (i.e., 2 pups y^{-1}) (Section 2.3.1).

1.1 Distribution, biology, and life history

1.1.1 Distribution and seasonal movements

Along the west coast of North America, common thresher sharks are seasonally distributed in coastal waters from British Columbia, Canada to central Baja California, Mexico. The highest concentration of common thresher sharks occurs in the Southern California Bight (SCB), which extends from Point Conception, California to Cabo Colonet, Mexico (Hanan et al. 1993; Smith et al. 2008a). The horizontal distributions of common and bigeye thresher sharks are thought to overlap partially, with bigeye thresher sharks generally exploiting deeper waters (Smith et al. 2008a). In contrast, there is relatively little overlap in the distributions of common and pelagic thresher sharks, except for years with strong El Nino-Southern Oscillation (ENSO) conditions, when the distribution of pelagic thresher sharks shifts northwards (Smith et al. 2008a).

Seasonal movements of common thresher sharks are not well known but they are thought to move north from Baja California into Southern California in early spring (Hanan et al. 1993). Large adult sharks are hypothesized to continue northward to as far as British Columbia, with the reverse movement occurring in winter (Hanan et al. 1993). Juvenile sharks tend to remain in shallow, nearshore areas over the continental shelf, especially within the SCB, which is an important nursery area (Holts and Bedford 1989; Cartamil et al. 2010).

1.1.2 Stock structure

In this assessment, common thresher sharks along the west coast of North America are assumed to be a single, well mixed stock, which is supported by their genetics and seasonal movements. Trejo (2005) analyzed a 1,082 bp segment of the mitochondrial DNA control region and found that common thresher sharks from California waters were not significantly different from sharks in Oregon-Washington waters but both were significantly different from all other common thresher shark stocks, noting that there were no samples from Mexico. In addition, there is no evidence of pupping and nursery grounds outside of the SCB, and common thresher sharks migrate seasonally along the coastal waters from Baja California to as far north as British Columbia, Canada (Smith et al. 2008a). Limited tagging data also support the assumption that this is a local population of common thresher sharks limited to the coastal waters of the west coast of North America (Cartamil et al. 2010; Cartamil et al. 2011a). There is also unlikely to be substantial interchange of individuals between this stock and other common thresher shark stocks because the geographically closest stock is likely to be along the west coast of Chile. Due to species misidentification, thresher sharks previously reported as common thresher sharks from many other parts of the Pacific Ocean have turned out to be pelagic thresher sharks after using genetic tools to identify the species (J. Hyde, Southwest Fisheries Science Center, NOAA Fisheries, pers. comm.; Velez-Zuazo et al. 2015).

1.1.3 Reproductive biology

Common thresher sharks are ovoviviparous, where after the absorption of the yolk sac, developing fetuses consume eggs still developing in the uterus (Smith et al. 2008a). The reproductive cycle is seasonal, with mating thought to occur in summer and pupping occurring in spring after a gestation period lasting 9 months (Smith et al. 2008a). Common thresher sharks have small litter sizes, usually giving birth to two to four pups (Gubanov 1978; Cailliet et al. 1983; Bedford 1992; Natanson and Gervelis 2013) but litter sizes of up to seven have been recorded off Spain (Moreno et al. 1989).

Previous studies on the reproductive biology of common thresher sharks have resulted in inconsistent conclusions about their fecundity. Smith et al. (2008b) thought that common thresher sharks in the eastern North Pacific produced two female pups per year (i.e., an annual reproductive cycle with four pups per litter, assuming an equal sex ratio at birth), when they estimated intrinsic rates of increase for several pelagic shark species. This was supported by Castro (2009), who suggested that thresher sharks exhibited an annual reproductive cycle based on concurrent vitellogensis and gestation coupled with continuous ovulation. However, Natanson and Gervelis (2013) suggested that common thresher sharks in the western North Atlantic had a biennial or triennial reproductive cycle with an average litter size of 3.7 pups.

There also appear to be substantial differences in the estimated median age and size of maturity between common thresher sharks in the eastern North Pacific and western North Atlantic Oceans. Smith et al. (2008a) estimated that the female common thresher sharks in the Pacific Ocean reach maturity at about 5.3 years of age (~160 cm FL). However, Natanson and Gervelis

(2013) estimated that the median age of maturity for female common thresher sharks in the western North Atlantic Ocean was 12 years of age (~216 cm FL). In an additional study from the eastern North Pacific Ocean in 1987, Bedford (unpublished) examined 207 common thresher sharks and found that the smallest mature female shark, based on the presence of embryos and/or egg capsules, was 217 cm FL.

Aryafar et al. (2017; Appendix B) subsequently re-evaluated the reproductive biology of this stock and found that the conclusions of Smith et al. (2008a) were uncertain due to: 1) potential misidentification of pelagic thresher sharks as common thresher sharks; and 2) inconsistency between observers' records on the presence of egg capsules or fetuses, and subsequent examination of the same specimens. Therefore, Aryafar et al. (2017; Appendix B) recommended that until further studies on the eastern North Pacific stock occurs, the age and size at maturity, and breeding periodicity for this stock should be based on Natanson and Gervelis (2013) even though that study was based on sharks from the western North Atlantic Ocean. The CIE review panel concurred with this recommendation, especially after considering that similar problems had occurred in the tropical Indian Ocean (Romanov 2015).

One major drawback of the Smith et al. (2008b) study was the dependence on fishery observers to identify the sampled species and to detect the presence of egg capsules and/or embryos in sampled reproductive tracts. A close examination of observer records showed that some thresher sharks were misidentified during data collection, the debriefing process, or both, and were only corrected subsequently through photographs or DNA analysis. However, photographs or DNA samples were not available for all the mature female samples in the Smith et al. (2008b) study. Importantly, no photographs or DNA samples were available for the five smallest female sharks with egg capsules or embryos, which were used to determine size-at-maturity by Smith et al. (2008b). Furthermore, 14 (including the 13 smallest) of the 19 sharks with eggs or embryos were collected in 1997, which was associated with strong ENSO conditions and the year with the largest recorded number of pelagic thresher sharks. The size of the five smallest mature female thresher sharks in the Smith et al. (2008b) study also coincided with the size of maturity of pelagic thresher sharks. Although there is no conclusive evidence that the samples used in the Smith et al. (2008b) study were misidentified, there is strong circumstantial evidence that some of samples may have been misidentified. In addition, seven out of the 19 sharks identified as mature in the Smith et al. (2008b) study were still available and re-examined by Aryafar et al. (2017, Appendix B). However, only two of the seven fish were positively identified to be mature by Aryafar et al. (2017, Appendix B), based on the presence of egg capsules or fetuses.

1.1.4 Growth

Common thresher sharks are large pelagic sharks with sexually dimorphic growth and intermediate to relatively rapid growth rates (Cailliet et al. 1983; Smith et al. 2008a; Gervelis and Natanson 2013). Sharks are aged by examining band pairs consisting of one opaque and one translucent band in vertebral cross-sections (Cailliet et al. 1983) and this aging method has been validated for juvenile common thresher sharks (Spear 2017). There have been three studies on the growth of common thresher sharks, with two in the eastern North Pacific Ocean (Cailliet et al. 1983; Smith et al. 2008a) and one in the western North Atlantic Ocean (Gervelis and Natanson 2013). The initial growth curves by Cailliet et al. (1983) lacked older, larger fish and resulted in high estimates of asymptotic length. Smith et al. (2008a) fitted additional age-length data to a von Bertalanffy growth curve and estimated the following parameters for male and female common thresher sharks – Male: L_∞ = 221.5 cm, K = 0.189 y^{-1}, and t_0 = -2.08 y; Female: L_∞ = 247.3 cm, K = 0.124 y^{-1}, and t_0 = -3.35 y, where L_∞ is the asymptotic length (FL), K is the growth rate coefficient, and t_0 is the theoretical age at length 0. Common thresher sharks in the western North Atlantic Ocean appeared to follow a relatively similar growth curve, albeit with slightly higher asymptotic lengths (Gervelis and Natanson 2013).

1.2 Historical and current fisheries in USA waters

The history of common thresher shark fisheries along the west coast of the USA is not well known prior to the 1970s but small amounts of catch were recorded by the California Department of Fish and Wildlife (CDFW) (Pearson et al. 2008). Prior to the 1970s, some species of sharks were exploited in the USA for food, vitamin-rich liver oil, pet food, leather, curios, and processing into protein and fertilizer but common thresher sharks did not appear to have been heavily exploited during that period (Holts 1988).

Demand for common thresher sharks as food began to increase in the mid-1970s on the west coast of the USA, along with other shark species like Pacific angel and shortfin mako sharks (Holts 1988). Ex-vessel prices for shark meat rose sharply due to this demand and common thresher sharks became one of several shark species with important west coast fisheries. For example, ex-vessel prices for thresher sharks rose several-fold between 1977 ($0.29 per pound; $1.13 per pound in 2014 dollars) and 1986 ($1.60 per pound; $3.46 per pound in 2014 dollars) (Holts 1988), which is substantially higher than the average price in 2014 ($0.82 per pound) (PFMC 2015).

The most important USA commercial fishery for common thresher sharks is the swordfish/shark drift gillnet (USDGN) fishery. Secondarily, nearshore set gillnets and small-mesh drift gillnets (USSN) occasionally catch young-of-year and juvenile common thresher sharks as bycatch. Common thresher sharks are also occasionally caught as bycatch by a variety of miscellaneous gears like purse seine and harpoon but catches are usually minimal. Some recreational fishermen in Southern California target adult common thresher sharks but catches are usually relatively low (PFMC 2015).

1.2.1 USA swordfish/shark drift gillnet (USDGN)

The most important commercial fishery for common thresher sharks is the USDGN fishery, which began in 1977 – 1978 (Hanan et al. 1993). The drift gillnet gear was inspired by the occasional catch of pelagic sharks in nearshore gillnets used to target barracuda and white seabass. The nets used by the USDGN fishery have larger mesh size than the nearshore gillnets, and regulations have required a minimum mesh size of 14 inches since 1982 (Hanan et al. 1993).

The USDGN fishery began with about 15 vessels in Southern California but the number of vessels grew rapidly (Hanan et al. 1993). By 1985, the number of California permits for the fishery totaled about 265, with about 35 of those permits limited to areas north of Point Arguello, California (PFMC 2003). Although the initial primary targets were common thresher and shortfin mako sharks, fishermen soon discovered that they could efficiently catch swordfish with the same gear and switched to primarily targeting swordfish because of substantially higher ex-vessel prices (Hanan et al. 1993). Since those early days, the primary target of the USDGN fishery has been swordfish, with common thresher and shortfin mako sharks being secondary targets.

The USDGN fishery expanded into Oregon and Washington in 1983, when these states began issuing experimental permits for a thresher shark fishery (PFMC 2003). Thresher shark landings for Oregon and Washington remained relatively low until 1986, when 37 vessels landed 293 t dressed weight of common thresher sharks. However, Oregon and Washington closed the experimental fishery in 1989 due to concern over the observed incidental bycatch of marine mammals and sea turtles (PFMC 2003).

Landings of common thresher sharks by the USDGN fishery peaked in 1982 at 1711 t (PFMC 2011a) and have declined since, dropping to approximately 10 t in 2014 (PFMC 2015). The number of USDGN vessels landing fish have also declined from 297 in 1985 (PFMC 2011a) to only 18 vessels by 2014 (PFMC 2015).

Fishing operations of the USDGN fishery have been heavily regulated to reduce adverse interactions with other fisheries, fishing mortality of common thresher sharks, and incidental bycatch of marine mammals and sea turtles (Hanan et al. 1993; PFMC 2003). The timeline of major changes in regulations and operations for the USDGN fishery can be found in Table 1.1. Details of current and historical regulations were provided by Hanan et al. (1993), PFMC (2003), and PFMC (2015). There appeared to be three major periods of fishery operations and regulations: 1) 1977 – 1991; 2) 1992 – 2000; and 3) 2001 – 2014. The first period (1977 – 1991) encompassed the initial expansion of the fishery and the switch from primarily targeting pelagic sharks to swordfish. There were also early attempts at regulating the fishery, which resulted in frequent changes in regulations that included gear restrictions, swordfish catch, swordfish to shark catch ratios, seasonal closures, and time-area closures (Table 1.1). In particular, time-area closures in California were enacted or modified in 1982, 1985, and 1989, which likely affected the catch-per-unit-effort (CPUE) of sharks for this fishery (Urbisci et al. 2016). Washington and Oregon also closed their drift gillnet fisheries in 1989. The time-area closures for the USDGN fishery were relatively stable during the second period (1992 – 2000), after the closure period for California was changed to May 1 through August 14 in 1992 (Table 1.1). The second period was a period of decline in the USDGN fishery, with the number of vessels landing fish declining from 119 in 1992 to 72 in 2000 (PFMC 2015). This decline continued in the third period (2001 – 2014), which was marked by the enactment of a large time-area closure in 2001 to protect leatherback turtles (Table 1.1). The number of vessels in the USDGN fishery landing fish declined from 61 in 2001 to 18 in 2014 (PFMC 2015).

1.2.2 USA nearshore set gillnet and small-mesh drift gillnet (USSN)

A secondary USA commercial fishery that catches common thresher sharks is the nearshore set gillnet and small-mesh drift gillnet (USSN) fishery in nearshore waters that target species like barracuda, white seabass, and halibut. The key differences between this fishery and the USDGN fishery are that the USSN fishery uses nets with smaller mesh size (typically <10 inches) and operates in shallow, nearshore waters. Most of the catch and effort of the USSN fishery centers around the SCB but some parts of the fishery operates in nearshore areas as far north as Mendocino, California.

The USSN fishery does not target common thresher sharks but occasionally catches common thresher sharks as bycatch. The USSN fishery predominantly catches young-of-year common thresher sharks because the continental shelf of the SCB is a nursery area for common thresher sharks (Cartamil et al. 2010).

In 1994, the California Marine Resources Protection Act of 1990 began prohibiting all gillnets and trammel nets within 3 nm of the California mainland and within 1 nm (or waters <70 fathoms deep) of the Channel Islands (Table 1.1). This resulted in the USSN fishery operating in slightly deeper waters since 1994.

1.2.3 USA recreational (USREC)

Common thresher sharks are targeted by the USA recreational fishery, especially in Southern California (Holts et al. 1998). Recreational fishing effort directed at large pelagic species, including sharks, is generally from anglers on Commercial Passenger Fishing Vessels (CPFVs) (Hill and Schneider 1999), as well as private vessels departing from sportfishing landings, marinas, and boat ramps. Almost all of the recreationally caught common thresher sharks are taken by anglers on private vessels (>99 %) rather than CPFVs. Captains of CPFVs are required to submit logbooks but not private vessels. Information on recreational fishing from private vessels is obtained using surveys, which are available in a comprehensive coastwide marine recreational fishery database (RecFIN; http://www.recfin.org). Information on common thresher sharks caught by anglers on private vessels is sparse.

1.3 Historical and current fisheries in Mexico waters

Subsistence fishing for sharks has historically been an important resource for rural communities along the Pacific coast of Mexico but commercial shark fishing in the Gulf of California developed during World War II to provide shark liver oil to the USA (Holts et al. 1998). Three Mexico fisheries have historically been or currently are important fisheries for common thresher sharks: 1) Mexico swordfish/shark drift gillnet (MXDGN); 2) Mexico pelagic longline (MXLL); and 3) Mexico artisanal (MXART) fisheries.

1.3.1 Mexico swordfish/shark drift gillnet (MXDGN)

Historically, the most important fishery for common thresher sharks in Mexico waters was the MXDGN fishery. A small fleet of MXDGN vessels began fishing for swordfish from Ensenada, Mexico in 1986, and the fleet increased to 31 vessels by 1993 (Holts and Sosa-Nishizaki 1998). Soon after that, the number MXDGN vessels began to decline as vessels began converting to longline gear in the mid-1990s. The MXDGN fishery has been prohibited since 2010 by federal regulations in Mexico (Sosa-Nishizaki 2013). Similar to the USDGN fishery, the primary and secondary targets were swordfish and pelagic sharks, respectively (Holts et al. 1998). The fishing gear and operations of this fishery were also similar to the USDGN fishery, except that nets in Mexico could extend to 4.8 km in length, whereas nets in the USA were limited to 1 nm (1.8 km). A 50 nm sportsfishing-only zone was established along the Mexico coast in 1983 but commercial fishing operations for sharks continued to be routinely conducted in this zone (Holts et al. 1998).

1.3.2 Mexico pelagic longline (MXLL)

Mexico and international pelagic longline fisheries have operated within 200 nm of the Mexico coast during various periods. From 1967 to 1976, Mexico issued permits to Japanese pelagic longline vessels to fish for swordfish, billfish, and tunas (Holts and Sosa-Nishizaki 1998). After Mexico established its Exclusive Economic Zone (EEZ) in 1976, all longline permits were withheld until 1980. From 1980 to 1990, a Mexico/Japan joint venture program for the longline fishery was established, which targeted swordfish, billfish, and tunas (Holts and Sosa-Nishizaki 1998). After the cessation of that program in 1990, no pelagic longline fishing occurred until the mid-1990s, when MXDGN vessels began converting to longline gear. Like the MXDGN fishery, the primary and secondary targets of the current MXLL fishery are swordfish and pelagic sharks, respectively. However, the pelagic sharks targeted are primarily blue and shortfin mako sharks instead of common thresher sharks.

1.3.3 Mexico artisanal (MXART)

The MXART fishery operates along the entire Pacific coast of Mexico, and fishes from small boats called pangas, which are small, open boats approximately 7-9 m long and powered by an outboard engine (Holts et al. 1998). Hence, the artisanal fishery is also often called the panga fishery. The history of this fishery is largely undocumented but it has likely existed throughout the 20th century and thought to have exceeded 2000 pangas by the late 1990s (Holts et al. 1998). Only a small portion of the pangas are permitted to fish for sharks. For example, Holts et al. (1998) stated that in the state of Baja California, there were 50 shark permits for this fishery in 1998, representing about 180 pangas. Pangas can range up to 40 km but usually fish closer to shore. A variety of gears are used, including gillnets and longlines, but the fishing gears are limited by the need to set and haul by hand. The MXART fishery is highly mobile and pangas can be easily trailered to other locations with better fishing or market prices. Given the nature of the MXART fishery, it is generally difficult to obtain data from this fishery.

1.4 Historical and current fisheries in Canadian and international waters

There are no historical nor current fisheries along the west coast of Canada that target common thresher sharks and bycatch of common thresher sharks appears to be rare (McFarlane et al. 2010). McFarlane et al. (2010) reported some bycatch of bigeye thresher sharks, which may have been misidentified common thresher sharks. However, further enquiry indicated that these reports of bigeye thresher shark bycatch were erroneous due to miscoded unidentified shark species (J. R. King, pers. comm.). There are also no known historical nor current fisheries that target this stock of common thresher sharks in international waters and bycatch is expected to be minimal, given the largely coastal distribution of this population.

1.5 Management history

Common thresher sharks have been managed in USA waters under the fishery management plan (FMP) for highly migratory species (HMS) by the Pacific Fishery Management Council (PFMC) (PFMC 2003; PFMC 2011b). A summary of major changes in the management history is shown in Table 1.1 and described in more detail in sections 1.2 and 1.3. Most important for this assessment is the implementation and changes to various time-area closures for the USDGN fishery in 1982, 1985, 1989, 1992, and 2001, and the USSN fishery in 1994, which likely affected the catchability and selectivity of these fisheries. Changes in the management and fishing operations of the Mexico fisheries probably also affected their catchability and selectivity but the lack of information on these fisheries, other than catch, during these periods precluded modeling such effects.

A harvest guideline of 340 t is currently in place for common thresher sharks in USA waters, based on an estimate of LMSY from an unpublished analysis (PFMC 2003). Since common thresher sharks are considered a vulnerable species with relatively low productivity, the harvest guideline is derived from the optimum yield (OY) for vulnerable species, which is defined as 0.75*MSY, or reasonable proxy. The maximum fishing mortality threshold (MFMT) for common thresher sharks is the ratio $F_{MFMT}/F_{MSY} = 1.0$, or an appropriate proxy. Therefore, the stock is considered to be experiencing overfishing if $F_{current}/F_{MSY} > 1.0$. The minimum stock size threshold (MSST) is the minimum biomass at which recovery measures are to begin. Since the common thresher shark has a natural mortality (*M*) of <0.5, $B_{MSST} = (1\text{-}M)^*B_{MSY}$, or reasonable proxy. Therefore, the stock is considered to be overfished if $B_{current} < (1\text{-}M)^*B_{MSY}$ or $B_{current}/(1\text{-}M)^*B_{MSY} < 1.0$. Landings of common thresher sharks by fisheries along the west coast of the USA have been less than the harvest guideline of 340 t since 1992 (PFMC 2015).

1.6 Response to CIE review panel

The CIE review panel met at NOAA's Southwest Fisheries Science Center in La Jolla, California during July 26 – 28, 2017 to review the stock assessment. The review panel agreed that the key uncertainty in the Teo et al. (2016) assessment was the reproductive biology of this stock, coupled with the interactions between the reproductive biology and important model parameters, especially *M* and stock-recruitment parameters (Appendix A). Based on this consideration and closely examining a suite of alternative models (Appendix C), the CIE review panel made several observations and recommendations. The most important recommendations and associated responses are listed below.

1) The review panel identified major uncertainties in the previously published reproductive biology of this stock from Smith et al. (2008b). The panel agreed with the conclusions of Aryafar et al. (2017; Appendix B) and recommended that the reproductive biology for the assessment be based on Natanson and Gervelis (2013) instead of Smith et al. (2008b), even though that study was based on the western North Atlantic Ocean stock.

   We agreed with this recommendation and the base case model is now based on the reproductive biology from Natanson and Geverlis (2013), with the following parameters: 1) length at 50% maturity: 215.1 cm FL; and 2) fecundity: 2 pups y^{-1} (i.e., biennial reproductive cycle with 4 pups per cycle) (Section 2.3.1).

2) The review panel identified important interactions between the reproductive biology parameters, and the natural mortality and stock-recruitment parameters. After closely examining a suite of alternative models, the panel recommended that the base case model use an M of 0.04 y^{-1} and the low fecundity stock-recruitment function (Taylor et al. 2013) with z_{frac} = 0.5 and an estimated β parameter (Section 3.4.2).

   Similar to the panel, we were concerned that M was unrealistically low but given the reproductive biology, a very low M and z_{frac} of around 0.5 were required to obtain a converged model with reasonable model fit and diagnostics. Therefore, the base case model in this assessment used the above parameters. In addition, several models with alternative parameterizations were developed as sensitivity models.

3) While the panel was confident of the resulting stock status, the panel was less confident of using the base case model to perform stock projections because of the large uncertainties in the reproductive biology, stock-recruitment, and natural mortality parameters.

   In response to this concern about projections, we have not provided quantitative information from projections in this assessment. Instead, we only provide information on the stock status under the current harvest guideline.

4) Data and model structure of this assessment were considered by the panel to be reasonable and adequate for determining stock status and providing management information. However, the panel recommended that several stock-recruitment functional forms be investigated in sensitivity runs. In addition, the panel recommended several avenues for future research, which may improve future assessments.

Given the panel's comments about the respective sources of data, no changes were made to the input data, relative to Teo et al. (2016). In addition, we used alternative stock-recruitment functional forms (i.e., Beverton-Holt) in sensitivity runs to determine if the assessment results were robust to this assumption. We agreed with the panel's recommendations on future research efforts, which are presented in the section on research and data needs (Section 11).

2. Assessment data

The data used for this assessment are summarized in Figure 2.1, and included both fishery-dependent and fishery-independent data. The time period of this assessment was 1969 – 2014 because recorded landings for USA fisheries were unreliable before 1969. In addition, total landings from 1969 through 1976 were relatively minimal before the development of the USDGN fishery. The data were divided into fishing years, which were defined as February 1 to January 31 because fishing operations for the USDGN fishery end on January 31. Each fishing year was further subdivided into four seasons of three months each (1: Feb-Apr; 2: May-Jul; 3: Aug-Oct; and 4: Nov-Jan). Data for the assessment included fishery removals (i.e., catch), abundance indices, length composition, and conditional age-at-length data. The fleet structure of the assessment model consisted of eight fleets based on country, fishing gear, and season; and six abundance indices. See subsections in this section and Table 2.1 for details on the fleet structure and nomenclature.

2.1 Fishery-dependent data

The USA fleets in the assessment model were based on the USDGN, USSN, and USREC fisheries. The catch from a variety of miscellaneous gears like purse seine and harpoon were added to that of the USDGN fishery because the catch was minimal and the size composition of the catch was unknown but assumed to be similar to the USDGN fishery. The USDGN and USREC fisheries were further subdivided into separate fleets for season 2, and seasons 1, 3, and 4 because preliminary examination of the size composition data indicated that large adult common threshers were caught by these fisheries in season 2, which is the pupping season. Therefore, the assessment model contained five USA fleets: F1: USDGN; F2: USDGN season 2 (USDGNs2); F3: USSN; F4: USREC; and F5: USREC season 2 (USRECs2) (Table 2.1).

The Mexico fleets in the assessment model were based on the MXDGN, MXLL, and MXART fisheries. However, the catches from the MXLL and MXDGN fisheries were combined because the only data available for the MXLL fishery was catch and anecdotal evidence suggested similarly sized common thresher sharks were caught by these fisheries. Similar to the USDGN fishery, the MXDGN fishery was subdivided into separate fleets for season 2, and seasons 1, 3, and 4. Therefore, the assessment model contained three Mexico fleets: F6: Mexico drift gillnet and longline (MXDGNLL); F7: MXDGNLL season 2 (MXDGNLLs2); and F8: MXART (Table 2.1).

2.1.1 Commercial removals

The estimated removals for the eight USA and Mexico fleets are shown in Table 2.2 and Figure 2.2.

2.1.1.1 USA fisheries

Estimates of commercial landings of common thresher sharks from 1981 through 2014 were obtained from the Pacific Fisheries Information Network (PacFIN), a regional fisheries database that manages fishery-dependent information in cooperation with USA West Coast state agencies, and NOAA Fisheries (http://pacfin.psmfc.org). Catch data were extracted by gear type and assigned to the fishing fleets used in the assessment. Several types of net gear recorded in PacFIN could not be clearly separated into USDGN and USSN gears. The catch from these net gears were aggregated and then subdivided into USDGN and USSN gears based on the seasonal proportion of catch for USDGN vs. USSN fisheries during three periods (1981-1985; 1986-1993; and 1994-2014). The largest amount of catch for these unknown net gears was 281 t for 1985 season 2, and the amount of catch for these unknown net gears was negligible after 1994. The catch from miscellaneous gears was added to the USDGN (F1) and USDGNs2 (F2) fleets.

Estimates of commercial landings of common thresher sharks from 1969 through 1980 were obtained from the CALCOM database (Pearson et al. 2008; http://calcomfish.ucsc.edu). The CALCOM database is the repository for commercial groundfish market sample data managed by the California Cooperative Groundfish Survey (CCGS). Since there were no commercial fisheries for common thresher sharks in Oregon and Washington prior to 1983, relying only on catch data from California for this early period was considered adequate for the assessment. The landings recorded in the CALCOM database were based on dressed weight, which were converted into round weights using the PacFIN conversion factor. The gear types in the CALCOM database (Net; Hook-and-Line; and Other) do not differentiate between USDGN and USSN fisheries. The seasonal proportions of catch for USDGN vs USSN fisheries during 1981-1985 were used to split the net catch for 1969-1980 into USDGN and USSN catch. The catch data from the hook-and-line and other gears were added to the USDGN (F1) and USDGNs2 (F2) fleets.

Some of the commercial landings for common thresher sharks were likely recorded as unspecified sharks (Pearson et al. 2008). A correction to the estimated removals by USA fisheries for this apparent misrecording was performed by estimating the proportion of unspecified shark landings that was likely to be common thresher sharks. We assumed that the proportion of common thresher sharks in the unspecified shark landings was the same as that for the specified sharks, and added the estimated amount of common thresher sharks in the unspecified shark catch to the estimated removals of the USDGN (F1), USDGNs2 (F2), and USSN (F3) fleets. In addition, we estimated the proportion of common thresher sharks that were discarded at sea as dead fish from observer records of the USDGN and USSN fisheries, which was then used that to expand the total removals of USDGN, USDGNs2, and USSN fleets to include dead discards.

2.1.1.2 Mexico fisheries

Until recently, shark landings in Mexico were not reported by species. Instead, shark landings were divided into two groups, "Tiburon" and "Cazon", based on length. Sharks larger than 150 cm TL were considered tiburon while sharks smaller than 150 cm TL were classified as cazon. Thresher sharks (or "zorro" in Spanish) are generally classified as tiburon. Since 2006, species-specific landings reports have been publicly available from the Mexican fisheries agency, Comision Nacional de Acuacultura y Pesca (CONAPESCA), through a website (http://www.conapesca.sagarpa.gob.mx/wb/cona/consulta_especifica_por_produccion) but all three species of thresher sharks are combined into a single category (Zorro).

For this assessment, the fishery removals for Mexican fisheries were therefore estimated from annual reports of state-specific aggregated shark (Tiburon) landings from the Instituto Nacional de Pesca (INAPESCA) that were available from 1976 through 2013. The southern extent of the distribution of common thresher sharks coincides approximately with the border between the Mexican states of Baja California and Baja California Sur, so catch data from only Baja California were used to estimate removals. Since common thresher sharks are only landed on the Pacific coast, the proportion of aggregated shark catch that comes from the Pacific coast of Baja California was estimated using statistics from the Mexican fisheries agency office in Ensenada, Mexico, and then used to estimate aggregated shark catches for the Pacific coast of Baja California.

Based on the work of Sosa-Nishizaki et al. (2002), Sosa-Nishizaki et al. (2008), and Cartamil et al. (2011a), we estimated the proportion of common thresher sharks in the aggregated shark catch of the Pacific coast of Baja California for specific periods since 1976. The estimated proportion of common thresher shark catch ranged from 0.06 in 1976 to a high of 0.2 in the mid-1980s, when the MXDGN fishery developed, before declining as the MXDGN fishery changed gradually to longline gear and was eventually prohibited. The estimated common thresher shark catch was then separated into monthly catch by the MXDGN, MXLL, and MXART fisheries based on the work of Sosa-Nishizaki et al. (2002), Sosa-Nishizaki et al. (2008), and Cartamil et al. (2011a). The estimated monthly catch was then aggregated into seasonal removals by the MXDGNLL (F6), MXDGNLLs2 (F7), and MXART (F8) fleets for the assessment.

The estimated removals from 1976 – 2013 for each fleet were extrapolated to the 1969 – 1975 period and 2014 in order to match the 1969 – 2014 assessment period. The 2014 seasonal catch was assumed to be the average of the 2011 – 2013 seasonal catch. The 1969 – 1975 seasonal catch was assumed to be the average of the 1976 – 1978 seasonal catch.

2.1.2 Recreational removals

Estimated removals of common thresher sharks by USA private vessel recreational anglers from 1981 through 2014 were obtained from the Recreational Fisheries Information Network (RecFIN) (http://www.recfin.org), which is a recreational fisheries database maintained by the Pacific States Marine Fisheries Commission. The RecFIN removal estimates are based on angler surveys in California, Oregon, and Washington. From 1980 through 2003, the angler survey data were provided in “waves”, which were bimonthly periods (e.g., Jan-Feb; Mar-Apr). Since the definition of seasons for this assessment was not consistent with these bimonthly periods, it was assumed that the removals within a bimonthly period were split equally between the two months in a single wave. Survey data after 2003 were provided on a monthly basis and did not require this assumption.

Estimates of common thresher shark removals by USA recreational anglers on CPFVs from 1969 through 2014 were obtained from the CPFV logbook database maintained by CDFW. The logbook data contained the daily species-specific catch of the CPFVs (Hill and Schneider 1999).

The seasonal removals by recreational anglers on private vessels and CPFVs were summed into the USREC (F4) and USRECs2 (F5) fleets. It should be noted that estimated removals for the USREC (F4) and USRECs2 (F5) fleets were in 1000s of fish rather than metric tons for all other fleets.

2.1.3 Abundance indices

Indices of relative abundance were derived from logbook data of the USDGN and USSN fisheries using generalized linear models (GLMs). Details and diagnostics of the GLMs used to derive the abundance indices for the USDGN and USSN fisheries can be found in Appendices D and E respectively. A delta-lognormal approach (Lo et al. 1992) was taken to explicitly account for proportion of sets having zero versus non-zero catch. A binomial GLM was used to estimate the expected probability of non-zero catch for a given set and a lognormal GLM was used to estimate the expected catch for a given set with non-zero common thresher shark catch. The binomial and lognormal GLMs were independent and the explanatory variables used in each GLM were not necessarily the same, except for the year factor, which was present in every GLM. A stepwise model selection process using Akaike’s Information Criteria (AIC) as the selection criteria was used. Uncertainty in each index was estimated by jack-knifing the data used to calculate the index. The abundance indices and corresponding uncertainty are shown in Table 2.3.

2.1.3.1 USA swordfish/shark drift gillnet fishery

The USDGN fishery is the most important fishery in this assessment, and primarily catches sub-adult and adult sharks. The abundance indices from this fishery are therefore expected to be the most important indices for this assessment.

Three indices representing different regulatory and operational periods were developed for the USDGN fishery: 1) 1982 – 1984 (S1); 2) 1992 – 2000 (S2); 3): 2001 – 2013 (S3). Changes in the regulations and fishery operations of this fishery have likely affected the catchability of this fishery (Urbisci et al. 2016). The most important regulatory changes occurred in 1982, 1985, 1989, 1992, and 2001, when time-area closures were implemented or changed. For this assessment, we did not attempt to account for the effect of these time-area closures in our GLMs.

Instead, we developed shorter time series within the periods when regulatory changes were likely less important. Logbook data for 2014 were also not available by the time that development of abundance indices was completed. An abundance index was not developed for the 1985 – 1991 period because of changing regulations and fishery operations. In addition, preliminary examination of the logbook data indicated that the CPUE rapidly increased and decreased several fold during this period, which indicated that changing regulations and fishing operations likely resulted in the exploitation of some local areas of high abundance.

Regulatory changes over the years have also affected the start of the fishing season. Therefore, only data from seasons 3 and 4 (i.e., Aug – Oct and Nov – Jan) were used for the abundance indices because fishing consistently occurred during these seasons. Three bimonthly periods within the six month period were used as factors in the GLMs to account for changes in thresher CPUE due to time of year.

In the initial development of the fishery, the primary target of the fishery changed from pelagic sharks to swordfish because of higher market prices. However, the targeting switch was constrained by regulations restricting the total amount of monthly swordfish landings and requirements to land equal amounts of shark (Table 1.1). Even after regulations restricting swordfish catch were removed, USDGN vessels likely switched between swordfish and pelagic sharks depending on availability and market prices. The annual decile rank of swordfish catch of a given set was included in the GLMs to account for changes in the targeting of the fishery from pelagic sharks to swordfish. The annual decile rank of swordfish catch was determined by ranking the swordfish catch from all sets within a given year, and then splitting the ranks into deciles (e.g., 0-10%, 10-20%).

Additional initial uncertainty was estimated and assigned to each USDGN index in addition to the data uncertainty estimated using a jackknife procedure. Since the USDGN indices represented the relative changes in the stock abundance of sub-adult and adult sharks, changes in the indices over time should be relatively smooth. Therefore, variability in the indices above and beyond that expected by the uncertainty in the data (i.e., estimated from the jackknife procedure) and a smoothly changing adult population, is largely due to variability in the catchability of the fishery. In this assessment, we model the variability in catchability with additional uncertainty. The USDGN indices were fit to a loess curve and the coefficient of variation (CV) of the index relative to the loess curve was calculated. If this CV was greater than the mean CV calculated with the jackknife procedure, the additional uncertainty added was the difference in the CVs. Otherwise, no additional uncertainty was added unless the mean CV from the jackknife procedure was <0.2. In that case, additional uncertainty was added to the index until the mean CV was equal to 0.2. The estimated additional CVs for the three indices were: S1: 0.000; S2: 0.123; and S3: 0.392. These additional CVs were only included as initial inputs into the assessment model and were adjusted based on model fit to the indices (Section 3.5).

The S1 index (1982 – 1984) showed a general decline but being a short time series, it was not expected to be strongly influential (Table 2.3). The S2 index generally increased from 1992 through 2000 (Table 2.3). However, the S3 index exhibited high variability from year to year during 2001 through 2013 (Table 2.3). This was caused by the substantial reduction in the number of vessels in the USDGN fishery and consequently, a large reduction in effort.

2.1.3.2 USA set net fishery

The USSN fishery primarily catches age-0 common thresher sharks. The abundance indices from this fishery can therefore be considered as recruitment indices.

Two indices representing different regulatory and operational periods were developed for the USSN fishery: 1) 1986 – 1993 (S4); and 2) 1994 – 2014 (S5). In 1994, the California Marine Resources Protection Act prohibited all gillnets and trammel nets within 3 nm of the California mainland and 1 nm of the Channel Islands. Since age-0 common thresher sharks are known to be distributed close to shore (Cartamil et al. 2010), this regulatory change may have affected the catchability of the USSN fishery.

Logbook data from the USSN fishery were available from 1981 through 1985 but the data from this period were not used to develop abundance indices because the USSN data were mixed with the USDGN data and could not be easily separated. After 1985, when the USDGN fishery moved out of the 75 nm zone due to regulations, it became easier to separate the USSN fishery data from that of the USDGN fishery because the operations of the two fisheries became very different.

Unlike the USDGN indices, data from all four seasons were used in the USSN indices. In addition, it was not necessary to correct for the USSN fishery targeting swordfish instead of pelagic sharks because neither swordfish nor pelagic sharks are targets of the fishery.

No additional CVs were assigned to the USSN indices in addition to the data uncertainty estimated using a jackknife procedure. The USSN indices were not fit to a loess curve because we expected these recruitment indices to be highly variable unlike the USDGN indices. A minimum CV of 0.2 was assumed for all indices but the mean CVs from the jackknife procedure for both indices were >0.2.

2.1.4 Length composition data

In both the USA and Mexico, the sampling programs used to sample the length composition of the catch varied over time, depending on country and fishery. This resulted in changes in the types of length data collected (alternate versus fork lengths), availability of sex composition data, and sample sizes.

Common thresher sharks were predominantly landed as “trunks”, without heads and tails (this practice has recently been prohibited by USA regulations). This practice made it impossible for port samplers to measure the fork lengths of landed sharks. They therefore measured alternate lengths instead, which is the distance between the origins of the first and second dorsal fins (Childers and Halko 1994). However, onboard observers were able to measure the fork length of the sharks. It was therefore necessary to use a relationship between alternate and fork lengths to convert alternate lengths to fork lengths. Based on 3043 samples, Kohin et al. (pers, comm.) estimated the relationship as: FL = 2.3627 × AL + 16.82 (Fig. 2.3), where FL and AL were the fork lengths and alternate lengths in cm, respectively. Using such a relationship resulted in aliasing of the length composition data. Preliminary analysis indicated that using 7 cm bins reduced aliasing to negligible levels for this relationship. We therefore used 7 cm bins for length composition data that were derived from measured alternate lengths. Smaller bins of 2 cm were used for data that were derived from measured fork lengths.

The genders of individual size samples were collected at the same time for some sampling programs. In general, port samples had very few and inconsistent number of length samples with associated sex information. However, onboard observers often collected sex information with their size samples.

A summary of the annual sampling effort by fleet, length type, and year used to generate the seasonal length frequency distributions are shown in Table 2.4. The initial input sample sizes (N_{input}) for the length composition data by season were the number of trips sampled, if available. For USA commercial fisheries, seasonal length frequency distributions with N_{input} <5 were not used in the assessment, which eliminated 5 out of 69, 7 out of 18, and 22 out of 42 seasons of length composition data available for the USDGN (F1), USDGNs2 (F2), and USSN (F3) fleets respectively. Mexico fisheries had much poorer sampling effort, so the minimal N_{input} required for seasonal length frequency distributions to be used in the assessment was 2, which eliminated 0 out of 3 seasons of length composition data available for the MXDGNLL (F6) fleet. The ranges of N_{input} for USA and Mexico commercial fisheries were 5 – 124 and 2 – 3 respectively.

2.1.4.1 USA fisheries

Length composition data from California port sampling and onboard observer programs were available for the USDGN and USSN fisheries. From 1981 through 1990, CDFG’s port samplers collected length information from common thresher sharks landed by the USDGN and USSN fisheries (Childers and Halko 1994). These length samples were in alternate lengths rather than fork lengths, and were therefore converted to fork lengths for use in this assessment (Fig. 2.3). There was a negligible number of port samples with associated sex information and the sex composition data from these samples were not used in this assessment. In contrast, the onboard observer program (1990 – present) for both fisheries recorded sex information on almost all of their length samples, which were measured as fork lengths. The sex composition data from the onboard observer program were incorporated into this assessment.

No length composition data were available for the USREC and miscellaneous fisheries. Based on anecdotal evidence, we assumed that the size of common thresher sharks caught by these fisheries were similar to the USDGN fishery.

2.1.4.2 Mexico fisheries

Length composition data from Mexico fisheries were much sparser than for the USA fisheries (Table 2.4). Scientists from Mexico sampled the lengths of common thresher sharks landed by the MXDGN and MXLL fisheries over several fishing trips during 2007 and 2008. These length composition data were in alternate lengths and were mostly unsexed. The MXART fishery was sampled over a period of time from 2006 till the present by scientists visiting fishing camps along the Baja California coast (Cartamil et al. 2011b). These length data were in fork lengths and were a mixture of sexed and unsexed samples. However, the number of fishing trips from which the samples were taken was unknown.

Preliminary examination of the length composition data from the MXART fishery suggested that the size of sharks taken was different from the USSN fishery. Given the lack of sample size information, uncertainty in the sampling period, and the sparse data, we used a “super-year” approach when using the data in the assessment model. This approach combined all the length data from the fishery into a single length composition and assumed that was the average length composition for the entire time period.

Preliminary model runs fitting the length composition data from the MXGDNLL (F6) fleet resulted in highly uncertain and variable selectivity, and poor fits to the length composition data because of the sparse and variable length composition data. Examination of the data suggested that the overall size of common thresher sharks caught by the MXDGNLL (F6) fleet was similar to the USDGN (F1) fleet, which was likely due to their similar gear and fishing operations. Therefore, the length composition data from the MXDGNLL (F6) fleet were not fit in the base case model. Instead, the MXDGNLL (F6) and MXDGNLLs2 (F7) fleets were assumed to have the same selectivities as the USDGN (F1) and USDGNs2 (F2) fleets respectively.

2.1.5 Conditional age-at-length data

Sex-specific conditional age-at-length data from the age and growth study by Smith et al. (2008a) were used in this assessment. Most of the samples came from the USDGN (F1) fleet (N=183) and one sample came from the USSN (F3) fleet. These vertebral samples were aged by three independent readers at SWFSC using the techniques described in Cailliet et al. (1983).

Aging imprecision was estimated with the method described by Punt et al. (2008), using the R package “nwfscAgeingError” (Thorson et al. 2012). Each reader was assumed to be unbiased in turn, and the aging imprecision and bias (for the other two readers) were estimated. The best fitting model, based on AIC, suggested that the age readings by the lead reader (S. E. Smith) were unbiased and had a constant CV (0.176). The age readings and associated uncertainty were incorporated into the base case assessment model and all sensitivity runs with estimated growth.

2.2 Fishery-independent data

This assessment used fishery-independent data from a longline juvenile thresher shark survey conducted in nearshore waters of the SCB by NOAA Fisheries’ Southwest Fisheries Science

Center (SWFSC). Overall catch and effort from the survey can be found in Table F.1 in Appendix F. The SWFSC juvenile thresher shark survey was conducted annually in September from 2006 through 2014. This survey was developed after an initial study on the common thresher shark nursery grounds (Smith 2005). The study indicated that longline gear in nearshore waters would be successful in catching age-0 and juvenile common thresher sharks.

The basic survey design consisted of 12 area blocks and a minimum of three longline sets were required for each block (Fig. F.1 in Appendix F). Each longline set consisted of a one mile long anchored monofilament longline with 100 hooks deployed from a small commercial longline vessel. The hooks were expected to fish approximately 6 – 8 m below the surface and were baited with primarily sardines but mackerels were sometimes used when sardines were not available. The longline sets were deployed in areas where bottom depth was <25 fathoms (~45 m). Sharks were tagged and released alive, whenever possible.

Several operational factors of this survey impacted how the survey data were utilized in this assessment. Most importantly, the location and timing of each set was determined by the captain of the vessel, within constraints set by SWFSC scientists. The sets were in effect targeted at common thresher sharks and were somewhat similar to commercial longline sets. In addition, after the initial three sets within a block were completed and there was time available, the captain was free to set again in the same area. Therefore, the first three sets in an area were possibly used as learning sets, providing information on where it was more likely to encounter threshers in subsequent sets in the same block. Preliminary analysis of the CPUE indicated that sets after the first three sets do have a significant positive effect on encountering non-zero thresher catch.

Another important factor was that soak times of sets were inconsistent and varied substantially. When relatively large numbers of sharks were caught, soak times were sometimes cut to reduce shark mortality and possible hook saturation. Therefore, we included soak time as part of the fishing effort. Occasionally on some sets in the past, if a shark was seen hooked, the shark would be brought aboard and released, and the hook was then rebaited and put back into the water. This practice was considered inappropriate and has since been discontinued.

Other secondary factors likely impacting the CPUE of the survey were Marine Protected Areas (MPAs) and consumption of baits by sea lions. In 2012, several areas within survey blocks became unavailable to the survey due to MPAs being implemented. Preliminary analysis indicated that sets within those areas before they became MPAs had higher CPUEs. Sea lions would also occasionally consume the baits on the longlines, making the longlines less effective in catching fish. If the survey data indicated that baits were consumed by sea lions, the data from the set would be discarded before further analysis.

2.2.1 USA juvenile thresher shark survey index (USJUV0614)

A similar approach to the USDGN and USSN indices was used to derive an index of relative abundance for the juvenile thresher shark survey. Details and diagnostics of the GLMs used to derive the abundance index can be found in Appendix F. A delta-lognormal approach was taken, using binomial and lognormal GLMs (Lo et al. 1992). The effects of a set being in one of the first three sets within a block or within an MPA were accounted for by incorporating those factors as candidate factors in the GLMs. An AIC-based stepwise model selection process was used to select the final GLMs used to derive the index. Uncertainty in the index was estimated by jack-knifing the data.

Based on the size composition data, the juvenile thresher shark survey catches a mixture of age-0 and juvenile thresher sharks. This index should therefore be considered as a recruitment index. The estimated abundance index and uncertainty are shown in Table 2.3.

Additional CVs were not assigned to this index because the estimated CVs from the jackknife procedure were relatively high, with a mean CV of 0.485. The high CVs were due to the highly patchy distribution of juvenile thresher sharks and relatively low number of longline sets in the survey. In addition, we expect a recruitment index to have relatively high variability unlike the indices based on the USDGN fishery.

No obvious trends were observed in the estimated index because of the highly variable index and high estimated CVs. The large estimated CVs resulted in this index being uninformative in preliminary models. The juvenile thresher shark survey index was therefore not fit in the base case model, and was instead used in a sensitivity analysis (Section 6.1.3).

2.2.2 Length composition data

Common thresher sharks caught by the juvenile thresher shark survey were measured (fork length) and sexed. The length and sex composition data from the survey were fit in the base case model. The number of sets and fish used to generate the seasonal length frequency distributions are shown in Table 2.4. The initial input sample sizes (N_{input}) for the length composition data by season were the number of sets sampled.

2.3 Biological parameters

Several biological parameters used in this assessment were fixed at externally determined values that were obtained from published sources.

2.3.1 Maturity and fecundity

The females of this common thresher shark stock were assumed to be 50% mature ($L_{50\%}$) at 215.1 cm FL with a slope of -0.2409 cm^{-1}, and the proportion of mature females was assumed to be related to the fork length in cm by, $maturity = 1/[1 + \exp(slope * (FL - L_{50\%}))]$. In this study, observations of maturity of individual females from Natanson and Gervelis (2013) were fit to a logistic curve to estimate the $L_{50\%}$ and slope parameters. Observations from the Natanson and Gervelis (2013) study were obtained from the authors (L. Natanson, pers. comm.) and fit to a binomial generalized linear model with a logit link function. The $L_{50\%}$ and slope parameters were estimated to be 215.1 ± 45.8 cm FL and -0.2409 ± 0.0363 cm^{-1}, respectively (Fig. 2.4).

Natanson and Gervelis (2013) suggested that the western North Atlantic stock had at least a biennial reproductive cycle with litter sizes of 3.7 pups. We therefore assumed that this stock of common thresher sharks produced two pups per year and did not exhibit changes in fecundity with respect to female size or age. However, the evidence for a biennial reproductive cycle remains relatively equivocal. Therefore, a sensitivity analysis was performed to determine the effect of assuming an annual reproductive cycle (4 pups y^{-1}) (Section 6.1.1.1).

2.3.2 Natural mortality

The instantaneous rate of natural mortality (M) was assumed to be a constant 0.04 y^{-1} for both sexes of this common thresher shark stock. A probability distribution for M was developed by applying meta-analytical methods to empirical relationships between M and life history parameters (Hamel 2015; Then et al. 2015; Appendix C). The median of the resulting M distribution was 0.14 y^{-1} and the 95% prediction interval was 0.066 – 0.297 y^{-1}. However, once the reproductive biology of this stock was assumed to be based on the western North Atlantic stock (Natanson and Gervelis 2013), a very low M of approximately 0.04 y^{-1} was required to obtain a converged model with reasonable model fit and diagnostics. Although an M of 0.04 y^{-1} was outside the 95% prediction intervals for this parameter, the CIE review panel considered that this was the most appropriate value given the model structure and data for this assessment (Appendix A). However, given the uncertainty of this parameter, a sensitivity analysis was performed to determine the effect of assuming different M values in conjunction with different reproductive biology and stock-recruitment parameters (Section 6.1.1.1).

2.3.3 Weight-length relationship

The weight-length relationship used in this assessment followed the relationship estimated by Kohler et al. (1995): $WT = 1.8821\times10^{-4}\ FL^{\ 2.5188}$, where WT was the weight in kg and FL was the fork length in cm. This relationship was based on data from the western North Atlantic stock but visual examination of limited weight-length data suggested that this weight-length relationship was representative of this stock as well (S. Kohin, pers. comm.). Male and female sharks were assumed to have the same weight-length relationship.

3. Model description

The base case model used for this assessment is described below.

3.1 Modeling software platform

The assessment model was developed using the 3.24U version of the Stock Synthesis (SS) modeling platform (Methot and Wetzel 2013).

3.2 General model specifications

This assessment incorporated information from the entire distribution of common thresher sharks along the west coast of North America, from Baja California, Mexico to British Columbia, Canada. Based on currently available evidence, we assumed that this was a single, well-mixed stock (Section 1.1).

The start year of the base case model was 1969, which was the earliest year of reliable information on fishery removals, and the terminal year was 2014, which was the last year of available data. Each fishing year was divided into four seasons (1: Feb-Apr; 2: May-Jul; 3: Aug-Oct; and 4: Nov-Jan) (Section 2). The model was sex-specific due to differences in biology between genders, and the sex ratio at birth was assumed to be 1:1. Fishery removals were divided among 8 fleets (Section 2.1 and Table 2.2). Six indices of relative abundance were available for the model but only 5 were fit in the base case model (Section 2.2). The configuration and nomenclature of the eight fleets and six abundance indices in the base case model can be found in Table 2.1. For convenience, abundance indices were input into the model as surveys and named accordingly (e.g., S1, S2). A summary of the data can be found in Fig. 2.1.

The length frequency distributions were based on fork lengths (cm) divided into 130 2-cm bins (40 – 300 cm) for measured fork lengths, and 38 7-cm bins for measured alternate lengths converted into fork lengths. However, length frequency distributions for the USSN fleet required a modification to this length bin structure. Preliminary models indicated that length compositions of age-0 fish from the USSN fleet were poorly fit in all preliminary model configurations and tended to degrade the fit to other fleets with age-0 observations. Visual examination of the length compositions of the USSN fleet suggested that the quality of the length observations of age-0 sharks in this fleet was relatively poor compared to the length observations from the juvenile thresher survey. Given that most of the common thresher sharks (>95% in number) caught by the USSN fleet were age-0, the bins from 40 – 93 cm were aggregated into a single bin to approximate the age-0 size classes, and an age selectivity process was used to represent the selectivity of the USSN fleet; doing so resulted in better fits to the size composition data. Additionally, sensitivity analysis was performed to examine the robustness of model results to this structural change (Section 6.1.4.2).

3.3 Likelihood components

In the assessment model, likelihoods for the various data components were obtained by comparing the expected values from the model with the observations in the data based on ‘goodness of fit’ procedures for the appropriate likelihood distribution of each data component. The main likelihood components in the model included: 1) abundance indices (lognormal); 2) fleet and survey length frequency compositions (multinomial); and 3) conditional age-at-length data (multinomial).

3.4 Model parameterization

Four main types of parameters were in the assessment model: 1) life history; 2) stock-recruitment; 3) selectivity; and 4) initial conditions. These parameters were either fixed or estimated within the model. Reasonable bounds were specified for all parameters. Catchability was estimated for each index of abundance without any prior assumptions.

3.4.1 Life history

Except for growth, all other life history parameters were fixed in the model, including natural mortality, weight-length relationship, maturity-at-length, and fecundity. These fixed parameters were derived from available data or published literature (Section 2.3 and Fig. 3.1). Sensitivity of the model to the natural mortality, maturity, and fecundity parameters was analyzed (Section 6.1.1).

3.4.1.1 Growth

In this assessment, growth was estimated within the model, assuming that growth was sex-specific and time-invariant. Preliminary models using fixed growth parameters from a previous study on this stock (Smith et al. 2008a) (Section 1.1.4) had poor fits to the size compositions of age-0 fish from the USSN fishery and the USA juvenile thresher shark survey because age-0 fish in the data were substantially smaller and did not show the sex-specific differences in size expected by the fixed growth models. The age-0 size composition data could have been better fit if the selectivity of male and female age-0 sharks were very different but this was considered to be unlikely because the behavior of age-0 sharks did not appear to be sex-specific and the sex ratio of age-0 sharks caught in the USA juvenile thresher shark survey was approximately 1:1 in the same area. It was considered more likely that the estimated size at age-0 from the published studies were unrepresentative due to limited samples from age-0 fish. Estimating growth within the model substantially improved the fits to the size composition and conditional age-at-length data. Growth of male and female sharks were modeled separately because all previous studies on common thresher shark growth indicated that these sharks exhibited sex-specific growth (Cailliet et al. 1983; Smith et al. 2008a; Gervelis and Natanson 2013).

A von Bertalanffy growth function, as parameterized by Schnute (1981), was used to model the relationship between fork length (cm) and age:

$$L = L_\infty + (L_1 - L_\infty)e^{-K(A-A_1)}$$

where L_1 and L were the sizes associated with ages A_1 and A respectively, L_∞ was the asymptotic length, and K was the growth coefficient. The L_1, K, and L_∞ parameters were estimated for both male and female common thresher sharks and A_1 was set at 0.125. The coefficients of variation (CVs) of size-at-age for L_1 (CV_1) and L_∞ (CV_2) were fixed at 0.08 and 0.05 for both sexes, based on an estimate of the overall CV for age-0 fish caught by the USA juvenile thresher shark survey and estimated from preliminary model runs respectively.

Sensitivity of the model to the estimated growth model was analyzed by performing alternative model runs with growth parameters fixed at the values estimated by Smith et al. (2008a) (Section 6.1.1.4).

3.4.2 Stock-recruitment

Common thresher sharks produce only a few pups per litter, with relatively little variability in litter size between individuals. In addition, the pups are born at a relatively large size. This suggests that common thresher sharks have lower potential productivity than teleosts producing millions of eggs. In addition, there is likely a more direct connection between spawning abundance (i.e., number of mature female sharks) and recruitment than for teleosts.

Therefore, the stock-recruitment relationship was modeled using a relatively new functional form developed by Taylor et al. (2013) for low fecundity fish that explicitly modeled the pre-recruit survival during the period from pupping to recruitment at age-0. The number of pups produced by the stock (i.e., reproductive output) was calculated as the product of the stock's spawning abundance and fecundity (two pups produced per year per mature female shark in the base case model; Section 2.3.1). The pups were then assumed to experience density-dependent pre-recruit survival processes before becoming recruits. The survival of pre-recruit pups, S_0, was calculated as,

$$S_0 = \frac{R_0}{B_0}$$

where R_0 was the recruitment at equilibrium without fishing, and B_0 was the equilibrium reproductive output (number of pups) under unfished conditions. Expected recruitment in year *y*, R_y, was then calculated as,

$$R_y = S_y B_y$$

where B_y was the reproductive output in year *y*, and S_y was the pre-recruitment survival given by,

$$S_y = \exp\left[-z_0 + (z_0 - z_{min})\left(1 - \left(\frac{B_y}{B_0}\right)^{\beta}\right)\right]$$

where z_0 was the pre-recruitment mortality rate at equilibrium calculated as $-\log(S_0)$; z_{min} was the limit of the pre-recruitment mortality as depletion approaches 0 calculated as $z_0(1 - z_{frac})$, and z_{frac} represented the reduction in mortality as a fraction of z_0 (z_{frac} therefore ranged from 0 to 1); and β was the shape parameter of the density dependence between the spawning population and pre-recruitment survival. It should be noted that this stock-recruitment curve is mathematically related to the generalized Ricker stock-recruitment curve.

The steepness, *h*, of the stock-recruitment curve (i.e., expected recruitment relative to R_0 at a spawning depletion of 0.2) can be derived from the parameters using,

$$h = 0.2 \exp\left[z_0 z_{frac}(1 - 0.2^{\beta})\right]$$

A suite of preliminary simulations, with model structures consistent with this assessment, were performed to examine if the β and/or z_{frac} parameters were estimable given the model structure and available data. Results from the simulations indicated that the available data were likely to be informative on the β parameter but not the z_{frac} parameter. Based on a suite of preliminary models, it was clear that the β and z_{frac} parameters interacted with the M and reproductive biology parameters (Appendix C). When the reproductive biology of this stock was based on Natanson and Gervelis (2013) (Section 2.3.1), the range of possible values for z_{frac} that resulted in a converged model was relatively limited and depended on the assumed M (Appendix C). Given these constraints, the base case model for this assessment assumed a z_{frac} of 0.5 and estimated β. Sensitivity analyses were performed to evaluate the sensitivity of the model to a range of z_{frac} values (Section 6.1.1.1). In addition, we also conducted sensitivity analyses using a Beverton-Holt stock-recruitment relationship with similar steepness to the low fecundity stock-recruitment relationship (Section 6.1.1.2).

Annual deviations in recruitment were modeled by replacing the B_y with,

$$B_y \exp\left[-0.5 b_y \sigma_R^2 + \tilde{R}_y\right], \tilde{R}_y \sim N(0, \sigma_R^2)$$

where b_y was the bias adjustment fraction applied for year y, σ_R was the standard deviation of the recruitment deviations in log space, and $\tilde{R}_y$ was the lognormal recruitment deviation for year y. The bias adjustment factor ensured that estimated recruitment during even 'data poor' eras, when the estimated $\tilde{R}_y$ was near 0, was unbiased (Methot and Taylor 2011). The bias adjustments for the base case and sensitivity analysis models were performed by estimating the expected bias adjustments using the R package 'r4ss' (v1.23.5) and then re-running the model again with the new bias adjustments. This bias adjustment procedure was performed once or twice depending on whether the estimated and expected bias adjustments were well matched after a single pass.

In this assessment, σ_R was assumed to be 0.5, which was consistent with the expected variability. A sensitivity analysis was conducted assuming a lower σ_R of 0.3 (Section 6.1.1.3).

3.4.3 Selectivity

The assessment model had a sex-specific structure, with sex-specific growth curves. However, we assumed that male and female common thresher sharks have identical selectivity for each fleet because the size composition data were adequately fit with this assumption, sex-specific size composition data were not available prior to 1990, and there was no available information that suggested selectivity differed by sex.

The USSN fleet (F3) was assumed to have an age-based selectivity because preliminary models using size-based selectivity fit the size composition data poorly and degraded the fit of other fleets with age-0 observations (Section 3.2). Using an age selectivity process together with a size bin structure that approximately aggregated age-0 observations resulted in better fits to the data. The selectivity of each age class from age-0 through age-2 was freely estimated, and the selectivity of ages >2 was assumed to be negligible for this fleet. A sensitivity analysis was performed to examine the sensitivity of model results to using size selectivity for this fleet rather than age selectivity (Section 6.1.4.2).

All other fleets were assumed to have size-based selectivity processes. Size selectivities were estimated for four fleets with size composition data (F1, F2, F8, and S6) and the size selectivities of other fleets were mirrored to one of these fleets (Table 3.1). The MXDGNLL (F6) fleet had several size composition observations in 2007 – 2008 (Table 2.4) but preliminary models indicated that the low sample sizes and variability of these observations resulted in the model poorly fitting these observations. Given that the size of common thresher sharks caught by this fleet was similar to the USDGN fleets (F1 and F2), we assumed that their size selectivities were also similar. Visual examination of the expected and observed size composition of the removals suggested that this assumption was adequate. A sensitivity analysis was performed that fit to the size observations from the MXDGNLL (F6) fleet (Section 6.1.4.3).

The selectivity curves for the USDGN (F1) and MXART (F8) fleets, and the USJUV0614 (S6) index were assumed to be dome-shaped and parameterized as double-normal curves (Table 3.1). Each double-normal selectivity curve had six parameters: 1) peak, the initial length at which the fish is fully selected; 2) width of the plateau at the top; 3) width of the ascending limb of the curve; 4) width of the descending limb of the curve; 5) selectivity of the first size bin; and 6) selectivity of the last size bin. The parameters for peak, width of ascending limb, and width of descending limb were estimated for all three double-normal curves. In addition, the selectivity of the first size bin was estimated for the USDGN (F1) fleet but assumed to be controlled by the width of the ascending limb for the other two fleets and therefore not estimated. The selectivity of the final size bin was assumed to be controlled by the width of the descending limb and therefore not estimated for all three selectivity curves. The width of the plateau was assumed to be negligible and fixed at a very small value for all three selectivity curves because preliminary models indicated that this parameter was always estimated to be a very small value and at the lower bound for all three curves.

The size selectivity curves of the USDGNs2 (F2) fleet were parameterized as cubic splines with four knots because of bimodal size composition data. Preliminary models indicated that cubic splines with four knots at 75, 125, 175, and 225 cm allowed for flexible selectivity curves that adequately fit the size composition data.

Selectivities of the USDGN (F1), USDGNs2 (F2), and USSN (F3) fleets were allowed to vary through time. The selectivities of these fleets were likely affected by major regulatory changes (Table 1.1), which forced the fleets to change their fishery operations. Therefore, the selectivities of these fleets were grouped into blocks of time when their regulations and fishery operations were relatively consistent (Table 3.1). A sensitivity analysis was performed to examine the effect of alternative time blocks of selectivity (Section 6.1.4.1).

3.4.4 Catchability

Catchability, q, was estimated assuming that the abundance indices were proportional to vulnerable biomass with a scaling factor of q. It was assumed that q was constant over time for each index.

3.4.5 Initial conditions

In this assessment, we started the main population dynamics of the model in 1969, which was prior to the start of targeted commercial fishing in 1977 – 1978. Although there was some low level of exploitation of this stock prior to 1969, the level of exploitation was substantially lower than during the period of targeted fishing. It was therefore assumed that the population was relatively close to equilibrium in a near unfished state. The level of pre-1969 equilibrium catch was assumed to be the average of 1969 – 1971, and grouped into three fleets based on the approximate size and unit of catch: 1) the USDGN (F1 and F2) and MXDGNLL (F6 and F7) fleets for all seasons; 2) USREC (F4 and F5) for all fleets; and 3) the USSN (F3) and MXART (F8) fleets. The initial fishing mortality rates that remove these equilibrium catches were estimated to allow the model to start at an appropriate depletion level, albeit near an unfished condition. No early recruitment deviations (i.e. recruitment deviations prior to 1969) were estimated because the earliest size composition and abundance index observations were from 1981 and 1982 respectively, and the recruitment deviations during the period from 1969 to 1980 acted like early recruitment deviations, which allowed the model to develop a non-equilibrium age structure when the main observations started. A sensitivity run was used to examine the effect of starting the model in an unfished condition (Section 6.1.2.2).

3.5 Data weighting

Statistical stock assessment models fit a variety of data components, including abundance indices and size composition data. The results of these models can depend substantially on the relative weighting between different data components (Francis 2011). In this assessment, we use the method proposed by Francis (2011) (Method TA1.8) to weight the size composition data, using the SSMethod.TA1.8 function in the 'r4ss' package (v1.23.5). All estimated Francis weights of the size composition for all fleets were >1, which suggested that the size composition data did not have to be down-weighted. A R_0 profile of the data components (Lee et al. 2015) also suggested that the size composition data were relatively consistent with abundance indices with respect to estimated population scale (Section 4.4). Visual examination of the residual patterns of the size composition data suggested that the size composition data were relatively well fit and the scale of the Pearson's residuals for each data component were consistent with the statistical assumptions (i.e., approximately 95% of the residuals were within ±2 standard deviations) except for the 2 cm bin data for the USDGN (F1) and USSN (F3) fleets. The larger than expected residuals for these two data components were due to large spikes in single bins, which were primarily attributed to noisy data and small sample sizes. Therefore, no adjustments were made to the input sample size (N_{input}) for the size composition data for all fleets.

Sensitivity analyses were performed where the variance adjustment factors for N_{input} followed the estimated Francis weights and were allowed to exceed 1.0; and where the N_{input} were down-weighted in turn using likelihood component weighting factors (i.e., lambda factors) of 0.2 (Section 6.1.3).

A similar data weighting process was performed for the conditional age-at-length data. Estimated Francis weights of the conditional age-at-length data using the SSMethod.Cond.TA1.8 function in the 'r4ss' package were >1, which indicated that the conditional age-at-length data did not have to be down-weighted. However, preliminary R_0 profiles suggested that the conditional age-at-length data were inconsistent with the abundance indices in terms of estimated population scale. We decided to down-weight the influence of the conditional age-at-length data because the data were intended to provide information on the growth of the fish but not to influence estimates of population scale, which was better represented by abundance indices. In the base case model, the contribution of the overall likelihood by the conditional age-at-length component was down-weighted by a lambda weighting factor of 0.2.

Input variances of the abundance indices were adjusted to make them consistent with the statistical assumptions of the model. The initial input coefficients of variance (CV_{input}) of the abundance indices were the sum of the estimated observation error and variance adjustment factors based on the estimated additional process errors (USDGN indices only) (Section 2.1.3). After the initial model was run, the estimated root-mean-square errors of the model fit to the abundance indices were used to adjust the variance adjustment factors to allow the total expected errors to be consistent with the estimated errors. The minimum value allowed for variance adjustment factors was 0.0, in order to limit the minimum expected error to the observation errors estimated by jack-knifing the data.

4. Model selection and evaluation

4.1 Alternative model configurations

A large number of alternative model configurations were explored to develop the base case model, which provided a realistic but parsimonious description of common thresher shark population dynamics based on the best available scientific information. The alternative models were evaluated on overall model fit and convergence criteria, as well as consideration of whether model assumptions, structural choices, estimated parameters, and outputs were reasonable and consistent with available information for the stock. The base case model reflected the best aspects of these exploratory models. Overall, the base case model fit the observed data well, with plausible model processes and estimated parameters were within reasonable bounds.

Several models that describe alternative states of nature are described in the sensitivity analyses section (Section 6.1). These include alternative assumptions on growth, reproductive biology, natural mortality, stock-recruitment relationship, total removals, data weighting, and selectivity.

4.2 Model convergence

Convergence of the base case model was indicated by all of the tests that were conducted. The base case model had a maximum gradient component that was very close to zero (4.031E-5), a positive definite Hessian matrix, and all estimated parameters were within reasonable bounds. We also explored the likelihood surface of the model using 50 runs with different phasing and initial values. Total negative log-likelihood from the model run using the phasing and initial parameters from the base case model was the lowest (i.e., best) among these runs, and 33 out of 50 runs also obtained the same total negative log-likelihood (Fig. 4.1). In addition, the estimated virgin recruitment in log-scale [ln(R_0)] was similar from runs with similar likelihoods to the base case model (Fig. 4.1).

4.3 Model fit

The fit of the base case model to observations were determined by examining the residuals of the abundance indices, size compositions, and conditional age-at-length data.

4.3.1 Fit to abundance indices

The base case model was able to adequately capture the trends indicated by the sub-adult/adult (S1, S2, and S3) and recruitment (S4 and S5) abundance indices that were fit (Fig. 4.2). Importantly, the base case model results were consistent with the population decline observed by the S1 index during 1982 – 1984, and the increasing population trend observed by the S2 index during 1992 – 2000. However, we note that the observed trends during these two periods were slightly steeper than expected. The lack of contrast and large uncertainties of the observations for S3 during 2001 – 2013 made it difficult to ascertain how well the base case model matched the observed population trends during that period. The base case model captured the trends in recruitment observed by the S4 and S5 indices.

Overall, the model fits to the sub-adult/adult indices (S1, S2, and S3) were poorer than the recruitment indices (S4 and S5) but were considered to be adequately representative of abundance trends and consistent with model input CVs. The RMSEs of the S1, S2, and S3 indices were 0.111, 0.274, and 0.545 respectively while the RMSEs of the S4 and S5 indices were 0.175 and 0.178 (Table 4.1). The RMSEs of the S1, S4, and S5 indices were smaller than their input CVs based on observation errors while the RMSEs of the S2 and S3 indices were approximately equivalent to the sum of their input CVs and variance adjustments after tuning.

4.3.2 Fit to size compositions

Base case model fits to the size composition data were generally good. Overall, the model predicted size compositions that matched observations well (Fig. 4.3 – 4.5). Examination of the input sample size (N_{input}) and model estimated effective sample size (N_{eff}) also showed reasonably good model fits (Table 4.2). A higher N_{eff} indicates better model fit, with a mean N_{eff} > 30 indicating good model fit. In addition, ratios of the harmonic mean of the N_{eff} to mean N_{input} were all ≥1, which indicated that the base case N_{input} did not assume less error than was evident in the model fits.

Pearson residuals of the model fit to the size composition data did not reveal substantial patterns in the residuals (Fig. 4.6 – 4.7). In addition, the scale of the residuals were generally small, with most lying within ±2 standard deviations. Exceptions to this occurred in the USDGN (F1) and

USSN (F3) fleets when 2-cm bins were used because of several large spikes in the size compositions, which could not be fit with reasonable model processes.

4.3.1 Fit to conditional age-at-lengths

Base case model fits to the conditional age-at-length data were generally good. Overall, the model predictions matched observations well although some large fish appeared to have been aged at unreasonably young ages (Fig. 4.8). The ratios of the harmonic mean of the N_{eff} to mean N_{input} were approximately ≥1, which indicated that the base case N_{input} did not assume less error than was evident in the model fits (Table 4.3).

4.4 Retrospective analysis

Retrospective analysis did not reveal any substantial pattern in the estimates of female spawning abundance and fishing intensity (1-SPR) with successive elimination of up to five years of terminal year data (Fig. 4.9).

4.4 Likelihood profiles on virgin recruitment (R_0 profile)

Results of the likelihood profiling on virgin recruitment, R_0, for the abundance indices and size composition data components of the model are shown in Fig. 4.10. Changes in the likelihood of each data component are a measure of how informative that data component is to the overall estimated population scale and what that scale is. Ideally, catch and abundance indices should be the primary sources of information on the population scale in a model (Lee et al. 2015).

In the base case model, the abundance indices appeared to be the primary sources of information on R_0. The USDGN9200 (S2) and USSN9414 (S5) indices had the largest influences on R_0 but the other three indices had negligible information on R_0. This was because both S2 and S5 indices had good contrast coupled with moderate amounts of observations and/or uncertainty. The maximum likelihood estimates of R_0 for the S2 and S5 indices were also relatively consistent with each other and the overall R_0 estimate. In comparison, the USDGN8284 (S1), USDGN0113 (S3), and USSN8593 (S4) indices had some combination of small number of observations, large uncertainties and/or limited contrast.

The size composition data was substantially less influential than the abundance indices on the overall R_0 estimate, with changes in log-likelihood values being several fold smaller than the abundance indices. The USDGN (F1) fleet had the largest influence among all the fleets with size compositions, especially at higher R_0 values. This was expected because the F1 fleet had the largest number of size composition observations. Surprisingly, the MXART (F8) fleet had a large influence at low R_0 values, which appeared to be due to a discontinuity in the selectivity of the F8 fleet. The size composition data using alternative binning structure (e.g., 7 cm bins) appeared to contradict the size composition data with 2 cm bins. This may indicate some mis-specification in the model that could have been resolved given enough time. However, given that the overall R_0 profile was consistent with the abundance indices and the limited time available, we considered the scale of the population to be adequately estimated, albeit with substantial uncertainty, by the base case model.

4.5 Age-structured production model analysis

Following the proposal by Maunder and Piner (2015), the base case model was modified into an age-structured production model to identify if the catch and sub-adult/adult abundance indices were consistent with the estimated scale and trends in the population. Maunder and Piner (2015) stated that "When catch does explain indices with good contrast (e.g., declining and increasing trends), it suggests that a production function is apparent in the data, therefore providing evidence that the index is a reasonable proxy of stock trend". In this assessment, the base case model was modified by fixing the stock-recruitment relationship, sex-specific growth curves, and selectivities of all fleets to those estimated in the base case model, not estimating annual recruitment deviates so that recruitment follows the stock recruitment curve, and not fitting to the size composition and conditional age-at-length data.

The age-structured production model had similar scale and populations trends to the base case model (Fig. 4.11). Model fits to the sub-adult/adult abundance indices (S1, S2, and S3) were also similar to the base case model (Fig. 4.11), which suggested that the sub-adult/adult indices were reasonable proxies of stock trend and the productivity of the stock was estimated reasonably well.

5. Model results

5.1 Model parameter estimates

The estimated or fixed values of the explicit parameters used in the base case model are shown in Table 5.1. All estimated parameters except initial fishing mortality were estimated within reasonable bounds. The initial fishing mortalities were estimated very close to the lower bounds (i.e., very close to 0), which is reasonable because the stock was close to being in an unfished condition at the start of the model.

5.1.1 Growth

Growth parameters of female and male common thresher sharks were estimated within the model and were consistent with what we know of the species (Fig. 5.1). Female sharks were slightly larger than male sharks for each age. However, the size difference between sexes appeared to be smaller than previously estimated. In addition, the size at age-0 appeared to be smaller than previously estimated.

5.1.2 Selectivity

Estimated selectivity curves are shown in Figures 5.2 – 5.4. Selectivity parameters were well estimated and selectivity curves were consistent with the known fishery operations of the fleets. Higher selectivities for smaller fish were estimated for the USSN (F3), and MXART (F8) fleets, and the USJUV0614 survey (S6), which catch predominantly small, juvenile common thresher sharks. The peak parameters for F8 and S6 were <85 cm and selectivity of age-0 sharks for F3 was substantially higher than age-1 and 2 sharks (Table 5.1). In contrast, the selectivity curves of the USDGN (F1) and USDGNs2 (F2) fleets, which catch primarily sub-adult and adult sharks, had peak selectivities closer to 150 cm. A bimodal selectivity pattern was estimated for the USDGNs2 (F2) fleet during 1985 – 1988 because a large number of large sharks >200 cm were caught during this period (Fig. 5.5), which may have been due to time-area closures affecting fishing operations.

5.1.3 Catchability

The catchability coefficient (*q*) was solved analytically in the base case model as a single value for each index (Table 4.1). Catchability was allowed to vary through time by separating the abundance index from a single fishery into multiple time series based on an examination of the fishery operations of the fishery.

5.1.4 Catch-at-age

Juvenile and sub-adult common thresher sharks formed the largest component of the catch (Fig. 5.6), even during the peak of the USDGN fishery in 1982. This is because the selectivity of all fleets select for a substantial proportion of juvenile and sub-adult sharks.

5.1.5 Sex ratio

The sex ratio (male/female) estimated in the base case model was close to 1:1 because the estimated female growth curve was similar to the male growth curve, and selectivity was assumed to be non sex-specific (Fig. 5.7).

5.2 Stock assessment results

5.2.1 Reproductive capacity and output

In this assessment, the reproductive capacity of the population was calculated as the number of mature female sharks (i.e., spawning abundance) rather than spawning biomass, because the size of mature female sharks did not affect the number of pups produced (i.e., larger female sharks did not produce more pups). The reproductive output of the stock (i.e., the number of pups produced by the stock) was calculated using two pups produced per year per mature female.

In the base case model, the estimated number of mature female common thresher sharks under unfished conditions was 220,000 sharks (95% CI: 125,600 – 314,300 sharks) with a reproductive output of 439,900 pups (95% CI: 251,300 – 628,600 pups) (Table 5.2 and Fig. 5.8). Prior to the start of targeted commercial fishing in 1977 – 1978, the estimated reproductive capacity was 242,700 mature female sharks (95% CI: 124,100 – 361,300 sharks) in the early 1970s. The start of targeted commercial fishing in 1977 – 1978 was quickly followed by a large increase in fishery removals, peaking in the early 1980s (Fig. 2.2). These relatively large removals resulted in the number of mature female sharks declining steadily over the next 3 decades. Although management actions to reduce fishing mortality on this stock began soon after the start of targeted commercial fishing, the effect of these actions on the adult population took a long time to show up because of the very low natural mortality and age structure assumed in the base case model. The historical low estimate occurred in 2006, with 116,900 mature female sharks (95% CI: 39,200 – 194,600 sharks). After 2006, the reproductive capacity gradually increased over the most recent decade. In 2014, the terminal year of the assessment model, the estimated number of mature female sharks reached 136,800 sharks (95% CI: 32,000 – 241,600 sharks) with a reproductive output of 273,600 pups (95% CI: 64,000 – 483,300 pups) (Table 5.2).

Depletion of the stock was estimated as the number of mature females in the second quarter (S) for a specific year divided by the number of mature females under unfished conditions (S_0) because the reproductive output of the stock (i.e., number of pups produced) was dependent on the number of mature females and not on the weight of the female sharks. Therefore, the estimated depletion followed the same trajectory as the number of mature female sharks, albeit scaled to S_0 (Table 5.2 and Fig. 5.8). The total (age-1+) and mature female biomass were both less important than the number of mature females as an indicator of the stock, but both also showed similar trends (Table 5.2 and Fig. 5.8).

5.2.2 Recruitment

The estimated recruitment and stock-recruitment relationship were generally consistent with the biology of the stock and assumptions in the base case model. Conditional on a fixed z_{frac} of 0.5, the base case model estimated a shape parameter, β, of 2.533, which indicated that the stock-recruitment relationship had a moderate curvature (Table 5.1 and Fig. 5.9). Unfished recruitment was estimated to be 30,600 sharks ($\log(R_0) = 3.421$) (Table 5.1). The estimated recruitment deviations from the expected spawner-recruit curve appeared to be relatively well estimated and consistent with the expected distribution of recruitment deviations ($\sigma_R = 0.5$), but there appeared to be a small amount of autocorrelation in the time series that was unaccounted for in the base case model (Fig. 5.9). The change in recruitment bias was consistent with expectations and accounted for in the base case model (Fig. 5.9).

The estimated recruitment fluctuated substantially during the assessment period (1969 – 2014), ranging from a low of 19,400 sharks (95% CI: 6,000 – 32,800 fish) in 1978 to a high of 88,000 sharks (95% CI: 25,900 – 150,200 fish) in 2006 (Table 5.2 and Fig. 5.9). Overall average recruitment during the assessment period was approximately 37,000 sharks but there appeared to be a period of relatively low recruitment from 1985 – 1995, with average recruitment at 28,300 sharks. In contrast, a more recent period from 2006 – 2012 had substantially higher recruitment, averaging approximately 67,200 sharks.

5.2.3 Fishing mortality

Fishing mortality-at-age (F-at-age) was estimated for female and male common thresher sharks in the base case model (Fig. 5.10). The fishing mortality was highest on the sub-adult sharks during the peak of the swordfish/shark drift gillnet fishery. In recent years, the declining catch and effort from this and other fisheries have resulted in substantially lower fishing mortality for all ages. There did not appear to be substantial differences in the fishing mortality between female and male sharks.

Female spawning potential ratio (SPR) was used to describe the fishing intensity on the stock. The SPR of a population is the ratio of spawning output per recruit under fishing to the spawning output per recruit under unfished conditions (Goodyear 1993). Therefore, 1-SPR is the reduction in the spawning output per recruit due to fishing and can be used to describe fishing intensity on a fish stock. The fishing intensity (1-SPR) on this common thresher shark stock ranged from a low of 0.119 in 1969, prior to the start of targeted commercial fishing, to a high of 0.983 in 1982 during the peak of the swordfish/shark drift gillnet fishery (Table 5.2 and Fig. 5.11).

5.2.4 Comparison with previous assessment

Changes in the reproductive biology, stock-recruitment relationship, and natural mortality parameters between this and the previous assessment (Teo et al. 2016), resulted in large differences in the estimated population dynamics (Fig. 5.12). It may be useful to think of these two assessments as bracketing the population dynamics of the stock: with the 2016 assessment representing a moderately productive shark stock, and this assessment representing a highly unproductive shark stock. Most importantly, the estimated number of mature females in this assessment is approximately two-fold larger and substantially slower to recover. The two-fold difference in the estimated population scale is largely due to the difference in fecundity between the two assessments. This assessment had an annual fecundity that was half that of the 2016 assessment (2 vs 4 pups y^{-1}) and the estimated number of mature females in the population became larger to compensate for the decreased fecundity. The slower response of the adult female population in this assessment is largely due to the differences in age structure between the two assessments, which was in turn due to differences in the age of maturity and natural mortality. In the 2016 assessment, the 50% age of maturity was assumed to be age-5 but in this assessment, the length at 50% maturity was assumed to be 215.1 cm FL (~age-13). In addition, the substantially lower natural mortality in this assessment (0.04 y^{-1} vs 0.179 y^{-1}) resulted in a large plus-group that dominated the dynamics of the mature female population. Therefore, it took substantially longer for changes in fishing intensity on the sub-adult age classes and increases in recruitment to manifest itself in the mature portion of the population. In general, the 2016 assessment assumed a moderately productive stock, similar to Smith et al. (2008b) and Cortes (2002). However, in this assessment, the stock was assumed to be a highly unproductive stock with a life history similar to bigeye thresher sharks.

6. Model uncertainty

The assessment explicitly estimated the model uncertainty due to uncertainty in parameter estimates. These uncertainties were reported as confidence intervals for key parameters and management quantities (Table 6.1). These confidence intervals captured the uncertainty in the model fits to the data sources in the assessment but did not include uncertainty in model specification and fixed parameters. We also used a suite of sensitivity runs to explore the uncertainty associated with alternative model specification and examine the sensitivity of important model outputs to different model assumptions.

6.1 Sensitivity analyses

A large number of alternative model specifications were used to examine the sensitivity of model results to different model assumptions. Only the most important ones are reported here. Summarized results of these sensitivity runs can be found in Table 6.1 and Figs. 6.1 – 6.14. Unless otherwise stated, input variances of abundance indices in the sensitivity runs were adjusted to make them consistent with the statistical assumptions of the model, and recruitment bias adjustments were performed. In addition, all sensitivity runs except for the run described in Section 6.1.3.2, used a data weighting approach that was consistent with the base case model. Essentially, a maximum weighting factor of 1 for all size composition data was used for the sensitivity runs and since estimated Francis weights of size composition data were all >1, all size composition weighting factors were set to 1 unless otherwise specified.

6.1.1 Alternative assumptions about life history and stock-recruitment

Uncertainty in the reproductive biology of this stock of common thresher sharks is the primary source of uncertainty in both the 2016 and current assessments (Teo et al. 2016; Appendix A). In the 2016 assessment, there was substantial uncertainty in the both the maturity schedule and fecundity of this stock (Teo et al. 2016). However, a recent re-examination by Aryafar et al (2017; Appendix B) indicated that the results of Smith et al. (2008a) may have been contaminated by pelagic thresher shark samples, although the evidence for this was circumstantial rather than conclusive. Given this and other evidence, the CIE review panel recommended that the current assessment use the maturity schedule from the northwest Atlantic stock (Natanson and Gervelis 2013; Appendix A; Section 2.3.1). While some uncertainty on the maturity schedule remained, there was thought to be more uncertainty in the reproductive cycle (annual vs biennial) and hence fecundity (4 vs 2 pups y^{-1}) (Aryafar et al. 2017; Appendix B; Section 1.1.3). In addition, preliminary models indicated that uncertainty in the reproductive biology of this stock interacted strongly with the uncertainty in the natural mortality and stock-recruitment parameters (Appendix C). A suite of models was therefore used to assess the sensitivity of model results to uncertainty in the reproductive cycle of this stock in combination with the uncertainty in natural mortality and stock-recruitment. Based on the recommendations of the CIE review panel, three models from this suite of models were selected to represent the overall uncertainty of this assessment with respect to management quantities.

Other models were also developed to illustrate the sensitivity of model results to uncertainty in other life history and stock-recruitment parameters. However, these were considered to be lower importance relative to the uncertainty in reproductive cycle in combination with natural mortality and stock-recruitment.

6.1.1.1 Alternative reproductive cycle, natural mortality, and z_{frac} values

A suite of models was used to assess the sensitivity of model results to uncertainty in the reproductive cycle (i.e., fecundity) of this stock in combination with the uncertainty in M and stock-recruitment, specifically the z_{frac} parameter. Two alternative reproductive cycles were explored: 1) the base case scenario of a biennial reproductive cycle (2 pups y^{-1}); and 2) an annual reproductive cycle (4 pups y^{-1}). For each reproductive cycle, a large number of models with M and z_{frac} fixed at a range of values were developed but only certain combinations of these parameters resulted in models that showed good convergence and reasonable diagnostics (Appendix C). Only models showing good convergence and reasonable diagnostics are shown (Figs. 6.1 and 6.2).

The estimated number of adult females varied greatly between models but the estimated depletion levels were relatively similar (Figs. 6.1 and 6.2). In general, a higher M resulted in a faster recovery and a more optimistic stock level in the terminal year. A higher z_{frac} resulted in a lower absolute scale of the population but the depletion levels were very similar.

Based on the recommendations of the CIE review panel, three models from this suite of models (in addition to the base case model with fecundity = 2 pups y^{-1}, M = 0.04 y^{-1}, and z_{frac} =0.5) were selected to represent the overall range of structural uncertainty of this assessment with respect to management quantities. These models were: 1) fecundity = 2 pups y^{-1}, M = 0.08 y^{-1}, and z_{frac} = 0.5; 2) fecundity = 4 pups y^{-1}, M = 0.08 y^{-1}, and z_{frac} =0.5; and 3) fecundity = 4 pups y^{-1}, M = 0.10 y^{-1}, and z_{frac} =0.5. Management quantities for these three runs are shown in Table 6.1.

6.1.1.2 Beverton-Holt stock-recruitment

The base case model used the relatively new stock-recruitment relationship developed by Taylor et al. (2013) for low fecundity fish like common thresher sharks (Section 3.4.2). However, common thresher sharks may instead have a Beverton-Holt stock-recruitment relationship. Therefore, we explored the effect of using a Beverton-Holt stock-recruitment relationship at several levels of steepness (h): 1) h = 0.74 (equivalent to steepness in base case model; Section 3.4.2); 2) h = 0.5; 3) h = 0.6; and 4) estimated h. The estimated h was 1.0.

The use of Beverton-Holt stock-recruitment relationships resulted in similar trends in the estimated number of mature females, recruitment, depletion, and fishing intensity (Fig. 6.3). However, the recovery of the stock was slower when Beverton-Holt stock-recruitment relationships were assumed, resulting in lower S_{2014}/S_0 ratios (Table 6.1 and Fig. 6.3).

6.1.1.3 Recruitment variability (sigma-R)

The expected recruitment variability in the base case model was set at a moderate level (σ_R = 0.5) that was consistent with estimated recruitment deviates for the base case model. The recruitment variability for sharks born at a moderately large size like common thresher sharks could conceivably be smaller than a σ_R of 0.5. The effects of using a σ_R of 0.3 were examined.

It should be noted that the sensitivity model with σ_R of 0.3 may not have converged because the Hessian matrix did not appear to be positive definite. However, the results of the model are still presented here for qualitative informational purposes. As expected, the estimated recruitment was slightly less variable when a σ_R of 0.3 was used, with lower recruitment since 2000 (Fig. 6.4). However, the trends in the estimated number of mature females, depletion, and fishing intensity were highly similar. The estimated recruitment deviates when using a σ_R of 0.3 were less variable than the base case model but many estimated deviates approached 0.5, suggesting that the base case model parameterization was likely more consistent with the data.

6.1.1.4 Alternative growth parameterization

Sex-specific growth was estimated in the base case model but growth of this stock was previously estimated by Smith et al. (2008a). In this sensitivity run, we fixed the growth of male and female sharks to the Smith et al. (2008a) estimates and did not fit to the conditional age-at-length data.

It should be noted that the sensitivity models with fixed growth parameters may not have converged because the Hessian matrix did not appear to be positive definite. However, the results of the model are still presented here for qualitative informational purposes. The estimated number of mature female sharks appeared to be relatively higher in the model with fixed growth but spawning depletion was relatively similar (Fig. 6.5). Importantly, the model fit of the size compositions of age-0 female sharks caught by the USA juvenile thresher shark survey (S6) was substantially better in the base case model than the sensitivity run (Fig. 6.5).

6.1.2 Alternative assumptions about fishery removals

6.1.2.1 High and low catch

Commercial landings of common thresher sharks by the USA West Coast commercial fisheries were relatively well known due to the CALCOM and PacFIN databases. However, there was uncertainty associated with potential misidentification of common thresher sharks as unspecified sharks (Pearson et al. 2008) or other less common species of thresher sharks (i.e., pelagic and bigeye thresher sharks). The commercial landings from Mexico fisheries were less well known but we assumed that the uncertainty associated with our estimates of removals by the Mexico drift gillnet, longline, and artisanal fisheries were approximately ±30%.

To explore the sensitivity of model output to the uncertainty in fishery removals, we developed two alternative fishery removal time series: 1) high catch, and 2) low catch. The high catch scenario was based on including all landings of unspecified sharks, and pelagic and bigeye thresher sharks by the USA West Coast commercial fisheries as landings of common thresher sharks, and setting the Mexico commercial landings to base case +30%. Conversely, the low catch scenario was based on excluding all landings of unspecified sharks, and pelagic and bigeye thresher sharks by the USA West Coast commercial fisheries, and setting the Mexico commercial landings to base case -30%. The dead discard rates for USA commercial fisheries were assumed to be the same for the base case model and both alternative catch scenarios. The removals by the USA recreational fishery were relatively minor compared to the commercial fisheries and were not adjusted for either catch scenario. However, the initial equilibrium catches for the high and low catch scenarios were adjusted accordingly to be the average of 1969 – 1971 for their respective scenario.

Although the absolute scale of the estimated unfished and current reproductive output changed, the trends in the estimated depletion levels as well as the status of the stock relative to reference points differed only slightly (Table 6.1 and Fig. 6.6).

6.1.2.2 Unfished initial conditions

In the base case model, we assumed that the level of pre-1969 equilibrium catch was the average of 1969 – 1971, and the initial fishing mortality was estimated from that initial catch. However, the population could have been in an unfished state at the start of the model. Therefore, we explored the effect of starting the model in an unfished state by fixing the initial fishing mortality to zero for all fleets and not fitting to the initial catch. The absolute scale of the unfished reproductive output was lower if the model was started under unfished conditions but the trends in reproductive capacity were highly similar (Table 6.1 and Fig. 6.7).

6.1.3 Alternative data sources and weightings

6.1.3.1 Including S6 as juvenile index

In the base case model, abundance indices based on the USDGN (S1, S2, and S3) and USSN (S4 and S5) fisheries were used to represent the sub-adult/adult and recruitment population trends respectively. In addition, an abundance index from the USA juvenile thresher survey (S6) was available but not used in the base case model (Section 2.2). The effect of fitting to the S6 index was investigated in this sensitivity run. There were negligible differences in the estimated population dynamics between the base case model and including the S6 index (Table 6.1 and Fig. 6.8). The negligible influence of S6 was expected because of the large input CVs (mean input CV = 0.485) that were estimated by jack-knifing the data set.

6.1.3.2 Maximum weighting factors >1

In the base case model, the variance adjustment factors of the size composition and conditional age-at-length data were based on estimated Francis (2011) weights but were also limited to a maximum of 1 in order to limit the influence of these data on estimated population scale (Maunder and Piner 2015). However, such a procedure may lead to the under-weighting of these data, and result in potential bias and inappropriate uncertainty. In this sensitivity analysis, we allow the weighting factors of the size composition and conditional age-at-length data to be >1. Reweighting with estimated Francis weights were performed twice.

The effect of allowing the maximum weighting factors to be >1 were limited (Table 6.1 and Fig. 6.9). The trend and scale of the estimated population dynamics in the sensitivity run were similar to the base case model. However, the estimated 95% confidence intervals were slightly smaller in the sensitivity run.

6.1.3.3 Down-weighting size composition data

Inappropriate weighting, especially over-weighting, of size composition data can result in biased results (Francis 2011; Maunder and Piner 2015). A series of sensitivity runs were performed to examine the influence of size composition data from each fleet on the estimated population dynamics. The size composition data from each fleet (F1, F2, F3, F8, S6) were down-weighted by a weighting factor of 0.2 in turn. Down-weighting the size composition data resulted in similar estimated population dynamics to the base case model (Table 6.1 and Fig. 6.10). Down-weighting the size composition data of the USSN (F3) fleet resulted in a non-positive definite Hessian matrix, indicating that the model likely did not converge.

6.1.3.4 Up-weight conditional age-at-length data

The conditional age-at-length data in the base case model were down-weighted by a weighting factor of 0.2 to reduce the influence of these data on the estimated population dynamics while maintaining the ability to estimate growth inside the model. Here, we examined the sensitivity of model results to this decision by allowing the data to be fully weighted (i.e., weighting factor of 1). Model results were largely similar with this change in data weighting, albeit with a slightly larger absolute scale (Table 6.1 and Fig. 6.11). However, the estimated growth for female sharks were different from the base case model. If the conditional age-at-length were fully weighted, the estimated L_∞ was larger than the base case model (284.1 cm vs 245.8 cm) and a concomitantly smaller K (0.1052 y^{-1} vs 0.1360 y^{-1}). Differences in the estimated growth of male sharks were substantially smaller than for female sharks. Fully weighting the conditional age-at-length data resulted in a non-positive definite Hessian matrix, indicating that the model likely did not converge.

6.1.4 Alternative assumptions on selectivity

6.1.4.1 Alternative time blocks

Regulatory changes, especially different time-area closures, likely affected the fishing operations of the USDGN and USSN fisheries, and hence changed the selectivities of the F1, F2, and F3 fleets over time. In the base case model, we accounted for this by allowing selectivities of these three fleets to vary over time in time blocks defined by regulatory changes. However, alternative time periods may be used to define the selectivity time blocks. In this sensitivity model, we simplified the selectivity time blocks for the F1 (1969 – 1984, 1985 – 2000, and 2001 – 2014) and F2 (1969 – 1984, and 1985 – 2014) fleets (cf. Table 3.1). The estimated scale of the population dynamics for this sensitivity model were highly similar to the base case model (Table 6.1 and Fig. 6.12).

6.1.4.2 Size selectivity for F3

In the base case model, the USSN (F3) fleet was assumed to have an age-based selectivity and used an aggregated age-0 size bin because of the difficulty in fitting the size composition data with a reasonable size-based selectivity process. In this sensitivity run, the effect of this decision was explored by using a size-based selectivity process for the F3 fleet and not aggregating the age-0 size bins into a single bin. The estimated selectivity and model fits indicated relatively poor model fit to the data in the sensitivity run (Fig. 6.13). However, the effect on the estimated population dynamics was relatively minor (Table 6.1 and Fig. 6.13).

6.1.4.3 Estimate F6 selectivity

The selectivity of the MXDGN (F6) fleet was assumed to be the same as the USDGN (F1) fleet in the base case model because of difficulty in fitting the limited size composition data in preliminary models and similarities in fishing gear and operations for both fleets. In this sensitivity run, the selectivity of the F6 fleet was estimated and we examined the effect of doing so on the estimated population dynamics. The estimated selectivity for F6 was highly similar to that of F1, albeit without any time blocks due to the limited size composition data, and there were minimal differences in the estimated population dynamics (Fig. 6.14).

7. Reference points

The current USA fishery management plan for USA West Coast fisheries associated with highly migratory species (PFMC 2011b) uses status determination criteria (SDC) for common thresher sharks that are based on maximum sustainable yield (MSY). Overfishing is declared to be occurring if the estimated current fishing mortality or a reasonable proxy exceeds the maximum fishing mortality threshold (MFMT) defined as F_{MSY} or reasonable proxy. The stock is declared in an overfished condition if current spawning biomass is less than the minimum stock size threshold (MSST), which is defined as $(1-M)*B_{MSY}$ or an appropriate proxy, when $M \leq 0.5$ and M is the instantaneous rate of natural mortality. Based on an unpublished assessment of the USA portion of the stock, a harvest guideline of 340 t was established using the alternative optimum yield (OY) control rule for vulnerable species (i.e., 0.75*MSY) (PFMC 2011b).

For the base case model of this assessment, the estimated MSY for this stock was 717.7 t (95% CI: 354.9 – 1080.4 t), and the number of mature female sharks at MSY was estimated to be 101,500 sharks (95% CI: 58,500 – 148,500 sharks), with a reproductive output of 203,000 pups (95% CI: 105,700 – 300,400 pups) (Table 7.1). The fishing intensity (1-SPR; where SPR is the spawning potential ratio) corresponding to MSY was estimated at 0.45 (95% CI: 0.42 – 0.49). Based on these estimates, the MFMT was 0.45 (using $1 - SPR_{MSY}$ as a proxy for F_{MSY}) and the MSST was 95,500 mature female sharks (using S_{MSY}, the number of mature female sharks at MSY, as a proxy for B_{MSY}) (Table 7.1).

8. Status of the stock

The estimated fishing intensity (1-SPR) on the common thresher sharks off the west coast of North America is currently relatively low at 0.097 (average of 2012 – 2014) (Table 5.2) and substantially below the estimated overfishing threshold (MFMT), with $(1-SPR_{1214})/(1-SPR_{MSY})$ at 0.21 (Table 8.1 and Fig. 8.1). Similarly, the estimated number of mature female sharks in 2014 (S_{2014}) for this stock is at 62% of its unexploited level and is substantially larger than the estimated MSST, with S_{2014}/MSST at 1.40 (Table 8.1 and Fig.8.1). Thus, this stock of common thresher sharks is unlikely to be in an overfished condition nor experiencing overfishing.

The stock began declining soon after the onset of the USA swordfish/shark drift gillnet fishery in the late 1970s. The stock was relatively slow to respond to management measures because of slow maturity and very low natural morality. Spawning depletion reached a minimum of 0.53 in 2006. However, the population have begun to recover slowly but steadily since 2006. (Table 5.2 and Fig. 5.8).

Besides the base case model, the status of the stock was also examined under three alternative states of nature, based on alternative life history assumptions recommended by the CIE review panel: 1) biennial reproductive cycle (i.e. 2 pups y^{-1}), natural mortality of 0.08 y^{-1}, and z_{frac} of 0.5; 2) annual reproductive cycle (i.e. 4 pups y^{-1}), natural mortality of 0.08 y^{-1}, and z_{frac} of 0.5; and 3) annual reproductive cycle, natural mortality of 0.10 y^{-1}, and z_{frac} of 0.5 (Table 8.1). These alternative states of nature addressed the most important sources of uncertainty identified in the sensitivity analysis (Section 6.1.1). The estimated management quantities from models assuming these alternative states of nature all indicated that this stock of common thresher sharks is unlikely to be in an overfished condition nor experiencing overfishing (Table 8.1 and Fig. 8.2).

9. Decision table

Given the recommendations of the CIE review panel and large uncertainties in the reproductive biology, *M*, and stock-recruitment parameters of this stock, we did not perform quantitative stock projections (Section 1.6). Therefore, this stock assessment of common thresher sharks along the west coast of North America does not include future projections of the base case model, and a decision table is not provided. However, the current low catch coupled with the estimated current status and population dynamics for the base case model and alternative states of nature suggest that the adult population is expected to continue increasing and stock depletion is expected to continue improving over the next several years, if future catch remain around current low levels.

10. Regional management considerations

Common thresher sharks are migratory, large pelagic sharks and this stock along the west coast of North America is abundant from Baja California, Mexico to Washington, USA. This stock assessment included data from both USA and Mexico waters, encompassing the predominant range of the stock. Small numbers of common thresher sharks are caught by Canada fisheries but the catch is small enough to be negligible. Although this stock assessment encompasses the entire stock, management of this stock is dependent on the domestic regulations of the USA and Mexico, which are largely uncoordinated. However, catch and effort from both USA and Mexico fisheries have been relatively low in recent years compared to historical catch and effort.

11. Research and data needs

In this stock assessment, several critical assumptions were made based on limited supporting data and research. There are several research and data needs that if satisfied, could improve future assessments, including:

1. The reproductive biology of this stock of common thresher sharks requires further research. Previous research on the reproductive biology of this common thresher shark stock suggested that the median age of maturity for female sharks was age-5 and that common thresher sharks had an annual reproductive cycle (Smith et al. 2008a). However, a re-examination of the Smith et al. (2008a) study suggests that those conclusions are uncertain (Appendix B). A recent study on the reproductive biology of the western North Atlantic stock of common thresher sharks (Natanson and Gervelis 2013) demonstrated a much higher median age of maturity for female sharks (age-12) and longer reproductive cycle (biennial or triennial cycle) for that stock. Sensitivity model runs indicated that changing the maturity and fecundity schedules resulted in substantial differences in the trend and scale of the estimated population dynamics, and was considered the most important uncertainty in this assessment. Therefore, it is important that research be conducted to re-examine the maturity ogive and reproductive schedule of this stock.
2. The low fecundity stock recruitment relationship has only been developed recently, has not been thoroughly investigated, and requires further research. In this assessment, we assumed a fixed level for z_{frac} and estimated the shape parameter. Preliminary model simulations suggested that the data in the assessment was adequate to estimate the shape parameter but more thorough examination of the use of this stock recruitment relationship is required.
3. The survey design and protocols of the USA juvenile thresher shark survey should be re-examined and improved. In this stock assessment, the abundance index derived from the USA juvenile thresher shark survey was not fit in the base case model because: 1) current protocols resulted in fishing operations that resembled commercial fishing operations with variable effort and catchability; 2) spatial coverage of the survey was relatively limited and likely covered only a small portion of the juvenile range; and 3) fishing effort of the survey was relatively low and the patchy distribution of common thresher sharks resulted in highly variable abundance index estimates (i.e., high CV). The design and protocols of the USA juvenile thresher shark survey should be re-examined to reduce these current drawbacks.
4. Catch and catch-at-size estimates from USA fisheries, especially the USA recreational fishery, should be improved. The USA recreational fishery on this stock of common thresher sharks consists mostly of private vessels, which are poorly sampled. Besides the usual difficulties in estimating the catch, there is also virtually no data on the size composition of the catch. In this assessment, the size of fish caught by the recreational fishery was assumed to be similar to that caught by the USDGN fishery but this assumption may be inappropriate. Therefore, some effort should be put into sampling the recreational catch in the near future. In addition, size composition data from the USSN fishery have also been lacking in recent years.
5. Catch and catch-at-size estimates from Mexico fisheries should be improved. The catch of common thresher shark from Mexico fisheries were estimated for this assessment

because of the lack of historical species-specific catch data for sharks. In addition, the collection of size composition data for common thresher shark from Mexico fisheries was ad hoc and opportunistic. Improving future data collection from Mexico fisheries will be difficult but likely to result in improvements to future stock assessments.

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TABLES

Table 1.1. Timeline of major changes in regulations and operations of the USA and Mexico swordfish/shark drift gillnet fisheries (USDGN and MXDGN), USA nearshore set gillnet and small-mesh drift gillnet fishery (USSN), and Mexican pelagic longline fishery (MXLL).

Year	Regulation or operational change
	USA swordfish/shark drift gillnet fishery (USDGN)
1977	Initial development of swordfish/shark drift gillnet fishery in Southern California, initially targeting pelagic sharks. Swordfish landings not authorized.
1980	Drift gillnet gear restrictions established with minimum mesh size of 8 inches, twine size at #18, and net length or 6000 feet or less. Nets could be fished only between 2 h before sunset and 2 h after sunrise. Swordfish landings for any given month limited to 25% of the number of swordfish landed by harpoon fishery for that month. Marlin bycatch limited to 10% of the number of marlin caught by recreational fishery for any given month.
1982	Minimum mesh size changed to 14 inches. Limited time-area closure (May 1 through July 31) around Channel Islands and between Channel Islands and mainland (February 1 through April 30). Swordfish (25% of harpoon fishery) and marlin (10% of recreational fishery) quotas replaced by limits on swordfish landings to no more than the landings of thresher and mako sharks for any permit holder during any given month during May 1 through September 15.
1983	Initial development of swordfish/shark drift gillnet fishery in Washington and Oregon. Experimental drift gillnet permits issued by Washington and Oregon.
1985	New time-area closures in California. Drift gillnets were prohibited within 75 nm of the California mainland from 1 June through 14 August, to reduce fishing pressure on thresher sharks; and within 25 nm from 15 December through 31 January to protect gray whales. Equal shark-swordfish landing requirement eliminated.
1986	California prohibited drift gillnet fishery within 12 nm of the California coast north of Point Arguello and certain areas in the Gulf of the Farallones. First substantial landings of thresher shark in Washington and Oregon ports (~293 mt dressed weight).
1989	Drift gillnet thresher shark fishery closed in Washington and Oregon. Closure period for 75 nm time-area closure in California (see 1985) changed to May 1 through July 14.
1990	Mandatory observer program for the USA swordfish/shark drift gillnet fishery began.
1992	Closure period for 75 nm time-area closure in California (see 1985) changed to May 1 through August 14.
2001	Additional time-area closures established by the NMFS. The drift gillnet fishery was closed from August 15 through November 15 in an area between Point Conception and 45 °N to protect leatherback sea turtles. In addition, if an El Nino is occurring, or predicted to occur, the area south of Point Conception will be closed to drift gillnet fishing from August 15 to August 31, and during the entire month of January, to reduce loggerhead sea turtle impacts.
2003	USA Pacific States Marine Fisheries Commission finalized coastwide thresher shark management plan. Harvest guideline of 340 t established for USA West Coast fisheries.

Table 1.1. continued. Timeline of major changes in regulations and operations.

Year	Regulation or operational change
	USA nearshore set gillnet and small mesh drift gillnet fisheries
1994	All gillnets and trammel nets prohibited within 3 nm of California mainland and within 1 nm (or waters < 70 fathoms depth) of Channel Islands (California Marine Resources Protection Act, 1990).
	Mexico swordfish/shark drift gillnet fishery
1983	50 nm sportsfishing-only zone along Mexico coast.
1986	Start of fishery.
2010	End of fishery due to Mexico federal regulations.
	Mexico pelagic longline fishery
1976	Declaration of Mexico EEZ. All longline permits withdrawn.
1980	Mexico-Japan joint venture longline fishery started.
1983	50 nm sportsfishing-only zone along Mexican coast.
1990	Mexico-Japan joint venture longline fishery ended.
1997	Mexico DGN vessels begin converting to longline gear.

Table 2.1. Description of fleets and abundance indices in the base case model.

Fleet ID	Short name	Fleet description
		Fleets with removals
F1	USDGN	USA swordfish/shark pelagic drift gillnet fishery for seasons 1, 3, and 4. Removals from USA miscellaneous fisheries for these seasons were included into this fleet.
F2	USDGNs2	USA swordfish/shark pelagic drift gillnet fishery for season 2. Removals from USA miscellaneous fisheries for season 2 were included into this fleet.
F3	USSN	USA nearshore set gillnet and small-mesh drift gillnet fishery for all 4 seasons.
F4	USREC	USA recreational fishery for seasons 1, 3, and 4. Catch units in number of fish.
F5	USRECs2	USA recreational fishery for season 2. Catch units in number of fish.
F6	MXDGNLL	Mexico swordfish/shark pelagic drift gillnet fishery for seasons 1, 3, and 4. Removals from the Mexico pelagic longline fishery for these seasons were included in this fleet.
F7	MXDGNLLs2	Mexico swordfish/shark pelagic drift gillnet fishery for season 2. Removals from the Mexico pelagic longline fishery for this season were included in this fleet.
F8	MXART	Mexico coastal artisanal fishery with mixed gillnet and longline gears. Also known as the panga fishery.
		Abundance indices inputted as surveys
S1	USDGN8284	Standardized annual index of relative abundance of sub-adult/adult common thresher sharks based on logbooks from the USA swordfish/shark pelagic drift gillnet fishery during 1982 – 1984.
S2	USDGN9200	Standardized annual index of relative abundance of sub-adult/adult common thresher sharks based on logbooks from the USA swordfish/shark pelagic drift gillnet fishery during 1992 – 2000.
S3	USDGN0113	Standardized annual index of relative abundance of sub-adult/adult common thresher sharks based on logbooks from the USA swordfish/shark pelagic drift gillnet fishery during 2001 – 2013.
S4	USSN8593	Standardized annual index of relative abundance of primarily age-0 common thresher sharks based on logbooks from the USA nearshore set gillnet and small-mesh drift gillnet fishery during 1985 – 1993.
S5	USSN9414	Standardized annual index of relative abundance of primarily age-0 common thresher sharks based on logbooks from the USA nearshore set gillnet and small-mesh drift gillnet fishery during 1994 – 2014.
S6	USJUV0614	Standardized annual index of relative abundance of juvenile common thresher sharks from a coastal longline survey conducted by the Southwest Fishery Science Center during 2006 – 2014.

Table 2.2. Estimated common thresher shark removals by fleet.

Year	USDGN (t)	USDGNs2 (t)	USSN (t)	USREC (1000 fish)	USRECs2 (1000 fish)	MXDGNLL (t)	MXDGNLLs2 (t)	MXART (t)
1969	84.4	17.4	1.8	0.6	0.6	0.0	0.0	20.9
1970	87.0	32.3	2.8	0.6	0.6	0.0	0.0	20.9
1971	21.4	39.8	2.4	0.6	0.6	0.0	0.0	20.9
1972	99.3	20.4	2.5	0.6	0.6	0.0	0.0	20.9
1973	42.0	70.8	1.2	0.6	0.6	0.0	0.0	20.9
1974	120.9	23.4	2.5	0.6	0.6	0.0	0.0	20.9
1975	143.9	97.2	5.1	0.6	0.6	0.0	0.0	20.9
1976	263.9	133.5	7.7	0.6	0.6	0.0	0.0	29.4
1977	246.1	167.0	8.9	0.6	0.6	0.0	0.0	16.8
1978	322.8	254.1	31.9	0.6	0.6	0.0	0.0	16.5
1979	745.2	380.3	55.5	0.6	0.6	0.0	0.0	21.1
1980	1638.8	486.4	36.1	0.4	0.0	0.0	0.0	39.7
1981	842.1	747.9	74.1	0.1	0.0	0.0	0.0	54.5
1982	963.0	846.7	143.4	1.9	0.2	0.0	0.0	84.7
1983	438.1	835.5	67.3	0.5	3.0	0.0	0.0	74.1
1984	447.3	754.3	102.3	0.6	0.0	0.2	0.0	47.6
1985	241.8	890.7	65.9	0.2	0.2	6.6	2.7	16.6
1986	661.0	325.9	8.8	1.4	0.0	27.8	11.8	30.7
1987	303.0	285.0	15.4	0.8	4.1	88.7	40.1	38.9
1988	432.6	134.5	3.7	0.0	0.9	102.5	47.0	43.6
1989	335.3	114.4	3.0	0.8	0.0	74.1	32.2	21.5
1990	337.7	104.6	3.9	0.0	0.0	174.1	79.6	32.9
1991	310.0	147.7	2.8	0.0	0.0	147.5	65.4	18.9
1992	138.9	154.9	2.4	0.0	0.0	266.1	120.8	32.3
1993	237.6	38.0	3.0	1.9	0.9	280.5	127.9	20.3
1994	280.5	63.5	9.3	1.9	1.7	245.9	112.8	17.7
1995	210.3	56.2	10.3	2.2	0.5	173.9	78.0	12.8
1996	278.4	84.5	10.7	0.1	0.6	248.4	112.5	18.1
1997	200.8	55.0	14.8	0.3	0.1	279.3	126.1	20.6
1998	271.3	84.8	13.2	0.6	0.5	325.2	148.8	26.5
1999	194.2	110.8	19.6	0.8	0.3	185.3	81.9	18.1
2000	174.6	106.1	30.7	1.5	0.8	227.8	98.9	30.9
2001	239.3	99.7	27.8	1.6	0.6	205.9	87.0	35.1
2002	266.3	88.2	22.5	0.7	1.0	197.9	83.7	33.7
2003	134.9	73.0	15.8	0.5	1.7	188.8	77.9	32.6
2004	63.8	23.9	16.7	4.2	0.3	285.5	122.2	48.3
2005	155.9	29.2	9.2	0.2	0.1	181.8	76.6	31.1
2006	110.0	31.4	18.4	0.2	0.8	189.2	79.5	32.4
2007	165.0	25.0	9.7	0.9	0.6	208.5	87.7	35.9
2008	117.9	19.7	12.9	0.7	0.5	208.6	87.5	42.2
2009	58.4	27.9	12.8	1.5	0.4	54.4	10.1	48.5
2010	54.9	22.8	16.5	0.4	0.8	48.8	9.1	43.6
2011	82.3	4.9	9.5	1.7	0.7	41.4	7.5	36.5
2012	49.0	11.2	7.4	0.3	0.1	47.3	8.6	41.9
2013	42.8	8.5	3.2	0.2	0.6	44.9	9.1	41.4
2014	12.9	19.2	5.4	0.2	0.3	44.5	8.4	39.9

Table 2.3. Indices of relative abundance and associated coefficients of variation (CV). Units are number of fish per unit effort.

	USDGN8284 S1		USDGN9200 S2		USDGN0113 S3		USSN8593 S4		USSN9414 S5		USJUV0614 S6	
Year	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**	**Index**	**CV**
1981												
1982	0.01229	0.28035										
1983	0.00921	0.27814										
1984	0.00763	0.27842										
1985							0.07149	0.22246				
1986							0.05076	0.22000				
1987							0.07998	0.23149				
1988							0.06265	0.23024				
1989							0.04039	0.23056				
1990							0.07087	0.23840				
1991							0.05103	0.23477				
1992			0.00047	0.11681			0.06788	0.24198				
1993			0.00066	0.11289			0.08320	0.23061				
1994			0.00107	0.11289					0.20827	0.25464		
1995			0.00076	0.12739					0.20266	0.23268		
1996			0.00099	0.12568					0.29486	0.21991		
1997			0.00112	0.11994					0.45911	0.19964		
1998			0.00214	0.12047					0.49911	0.20750		
1999			0.00126	0.12996					0.55780	0.19030		
2000			0.00191	0.14880					0.33207	0.20322		
2001					0.01269	0.19702			0.69024	0.21287		
2002					0.00631	0.20242			0.38927	0.22537		
2003					0.00575	0.21192			0.22220	0.20489		
2004					0.00518	0.21691			0.29735	0.20710		
2005					0.01830	0.20352			0.24872	0.22886		
2006					0.00687	0.19910			1.00752	0.19227	3.20419	0.54869
2007					0.02289	0.19697			0.69005	0.20402	1.70947	0.51328
2008					0.00685	0.22096			0.38999	0.21220	7.64873	0.46797
2009					0.00391	0.22504			0.69659	0.19518	3.04584	0.47143
2010					0.01745	0.23111			0.76876	0.19815	5.43268	0.43013
2011					0.01148	0.23021			0.51435	0.21067	8.82981	0.49681
2012					0.00711	0.22832			0.72856	0.19746	4.87355	0.45691
2013					0.01244	0.19884			0.21324	0.24029	5.18471	0.45535
2014									0.81005	0.41220	1.73476	0.52305

Table 2.4. Summary of sampling effort used to generate size compositions for the assessment by fleet, length type measured (alternate or fork length), and year. Alternate length samples are shown in italic, while fork length samples are shown in standard type.

	USDGN (F1 & F2)		**USSN (F3)**		**USJUV0614 (S6)**		**MXDGN (F6 & F7)**		**MXART (F8)**	
Year	**N trips**	**N fish**	**N trips**	**N fish**	**N sets**	**N fish**	**N trips**	**N fish**	**N trips**	**N fish**
1981	*64*	*1093*								
1982	*175*	*1224*								
1983	*178*	*1528*	*1*	*11*						
1984	*146*	*1292*	*8*	*21*						
1985	*126*	*977*								
1986	*142*	*802*	*18*	*38*						
1987	*97*	*678*	*14*	*44*						
1988	*168*	*820*	*6*	*34*						
1989	*113*	*1024*	*15*	*98*						
1990	28	221	10	27						
1991	26	285	30	54						
1992	28	230	32	87						
1993	23	286	55	87						
1994	51	582	8	9						
1995	23	174								
1996	32	691								
1997	57	516								
1998	51	757								
1999	40	314	11	22						
2000	42	683	1	1						
2001	41	611								
2002	33	414								
2003	31	440								
2004	29	162								
2005	37	959								
2006	26	218	2	10	29	236				
2007	20	173	3	6	22	129	*6*	*743*		
2008	15	165			39	280	*3*	*612*		
2009	7	50	3	10	32	200				
2010	8	1015	15	32	33	277				
2011	17	402	7	15	38	393			NA	349
2012	6	88	12	51	38	265				
2013	20	167	2	3	36	262				
2014					23	138				

Table 3.1. Selectivity patterns used in the base case model. Estimated parameters can be found in Table 5.1.

Fleet ID	Fleet name	Time periods	Selectivity pattern
			Estimated selectivity
F1	USDGN	1969 – 1981	Double-normal size selectivity
		1982 – 1984	
		1985 – 1988	
		1989 – 1991	
		1992 – 2000	
		2001 – 2014	
F2	USDGNs2	1969 – 1981	4-knot spline size selectivity
		1982 – 1984	
		1985 – 1988	
		1989 – 2014	
F3	USSN	1969 – 1993	Age selectivity; age-0 to 2 freely estimated; age-3+ at 0 selectivity
		1994 – 2014	
F8	MXART	1969 – 2014	Double-normal size selectivity
S6	USJUV0614	1969 – 2014	Double-normal size selectivity
			Mirrored selectivity
F4	USREC		Mirrored to F1
F5	USRECs2		Mirrored to F2
F6	MXDGNLL		Mirrored to F1
F7	MXDGNLLs2		Mirrored to F2
S1	USDGN8284		Mirrored to F1
S2	USDGN9200		Mirrored to F1
S3	USDGN0113		Mirrored to F1
S4	USSN8593		Mirrored to F3
S5	USSN9414		Mirrored to F3

Table 4.1. Analytical estimates of catchability, mean input variance, variance adjustment, and model fit (root mean square error, RMSE of expectations to observations) for sub-adult/adult (S1, S2, and S3) and recruitment (S4 and S5) annual abundance indices in the base case model.

Index	**Years**	**Catchability**	**Mean input CV**	**Variance adjustment**	**Input CV + Var. Adj.**	**RMSE**
S1	1982-1984	2.67E-4	0.279	0	0.279	0.111
S2	1992-2000	1.70E-5	0.124	0.165	0.288	0.274
S3	2001-2013	5.39E-5	0.212	0.333	0.546	0.545
S4	1985-1993	1.59E-3	0.231	0	0.231	0.175
S5	1994-2014	8.89E-3	0.221	0	0.221	0.178

Table 4.2. Mean input sample size (N_{input} after variance adjustment) and estimated mean effective sample size (N_{eff}) of the size composition data components of the base case model. Harmonic mean of the N_{eff} and the ratio of the harmonic mean of N_{eff} to the mean N_{input} are also provided. A higher N_{eff} indicates a better model fit. Number of observations corresponds to the number of quarters in which size composition data were sampled. Number of observations for F8 is not applicable (NA) because a super year was used to aggregate the size compositions for F8.

Fleet	**Bin structure**	**Number of observations**	**Mean N_{input} after var adj**	**Mean N_{eff}**	**Harmonic mean N_{eff}**	**Harmonic mean N_{eff}/ mean N_{input}**
F1	2 cm	43	14.9	104.4	39.0	2.6
F1	7 cm	21	40.9	95.5	61.7	1.5
F2	2 cm	2	7.5	107.8	96.1	12.8
F2	7 cm	9	40.3	183.1	140.0	3.5
F3	Age-0	20	10.5	31.2	14.5	1.4
F8	2 cm	NA	3.0	133.6	133.6	44.5
S6	2 cm	9	32.2	283.7	254.6	7.9

Table 4.3. Mean input sample size (N_{input} after variance adjustment) and estimated mean effective sample size (N_{eff}) of the conditional age-at-length data components of the base case model. Harmonic mean of the N_{eff} and the ratio of the harmonic mean of N_{eff} to the mean N_{input} are also provided. A higher N_{eff} indicates a better model fit. Number of observations corresponds to the number of sharks sampled in a fishery.

Fleet	**Number of observations**	**Mean N_{input} after var adj**	**Mean N_{eff}**	**Harmonic mean N_{eff}**	**Harmonic mean N_{eff}/ mean N_{input}**
F1	151	1.2	1.6	1.1	0.9
F3	1	1.0	9.0	9.0	9.0

Table 5.1. List of parameters used in the base case model. Sex-specific parameters are indicated by having female and male parameters, otherwise parameter values are the same for either gender.

Parameter		Value	Min	Max	Fixed	Estimation Phase
Natural Mortality		0.179			x	
Growth						
Female	L1	70.8	30	100		5
	L_∞	245.8	200	300		5
	K	0.136	0	0.2		5
	CV1	0.08			x	
	CV2	0.05			x	
Male	Offset from female L1	0.0125	-2	2		5
	Offset from female L_∞	-0.0179	-2	2		5
	Offset from female K	0.0080	-2	2		5
	Offset from female CV1	0			x	
	Offset from female CV2	0			x	
Weight-at-length						
	Coefficient	1.88E-4			x	
	Exponent	2.519			x	
Reproduction						
	Length at 50% maturity	215.1			x	
	Slope of maturity ogive	-0.2409			x	
	Fecundity at length intercept	2			x	
	Fecundity at length slope	0			x	
Stock-recruitment						
	$\log(R_0)$	3.421	1	15		1
	z_{frac}	0.5			x	
	Beta	2.533	0.4	7		1
Initial fishing mortality						
	F1	0.0288	0	3		1
	F2	0			x	
	F3	0			x	
	F4	0.0271	0	3		1
	F5	0			x	
	F6	0			x	
	F7	0			x	
	F8	0.0924	0	3		1
Size selectivity (F1: 1969 – 1981)						
	Peak	158.4	45	250		2
	Top	-4			x	
	Ascending width	6.606	-4	12		3
	Descending width	6.949	-4	9		3
	Selectivity at first bin	-2.101	-9	9		4
	Selectivity at last bin	-1000			x	

Table 5.1 (continued). List of parameters used in the base case model

Parameter	Value	Min	Max	Fixed	Estimation Phase
Size selectivity (F1: 1982 – 1984)					
Peak	155.3	45	250		5
Top	-4			x	
Ascending width	6.418	-4	12		5
Descending width	6.669	-4	12		6
Selectivity at first bin	-2.301	-9	9		6
Selectivity at last bin	-1000			x	
Size selectivity (F1: 1985 – 1988)					
Peak	146.9	45	250		5
Top	-4			x	
Ascending width	7.118	-4	12		5
Descending width	6.944	-4	12		6
Selectivity at first bin	-1.746	-9	9		6
Selectivity at last bin	-1000			x	
Size selectivity (F1: 1989 – 1991)					
Peak	149.7	45	250		5
Top	-4			x	
Ascending width	8.070	-4	12		5
Descending width	6.784	-4	12		6
Selectivity at first bin	0.336	-9	9		6
Selectivity at last bin	-1000			x	
Size selectivity (F1: 1992 – 2000)					
Peak	161.8	45	250		5
Top	-4			x	
Ascending width	6.724	-4	12		5
Descending width	6.782	-4	12		6
Selectivity at first bin	-3.831	-9	9		6
Selectivity at last bin	-1000			x	
Size selectivity (F1: 2001 – 2014)					
Peak	157.5	45	250		5
Top	-4			x	
Ascending width	6.713	-4	12		5
Descending width	6.963	-4	12		6
Selectivity at first bin	-3.173	-9	9		6
Selectivity at last bin	-1000			x	
Size selectivity (F2: 1969 – 1981)					
Spline gradient low: all periods	0.074	-1	1		3
Spline gradient high: all periods	-0.213	-1	1		3
Spline knot 1: all periods	75			x	
Spline knot 2: all periods	125			x	
Spline knot 3: all periods	175			x	
Spline knot 4: all periods	225			x	

Table 5.1 (continued). List of parameters used in the base case model

Parameter	Value	Min	Max	Fixed	Estimation Phase
Size selectivity (F2: 1969 – 1981) continued					
Spline value at knot 1	-2.893	-9	9		3
Spline value at knot 2	-0.388	-9	9		3
Spline value at knot 3: all periods	0			x	
Spline value at knot 4	-6.152	-9	9		3
Size selectivity (F2: 1982 – 1984)					
Spline value at knot 1	-2.936	-9	9		6
Spline value at knot 2	-0.594	-9	9		6
Spline value at knot 4	-5.159	-9	9		6
Size selectivity (F2: 1985 – 1988)					
Spline value at knot 1	-1.000	-9	9		6
Spline value at knot 2	0.153	-9	9		6
Spline value at knot 4	-3.499	-9	9		6
Size selectivity (F2: 1989 – 2014)					
Spline value at knot 1	-1.481	-9	9		6
Spline value at knot 2	1.058	-9	9		6
Spline value at knot 4	-4.707	-9	9		6
Age selectivity (F3: 1969 – 1993)					
Age-0	5.898	-9	9		2
Age-1	-3.649	-9	9		2
Age-2	-4.484	-9	9		2
Age-3 to age-25: all periods	-99			x	
Age selectivity (F3: 1993 – 2014)					
Age-0	7.023	-9	9		2
Age-1	-5.718	-9	9		2
Age-2	-5.380	-9	9		2
Size selectivity (F8)					
Peak	78.8	45	250		2
Top	-4			x	
Ascending width	3.997	-4	9		3
Descending width	6.668	-4	9		3
Selectivity at first bin	-1000			x	
Selectivity at last bin	-1000			x	
Size selectivity (S6)					
Peak	83.3	45	250		2
Top	-4			x	
Ascending width	4.922	-4	9		3
Descending width	7.530	-4	9		3
Selectivity at first bin	-1000			x	
Selectivity at last bin	-1000			x	

Table 5.2. Total biomass (Q1, age-1+), biomass and number of mature female sharks (Q2), depletion (S/S_0), recruitment, and fishing intensity (1-SPR) estimated in the base case model. Estimated virgin number of mature female sharks (S_0) and recruitment were 220,000 and 77,100 fish respectively. Reproductive output in number of pups was 2 * number of mature females.

Year	Total biomass age-1+ (mt)	Biomass of mature female sharks (mt)	Number of mature female sharks (1000s)	Depletion (S/S_0)	Number of recruits (1000s)	Fishing intensity (1-SPR)
1969	114723	44443	242.6	1.10	22.9	0.12
1970	114495	44447	242.6	1.10	22.5	0.14
1971	114102	44452	242.6	1.10	21.9	0.12
1972	113612	44460	242.7	1.10	21.3	0.15
1973	112901	44466	242.7	1.10	21.0	0.16
1974	112046	44468	242.7	1.10	21.2	0.18
1975	111021	44465	242.7	1.10	21.7	0.25
1976	109777	44444	242.5	1.10	21.5	0.36
1977	108238	44383	242.1	1.10	19.5	0.38
1978	106560	44276	241.4	1.10	19.4	0.52
1979	104571	44061	240.0	1.09	30.5	0.74
1980	102003	43656	237.4	1.08	31.2	0.92
1981	98346	42992	233.2	1.06	29.3	0.92
1982	95106	42276	228.8	1.04	27.4	0.98
1983	91242	41432	223.6	1.02	36.8	0.97
1984	87973	40456	217.7	0.99	27.2	0.96
1985	84866	39421	211.5	0.96	30.5	0.90
1986	81954	38209	204.4	0.93	29.0	0.91
1987	79244	37066	197.7	0.90	30.2	0.88
1988	76690	35856	190.8	0.87	25.2	0.81
1989	74436	34711	184.4	0.84	20.1	0.72
1990	72406	33617	178.3	0.81	25.1	0.77
1991	70349	32538	172.3	0.78	27.5	0.75
1992	68431	31475	166.6	0.76	37.3	0.73
1993	66745	30427	160.9	0.73	32.8	0.79
1994	65037	29396	155.5	0.71	26.2	0.79
1995	63345	28408	150.3	0.68	27.3	0.68
1996	62020	27493	145.5	0.66	40.1	0.66
1997	60945	26618	141.0	0.64	48.1	0.60
1998	60270	25792	136.7	0.62	48.5	0.65
1999	59655	25006	132.6	0.60	58.4	0.50
2000	59723	24283	128.9	0.59	40.2	0.54
2001	59697	23629	125.6	0.57	74.9	0.48
2002	60336	23053	122.8	0.56	44.6	0.44
2003	60951	22565	120.5	0.55	25.4	0.35
2004	61552	22171	118.7	0.54	36.3	0.43

Table 5.2 (continued). Total biomass (Q1, age-1+), biomass and number of mature female sharks (Q2), depletion (S/S_0), recruitment, and fishing intensity (1-SPR) estimated in the base case model.

Year	Total biomass age-1+ (mt)	Biomass of mature female sharks (mt)	Number of mature female sharks (1000s)	Depletion (S/S_0)	Number of recruits (1000s)	Fishing intensity (1-SPR)
2005	62027	21866	117.4	0.53	28.8	0.28
2006	62755	21681	116.9	0.53	88.0	0.27
2007	64337	21627	117.1	0.53	72.7	0.30
2008	66009	21711	118.2	0.54	50.9	0.28
2009	67732	21945	120.1	0.55	66.1	0.18
2010	70057	22324	122.8	0.56	69.1	0.14
2011	72737	22818	126.1	0.57	50.1	0.15
2012	75277	23382	129.7	0.59	73.7	0.10
2013	78378	23968	133.3	0.61	27.2	0.10
2014	80961	24566	136.8	0.62	52.6	0.09

Table 6.1. Estimated number of mature females under virgin conditions (S_0), and in 2014 (S_{2014}), average fishing intensity (1-SPR) in 2012 – 2014, maximum sustainable yield (MSY), and total negative log-likelihood for sensitivity runs conducted. Note that likelihoods may not be comparable between models. Lack of model convergence is indicated by NC.

Sensitivity run description	**S_0 (1000s of fish)**	**S_{2014} (1000s of fish)**	**1-SPR 2012 – 2014**	**MSY (mt)**	**Total likelihood**
Base case	220.0	136.8	0.097	717.7	654.279
Alternative life history & stock-recruitment (Section 6.1.1)					
Reproductive cycle, natural mortality & stock-recruitment (Represents main structural uncertainty of assessment)					
Biennial, M=0.08 y^{-1}, z_{frac}=0.5	169.5	130.7	0.054	911.9	659.383
Annual, M=0.08 y^{-1}, z_{frac}=0.5	98.8	63.8	0.087	726.5	656.955
Annual, M=0.10 y^{-1}, z_{frac}=0.5	100.8	78.6	0.060	893.1	658.242
Beverton-Holt					
h = 0.74 (h equivalent to base case)	218.1	80.2	0.170	555.8	656.374
h = 0.5	250.6	91.7	0.173	422.3	658.879
h = 0.6	233.6	85.6	0.173	482.6	657.634
h estimated (h = 1.0)	202.7	75.8	0.165	701.5	654.969
Sigma-R					
Sigma-R at 0.3 (NC)					
Growth					
Fixed growth (NC)					
Alternative removal scenarios (Section 6.1.2)					
High catch	250.7	156.2	0.097	813.9	654.294
Low catch	209.5	138.4	0.080	706.8	654.349
Unfished initial conditions	170.9	102.4	0.114	598.7	654.509
Alternative data sources and weightings (Section 6.1.4)					
Include S6 as juvenile index	220.5	137.5	0.094	721.0	652.505
Max weighting factors					
Max weighting factor >1	209.7	123.4	0.108	626.4	1978.680
Downweighting size composition data					
Downweight F1	211.0	125.3	0.106	671.3	250.100
Downweight F2	217.2	133.7	0.103	669.9	623.456
Downweight F3 (NC)					
Downweight F8	219.2	136.8	0.092	741.0	653.990

Sensitivity run description	S_0 (1000s of fish)	S_{2014} (1000s of fish)	1-SPR 2012 – 2014	MSY (mt)	Total likelihood
Downweight S6	231.5	150.1	0.089	754.2	604.879
Upweight CAAL data					
Upweight CAAL data (NC)					
Alternative selectivity assumptions (Section 6.1.5)					
Alternative time blocks	198.1	117.2	0.109	700.6	695.101
F3 size selectivity	189.0	102.6	0.127	591.8	683.752
F6 estimate selectivity	225.7	143.4	0.092	731.5	656.323

Table 7.1. Estimated reference points for the base case model.

	Estimate (95% CI)	Units
Virgin Conditions		
Number of mature female sharks (spawning abundance) (S_0)	220.0 (125.6 – 314.3)	1000s of sharks
Reproductive output	439.9 (251.3 – 628.6)	1000s of pups
Summary biomass at age-1+ (B_0)	103.5 (58.5 – 148.5)	1000s of metric tons
Recruitment at age-0 (R_0)	30.6 (17.1 – 44.1)	1000s of sharks
MSY-based reference points		
MSY	717.7 (354.9 – 1080.4)	Metric tons
Number of mature female sharks at MSY (spawning abundance) (S_{MSY})	101.5 (58.5 – 148.5)	1000s of sharks
Minimum stock size threshold (MSST) (1-M)* S_{MSY}	97.5 (50.7 – 144.2)	1000s of sharks
Reproductive output at MSY	203.0 (105.7 – 300.4)	1000s of pups
Fishing intensity at MSY (1-SPR_{MSY})	0.45 (0.42 – 0.49)	NA

Table 8.1. Summary of reference points and management quantities for the base case and three alternative states of nature. C_{2014} is the estimated fishery removals in metric tons in 2014. $1-SPR_{1214}$ is the average of the estimated fishing intensity (1-SPR) from 2012 through 2014. Key management quantities for the USA fishery management plan are in bold. Under the current USA fishery management plan, this stock is declared to be in an overfished state if S_{2014}/MSST is <1. Overfishing is considered to be occurring if $(1-SPR_{1214})/(1-SPR_{MSY})$ is >1.

	Base case (Biennial reproductive cycle; M = 0.04 y^{-1}; z_{frac} = 0.5)	**Alternative life history (Biennial reproductive cycle; M = 0.08 y^{-1}; z_{frac} = 0.5)**	**Alternative life history (Annual reproductive cycle; M = 0.08 y^{-1}; z_{frac} = 0.5)**	**Alternative life history (Annual reproductive cycle; M = 0.10 y^{-1}; z_{frac} = 0.5)**
MSY (t)	717.7	911.9	726.5	893.1
Number of mature female sharks at MSY (S_{MSY}) (1000s of sharks)	101.5	92.7	48.2	53.3
Number of mature female sharks under virgin conditions (S_0) (1000s of sharks)	220.0	169.5	98.8	100.8
Minimum stock size threshold (MSST) $(1-M)*S_{MSY}$	97.5	85.2	44.4	47.9
Fishing intensity at MSY ($1-SPR_{MSY}$)	0.453	0.351	0.411	0.368
C_{2014}/MSY	0.224	0.176	0.221	0.180
S_{2014}/S_{MSY}	1.348	1.411	1.323	1.476
S_{2014}/S_0	0.622	0.771	0.646	0.780
S_{2014}/MSST	1.404	1.534	1.438	1.640
$(1-SPR_{1214})/(1-SPR_{MSY})$	0.214	0.153	0.216	0.164

FIGURES

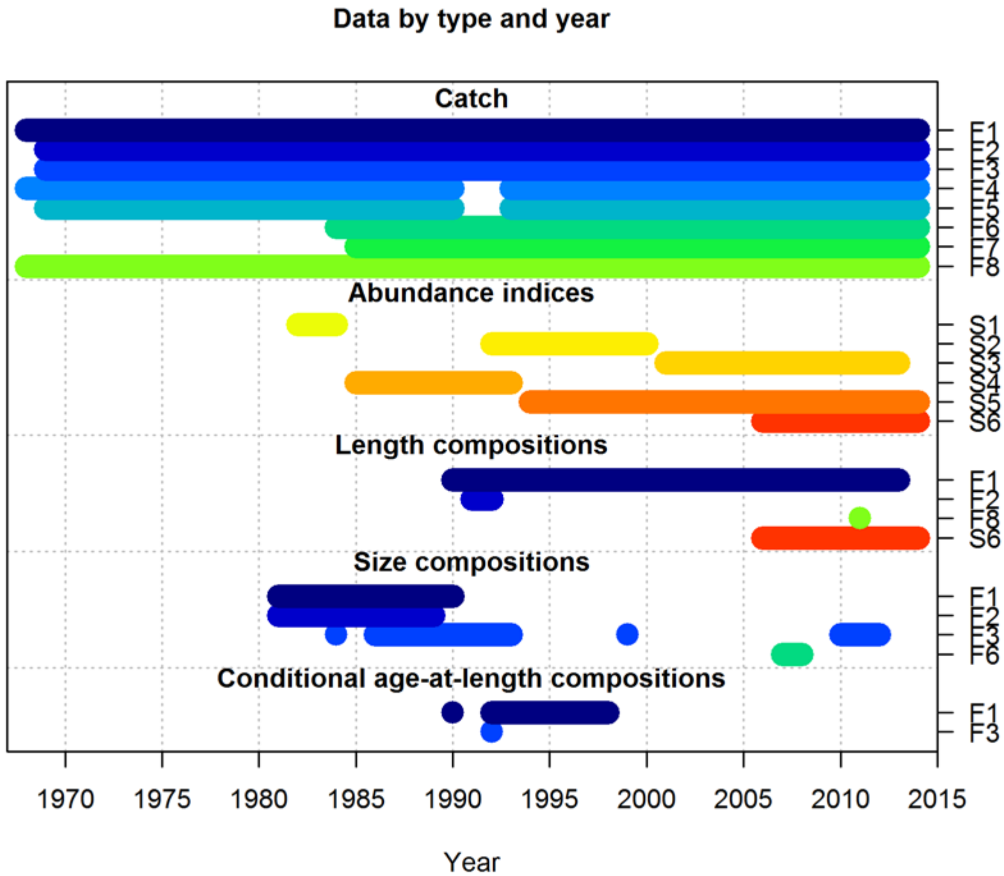


Figure 2.1. Summary of data used in the assessment. Description of fleets (F1 – F8) and abundance indices (S1 – S6) are found in Table 2.1.

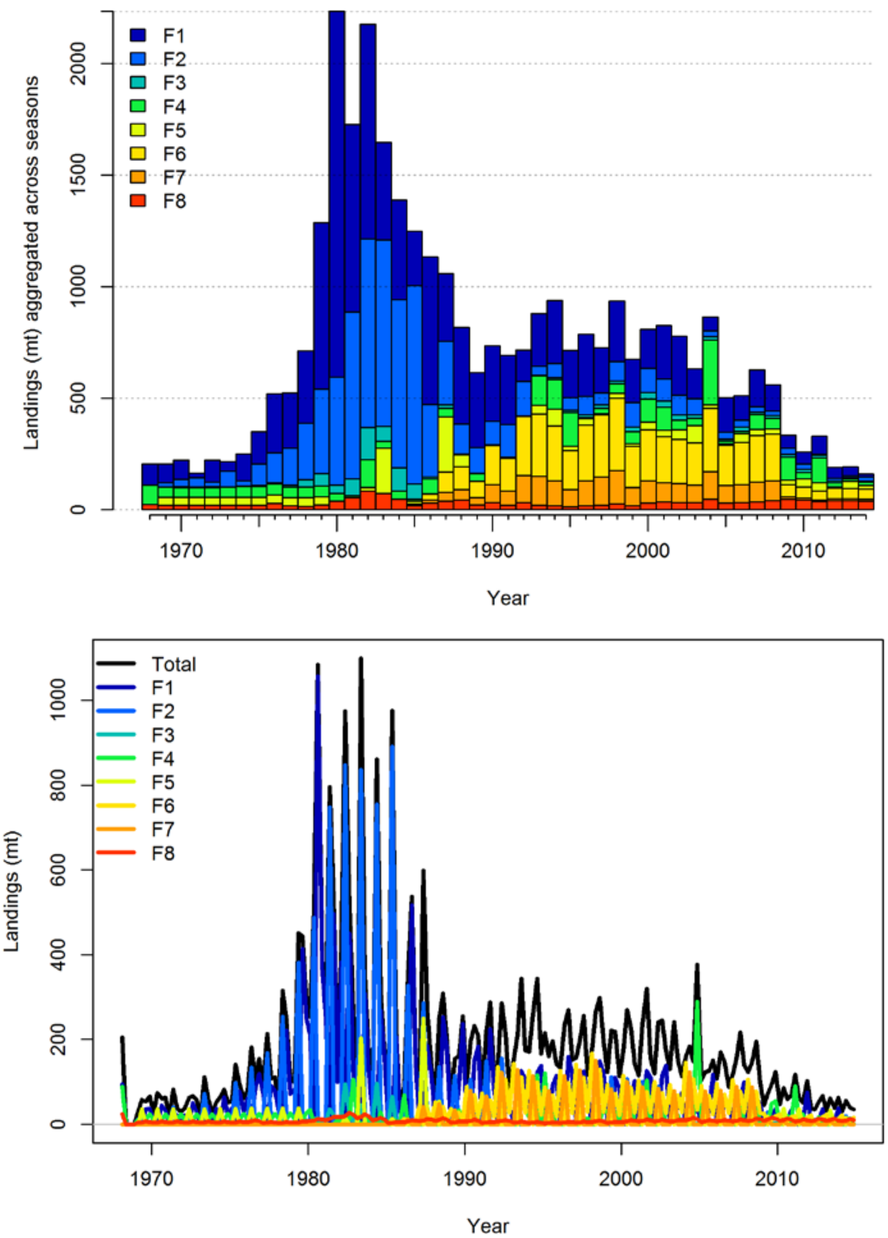


Figure 2.2. Estimated annual (upper) and seasonal (lower) common thresher shark removals by fleet. Description of fleets (F1 – F8) are found in Table 2.1. Note that removals in upper panel are stacked but not in lower panel.

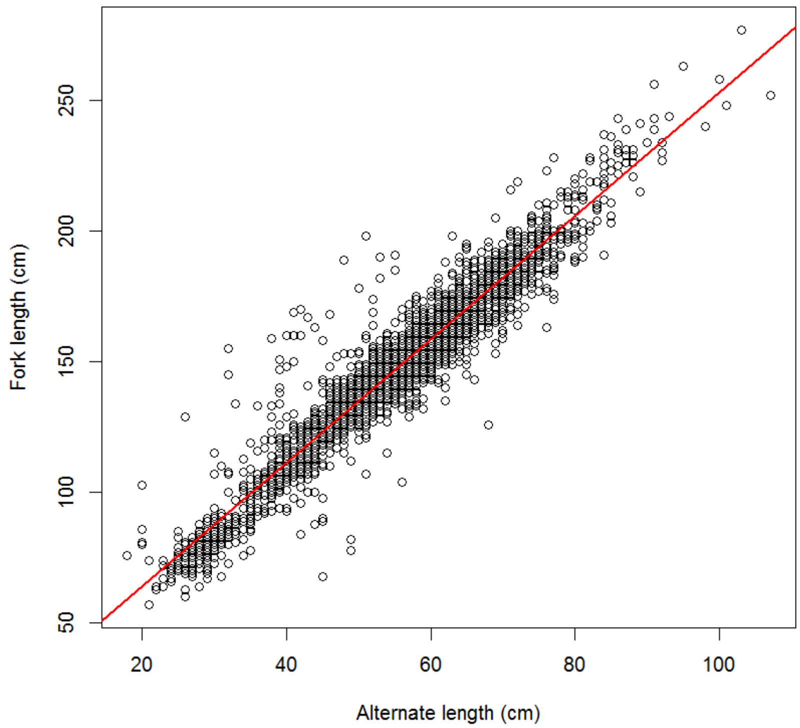


Figure 2.3. Estimated relationship between alternate and fork length for common thresher sharks along the USA West Coast. Fork length (cm) = 2.3627 × Alternate length (cm) + 16.82 (N = 3043 fish; adj. R^2 = 0.9165).

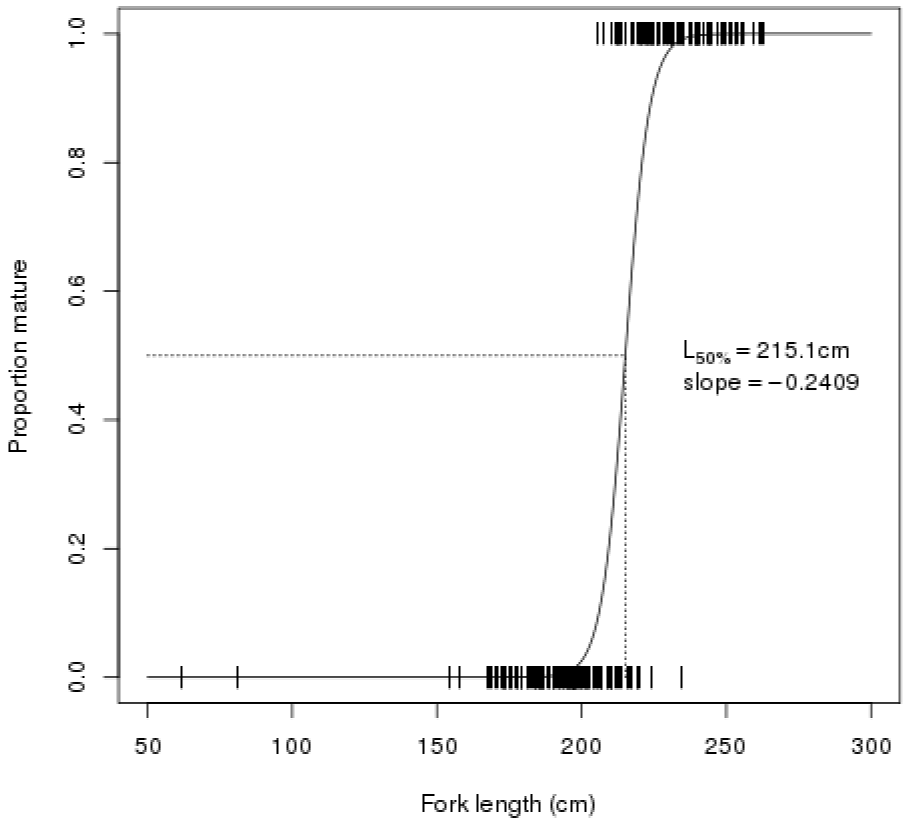


Figure 2.4. Estimated relationship between fork length and maturity for female common thresher sharks in the western North Atlantic. Data were from Natanson and Gervelis (2013) and re-fitted here. The estimated length at 50% maturity ($L_{50\%}$) and slope of the maturity ogive were 215.1 ± 45.8 cm FL and -0.2409 ± 0.0363 cm^{-1}, respectively.

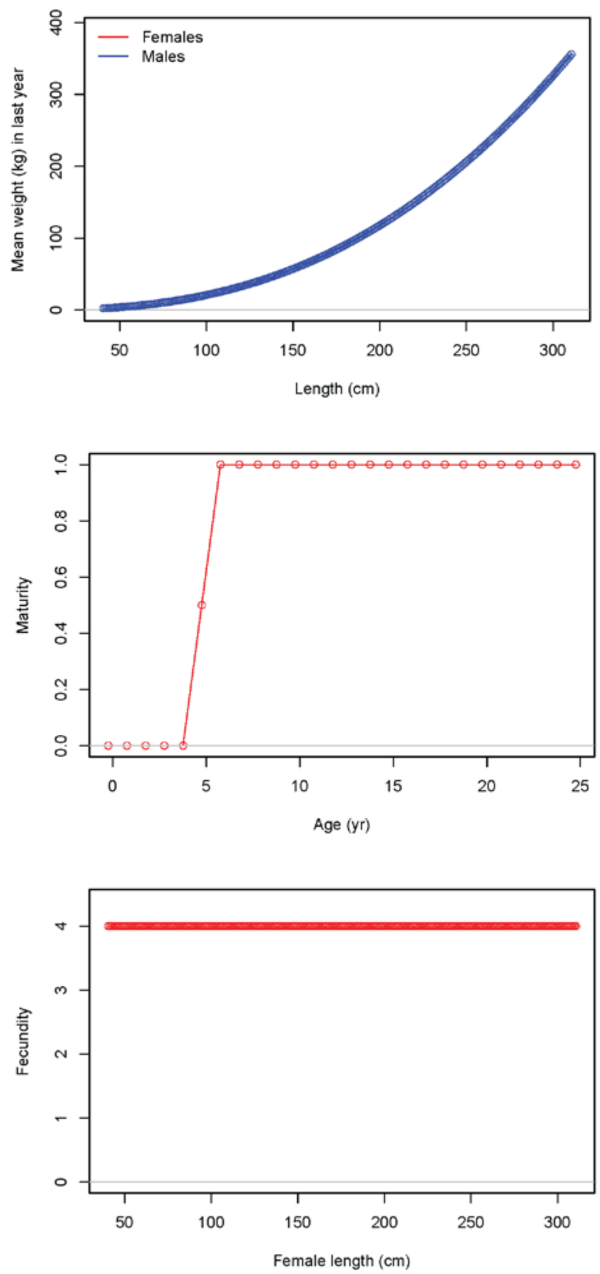


Figure 3.1. Fixed weight-at-length (upper), maturity-at-age (middle), and annual fecundity-at-length (lower) relationships used in the base case model. See Section 2.3 and 3.4.1.

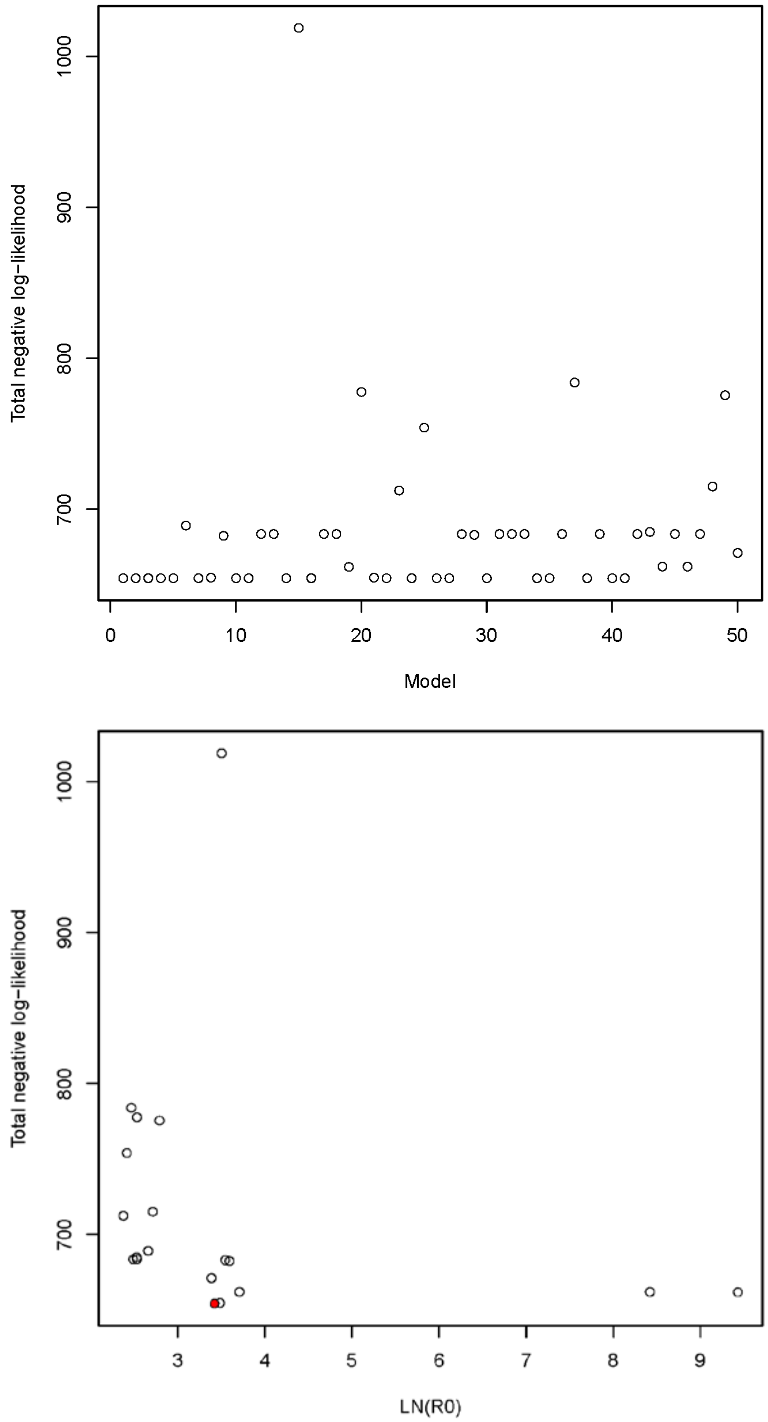


Figure 4.1. Convergence analysis of the base case model. Total negative log-likelihood of the base case model (Model 1) and 50 models using different phasing and initial parameters (upper); and estimated log virgin recruitment [LN(R0)], with the base case model in red (lower).

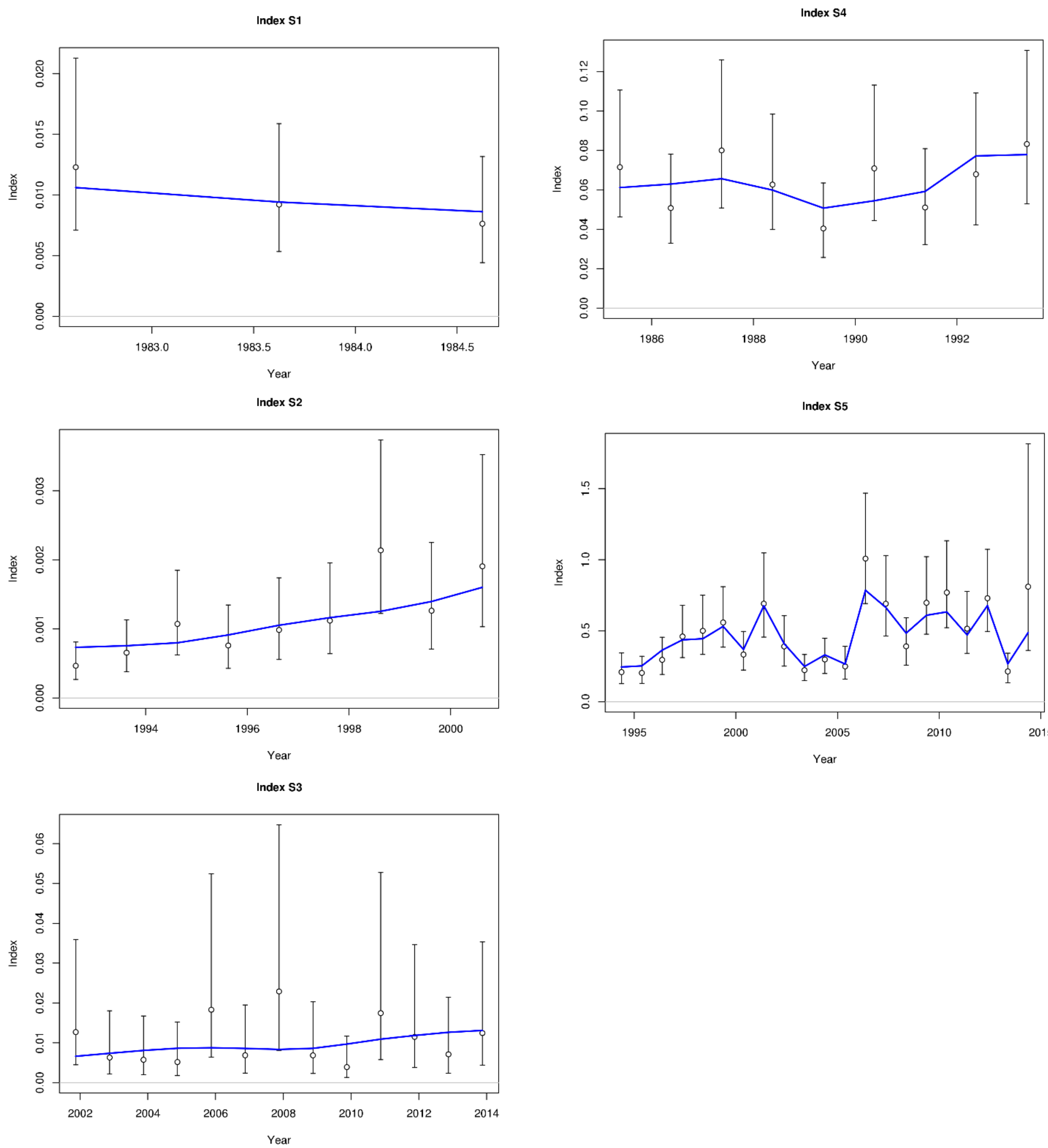


Figure 4.2. Observed (open circles) and expected (blue line) relative abundance of common thresher sharks from sub-adult/adult (S1, S2, and S3) and recruitment (S4 and S5) abundance indices in the base case model. Error bars indicate 95% confidence intervals.

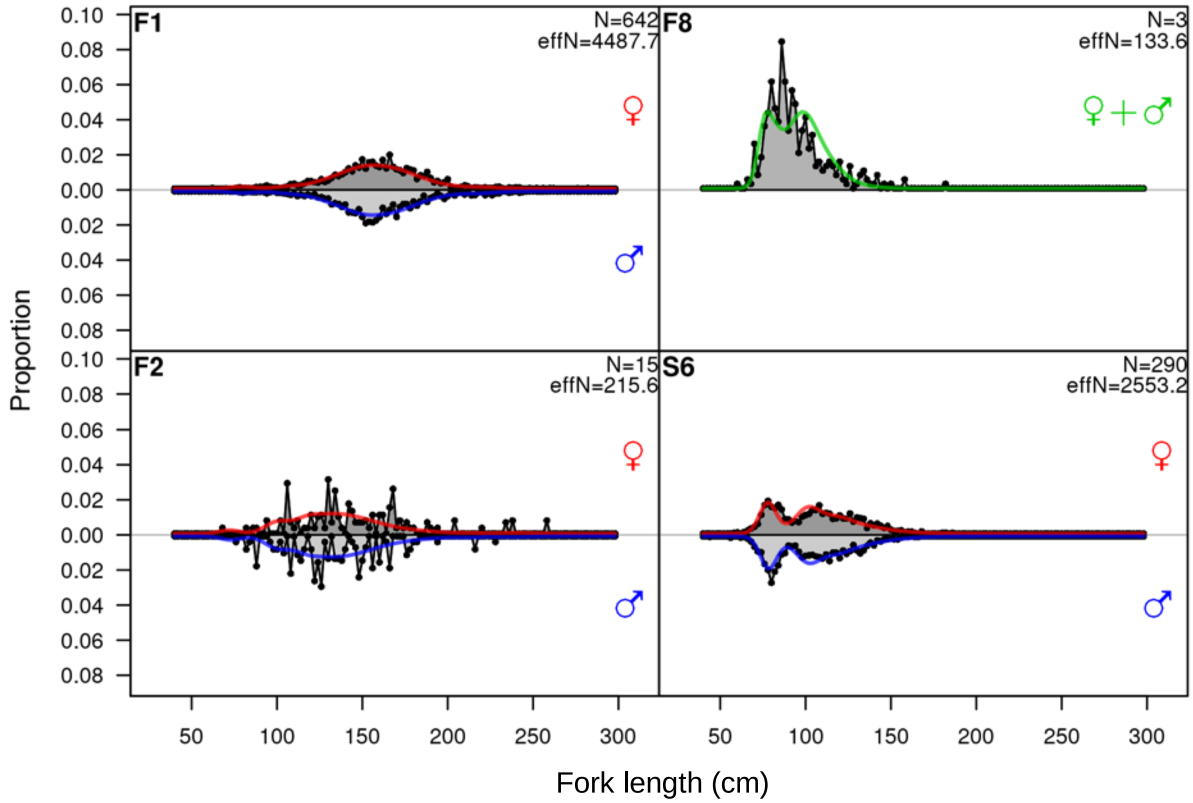


Figure 4.3. Observed (grey) and model predicted (red: female; blue: male; green: sex-combined) overall size compositions in 2 cm bins for the base case model. Size compositions for the MXART (F8) fleet were aggregated into a single year and input as a super year.

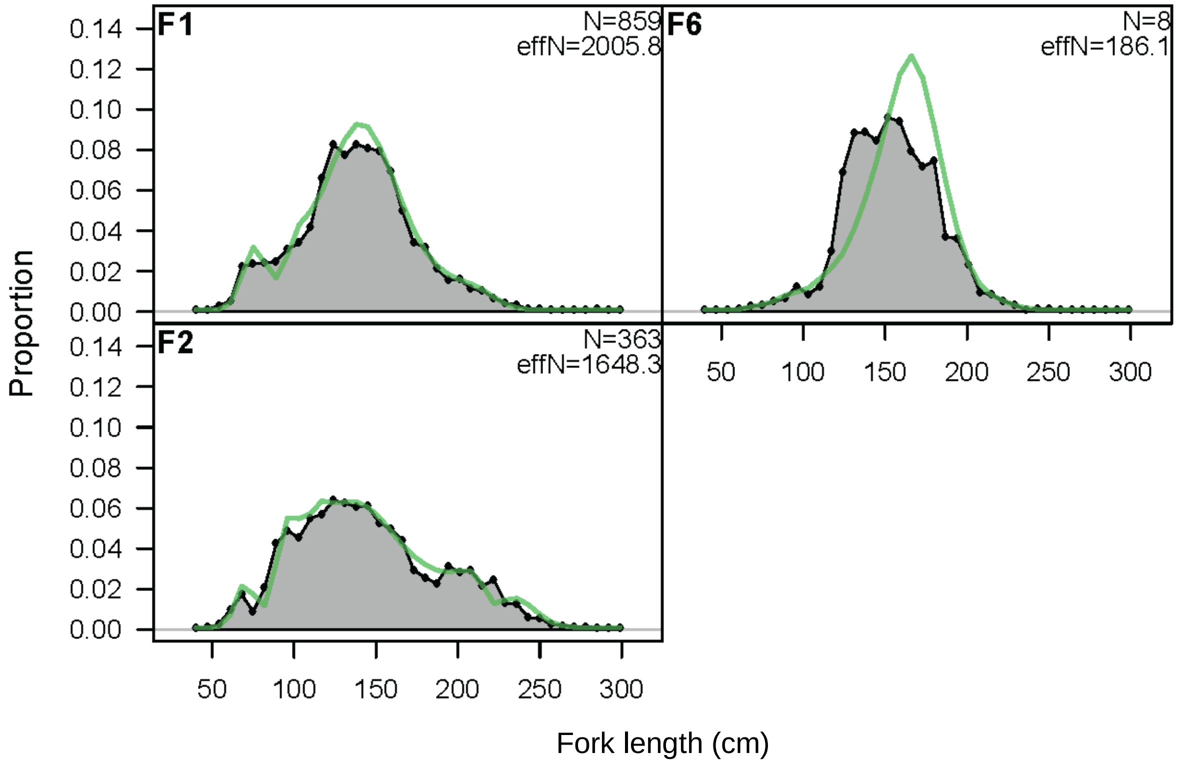


Figure 4.4. Observed (grey) and model predicted (green: sex-combined) overall size compositions in 7 cm bins for the base case model. Size compositions for the MXDGNLL (F6) fleet were not fit in the base case model but selectivity for F6 was assumed to be the same as the USDGN (F1) fleet.

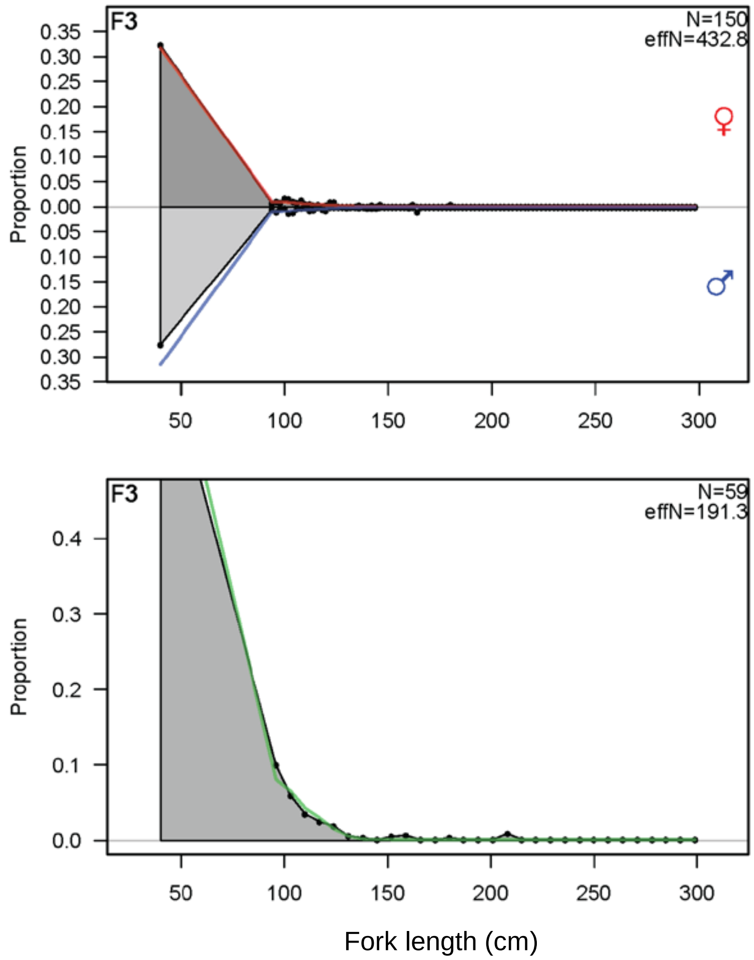


Figure 4.5. Observed (grey) and model predicted (red: female; blue: male; green: sex-combined) overall size compositions in 2 (upper) and 7 (lower) cm bins for the base case model. Size bins that approximated age-0 sized fish were aggregated into a single bin for the USSN (F3) fleet.

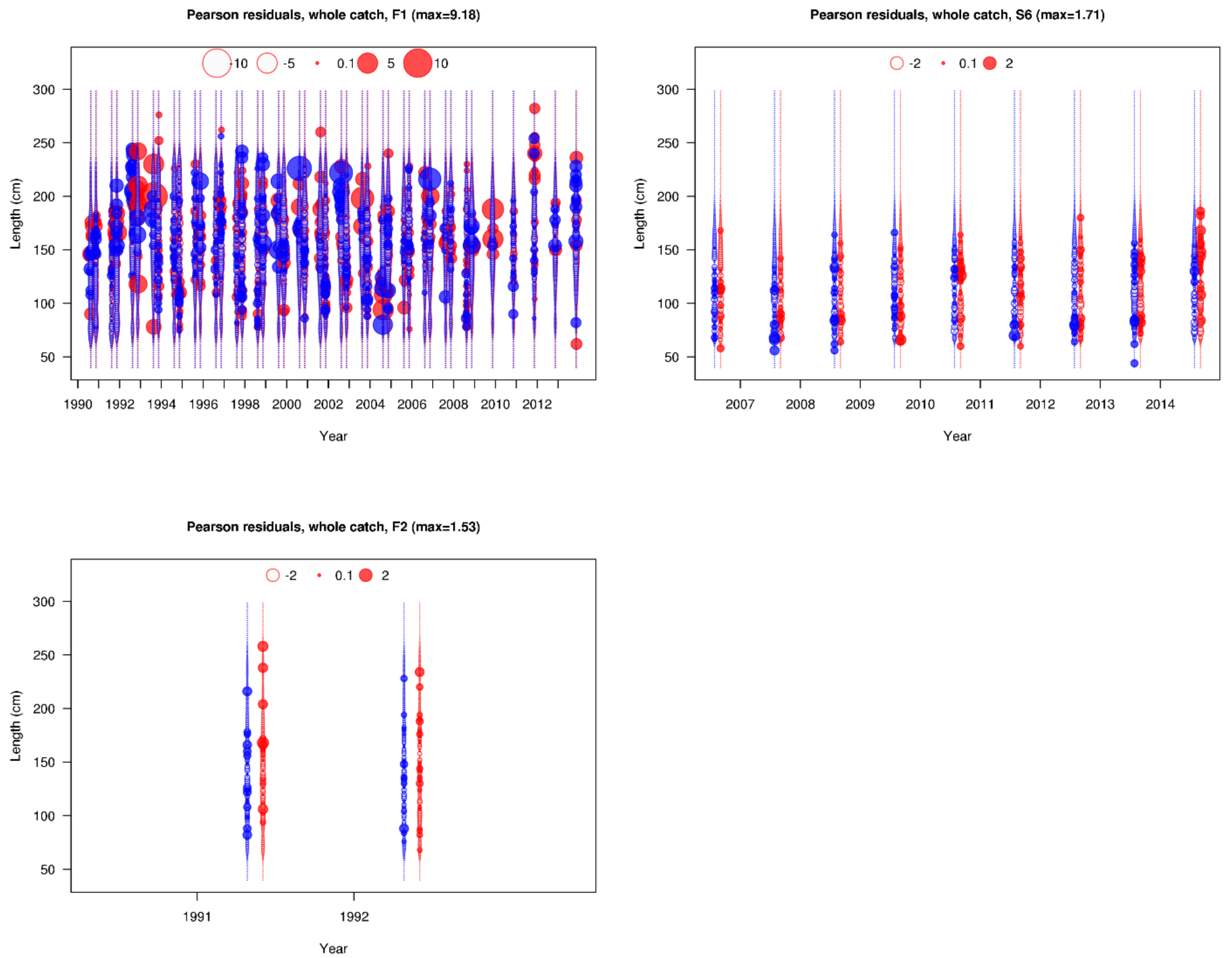


Figure 4.6. Pearson residuals of model fit to size composition data in 2 cm bins for the base case model. Filled and open circles represent observations (i.e., proportions at size) that are larger and smaller than model predictions, respectively. Blue and red circles represent male and female samples respectively. Area of circles are proportional to absolute values of residuals. Residuals of F8 are not shown here because its size composition data were input as a super year (i.e., a single year of observation) and residuals are better seen in Fig. 4.3.

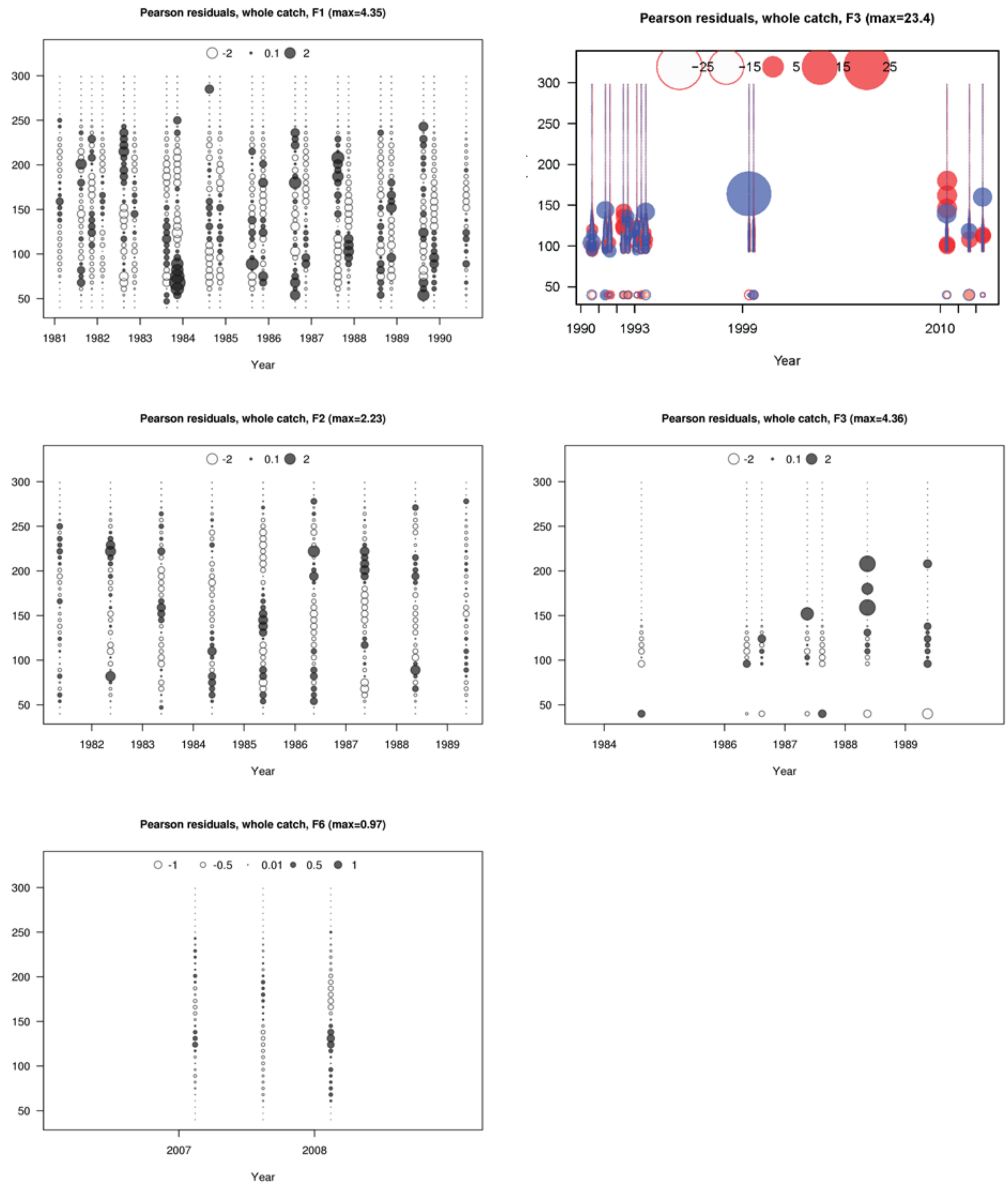


Figure 4.7. Pearson residuals of model fit to size composition data in 7 cm bins (left panels) and age-0 aggregated 2 cm (upper right; blue: male; red: female) and 7 cm bins (middle right) for the base case model. Filled and open circles represent observations that are larger and smaller than model predictions, respectively. Area of circles are proportional to absolute values of residuals.

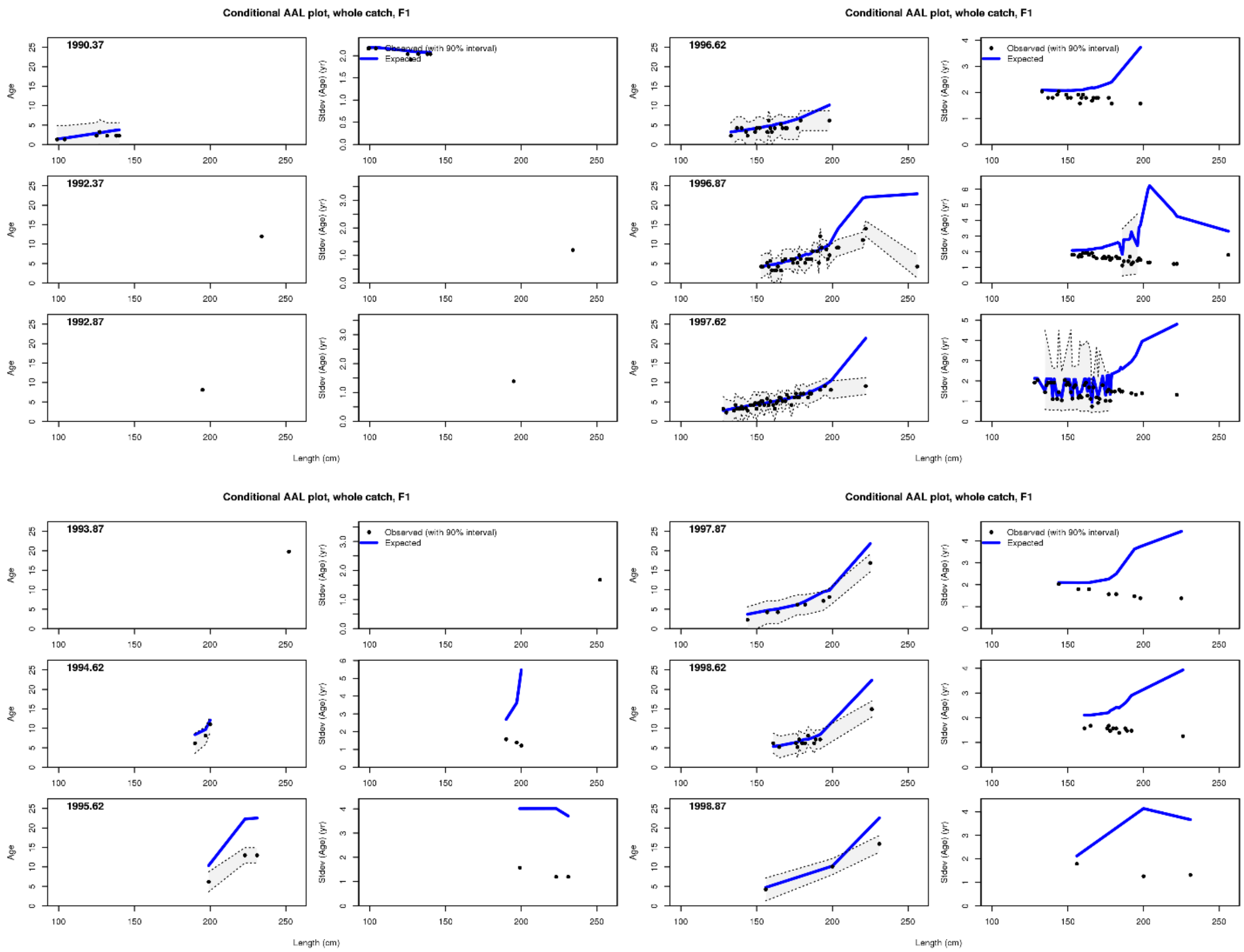


Figure 4.8. Base case model fit to conditional-age-at-length data from the USDGN (F1) fleet.

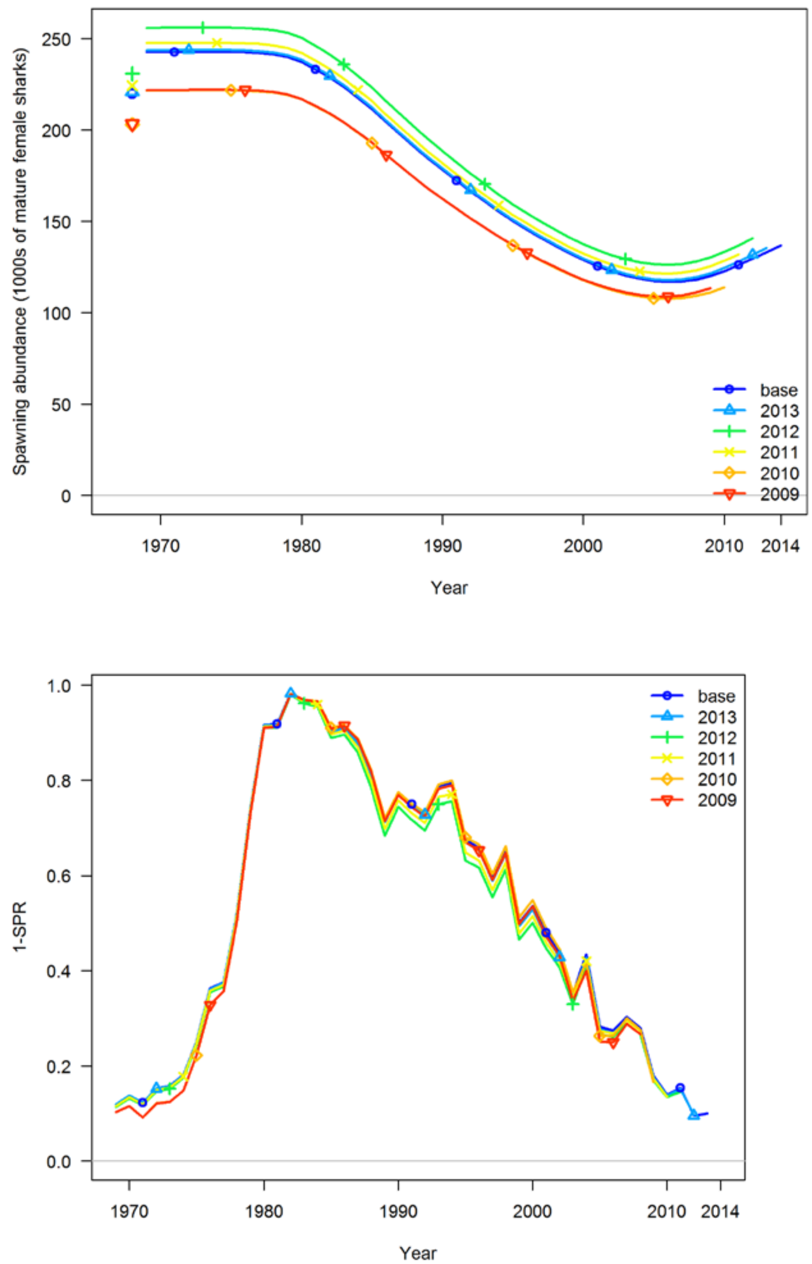


Figure 4.9. Retrospective analysis of base case model. Estimated spawning abundance (1000s of mature female sharks) (upper) and fishing intensity (1-SPR) (lower) with successive elimination of 1 – 5 years of terminal year data.

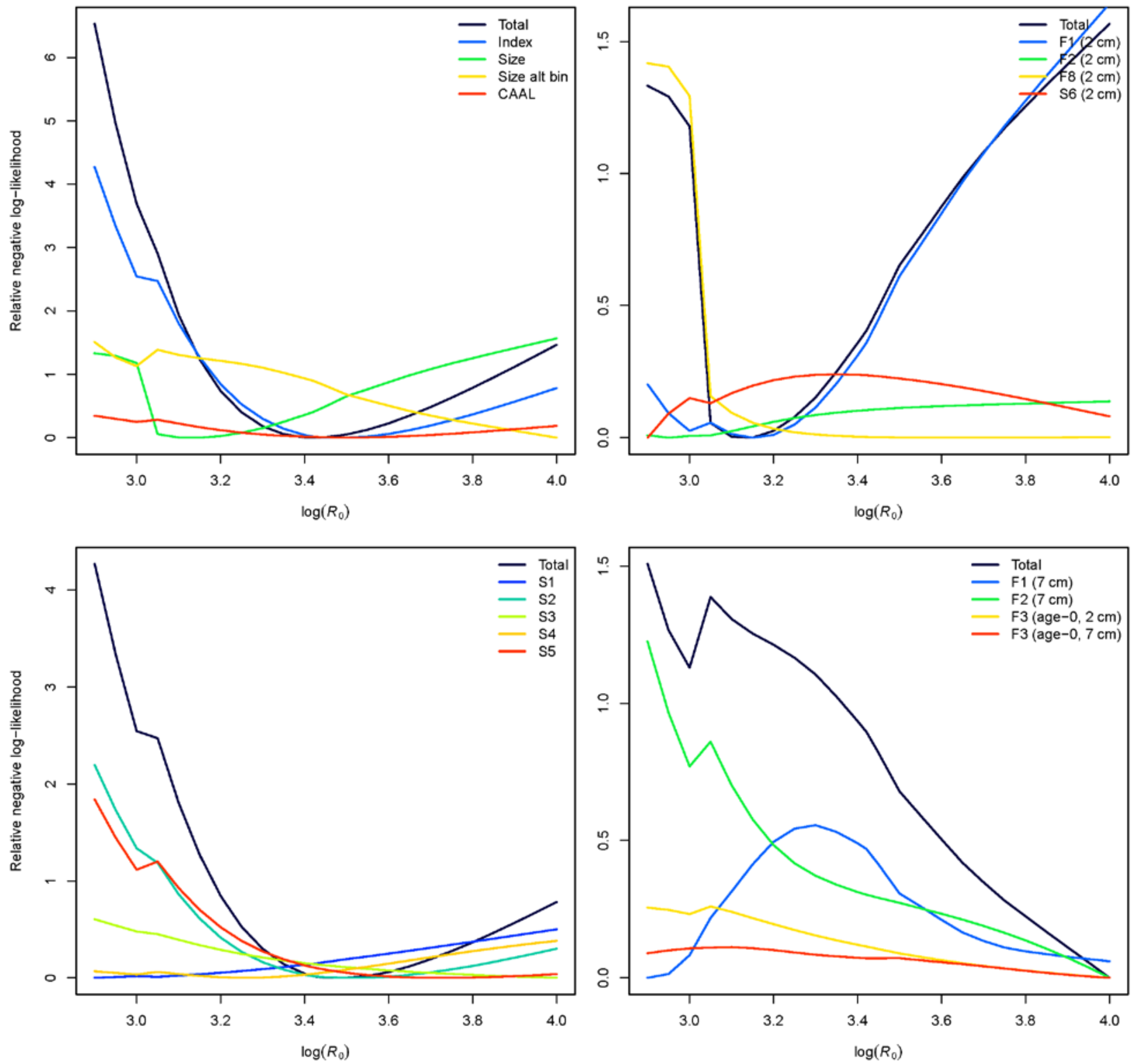


Figure 4.10. Likelihood profiles with respect to virgin recruitment [log(R_0)] of the main data components (upper left), abundance indices (lower left), main sex-specific size compositions using 2 cm bins (upper right), and size compositions using alternative binning structures (Section 2.1.4), of the base case model.

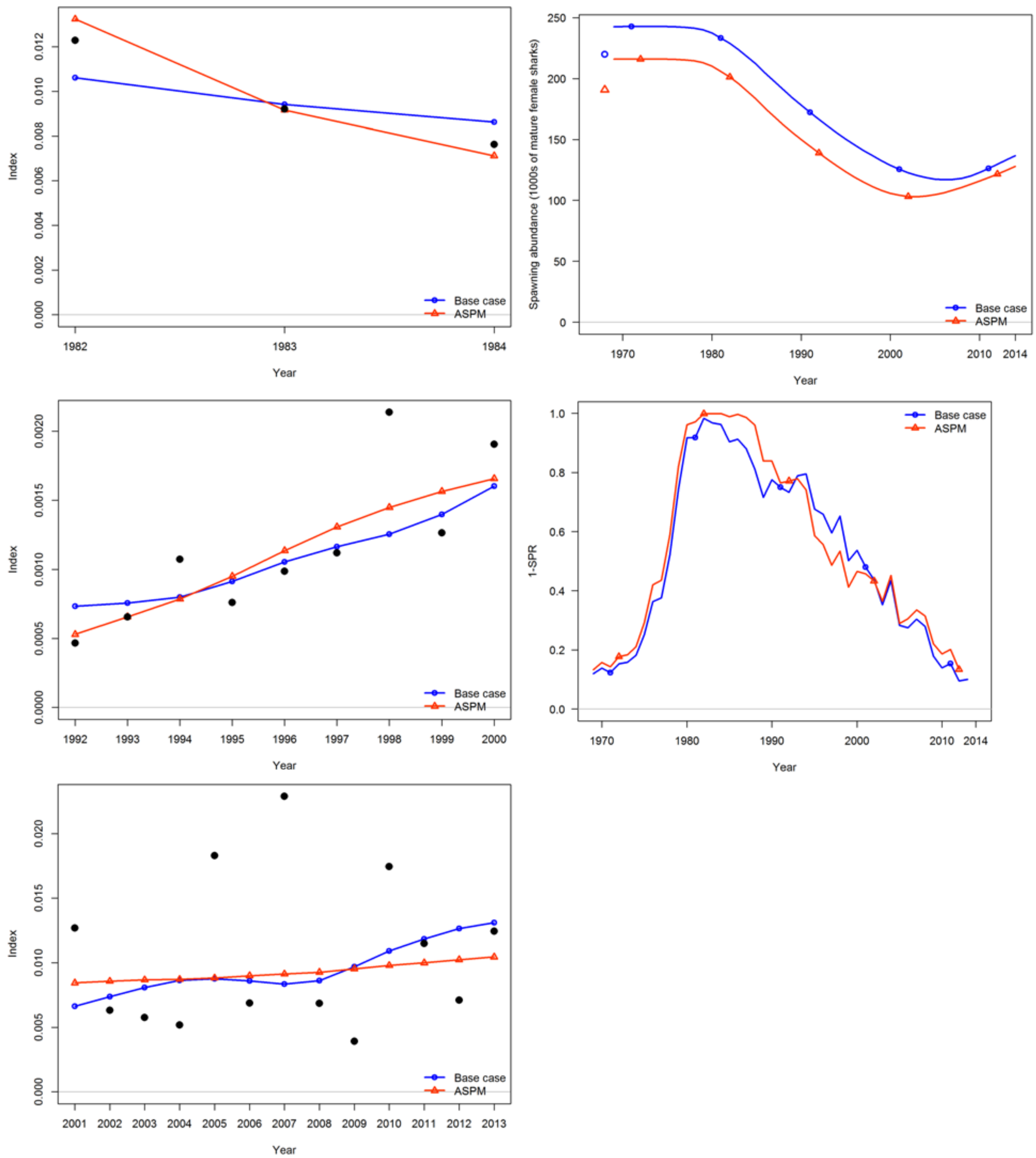


Figure 4.11. Model fits to sub-adult/adult abundance indices (S1: upper left; S2: middle left; S3: lower left), estimated female spawning abundance (upper right) (1000s of mature female sharks), and fishing intensity (middle right) (1 – SPR) of the base case model (blue) and an age-structured production model (red) with similar model specifications to the base case model but fitting only to the catch and sub-adult/adult abundance indices.

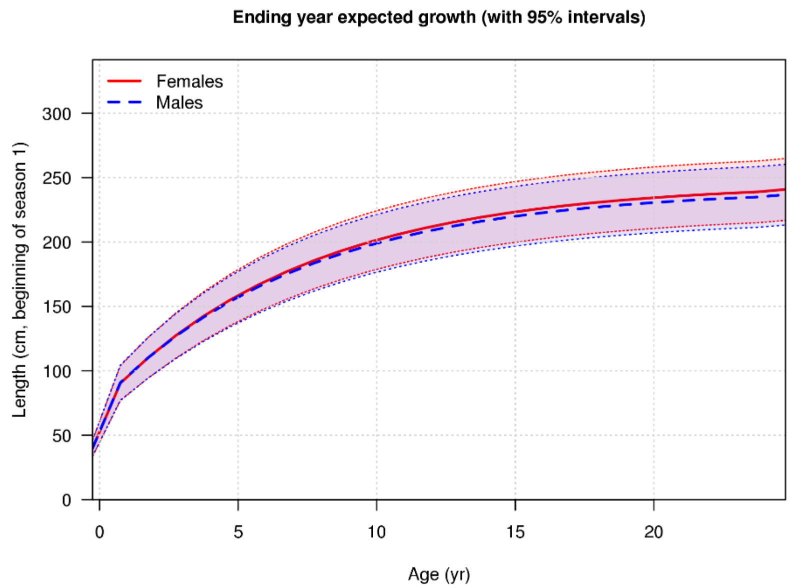


Figure 5.1. Estimated growth curve of female (solid red line) and male (dashed blue line) common thresher sharks. Shaded areas represent the 95% confidence intervals. The coefficient of variation of length at age were fixed at birth (0.08) and L_{inf} (0.05), and linearly interpolated between those two points.

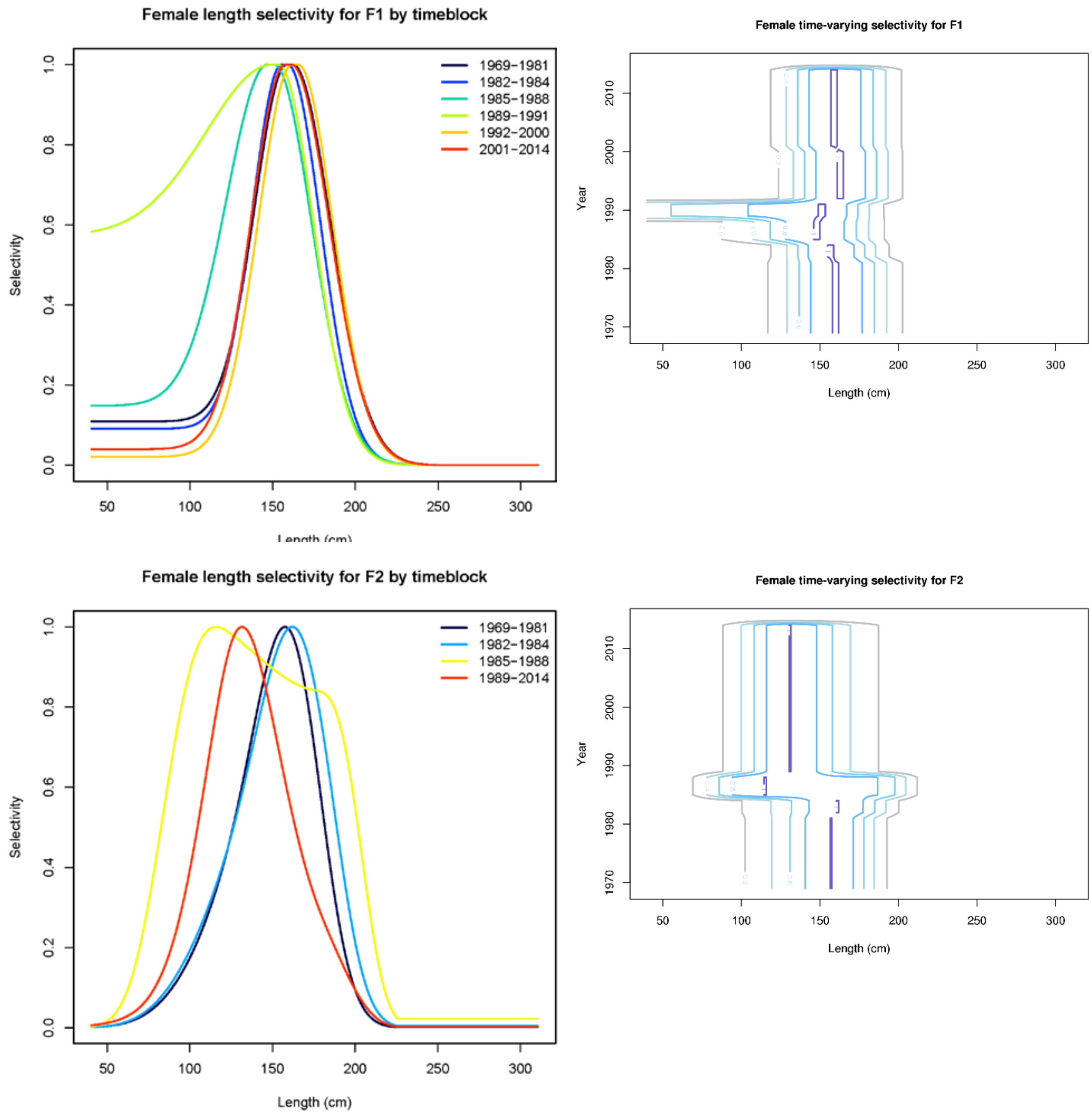


Figure 5.2. Estimated length selectivities of USDGN (F1) and USDGNs2 (F2) fleets by time period (left panels) and time-varying contour plots (right panels) in the base case model. Male selectivity was assumed to be the same as female selectivity for all fleets. Selectivities of F4, F6, S1, S2, and S3 were mirrored to F1, while F5 and F7 were mirrored to F2.

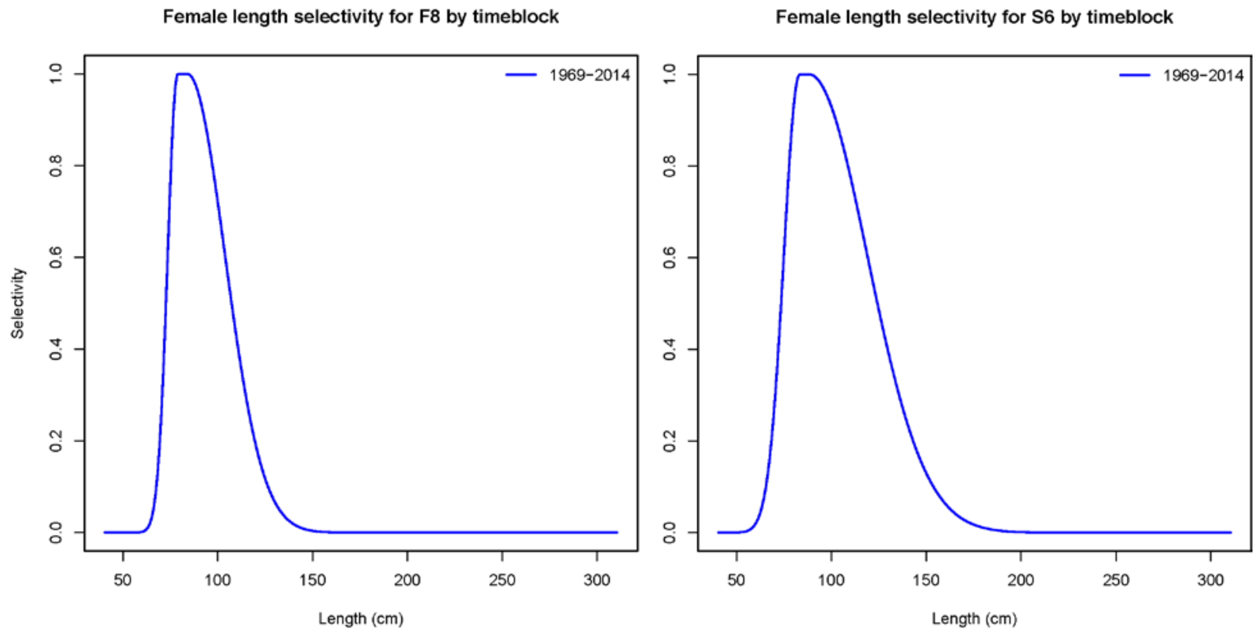


Figure 5.3. Estimated length selectivities of the MXART (F8) fleet and USJUV0614 (S6) survey in the base case model. Male selectivity was assumed to be the same as female selectivity for all fleets.

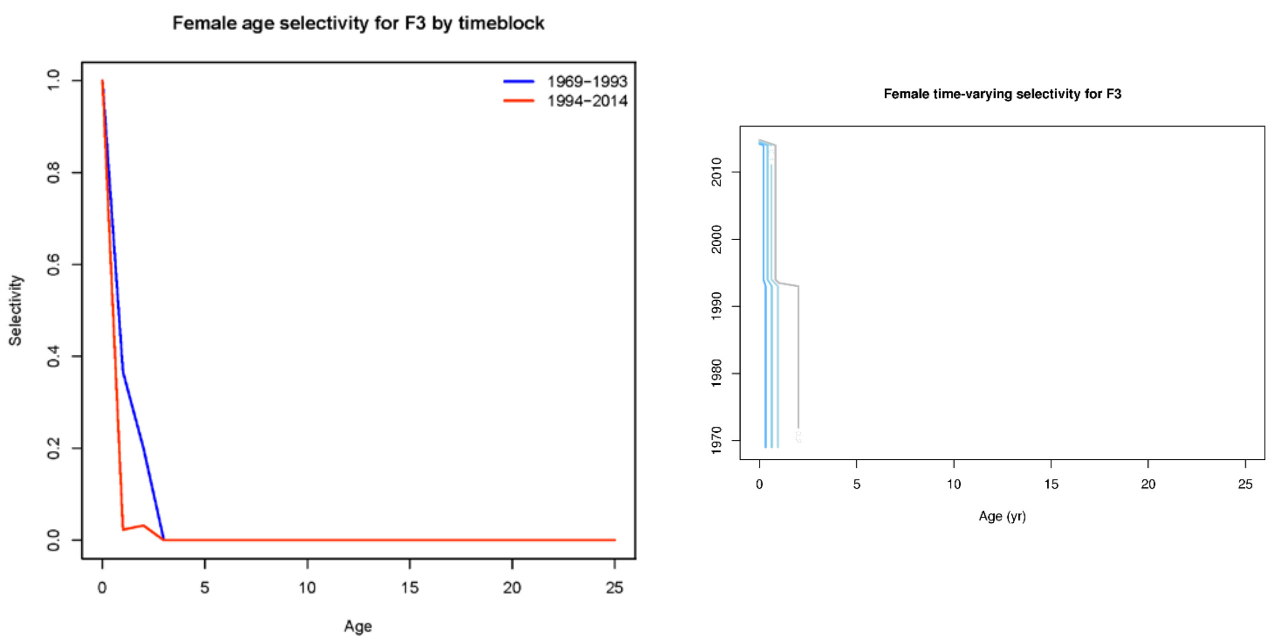


Figure 5.4. Estimated age selectivities of the USSN (F3) fleet by time period (left panels) and time-varying contour plots (right panels) in the base case model. Male selectivity was assumed to be the same as female selectivity for all fleets. Selectivities of S4 and S5 were mirrored to F3.

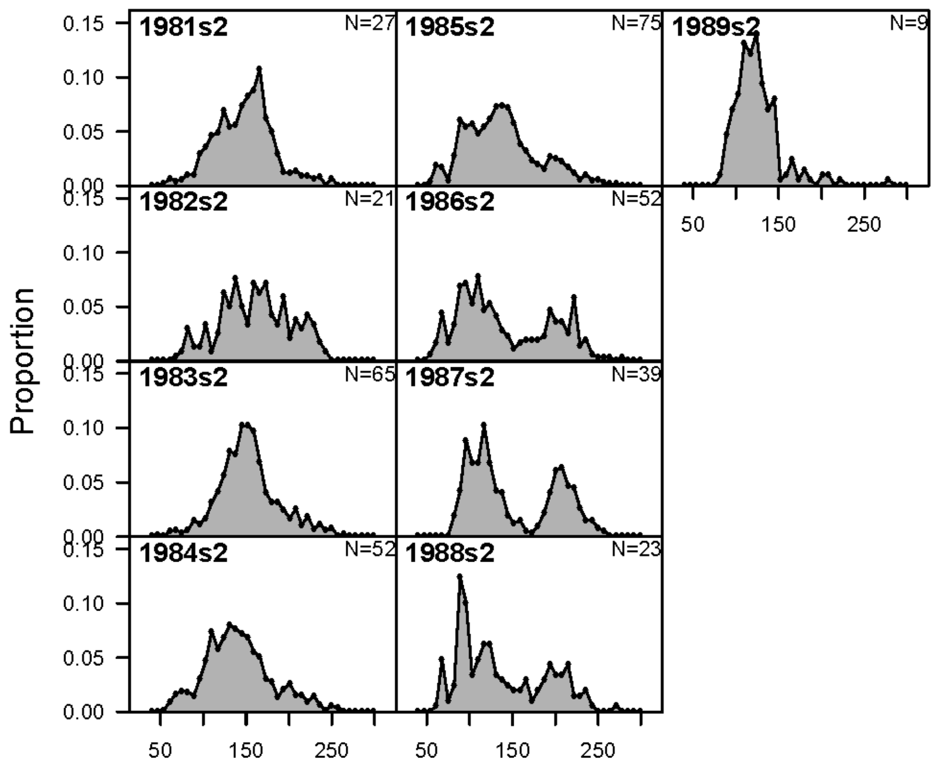


Figure 5.5. Size composition data of the USDGNs2 (F2) fleet during 1981 – 1989. Note the large number of large fish >200 cm between 1985 and 1988.

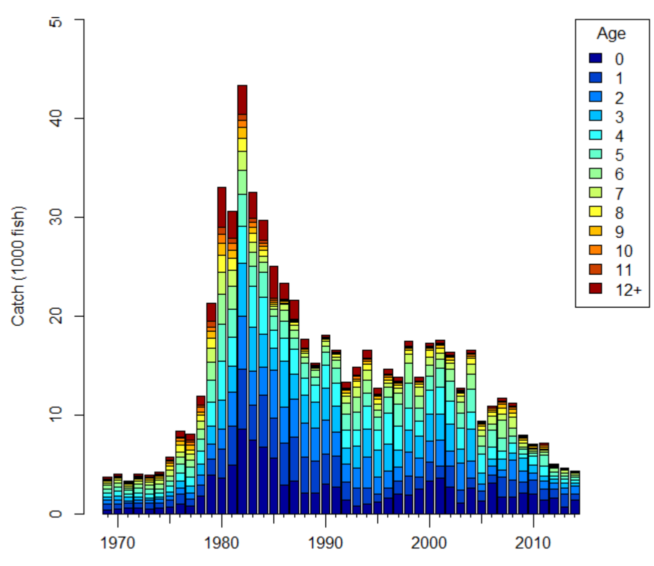


Figure 5.6. Historical catch-at-age (1000s of fish) estimated by the base case model. The base case model was parameterized with 26 age classes (age-0 to 25) but ages-6+ (100% maturity) were summed for clarity.

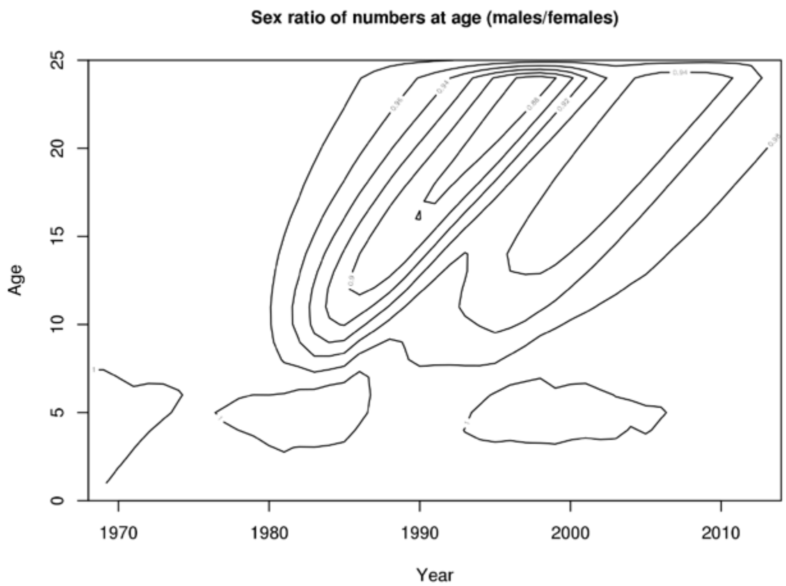


Figure 5.7. Sex ratio (male/female) of numbers at age estimated in the base case model.

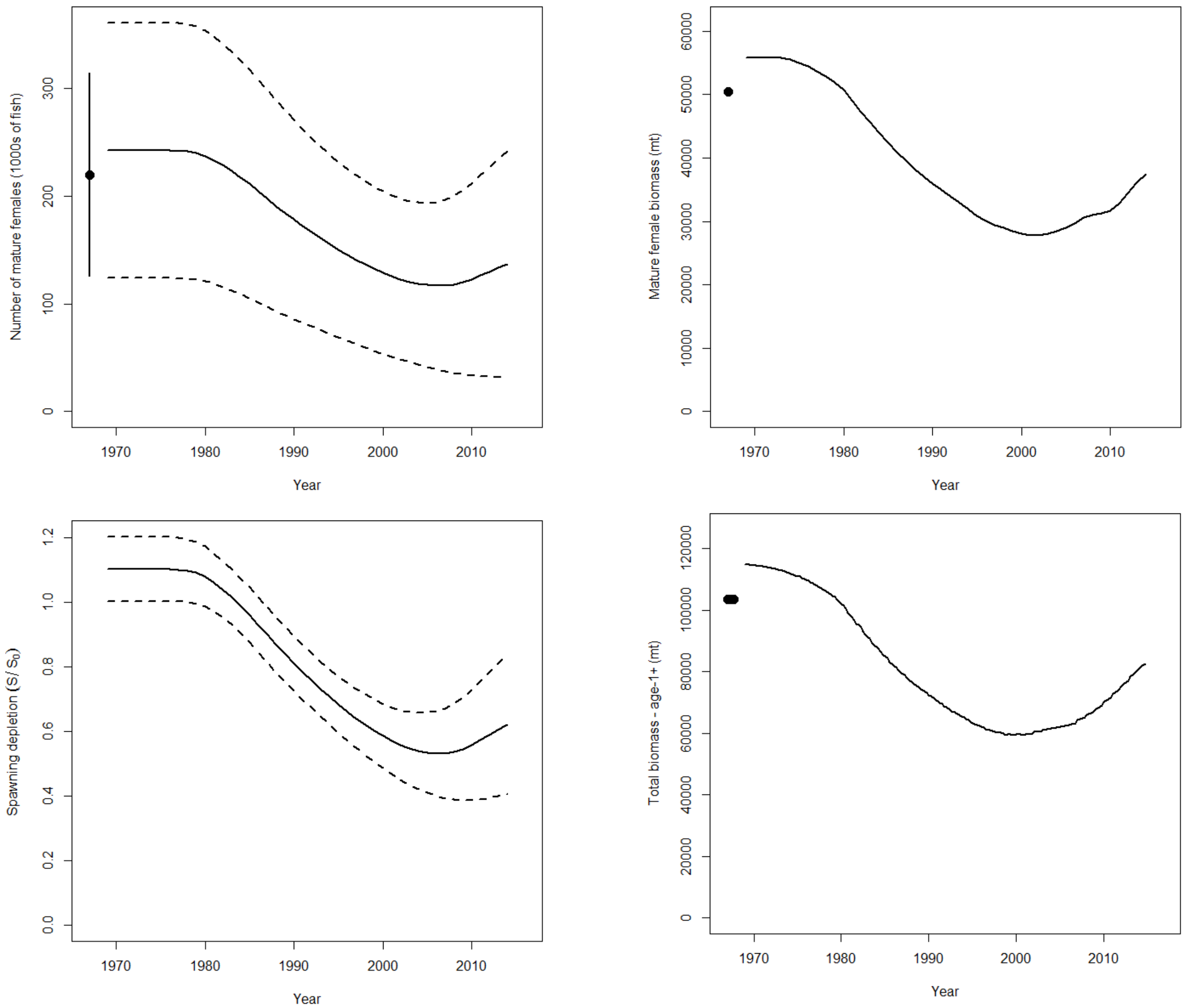


Figure 5.8. Estimated number of mature female sharks in Q2 (upper left); spawning depletion based on number of mature female sharks (S/S_0) (lower left); biomass of mature female sharks (upper right); and seasonal total biomass (age-1+) (lower right). Dashed lines indicate 95% confidence intervals; and closed circles and error bars indicate estimated quantities and 95% confidence intervals under virgin conditions, respectively. Estimated virgin number of mature female sharks (S_0) is 88,220 fish. Annual spawning output in number of pups is 2 * number of mature females.

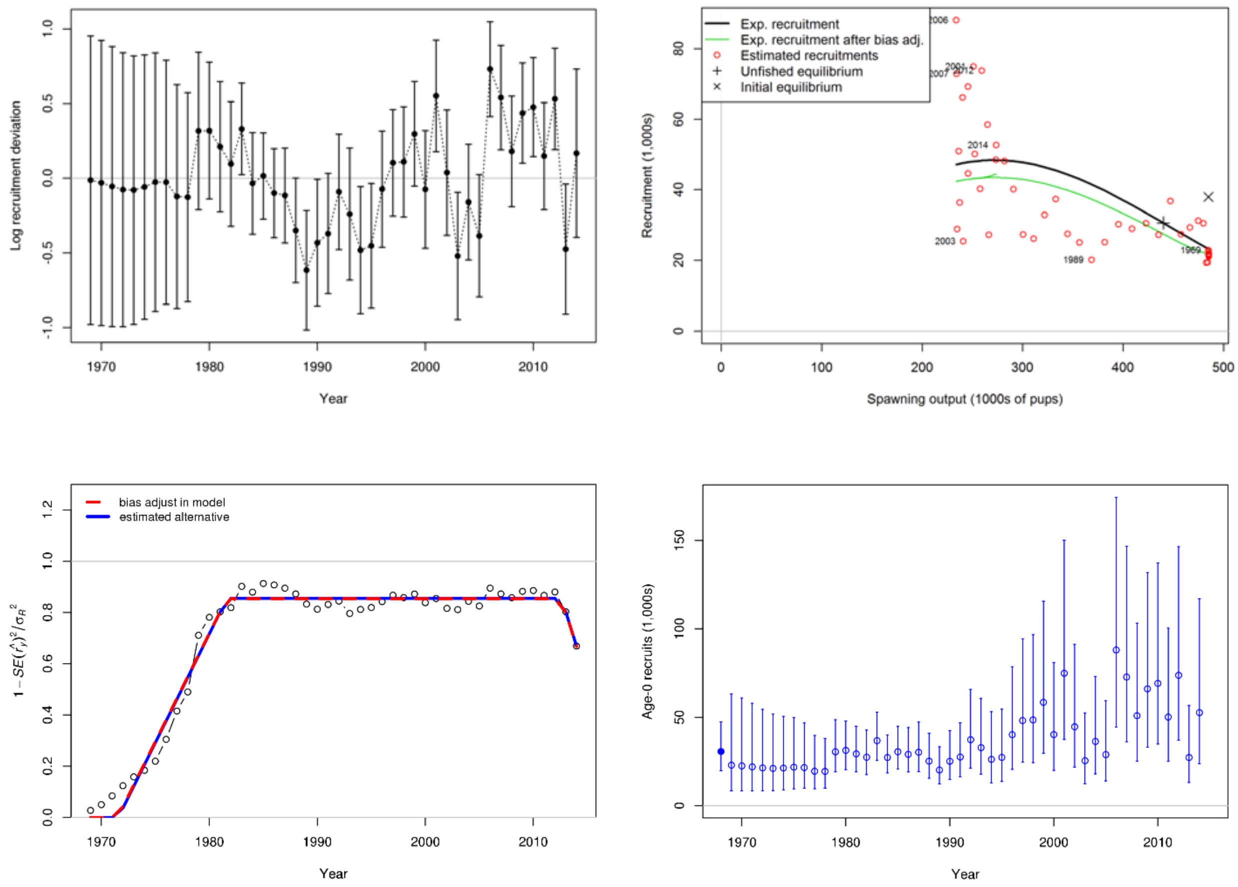


Figure 5.9. Estimated log-recruitment deviations (upper left), recruitment bias adjustment (lower left), spawner-recruit relationship (upper right), and recruitment time series (lower right) from the base case model.

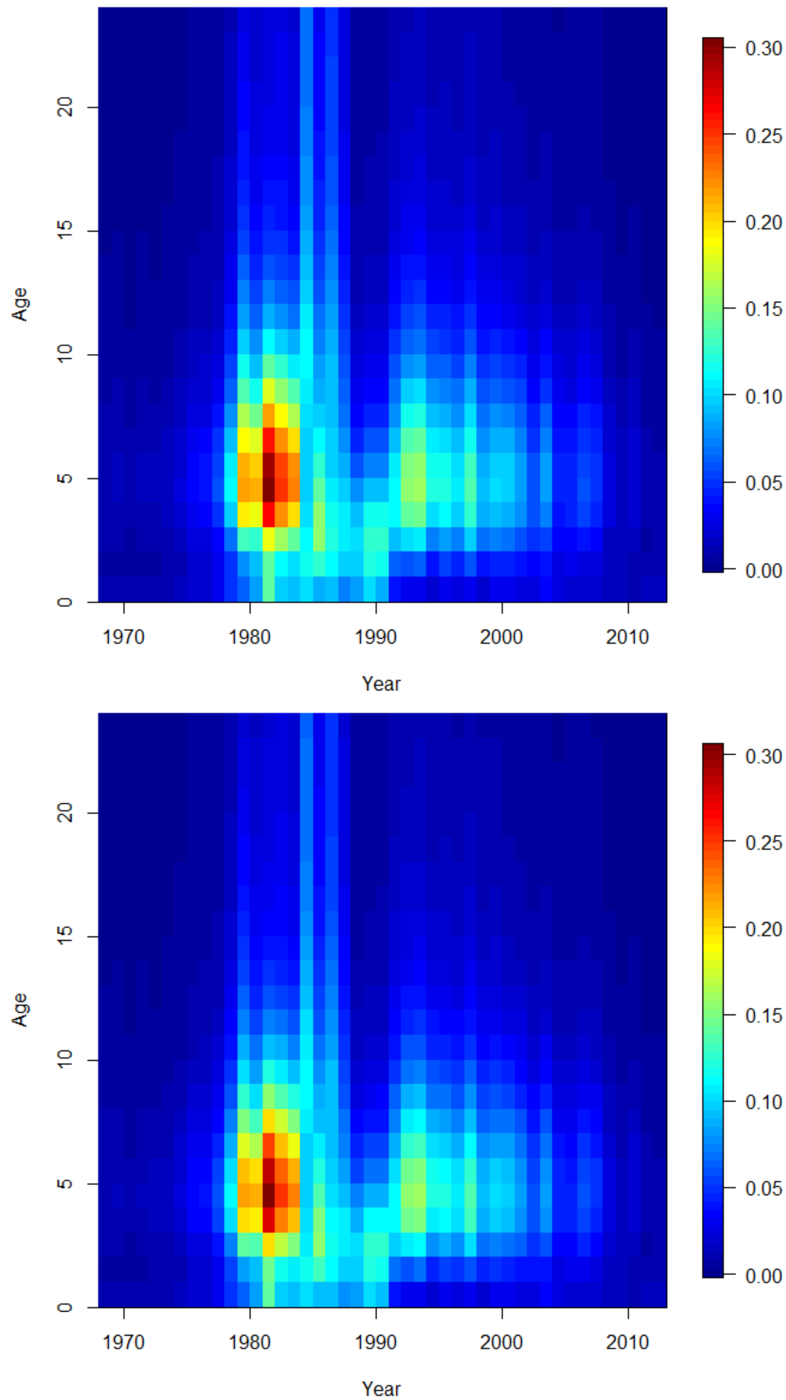


Figure 5.10. Estimated fishing mortality at age (F-at-age) for female (upper) and male (lower) common thresher sharks from the base case model. Fs for ages-25+ are negligible and are not shown.

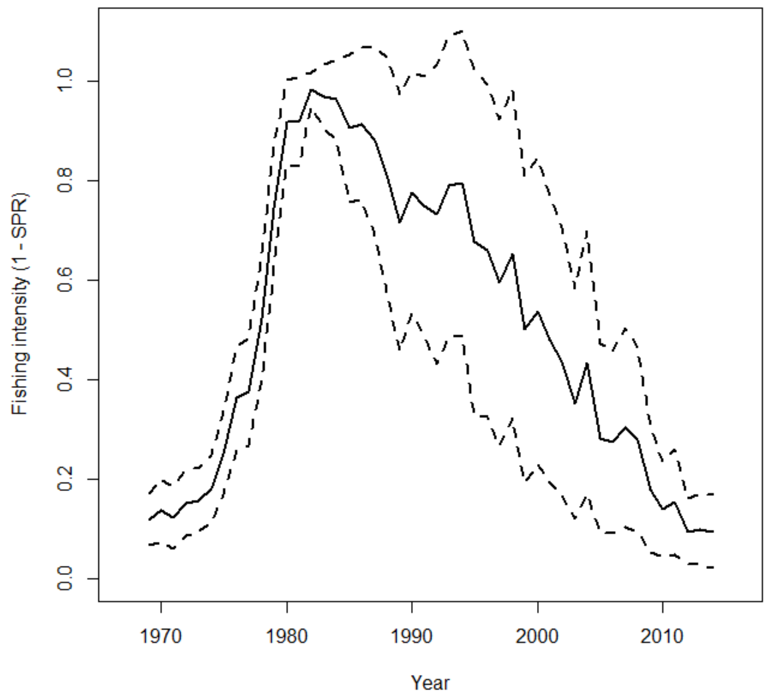


Figure 5.11. Estimated fishing intensity (1-SPR) from the base case model. Black line indicates the maximum likelihood estimate while dashed lines indicate 95% confidence intervals.

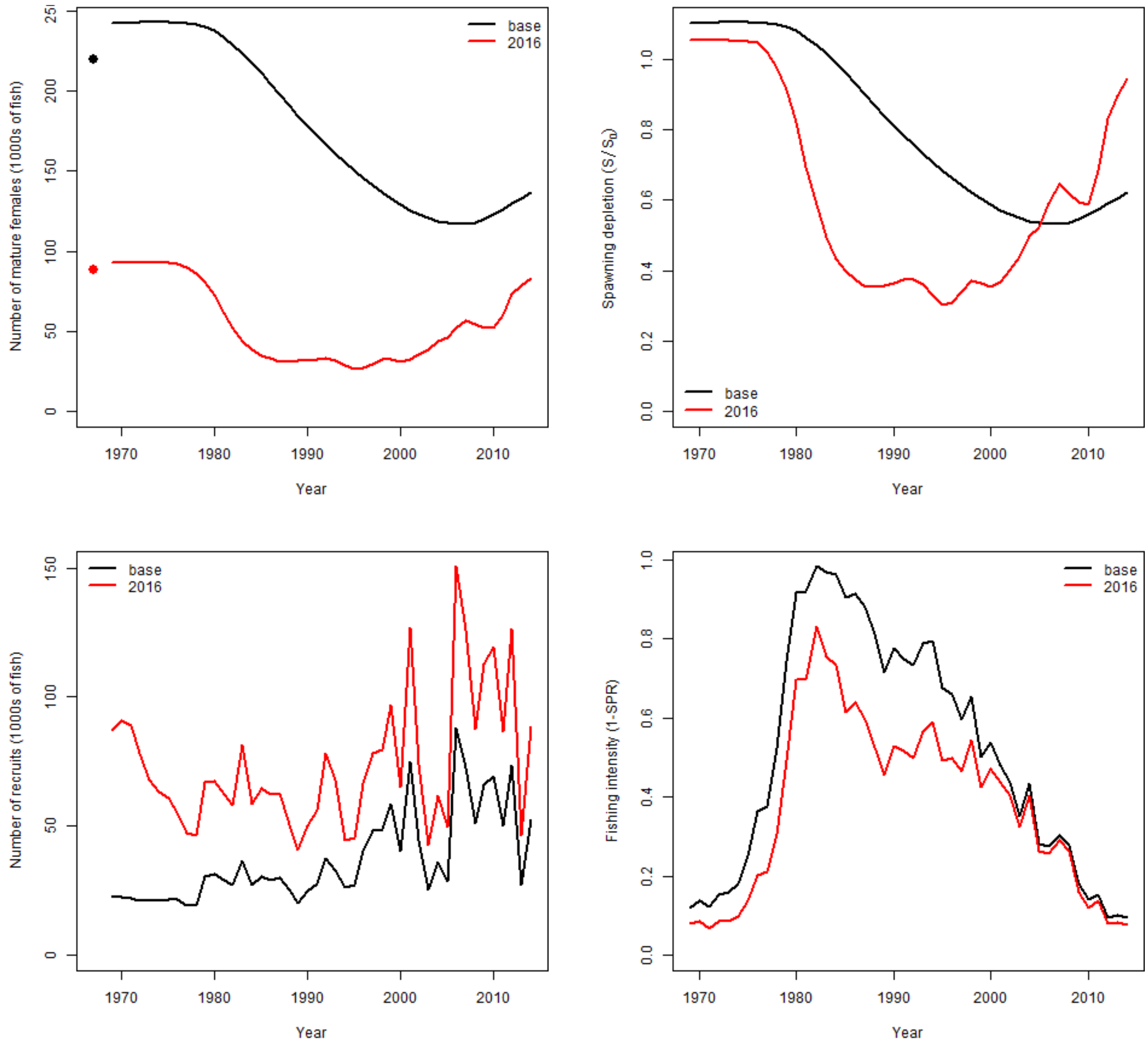


Figure 5.12. Estimated number of mature female sharks (upper left), recruitment (lower left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower right) for the base case model in this assessment (black) and the 2016 assessment (red; Teo et al. 2016). Note that the age classes for mature female sharks are approximately age-12+ and age-5+ for this assessment and the 2016 assessment, respectively. In addition, there were major differences in the fecundity, natural mortality, and stock-recruitment parameters between the two assessments.

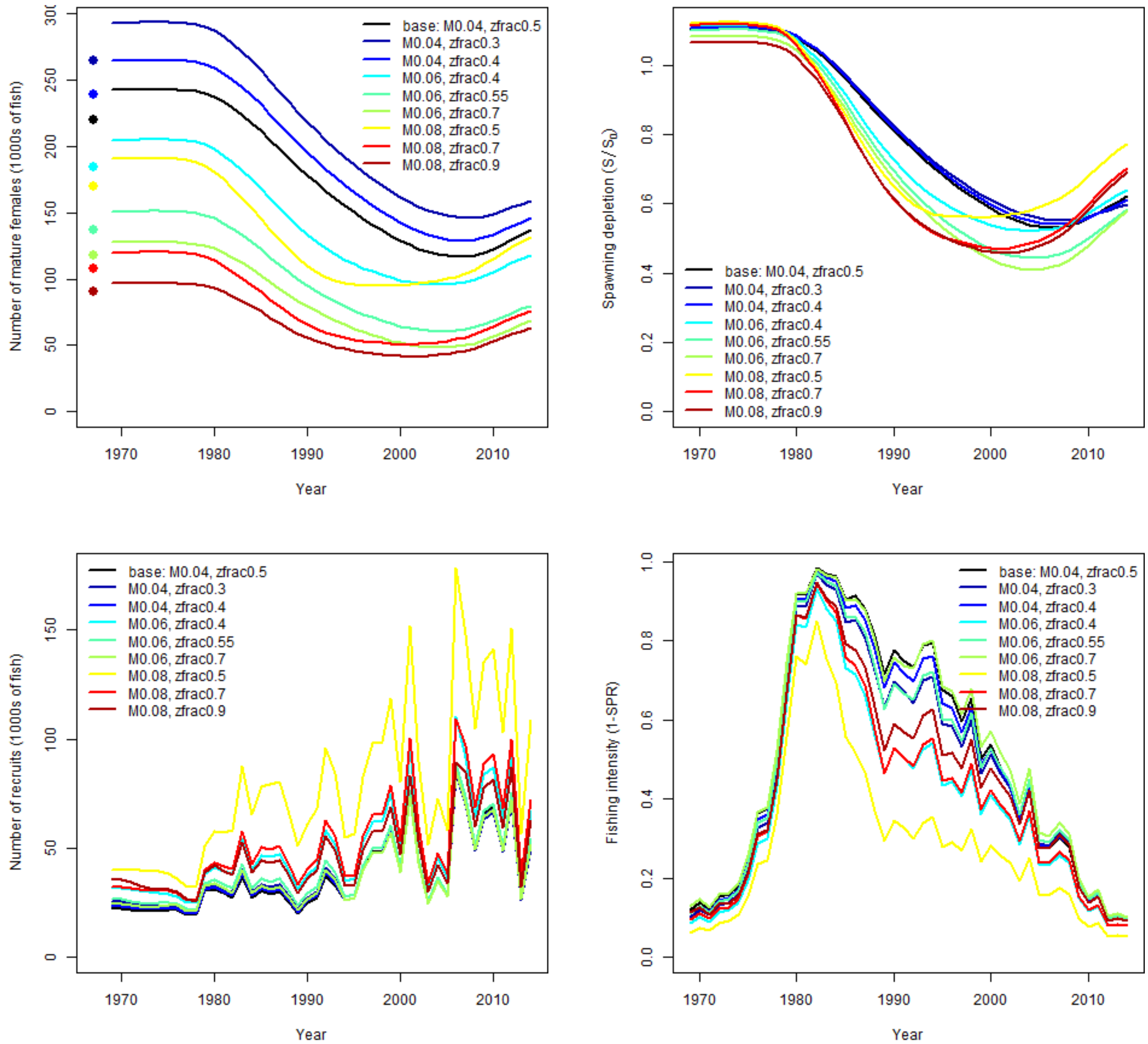


Figure 6.1. Estimated number of mature female sharks (upper left), recruitment (lower left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower right) for the base case model (black) and several sensitivity runs selected to represent the uncertainty of model results to assumptions on stock-recruitment (z_{frac} parameter), and natural mortality (M), using the base case reproductive biology ($L_{50\%}$ = 215.1 cm FL; biennial reproductive cycle). These assumptions were found to interact and therefore should not be considered independently.

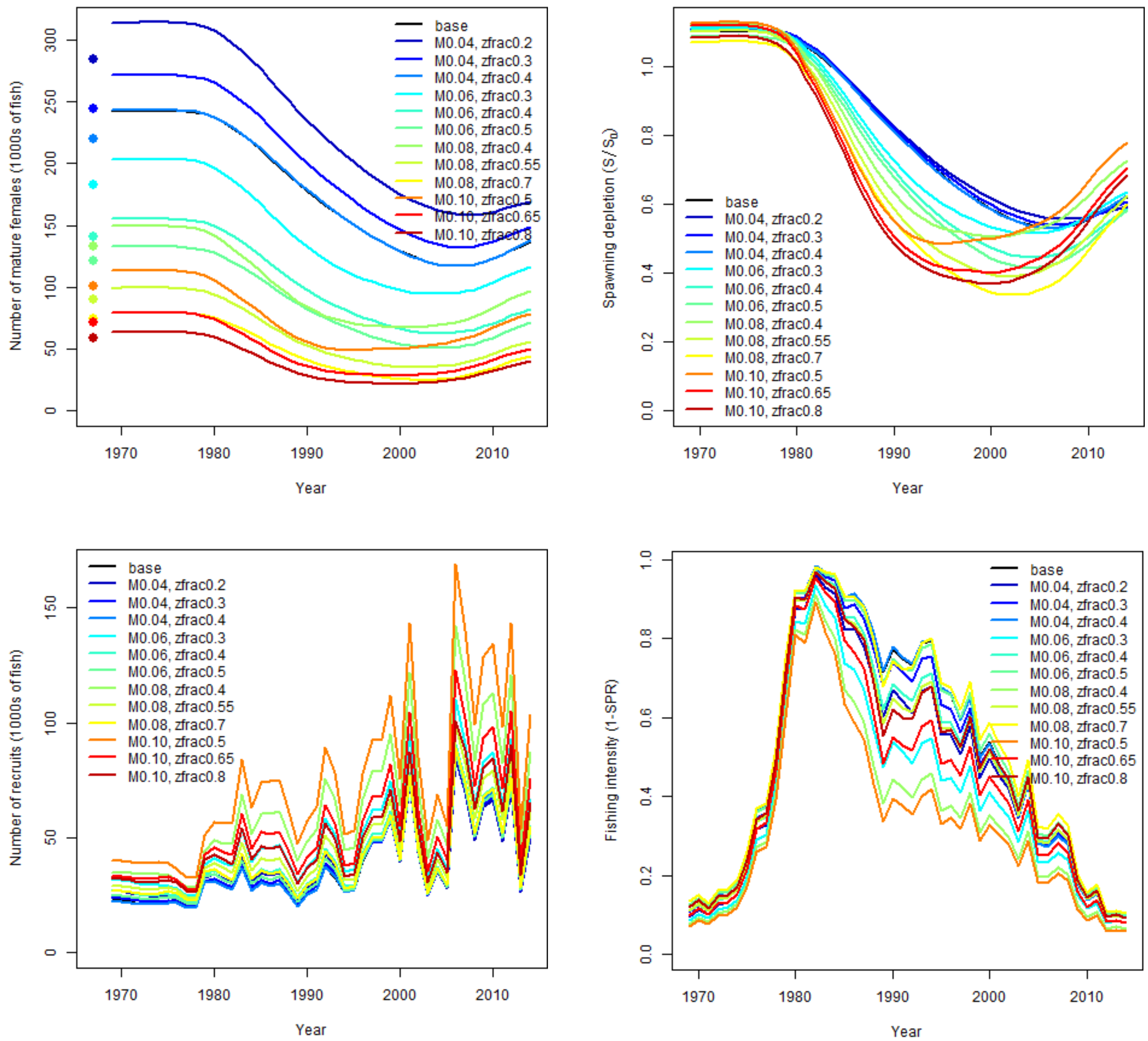


Figure 6.2. Estimated number of mature female sharks (upper left), recruitment (lower left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower right) for the base case model (black) and several sensitivity runs selected to represent the uncertainty of model results to assumptions on stock-recruitment (z_{frac} parameter), and natural mortality (M), using alternative reproductive biology ($L_{50\%}$ = 215.1 cm FL; annual reproductive cycle). These assumptions were found to interact and therefore should not be considered independently. Compare with Fig. 6.1 for influence of base case versus alternative reproductive biology (i.e., 2 versus 4 pups y^{-1}).

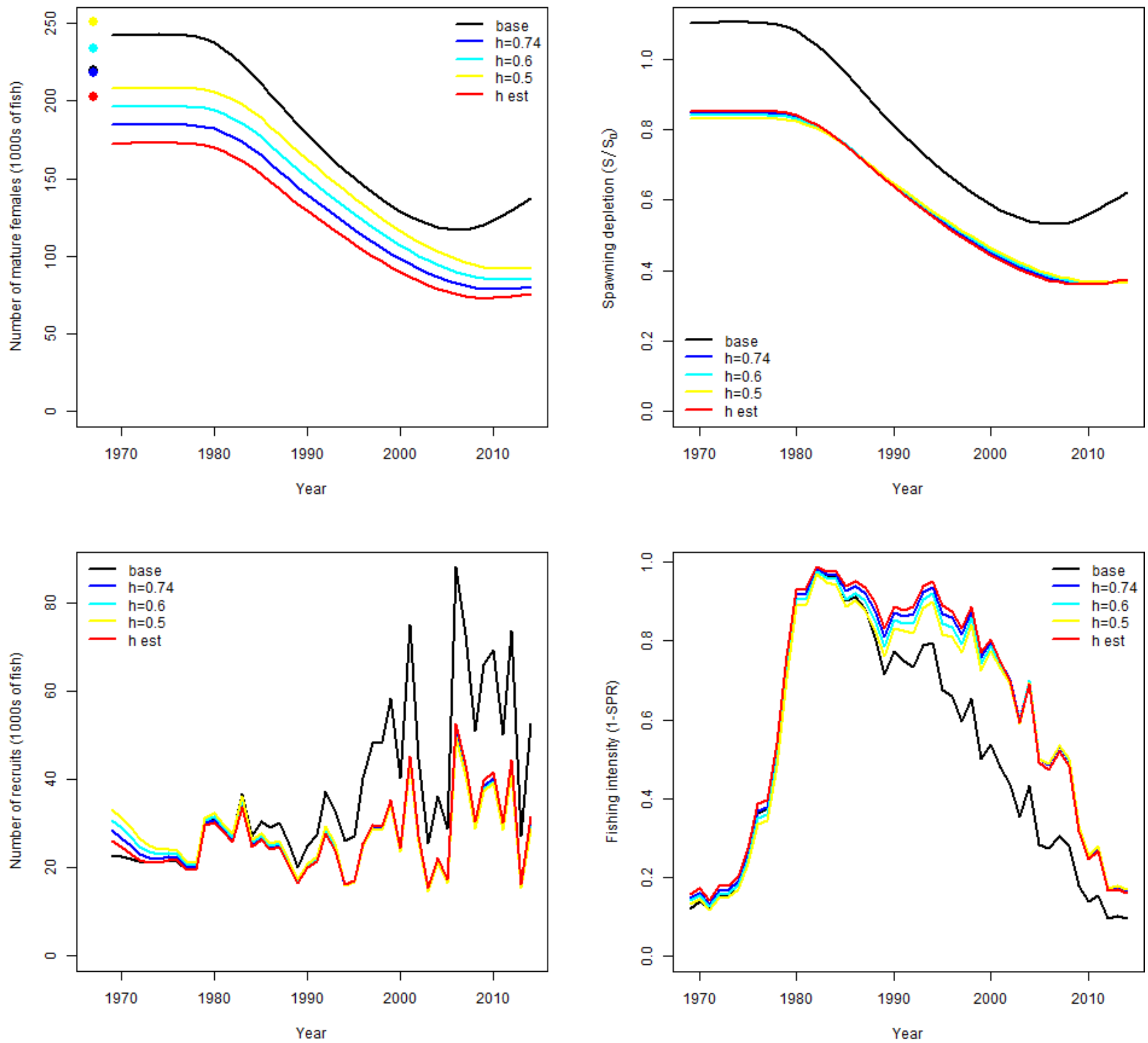
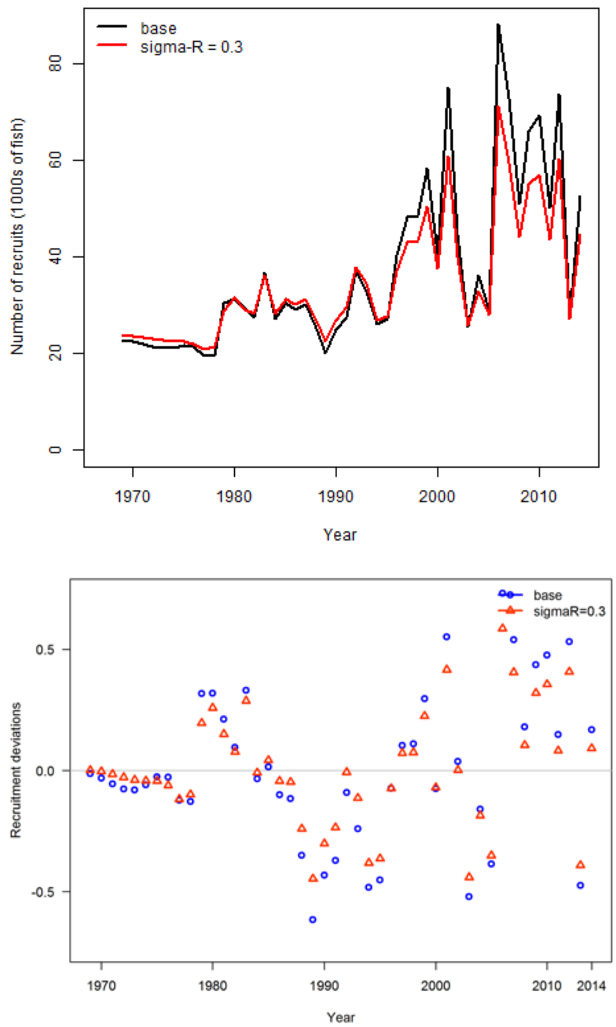


Figure 6.3. Estimated number of mature female sharks (upper left), recruitment (lower left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower right) for the base case model (black) and several sensitivity runs assuming Beverton-Holt stock-recruitment relationships with steepness (*h*) equal to the base case model (*h*=0.74; blue), slightly lower (*h*=0.6; turquoise) and much lower (*h*=0.5; yellow) than the base case model, and estimated steepness (*h*=1.0; red).



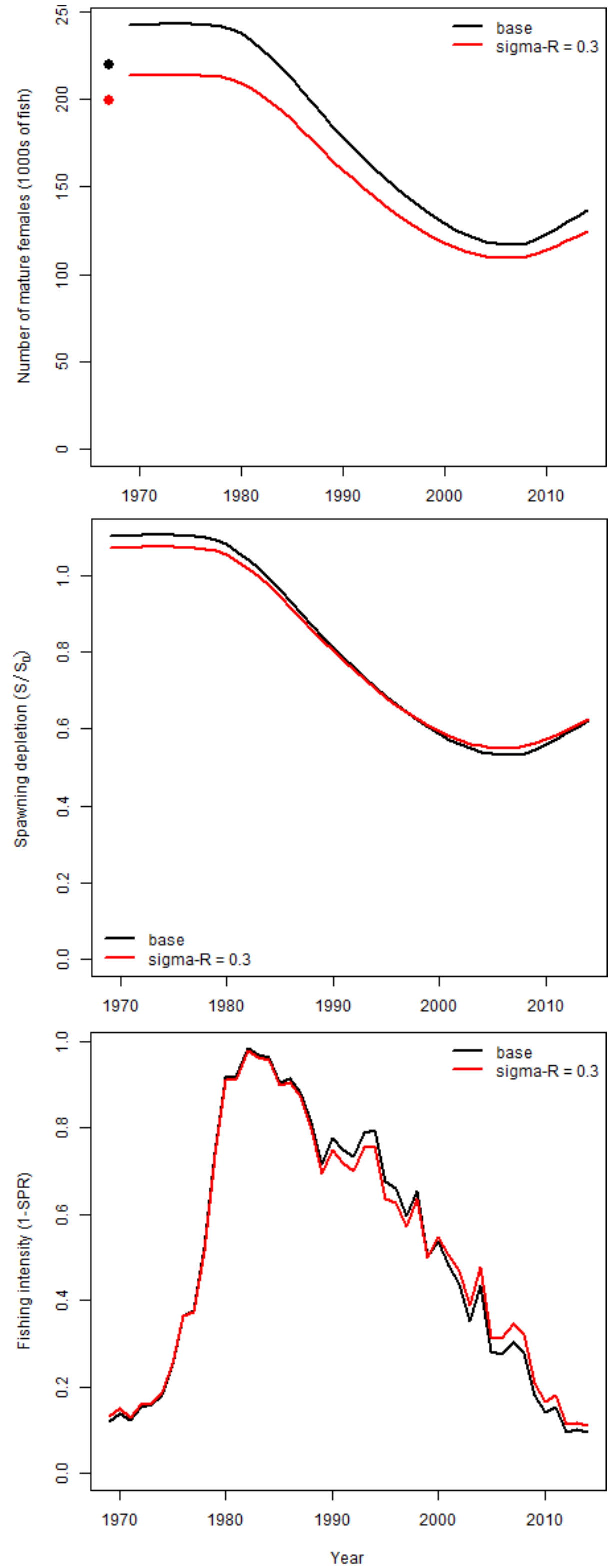
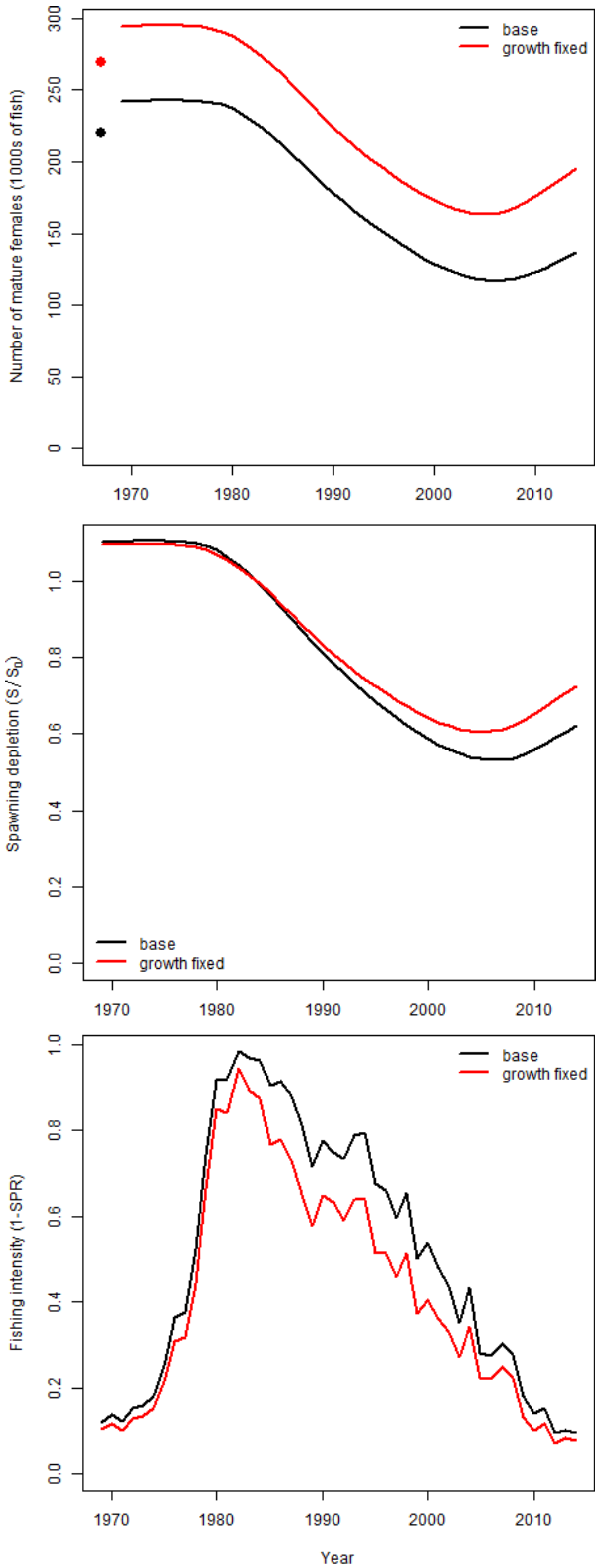


Figure 6.4. Estimated recruitment (upper left), recruitment deviates (lower left), number of mature female sharks (upper right), spawning depletion (middle right), and fishing intensity (1-SPR) (lower right) for the base case model (black) and a sensitivity run assuming a σ_R of 0.3 (red). Note that the model with a σ_R of 0.3 may not have converged due to lack of positive definite Hessian matrix.



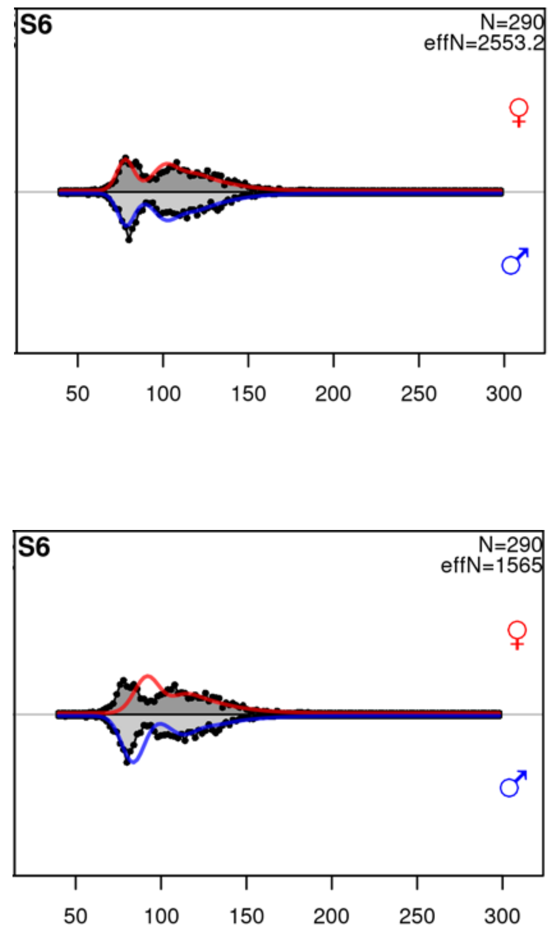


Figure 6.5. Estimated number of mature female sharks (upper left), spawning depletion (middle left), and fishing intensity (1-SPR) (lower left) for the base case model (black) and a sensitivity run assuming fixed sex-specific growth (Smith et al. 2008a). Overall model fits (red: female; blue: male) to the size compositions of the USJUV0614 (S6) survey (grey areas) are shown for the base case (upper right) and sensitivity run (lower right) models. Note that the model with fixed growth may not have converged because of the lack of a positive definite Hessian.

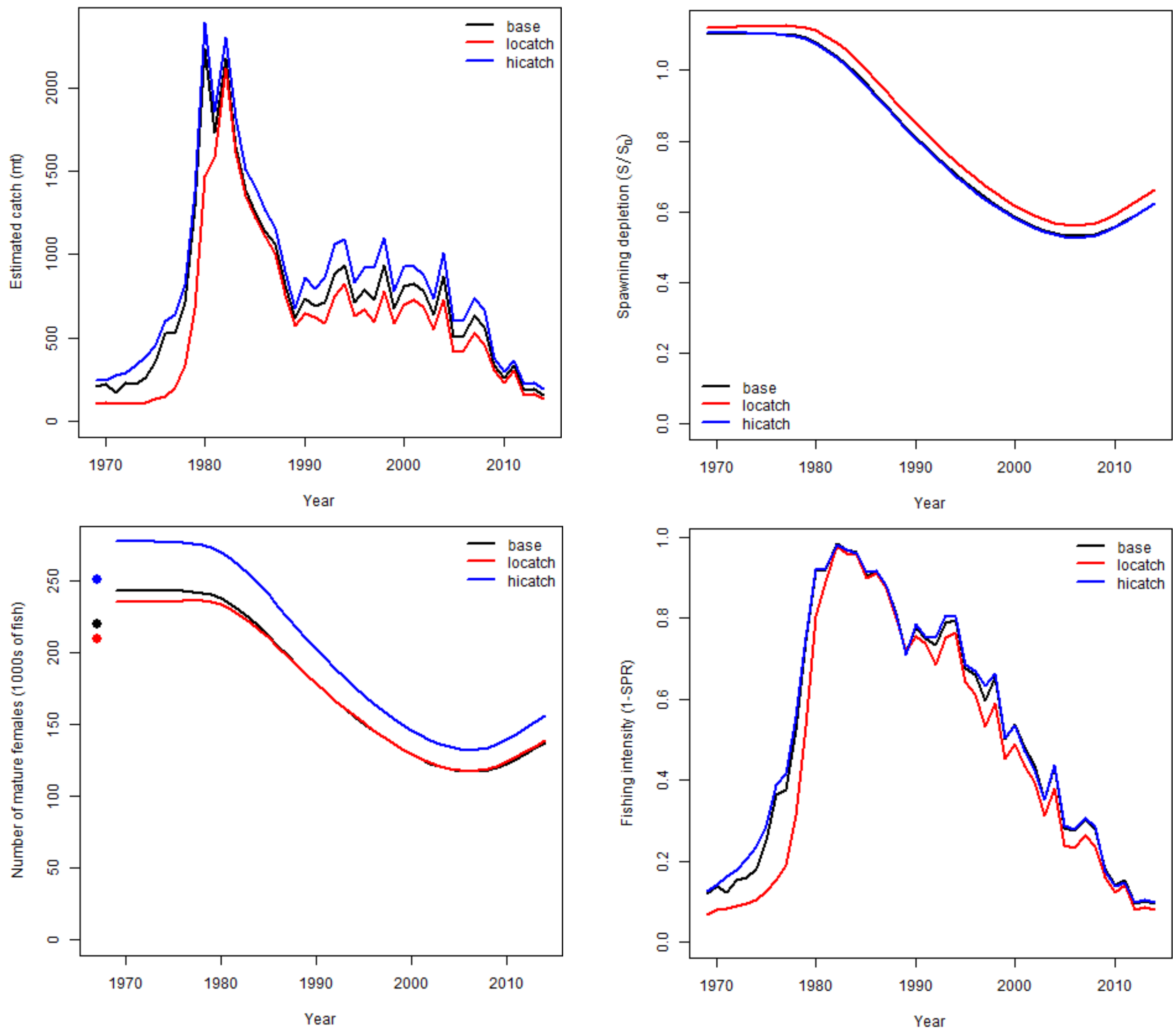


Figure 6.6. Estimated catch in metric tons (mt) (upper left), number of mature female sharks (lower left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower right) for the base case model (black) and sensitivity runs using high (blue) and low (red) catch scenarios.

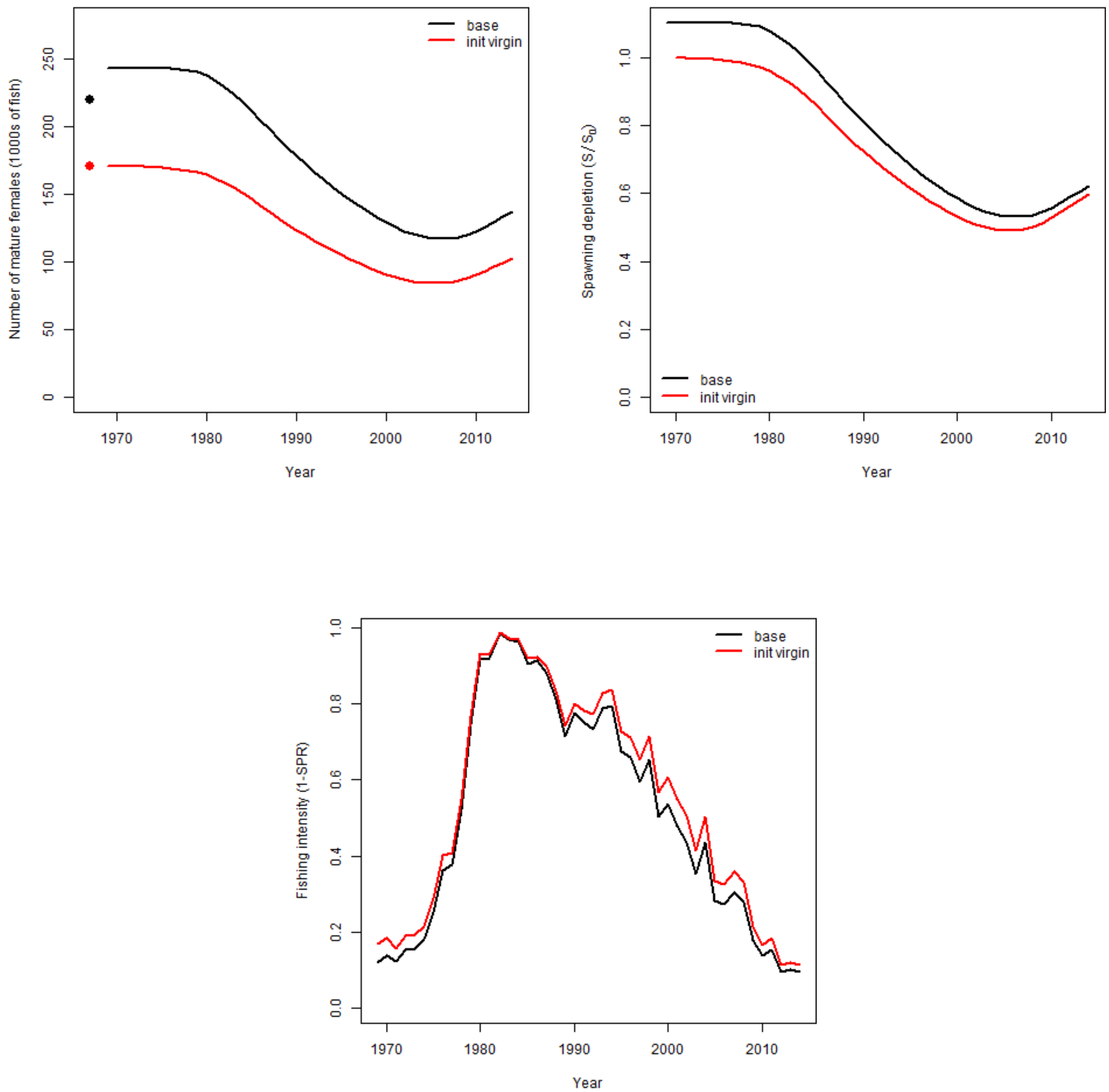


Figure 6.7. Estimated number of mature females (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the base case model (black) and a sensitivity run assuming that the model started under virgin conditions (red).

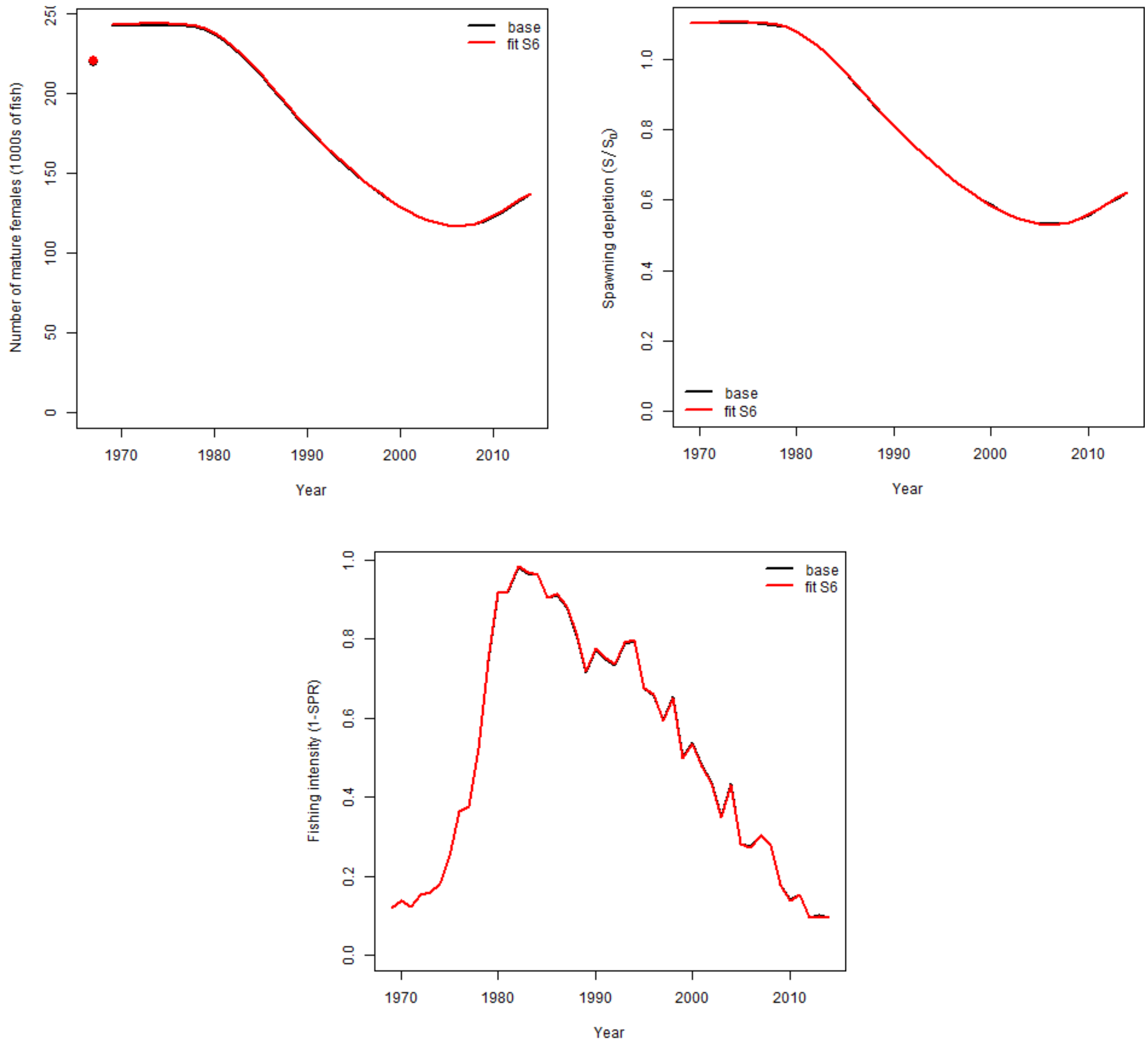


Figure 6.8. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the base case model (black) and a sensitivity run including the S6 index from the USA juvenile thresher survey.

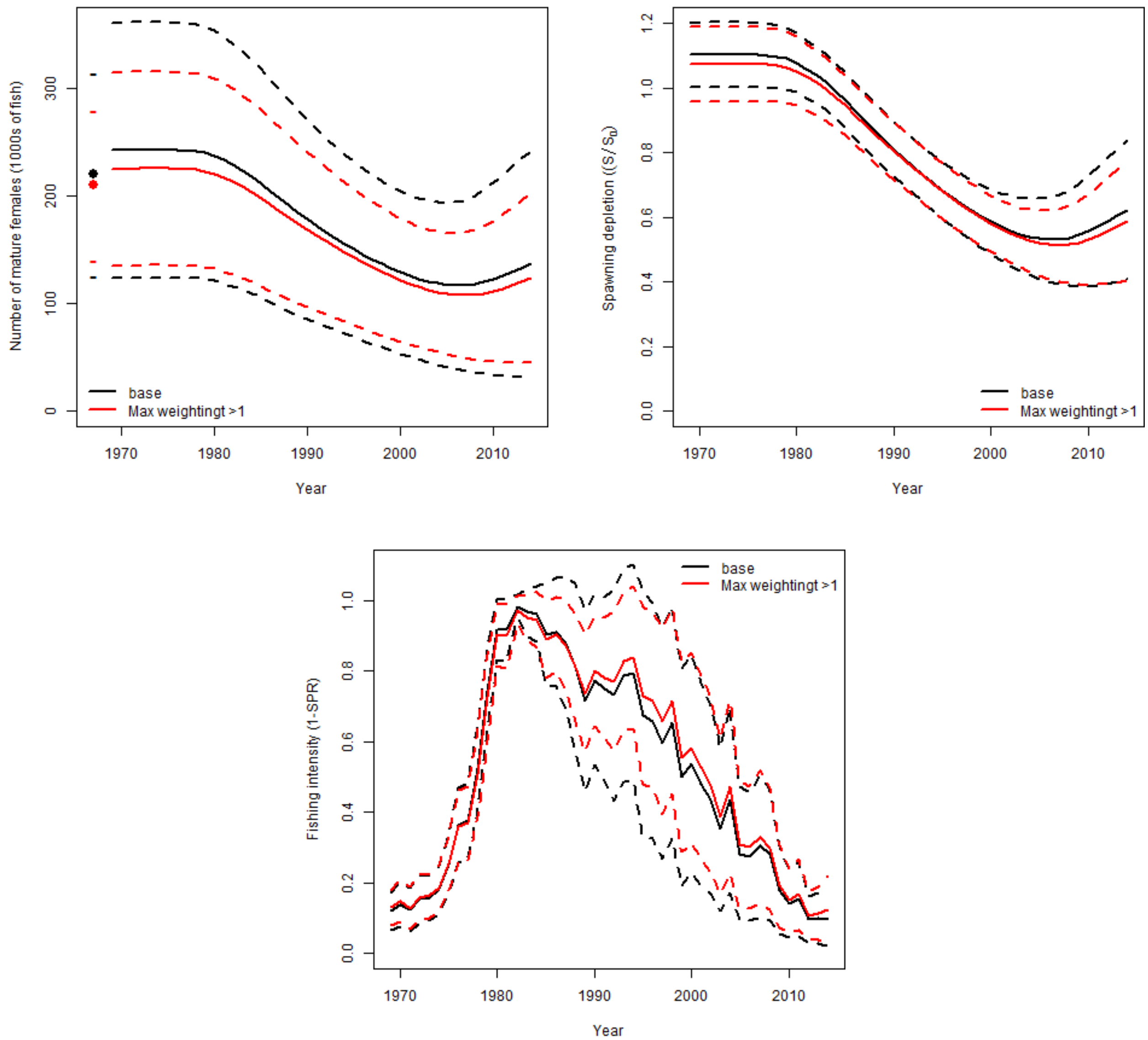


Figure 6.9. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the base case model (black) and a sensitivity run that allowed the weighting factors, calculated using the Francis (2011) method, for the size composition and conditional age-at-length data to be >1. Dashed lines indicate 95% confidence intervals.

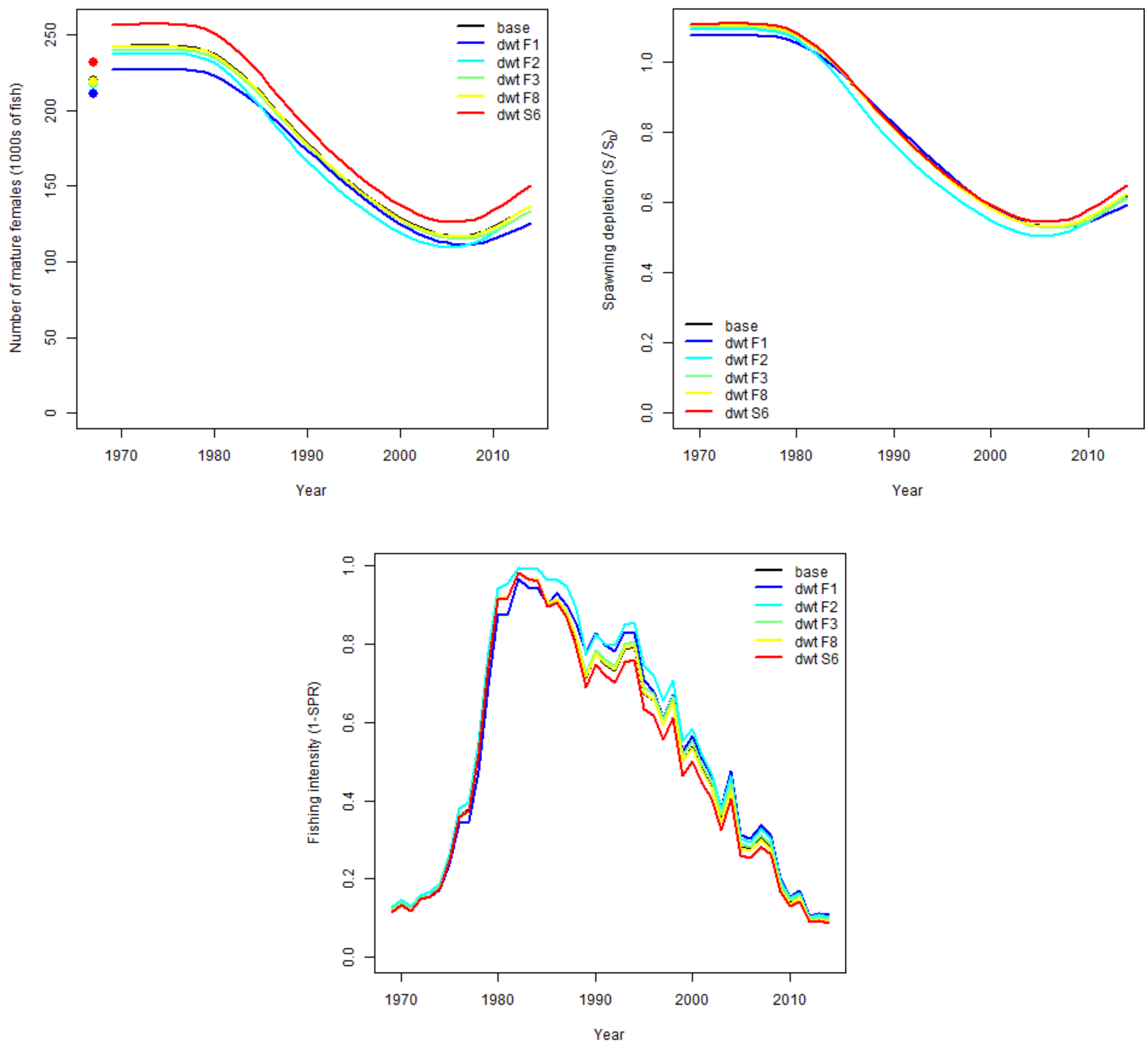


Figure 6.10. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the base case model (black) and sensitivity runs that down-weighted the size composition data from various fleets (F1, F2, F3, F8 and S6). Note that down-weighting the USSN (F3) fleet resulted in a non-positive definite Hessian matrix.

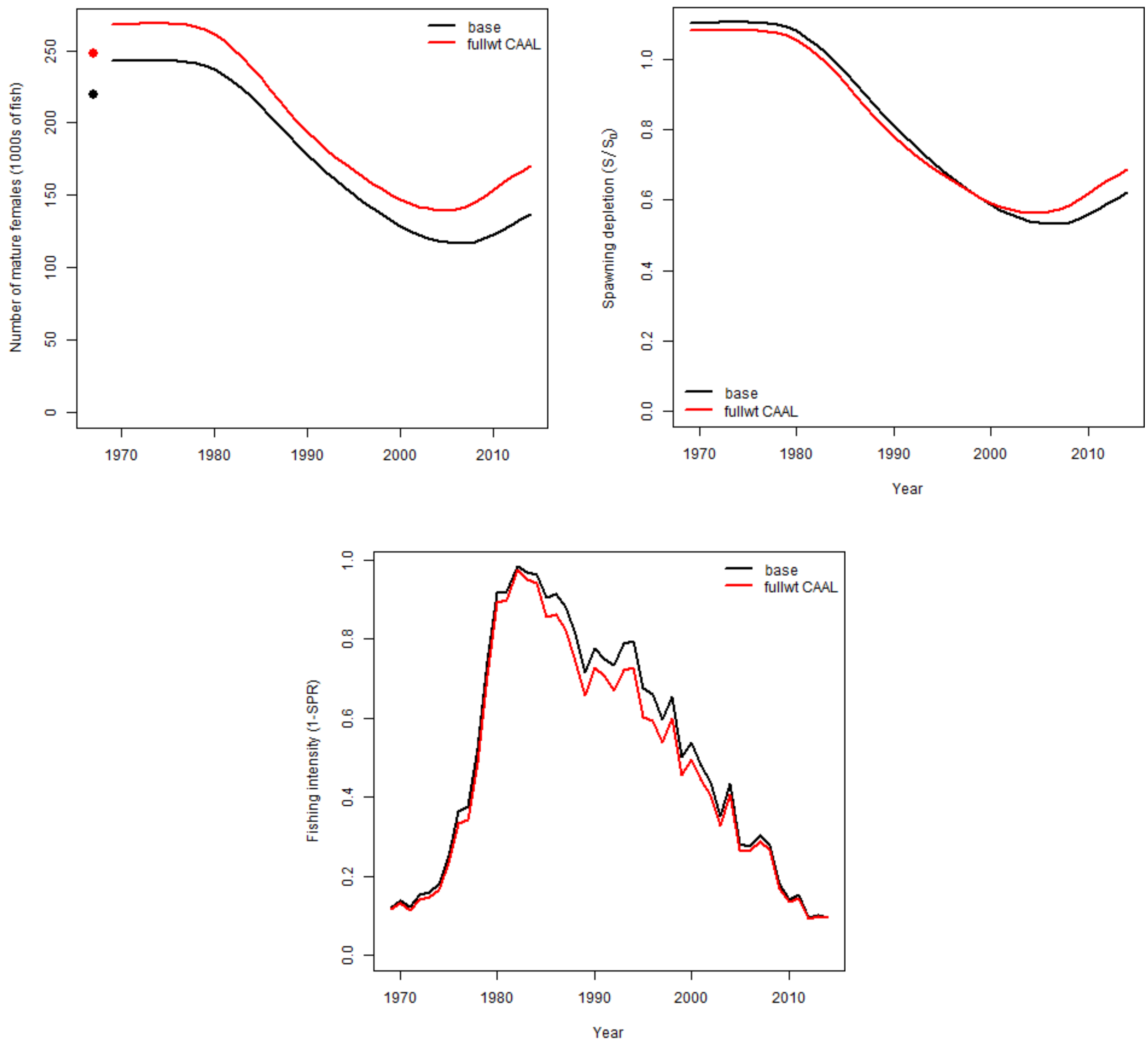


Figure 6.11. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the base case model (black) and a sensitivity run that up-weighted the conditional age-at-length data with weighting factors equal to 1. Note that fully weighting conditional age-at-length data resulted in a non-positive definite Hessian matrix.

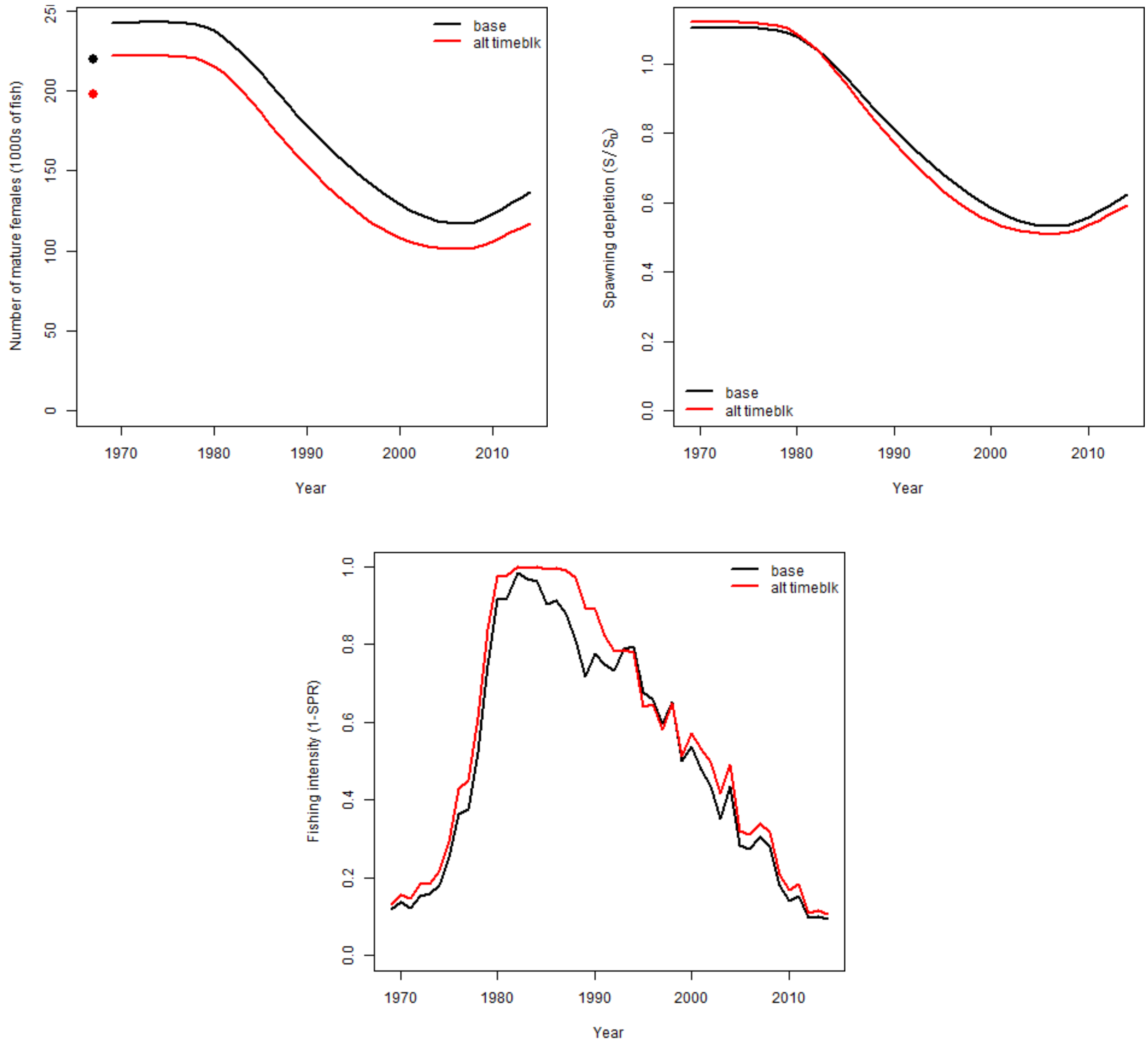


Figure 6.12. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the base case model (black) and a sensitivity run that used alternative selectivity time blocks (1985 – 2000 and 2001 – 2014).

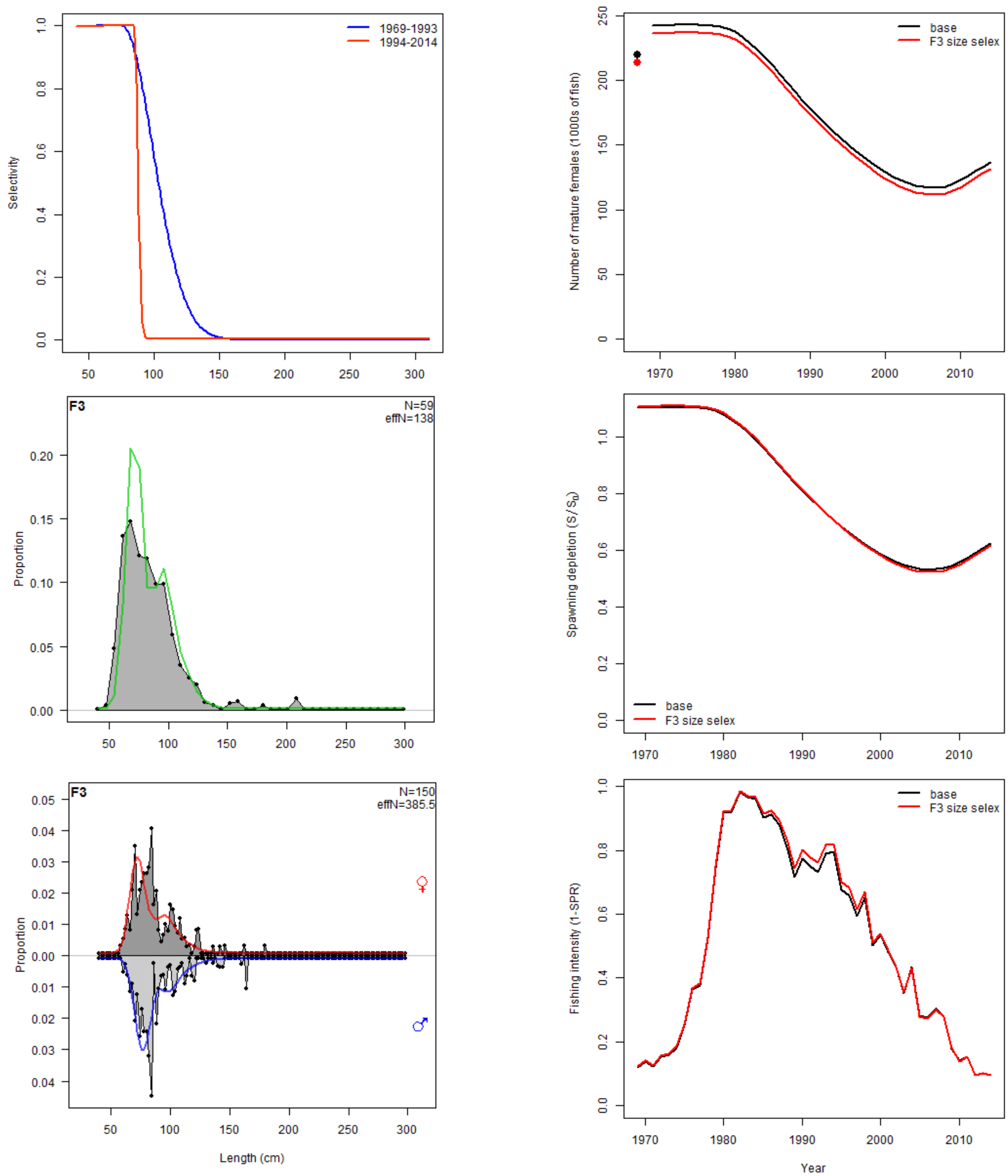


Figure 6.13. Estimated selectivity (upper left), and model fits to non-sex specific size composition (middle left) and sex-specific size composition (lower left) of the USSN (F3) fleet for a sensitivity run that used size selectivity for F3 instead of age selectivity. Estimated number of mature female sharks (upper right), spawning depletion (middle right), and fishing intensity (1-SPR) (lower right) for the base case model (black) and sensitivity run (red).

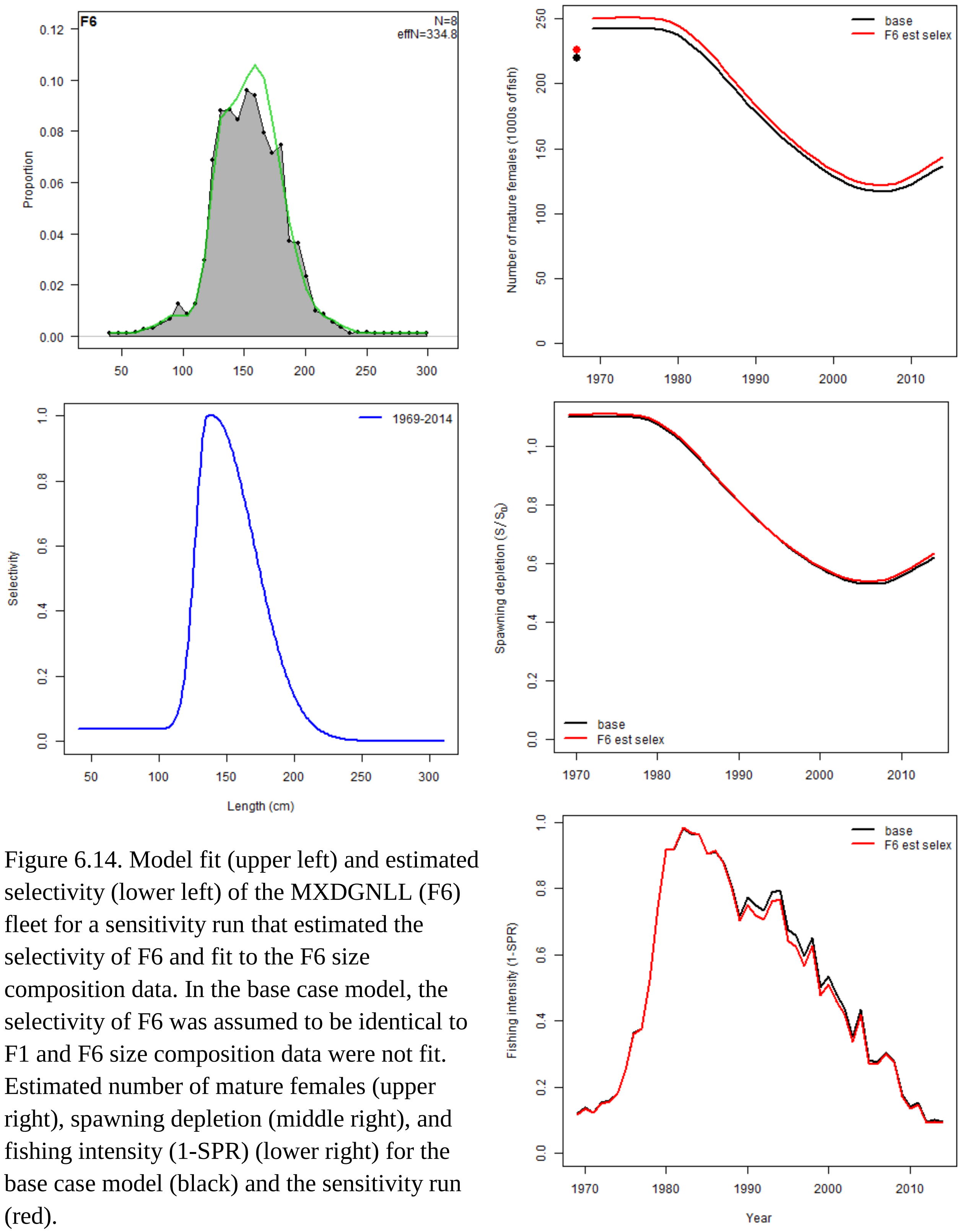


Figure 6.14. Model fit (upper left) and estimated selectivity (lower left) of the MXDGNLL (F6) fleet for a sensitivity run that estimated the selectivity of F6 and fit to the F6 size composition data. In the base case model, the selectivity of F6 was assumed to be identical to F1 and F6 size composition data were not fit. Estimated number of mature females (upper right), spawning depletion (middle right), and fishing intensity (1-SPR) (lower right) for the base case model (black) and the sensitivity run (red).

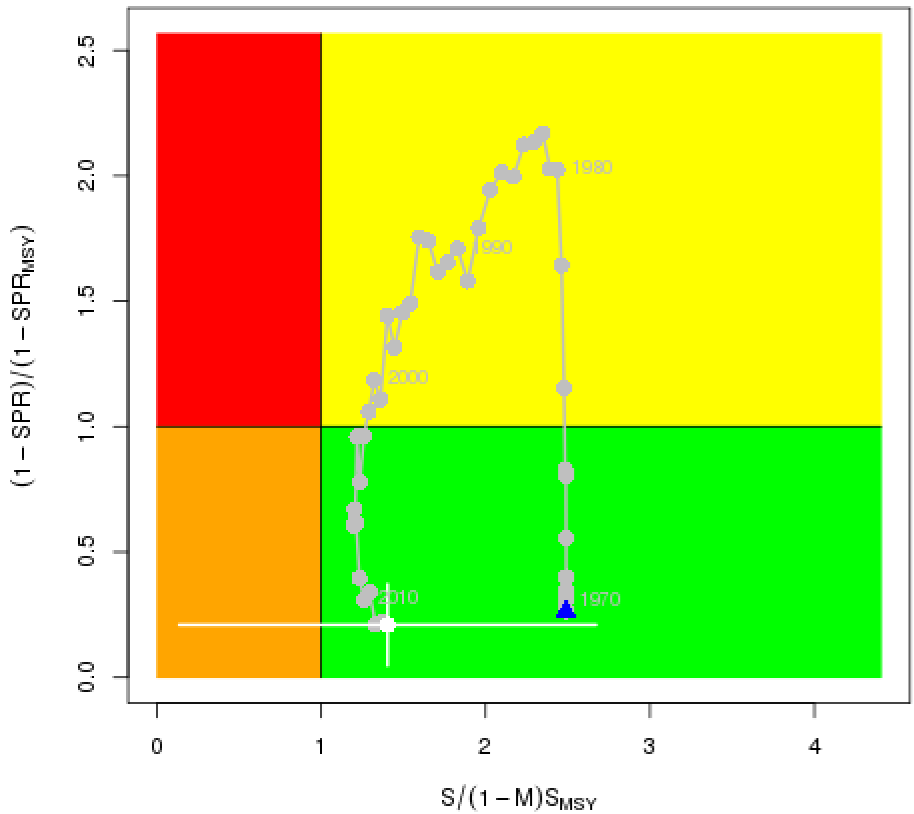


Figure 8.1. Kobe time series plot of the ratio of spawning abundance (S; number of mature female sharks) relative to the minimum stock size threshold reference point (MSST; (1-M)*S_{MSY}) and ratio of the fishing intensity (1-SPR) relative to the maximum fishing mortality threshold (MFMT; 1-SPR_{MSY}) for the base case model. Values for the start (1969) and end (2014) years are indicated by blue triangle and white circle, respectively. White lines indicate the 95% confidence intervals. Grey numbers indicate selected years.

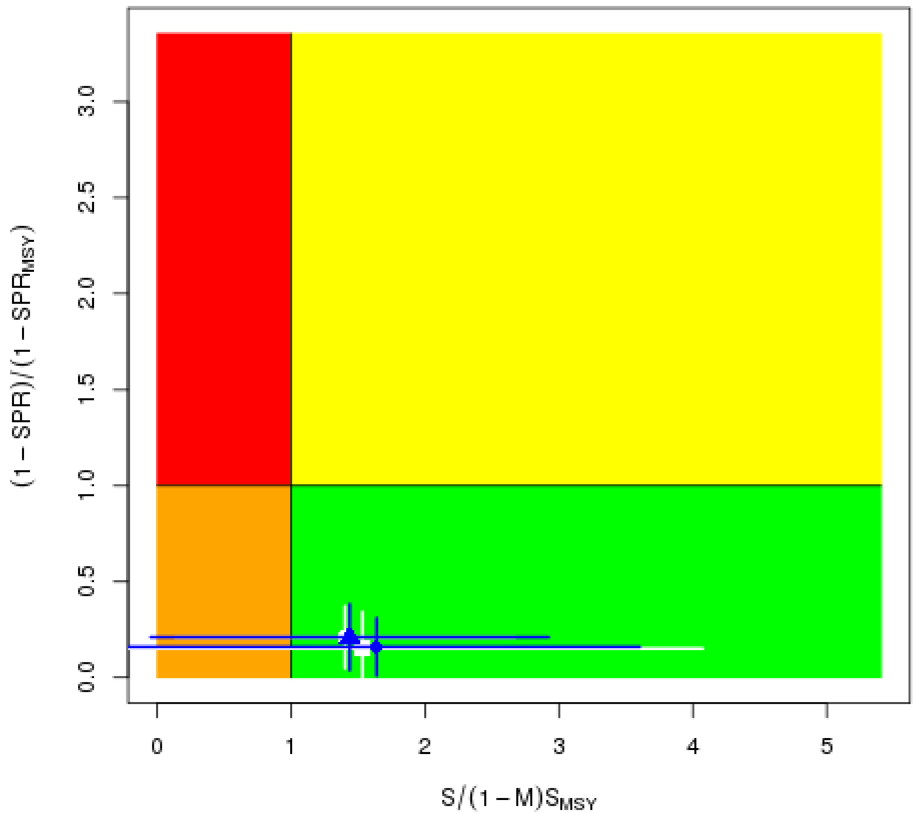


Figure 8.2. Kobe plot of the ratio of spawning abundance (S; number of mature female sharks) relative to the minimum stock size threshold reference point (MSST; (1-M)*S_{MSY}) and ratio of the fishing intensity (1-SPR) relative to the maximum fishing mortality threshold (MFMT; 1-SPR_{MSY}) for the end year (2014) of the base case model (white circle) and three alternative states of nature: 1) biennial reproductive cycle (i.e. 2 pups y^{-1}), natural mortality of 0.08 y^{-1}, and z_{frac} of 0.5 (white square); 2) annual reproductive cycle (i.e. 4 pups y^{-1}), natural mortality of 0.08 y^{-1}, and z_{frac} of 0.5 (blue triangle); and 3) annual reproductive cycle, natural mortality of 0.10 y^{-1}, and z_{frac} of 0.5 (blue diamond). White and blue lines indicate the respective 95% confidence intervals.

APPENDIX A: Independent peer review of the common thresher shark stock assessment off the west coast of North America by the Center of Independent Experts

INTRODUCTION

A review panel from the Center of Independent Experts (CIE) was assembled to perform an independent peer review of the stock assessment of common thresher sharks along the west coast of North America. The CIE review panel was chaired by Dr. Henrik Sparholt (Denmark) and consisted of Dr. Joseph Powers (USA) and Dr. Rui Coelho (Portugal). The review panel met at NOAA's Southwest Fisheries Science Center in La Jolla, California during July 26 – 28, 2017 to review the stock assessment.

This appendix includes the report of the Chair, as well as reports of the individual reviewers. For the sake of brevity, statements of work, terms of reference, and agenda of the meeting are not included in this appendix. All three reports may be found in full on the CIE website: https://www.st.nmfs.noaa.gov/science-quality-assurance/cie-peer-reviews/cie-review-2017.

Report

Chair Report on the Common Thresher Shark (*Alopias vulpinus*) Stock Assessment Review

June 26-28, 2017

Southwest Fisheries Science Center
8901 La Jolla Shores Dr., La Jolla, CA 92037
La Jolla, CA 92037
858-546-7000

September 2017

Henrik Sparholt

Table of Contents

1. Executive summary

The Stock Assessment Review Panel met at NOAA's Southwest Fisheries Science Center in La Jolla, California, from 26-28 July 2017 to review a stock assessment of Common Thresher Shark (*Alopias vulpinus*).

The Fisheries Resources Division (FRD) of Southwest Fisheries Science Center (SWFSC) requested an independent peer review of the benchmark stock assessment developed for the common thresher shark stock along the west coast of North America.

The common thresher shark fisheries of the USA and Mexico are independently managed by the Pacific Fishery Management council (PFMC) and the Instituto Nacional de Pesca (INAPESCA), respectively.

Common thresher shark fisheries in both the USA and Mexico have declined substantially since the start of commercial fisheries for this stock in the late 1970s, with total removals estimated to be <200 t in 2014. The current USA fishery management plan for this stock of common thresher sharks includes a harvest guideline of 340 t based on an unpublished analysis of USA data and is derived from the optimum yield for vulnerable species, which is defined as 0.75*MSY (or reasonable proxy).

This is the first stock assessment of common thresher sharks along the west coast of North America that incorporates information from all fisheries exploiting the population. The Stock Synthesis (SS) modeling platform was used to conduct the analysis. The model began in 1969, assuming the population was at equilibrium prior to 1969 in a near unfished state, and ended in 2014, which was the last year that data was available.

A key uncertainty in the stock assessment is the reproductive biology of this stock. Previous research suggested that female sharks had an age of maturity of 5 years of age and an annual reproductive cycle. The review scrutinized the evidence for this and found that potential mis-specification of pelagic thresher shark as common thresher shark and problems in determining the maturity stage pointed at an older age of maturity and maybe a biennial reproductive cycle. A recent study on the reproductive biology of the western North Atlantic stock of common thresher sharks demonstrated a much older median age of maturity (age-12) and longer reproductive cycle (biennial or triennial cycle). Another previous study from the Indian Ocean which showed that common thresher shark has an age of maturity of 5 years of age and an annual reproductive cycle was during the review, discovered to be a likely mis-specification of pelagic thresher shark to common thresher shark. A recent FAO paper working paper was provided by the reviewers, which described this likely mis-specification in details. The review found the evidence strongest for the late maturity and biennial reproduction. This was therefore selected for the base run of the assessment model. Sensitivity model runs indicated that changing the maturity and fecundity schedules resulted in substantial differences in the trend and scale of the estimated population dynamics. However, in all scenarios the stock was determined to be not overfished and that overfishing is not taken place, and that the current management harvest guideline of 340 t is living up to the US guidelines for fisheries management for this vulnerable species of an optimum yield of 0.75*MSY.

The other aspects of the assessment were judged to be based on the best available science and done in an un-biased, comprehensive way and with the use of an appropriate assessment tool. The data were judged to be compiled in an appropriate way. The assessment model configuration, catch assumptions, and input parameters (e.g., natural mortality, spawner-recruit relationship) were reasonable. The models were appropriately configured, assumptions were reasonably satisfied, and primary sources of uncertainty was well accounted for, partly within the models and partly by running sensitivity analysis of plausible alternative scenarios, mainly with varying natural mortalities and Z_{frac} (a spawner-recruit relationship parameter) values.

The Panel agreed that the assessments was effective in delineating stock status, determining *BRP*s and proxies. While an MSY-related stock size is calculated, the results indicate that small increases in fishing mortality above that at MSY could result in rapid declines in stock size. In other words, stock size at MSY is on the declining slope on the left side of the S-R curve. This suggests caution in implementing an MSY target as an objective.

The review process was effective in structuring a critical review of the work of the SWFSC and in identifying areas of concern and needs for additional work in future assessments.

2. Background

2.1 Introduction

The Stock Assessment Review Panel met at NOAA's Southwest Fisheries Science Center in La Jolla, California from 26-28 of July 2017 to review a stock assessment for Common Thresher Shark (*Alopias vulpinus*).

The Review Committee was composed of Joseph Powers (USA), Rui Coelho (Portugal) and Dr. Henrik Sparholt (Denmark).

The Review Committee was assisted by Steve Teo (SWFSC) who did the assessment, the presentations, and the extra model runs the Panel wanted during the meeting. Suzanne Kohin (SWFSC) presented the reproduction biology of thresher shark. Furthermore, the Panel was assisted by Kevin Hill, P.R Crone, Hui-Hua Lee, Helena Aryafar, Antonella Preti, and Heidi Dewar, all from the SWFSC.

The meeting was open to the public, but nobody from the public attended.

The Fisheries Resources Division (FRD) of Southwest Fisheries Science Center (SWFSC) requested an independent review of the benchmark stock assessment developed for the common thresher shark stock along the west coast of North America. The biological range of the stock spans the west coasts of Mexico, the United States of America (USA), and Canada. The common thresher shark fisheries of the USA and Mexico are independently managed by the Pacific Fishery Management council (PFMC) and the Instituto Nacional de Pesca (INAPESCA), respectively. However, there are no current nor historical fisheries along the west coast of Canada and in international waters that target common thresher sharks and bycatch appears to be rare. Common thresher shark fisheries in both the USA and Mexico have declined substantially since the start of commercial fisheries for this stock in the late 1970s, with total removals estimated to be <200 t in 2014. The current USA fishery management plan for this stock of common thresher sharks includes a harvest guideline of 340 t based on an unpublished analysis of USA data and is derived from the optimum yield for vulnerable species, which is defined as 0.75*MSY (or reasonable proxy).

This is the first stock assessment of common thresher sharks along the west coast of North America that incorporates information from all fisheries exploiting the population. The Stock Synthesis (SS) modeling platform was used to conduct the analysis. The model began in 1969, assuming the population was at equilibrium prior to 1969 in a near unfished state, and ended in 2014, which was the last year that data was available. The stock assessment considered this population to be a single, well-mixed, trans-boundary stock and relied heavily on data from both the USA and Mexico. However, it is important to note that the analysts who reconstructed the catch time series for Mexico's fisheries were not available for the peer review. A key uncertainty highlighted in the stock assessment is the reproductive biology of this stock of common thresher sharks. Previous research on this stock of common thresher shark suggested that female sharks had an age of maturity of 5 years of age and an annual reproductive cycle. However, a recent study on the reproductive biology of the western North Atlantic stock of common thresher sharks demonstrated a much older median age of maturity (age-12) and longer reproductive cycle (biennial or triennial cycle). Sensitivity model runs indicated that changing the maturity and fecundity schedules resulted in substantial differences in the trend and scale of the estimated population dynamics. The stock assessment provides the basis for scientific advice on the status of common thresher sharks along the west coast of North America. An independent peer review of the assessment is therefore essential. The Terms of Reference (ToRs) of the peer review are given below.

Supporting documentation for the common thresher shark assessment was prepared by the SWFSC.

2.2 Review of Activities and Process

Before the meeting, assessment documents and supporting materials on biology were made available to the Panel by email.

The meeting opened on the morning of Monday, 26 June, with welcoming remarks and comments on the agenda by Deputy Director Dr. Dale Sweetnam (SWFSC). All participants were introduced at the opening of the meeting. Following introductions, sessions on the 26 June were devoted to presentations and discussion of the assessment and reproductive biology of the stock.

The Panel requested additional analyses to re-evaluate the assessment based on selected input parameters for M (natural mortality) and Z_{frac} (parameter in the stock recruitment model). These were presented on Tuesday 27 June.

Between Monday and Tuesday, one of the reviewer contacted a colleague, expert in Indian Ocean sharks and he had just published an FAO paper about the likely mis-specification of common thresher shark in the Indian Ocean. This was relevant for the Panels' decision on the reproductive biology of the species, because it strongly indicated that all these common thresher shark from the Indian Ocean (which were the only substantial data on early maturity of common thresher shark) were instead pelagic thresher shark. Thus, this further weakened the support for the Smith (2008) conclusion of early maturation of specimens of the current Pacific stock. The Panel asked whether Smith was still around and could be contacted and asked about the issue. The SWFSC had actually already talked to her and she was very helpful and explained that she found the aspects presented in the paper by Aryafar *et al.* (2017) about the reproductive biology of the stock and tabled at the present meeting, quite sensible and she did not have strong views regarding sticking to her 2008 conclusion. The Panel found this reassuring, because often the material presented in a paper (here Smith 2008) are not the full picture of the case, but here it seemed to be.

Further analysis was requested using the late maturation and low fecundity scenario to look at model diagnostics for a new base case (Scenario A with M=0.08 and Z_{frac} =0.8). These were done and presented the same day, Tuesday 27 June.

An internal model/data inconsistency was discovered. The model ran with the juvenile S4 and S5 indices (abundance of primarily age-0 common thresher sharks based on logbooks from the USA nearshore set gillnet and small-mesh drift gillnet fishery during 1985 – 1993 resp 1994 – 2014), gave a quite different assessment of the stock's trend, in terms of not showing an improvement in stock size in recent years and only little reduction in F in recent years.

A new run was made with the very low M=0.04, and this made the problem described above to vanish. The Panel was quite uncertain what to believe most in, the higher M from meta-analysis or the low M from model/data indications. After reflection, the model run with this low M (of 0.04) was selected as the best model, and was selected as the base case. Sensitivity analysis was done for a set of plausible M and Z_{frac} values and fecundity at 4 pups per year, in order to illustrate for managers the level of uncertainties in the assessment. More precise knowledge on the reproductive biology and of M of this stock is needed in order to improve this assessment in the future.

The Panel spent the final day, Wednesday 28 June, looking at the diagnostics of the new base case assessment, to check that it did not contain any new "surprises". All diagnostics seemed ok and the Panel therefore decided to stick to that assessment as the best available one for this common thresher shark stock.

The Panel and SWFSC worked collectively during the meeting and reached agreement and consensus on the assessments. The meeting was collegial and conducted in a good and constructive atmosphere.

The completion of the Assessment Summary Report, was accomplished by correspondence on 14 July 2017, evaluating each ToR that had been put forward to the Panel. The Chair compiled and edited the draft Summary Report, which was distributed to the Panel for final review before being submitted to the SWFSC and CIE. Additionally, each of the CIE Panelists drafted and submitted an independent reviewer's report to the SWFSC and CIE.

The Panel agreed that the assessment was effective in delineating stock status, determining *BRP*s and proxies. Issues and concerns are discussed below. The review process was effective in structuring a critical review of the work of the SWFSC and in identifying areas of concern and needs for additional work in future assessments.

3. Review of common thresher shark

Common thresher sharks (*Alopias vulpinus*) along the west coast of North America are seasonally distributed in coastal waters from British Columbia, Canada to central Baja California, Mexico. Juvenile common thresher sharks tend to remain in shallow, nearshore areas over the continental shelf, especially within the Southern California Bight (SCB), which is an important nursery area. The distributions of common and bigeye thresher sharks are thought to overlap partially, with bigeye thresher sharks generally exploiting deeper waters. In contrast, there is relatively little overlap in the distributions of common and pelagic thresher sharks.

Common thresher sharks along the west coast of North America are assumed to be a single, well-mixed stock. This assumption is supported by their genetics, tagging data, and seasonal movements. The mitochondrial genetic sequences of common thresher sharks from California waters are not significantly different from Oregon-Washington waters, but both are significantly different from other sampling locations, noting that there have not been any published comparisons with samples from Mexico. There is also no evidence of pupping and nursery grounds outside of the SCB. Tags from common thresher sharks tagged in the SCB have been returned from California, USA, and Baja California, Mexico. There is also unlikely to be substantial interchange of individuals between this stock and other common thresher shark stocks, because the geographically closest stock is likely to be along the west coast of Chile.

The history of fisheries for this stock of common thresher sharks in USA waters is not well known prior to the 1970s, but small amounts of catch were recorded by a variety of USA commercial and recreational fisheries. The most important USA commercial fishery for common thresher sharks is the swordfish/shark drift gillnet (USDGN) fishery, which started in 1977 - 1978. Although the primary targets were initially common thresher and shortfin mako sharks, fishermen soon switched to primarily targeting swordfish because of substantially higher ex-vessel prices. Fishing operations of the USDGN fishery have been heavily regulated to reduce adverse interactions with other fisheries, fishing mortality of common thresher sharks, and incidental bycatch of marine mammals and sea turtles. Secondarily, nearshore set gillnets and small-mesh drift gillnets (USSN) occasionally catch young-of-year and juvenile common thresher sharks as bycatch. There is also a small USA recreational fishery in Southern California (USREC) that targets adult common thresher sharks but catches are usually relatively low.
The historically most important fishery for common thresher sharks in Mexico waters was the Mexico drift gillnet (MXDGN) fishery, which started in 1986. The fishing gear and operations of this fishery were similar to the USDGN fishery, with swordfish and pelagic sharks as the primary targets. The number of MXDGN vessels began to decline in the mid-1990s as vessels began converting to longline gear. The MXDGN fishery has been prohibited since 2010 by six Mexican federal regulations. The Mexico artisanal (MXART) fishery operates from small boats called pangas, using various nearshore gears that are set and hauled by hand, along the entire Pacific coast of Mexico. The size and history of this fishery is poorly known, but it has likely existed since the early 20th century. Only a small portion of pangas are allowed to fish for sharks. For example, there were 50 shark permits for this fishery in Baja California in 1998, representing about 180 out of more than 2000 pangas in total.

There are no historical nor current fisheries along the west coast of Canada that target common thresher sharks and bycatch appears to be rare. There are also no known historical nor current fisheries that target this stock of common thresher sharks in international waters and bycatch is expected to be minimal, given the largely coastal distribution of this population.

3.1 Evaluation of Terms of Reference 1-3

The evaluation of the first three Terms of Reference:

1. *Evaluate the assessment model configuration, assumptions, and input parameters (e.g., natural mortality, spawner-recruit relationship, reproductive biology) to determine if the data are properly used, input parameters are reasonable, models*

are appropriately configured, assumptions are reasonably satisfied, and primary sources of uncertainty are accounted for.

2. *Evaluate the ability of the model, combined with available data, to assess the current status and productivity of common thresher sharks along the west coast of North America.*
3. *Evaluate the adequacy of sensitivity analyses to represent the main axes of uncertainty in the assessment.*

3.1.1 Catch data

Generally, the construction of the time series of catches were done in a reasonable way. Clearly there are a lot of uncertainties especially back in time. One of some concern to the Panel was the artisanal Mexican fishery (*pangas*). There were around 2000 small boats, with only a minority having license to fish for sharks. The Panel raised the possible concern that a large number of those vessels (that do not have shark licenses) could also be by-catching sharks that had to be discarded due to not having shark licenses, likely with high discard/post-release mortality rates. This could represent an important source of fishing mortality not currently accounted in the catches of this fishery. This issue was discussed, but unfortunately the Mexican analysts who reconstructed the catch time series from Mexico were not present at the meeting. However, the modelers explained that the Mexican data is also coming from market sampling and not only port-sampling, and there is likely very little discarding on this fleet. The review meeting would have benefitted from a participation of a Mexican scientist with expert knowledge of the Mexican fishery.

3.1.2 CPUE standardization

It was nice to see that a proper GLM type analysis was done with the CPUE data in order to obtain a time series index that reflects the stock size dynamics over time. Often, in fish stock assessments, this is not done properly or only superficially. The CPUE standardization method used was similar for the various CPUE series, specifically GLM models using the Delta lognormal approach. The Panel recognized that this method is commonly used in CPUE data standardization. It is especially used when part of the data is composed by zeros, as is the case of the CPUE datasets analyzed.

The Panel noted that the catches were recorded and modeled in numbers (N, discrete distribution) that was then transformed into a continuous variable in the log scale (log (N)). Another possible approach suggested by the Panel would be to model the catch directly in numbers using a discrete distribution, as for example the Negative Binomial, possibly with zero inflation if needed. Another suggested alternative was a Tweedie distribution (generalization of the exponential family) that can model the mass of zeros and the continuous component for the positives in the same model. This is something that can be further explored in the future.

The Panel noted that the index from the main fishery (USDGN) had to be broken into 3 separate time series due to changes in regulations, and included a period in the middle without information (i.e., 1985-1991). The Panel recognized and accepted that this had to be done because of the difficulty of modeling changes in regulations in the GLM models, if a unique and continuous time series were to be used. However, by having to break the time series from the main fishery in 3 sections, the overall contribution to the model of each section was also lower (except for S2 in the middle period that still contributed significantly). The Panel suggested that in the future, a new attempt could be tried for the entire time series combined, trying to account for the changes in management regulations (mainly seasonal and spatial closures) as detailed spatial and seasonal effects in the GLM to try to compensate for those changes in the fishing operations through time.
Finally, the Panel commented and discussed the targeting variable that was used, based on ranking the swordfish catches within each year (used as a proxy of swordfish *versus* sharks targeting). One possible issue that was raised related with such method is that if within specific years there are consistently the same targeting for the same species, there will still be categorization and ranking within each year that is not necessarily consistent with the overall inter-annual variations in the targeting effects of the fleet. One possible suggestion by the Panel to address this issue in the future would be to test and consider interactions between year and targeting effects. The use of vessel effects, possibly as a random variable, was also suggested, as that could also bring to the CPUE standardization variability associated with the different practices of the various vessels operating in the fleet.

3.1.3 Reproductive biology

Biology, especially the reproductive biology, was a major source of uncertainty in the stock assessment. The base case model in the original stock assessment considered a hypothesis with a more productive biology, based on a smaller size at maturity and annual reproductive cycle. However, since then, there have been concerns about the original biological studies in the Pacific, with new hypothesis that size at maturity could be larger (more similar to the one described for the Atlantic) and periodicity could be biennial.

The main issues identified with the original biological studies are likely related with eventual species misidentification in threshers (between common and pelagic thresher), an issue that is now also suspected in some of the original studies in the tropical Indian Ocean. As pelagic thresher is a much smaller species, the size at maturity is also smaller, and if there is misidentification, this will have a great impact in the estimation of the size at maturity. There may have also been some issues with the original measurements from the observers.

The Panel agreed with the new hypothesis of the biology (larger size at maturity and possibly a biennial reproductive cycle). However, using this new biology created some additional convergence problems in some of the models that in general needed lower values of natural mortality (M) to converge. This issue was explored at great length during the meeting, with the modeler exploring multiple scenarios (especially combinations of M and Zf_{rac}) to investigate which combinations had problems of convergence, likely caused by conflicts in the data (CPUE, size and biology). The Panel agreed that the uncertainties in the reproductive biology of the common thresher shark in the Pacific are a source of major uncertainty in the stock assessment model and should be further studied.

3.1.4 Stock-Recruitment

The stock recruitment model chosen for use in the common thresher assessment was that of Taylor et al. (2013). This model is especially useful for species with very low fecundity like sharks. This model is essentially a modification of a Ricker function with an additional term, β, which defines the strength of the depensation effect at larger stock sizes. Importantly, the particular parameterization allows for the use of basic reproductive information more directly in the specification of the slope of the stock-recruitment curve at the origin. The parameterization used was:

$$R_y = B_y exp\left[-z_0 + (z_0 - z_{min})\left(1 - \left(\frac{B_y}{B_0}\right)^{\beta}\right)\right]$$

where recruitment R in year y is in number of pups, B_y is the number of pups born at the beginning of the recruitment process in year y (B_0 denotes equilibrium pup production when there is no fishing and $S_0 = R_0/B_0$ is the equilibrium survival when there is no fishing). Additionally,

$$z_{min} = z_0(1 - z_{frac}) = z_0 - z_0 z_{frac}\ ; \qquad z_0 = -ln(S_0)\ ;\ z_0 - z_{min} = z_0 z_{frac}$$

and z_{frac} is a fraction ranging from 0 to 1. Hence, knowing S_0, B_0, z_{frac} and β completely defines the function.

The Panel noted that the fraction z_{frac} functions similarly to the steepness parameter of more commonly used Beverton-Holt stock-recruitment models. It defines the slope of the S-R curve at the origin, i.e. the maximum recruitment rate that can be produced when stock sizes approach zero. And similar to steepness specifications, there was little information in the data to determine z_{frac} and, thus, alternatives were explored in the assessment through sensitivity analyses.

The Panel noted that there was not a strong biological explanation for how depensation was occurring in common thresher to support the choice of a Ricker-like form, other than it was originally applied to a shark species. Additionally, it was noted that similar to most fish stocks, the assessment model assumed that all density-dependence in common thresher over their lifespan occurred in the few months after their birth. In some fish stocks, this is a reasonable assumption. But, perhaps there are other stages in a shark's life where density-dependence can occur (nursery areas?). This supports the need for more basic research on reproductive biology and life history.

Other forms of the stock-recruitment function could have been explored which would have the same effect of rapid declines when the stock size was low. One example might be a basic hockey stick model where the recruitment is constant over stock size until it reaches a threshold at which it declines linearly to the origin. Care would then have to be taken in determining the slope because there is a maximum border of this due to the low fecundity of the species. However, this model and others would likely have produced similar results. Any function with steep declines at low stock sizes would be compatible with shark life history. The Panel believes that the resulting dynamics of common thresher stock-size over the years and basic status of the stock is relatively robust to the functional form chosen.

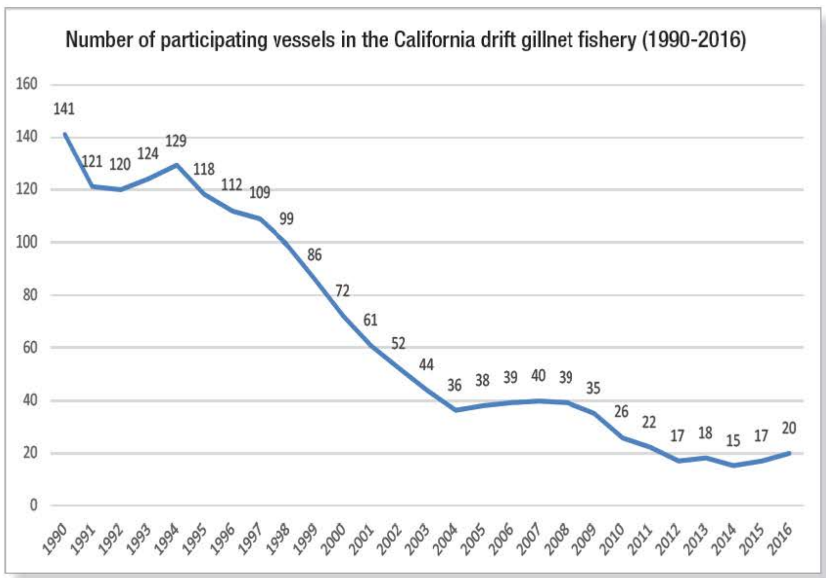
An implication of the stock-recruitment results and of shark life histories, in general, is that there is little surplus in recruitment to be taken as yield as the fish get older. While an MSY-related stock size is calculated, the results indicate that small increases in fishing mortality above that at MSY could result in rapid declines in stock size. In other words, stock size at MSY is on the declining slope on the left side of the S-R curve. This suggests caution in implementing an MSY target as an objective.

3.1.5 Natural mortality M

When the reproductive biology was decided upon M needed to be adjusted. This was because a low pup production per year by each female, means that the stock will collapse even in the case of no fishery, if M is assumed higher than 0.14. This was judged unrealistic.

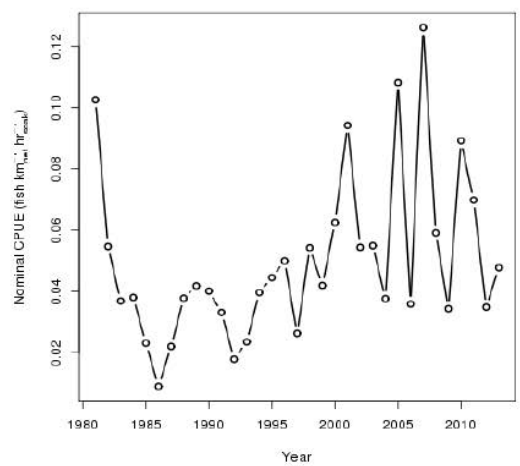
A model run where M was allowed to be estimated by the model gave very low values of M of about 0.03. Very low Ms corresponds to very high maximum age. M values of 0.04, 0.06 and 0.08 mean that 1% of the stock in case of no fishing will be about 115, 77 and 58 years old, respectively. Based on the meta-analysis of M's relation to age at first maturity and to max age, the lower 95% confidence interval was 0.06. Runs with M equal to 0.6 and 0.8 (and Z_{freac} between 0.6-0.9) did not deviate much from each other in terms of model performance. The Panel found that a max age of 58 years was more realistic than 77 years and therefore tentatively decided on that value for a new base run.

However, runs with M=0.08 and Z_{frac}=0.8 gave problems with internal consistencies of the model and data. Leaving out the S4 and S5 indices (abundance of primarily age-0 common thresher sharks based on logbooks from the USA nearshore set gillnet and small-mesh drift gillnet fishery during 1985 – 1993 resp 1994 – 2014), of the modelling gave a very different stock trend over the recent years, with very low stocks sizes compared to keeping these indices in the model. M had to be reduced to 0.04 and Z_{frac} to 0.5 before these inconsistencies vanished. After long discussions, it was agreed to use this run as the best description of the stock development and status, as the base run. This decision was reached knowing that it meant that M was quite outside the range indicated by the meta analysis of max age and age of maturity, that there would be a very substantial number of very old fish in the plus group (25+), which nobody seems to know where they are in the ocean, and that max age would be extremely high, 115 years. This was regarded as the best compromise between the conflicting signals in the data and knowledge about the reproductive biology. It gave a strong downward trend in fishing mortality which is consistent with the strong decline in fishing effort as documented in Anon. 2017, and shown in the figure below. Other scenarios were explored and selected to show in a balanced way, realistic alternative estimates of the stock development and status. Fortunately, they all gave the same overall picture of a stock not being overfished and overfishing not taking place at present.



Source: NOAA Fisheries West Coast Region Observer program records

3.1.6 Additional evaluation of the base model



Even though the commercial drift gill net fishery cpue time series was broken into three sets (S1 1982-1984, S2 1992-2000, and S3 2001-2013) due to shifts in targeting and regulations, one might use the entire time series (see figure above) as a validation of the model stock trends. The problem with breaking it up into three sets is that the information contained in the difference in levels between the three sets are not used in the assessment model. However, it can be expected that the level in S1 is too high due to targeting thresher shark in that period, and that the level in S3 is too low due to mainly protected area regulations. This leads to the conclusion that the stock must be higher in recent years than in the start of the time series and significant higher than in the middle period. Thus, this development of the stock over the period 1980-2013 should be reflected in any model that attempts to assess the historical development of the stock. The base model run did fulfill this criteria.

3.1.7 Stock Status

The assessment is relatively robust in showing that stock sizes declined in the early years while experiencing high catches. When catches were reduced, the stock recovered. The estimated degree and timing of recovery are heavily dependent on uncertainties in reproductive biology and life history characteristics. The assessment choices made by the assessment team and the Panel opted for statistical fits to the data, recognizing the apparent uncertainty in natural mortality rate, gestation, reproductive cycle. Nevertheless, the Panel is confident that current stock size is well-above MSY-related limits established in the US management system.

The base-case model indicates:

Number Adult Females in 2014	136,800
Number Adult Females at MSY	101,500
Number Adult Females at MSST	97,440
Fishing Intensity (1-SPR average 2012-14)	0.10
Fishing Intensity (1-SPR at MSY)	0.45
Catch in 2014	~160t
MSY	718t

MSST is Minimum Stock Size Threshold = (1-M) x stock size at MSY, where natural mortality rate M is specified as 0.04.

Therefore, common thresher is not overfished in that the adult female stock size is greater than that at both MSY and MSST and the stock is not undergoing overfishing because current fishing intensity is less than that which would produce MSY.

However, the Panel cautions that the uncertainties in life history, reproductive biology and the ensuing implications for the stock-recruitment relationship are large. Therefore, projections of stock size using the current assessment and stock-recruitment model will be extrapolating beyond the data and will also be very uncertain. While the Panel is confident that the stock is not currently overfished or undergoing overfishing, we are less certain about catch strategies that would be required to achieve MSY. If management were to pursue a policy of something close to MSY, then the ability to precisely determine the strategy to achieve this is severely limited by uncertainties in basic biological information as noted above. However, under current catch policies, the status is robust.

It is also noted that MSST and MSY stock size may not be particularly precautionary for this shark species. Generally, MSST is specified to allow some flexibility if stock size declines below that at MSY before a more rigorous management response is initiated. However, the stock sizes at both MSST and MSY for common thresher are both on the declining slope of the stock-recruitment curve at lower stock size. This further suggests that additional biological information is needed if an MSY policy is to be precisely pursued.

3.2 Evaluation of Terms of Reference 4

The evaluation of the fourth Term of Reference:

4. *Recommendations for future research priorities and further improvements to the assessment model.*

The Panel suggests the following:

- The survey design and protocols of the USA juvenile thresher shark survey could be reexamined and improved. Especially a random sampling design and access to MPAs could be considered.

- Catch and catch-at-size estimates from USA fisheries, especially the USA recreational fishery, should be improved. Information on recreational fishing from private vessels is obtained using surveys, which are available in a comprehensive coastwide marine recreational fishery database (RecFIN; http://www.recfin.org). The panel was informed that the information on common thresher sharks caught by anglers on private vessels is highly limited.

- It would be important for the quality of the assessment if the catch and catch-at-size estimates from Mexico fisheries could be improved following more traditional monitoring approaches.

- The use of the low fecundity stock recruitment relationship requires further research.

- It might be an idea to try a hockey stick S-R model following the ICES guidelines, allowing knowledge from other stocks, preferably shark stocks, to inform the modelling.

- There are clearly strong density dependent factors operating on the stock, preventing it from being much bigger than it was at the start of the time series and at the end of the time series where fishing also is very low. All of this density dependence is at present in the modelling assigned to the short life history period (a few months) from pub extrusion to recruitment to the fishery. This seems unrealistic. As a long term research issue it seems relevant to look into density dependent factors in growth, natural mortality, maturity (age at maturity, fecundity). One possibility could be to "learn" from other shark stocks, by way of meta-analysis.

- Reproductive biology: The current lack of knowledge and uncertainties associated with the reproductive biology of common thresher shark in the Pacific is likely the main cause of uncertainty in the stock assessment model. While most cases and sensitivities tested with various hypotheses do not affect the stock status, in some cases there are problems of data conflicts in the model that needs further exploration. As such, it is highly recommended to continue the biological studies to further investigate the reproductive biology of this population, especially in terms of the size at maturity, age at maturity, and reproductive cycle/periodicity.

- Size samples: size samples seemed adequate from some fisheries (e.g., USDGN) but very limited in others, especially for the US recreational (USREC) and the Mexico fisheries (MXDGN and MXLL). Especially in those cases with very limited information, there was the need to assume similar size structure (i.e. similar selectivity) to some of the other fisheries with more information. This might be an important source of uncertainty in the current model and as such we recommend more effort to be put in collecting size data from those fisheries, preferably with sex-information.

- CPUE standardization: While the overall CPUE standardization process seemed to follow the current practices in fisheries, especially with large pelagics, there were some issues that could be the focus for future work and research. Specifically, we recommend testing some alternative distributions (e.g., Negative Binomial or Tweedie), consider/test the inclusion of interactions, test the possibility of modeling the USDGN as a single time series (using detailed spatial and seasonal effects to try to account for spatial/seasonal changes in management), and consider using vessel effects as a random variable to add variability associated with different vessels of the fleet.

- Low fecundity stock recruitment relationship: The use of the relatively new low fecundity stock recruitment (Taylor *et al.* 2013) seems to be appropriate for sharks in general, particularly for Lamniformes as the common thresher that has some of the lowest fecundities within sharks. However, this low fecundity stock recruitment relationship is relatively new and has not yet been fully tested. Therefore, while we agree with its use for this assessment, we also recommend that further work and research is conducted to fully test this stock recruitment relationship.

3.3 Evaluation of Terms of Reference 5

The evaluation of the fifth Term of Reference:

5. *Brief description on Panel review proceedings highlighting pertinent discussions, issues, effectiveness, and recommendations.*

The process went very well. Description of the discussions of the main issues are given above. The SWFSC, especially Steve Teo, was very supportive and skillful in providing the Panel with several extra assessment model runs and plots of selected diagnostics in a speedy and effective way during the meeting and in the evenings between the meeting days.

Much of the discussion was around the basic reproductive biology of the common thresher shark stock. The data and knowledge available were scrutinized, and compared to data from other common thresher shark stocks especially from the West Atlantic.

The Panel was little bit uncertain about the required format of the Summary Report. This format was not described specifically in the "Statement of Work" document sent to the Panel. The format was therefore agreed with the SWFSC representatives at the meeting and it is the one followed in the present report. It would good if the Statement of Work" is more specific on the format of the Summary report.

4. Appendixes

4.1 Bibliography of materials provided for review

Teo, Steven L. H.; Rodriguez, Emiliano Garcia; and Sosa-Nishizaki, Oscar. 2016. Status of common thresher sharks, *Alopias vulpinus*, along the west coast of North America. NOAA-TM-NMFS-SWFSC-557.

Teo, Steven L. H. 2017. Population dynamics of common thresher sharks along the West Coast of North America, assuming alternative reproductive biology and natural mortality parameters. Fisheries Resources Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA.

Aryafar, Helena; Preti, Antonella; Dewar, Heidi; and Kohin, Suzanne. 2017. Re-examination of the reproductive biology of common thresher sharks along the west coast of North America. Fisheries Resources Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA.

Romanov, Evgeny. 2015. Do common thresher sharks *Alopias vulpinus* occur in the tropical Indian Ocean? IOTC Working Party on Ecosystems and Bycatch (WPEB) Olhão, Portugal.

Anon. 2017. FAQs: West Coast drift gillnet (DGN) fishery & protected species. U.S. Department of Commerce, National Oceanic & Atmospheric Administration, National Marine Fisheries Service, West Coast Region.

Independent Peer Review of the Common Thresher Shark (*Alopias vulpinus*) Stock Assessment

Independent Peer Review Report for the Center for Independent Experts (CIE)

Rui Coelho

June 26-28, 2017
Southwest Fisheries Science Center
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Contents

1. Executive summary

The Fisheries Resources Division (FRD) of the Southwest Fisheries Science Center (SWFSC) requested an independent review of the stock assessment of the common thresher shark (*Alopias vulpinus*) from the west coast of North America. The stock is described to range between the west coasts of Mexico, USA and Canada. There are no current or historical fisheries along the west coast of Canada and in international waters that target common thresher sharks. Bycatch from other fisheries appear to be rare. Common thresher shark fisheries in both the USA and Mexico have declined substantially since the start of commercial fisheries in the 1970s, with total removals estimated to be <200 t in 2014. The current USA fishery management plan for this stock includes a harvest guideline of a maximum of 340 t derived from the optimum yield for vulnerable species (0.75*MSY).

The Stock Assessment Review Panel met at NOAA's Southwest Fisheries Science Center in La Jolla, California, from 26-28 July 2017 to review a stock assessment of common thresher shark.

This is the first stock assessment of common thresher sharks along the west coast of North America that incorporates information from all fisheries known to be exploiting the population. The Stock Synthesis (SS) modeling platform was used to conduct the analysis. The model began in 1969, assuming the population was at equilibrium prior to 1969 in a near un-fished state, and ended in 2014, which was the last year that data was available.

The main uncertainty identified in the stock assessment was the reproductive biology of this stock. Previous research suggested that female sharks had an age of maturity of 5 years and an annual reproductive cycle. The review scrutinized the evidence for this and found that potential misidentification of pelagic with common thresher sharks and problems in determining maturity stage in some of the original studies, pointed to a more likely older age of maturity (age 12) and possibly a biennial reproductive cycle. This would be consistent with recent studies for the same species in the Atlantic. Additionally, another previous study from the Indian Ocean that also showed that common thresher has an age of maturity of 5 years and an annual reproductive cycle was also analyzed during the meeting, and a similar problem in species identification (misidentification between pelagic and common threshers) was also found. On this issue, a recent IOTC (*Indian Ocean Tuna Commission*) working paper was provided by the reviewers addressing precisely this issue. Therefore, the stock assessment review agreed that there was sufficient evidence to use the late age at maturity life history parameters.

Those changes in the reproductive biology were found to be the major source of uncertainty in the models. Therefore, a sensitivity analysis using this final reproductive schedule was carried out, mainly in using different combinations of natural mortality and parameters from the stock-recruitment function (Zfrac, from the relatively new low-fecundity stock-recruitment function). In general, using those different combinations resulted in differences in the scale of the estimated populations, but most of the scenarios determined consistently similar stock status, i.e., that the stock was not overfished and that overfishing was not taking place. Therefore, the stock status determination was considered to be robustly estimated, with a conclusion that the current management harvest guideline of 340t seems to be adequate according to the US guidelines for fisheries management of vulnerable species (0.75*MSY).

The other aspects of the assessment were agreed to be based on the best available science and carried out in an un-biased and comprehensive way. The assessment model configuration, catch assumptions, and input parameters (e.g., natural mortality, spawner-recruit relationship) were reasonable. The models were appropriately configured, assumptions were reasonably satisfied, and primary sources of uncertainty were well accounted for.

The review process was effective in structuring a critical review of the work of the SWFSC and in identifying areas of concern and needs for additional work in future assessments. Some particular recommendations for future work were listed. The main one was regarding the main axis of uncertainty of the current assessment model, in particular the need for continuing biological studies to further investigate the reproductive biology of this population, especially in terms of the size at maturity, age at maturity, and reproductive cycle/periodicity.

2. Background

2.1. Introduction

The Fisheries Resources Division (FRD) of the Southwest Fisheries Science Center (SWFSC) requested an independent peer review of the stock assessment for the common thresher shark (*Alopias vulpinus*) from the west coast of North America. The stock is described to range between the west coasts of Mexico, USA and Canada. The common thresher shark fisheries from USA and Mexico are independently managed by the Pacific Fishery Management council (PFMC) and the Instituto Nacional de Pesca (INAPESCA), respectively. There are no current or historical fisheries along the west coast of Canada or in international waters that target common thresher sharks. Bycatch from other fisheries appear to be rare. Common thresher shark fisheries in both the USA and Mexico have declined substantially since the start of commercial fisheries in the 1970s, with total removals estimated to be <200 t in 2014. The current USA fishery management plan for this stock of common thresher sharks includes a harvest guideline of a maximum of 340 t derived from the optimum yield for vulnerable species (defined as 0.75*MSY).

This is the first stock assessment of common thresher sharks along the west coast of North America that incorporates information from all fisheries exploiting the population. The Stock Synthesis (SS) modeling platform was used to conduct the analysis. The model began in 1969, assuming the population was at equilibrium prior to 1969 in a near un-fished state, and ended in 2014, which was the last year that data was available. The stock assessment considered this population to be a single, well-mixed, trans-boundary stock and relied heavily on data from both the USA and Mexico. However, it is important to note that the analysts who reconstructed the catch time series for Mexico's fisheries were not available for the peer review meeting. A key uncertainty highlighted in the stock assessment is the reproductive biology of this stock of common thresher sharks. Previous research on this stock of common thresher shark suggested that female sharks had an age of maturity of 5 years of age and an annual reproductive cycle. However, a recent study on the reproductive biology of the western North Atlantic stock of common thresher sharks demonstrated a much older median age of maturity (age-12) and longer reproductive cycle (biennial or triennial cycle). Sensitivity model runs indicated that changing the maturity and periodicity/fecundity schedules resulted in differences in the trend and scale of the estimated population dynamics, but is in general to be used for the estimation of stock status.

The stock assessment provides the basis for scientific advice on the status of common thresher sharks along the west coast of North America. An independent peer review of the assessment is therefore essential. The Terms of Reference (ToRs) of the peer review are given below. Supporting documentation for the common thresher shark assessment was prepared by the SWFSC.

2.2. Description of Reviewers roles

The Stock Assessment Review Panel met at NOAA's Southwest Fisheries Science Center in La Jolla, California from 26-28 July 2017 to review a stock assessment for Common Thresher Shark (*Alopias vulpinus*).

The Stock assessment work and presentations were provided by Steve Teo (SWFSC). Other SWFSC scientists provided additional presentations and contributions, particularly Suzanne Kohin on the reproductive biology. Other participants from the SWFSC that were present and provided additional inputs were Kevin Hill, P.R Crone, Hui-Hua Lee, Helena Aryafar, Antonella Preti and Heidi Dewar.

The CIE Review Panel was composed by Henrik Sparholt (Denmark, Review panel Chair), Joseph Power (USA) and Rui Coelho (Portugal). There was no formal separation of the independent Reviewers roles as all contributed to all points of the agenda and the discussion. The Review Panel Chair coordinated the preparation of the summary report, and all other Reviewers provided contributions and revisions to the final summary report.

3. Summary findings for each TOR

3.1. ToRs item # 1

The item # 1 of the ToRs requested an "*evaluation of the assessment model configuration, assumptions, and input parameters (e.g., natural mortality, spawner-recruit relationship, reproductive biology) to determine if the data are properly used, input parameters are reasonable, models are appropriately configured, assumptions are reasonably satisfied, and primary sources of uncertainty are accounted for*".

Most of the time spent during the meeting was on this point of the ToRs and agenda. The main items discussed were in terms of model configuration, assumptions and input parameters.

Those are described in detail bellow:

3.1.1. Stock definition

The current stock assessment assumes the population to be a single stock, relying mainly on data from the USA and Mexico. The discussion on this issue was relatively limited as the current evidence seems to support this single stock hypothesis, including genetics and tagging data. The panel agreed that there seems to be sufficient current information to assume this stock definition as was used in the current stock assessment.

3.1.2. Catch history data

It was noted that several assumptions had to be made on the catch history time series, especially as for the initial years there were very limited data and details in species-specific catch composition. In general, it seems that the work that was done on the catch reconstruction seems adequate.

One specific case that was noted and raised some possible concerns was the artisanal Mexican fishery (*pangas*). This fishery is composed of very small boats that can use several artisanal gears, and the number of boats operating is very large (around 2000). It was noted that from those, only a minority have licenses to fish for sharks. One concern from the panel at the meeting was that this large number of vessels without shark licenses could also be by-catching sharks that had to be discarded due to the vessels not having specific shark licenses. As the shark discard and post-release mortality is likely very high, this could be a very important source of fishing mortality not accounted for in the current catch history (as the catches are estimated from landings, but do not account for possible discard mortality).

This issue was discussed at the meeting, but unfortunately the analysts who reconstructed the catch time series from Mexico were not available to be present at the meeting. However, the modelers explained that the Mexican data is actually coming also from market sampling and not necessarily only from port sampling, and there is likely very little discarding in those fisheries. So, the market sampling should cover well the overall catch and there shouldn't be too much discarding in this fishery for this to be an issue. The panel understood this explanation and agreed that the catches used likely represent the best available information at this stage. However, it was also recommended to further explore this issue, as this fishery could represent some additional source of mortality not currently accounted for.

3.1.3. CPUE standardization

The CPUE standardization method was briefly described and the main methods and results shown. The method used was the same for all CPUE time series data, specifically GLMs with a Delta lognormal approach (combination of a binomial model for modeling the probability of a set being positive, and a lognormal model for the expected CPUE conditional to the set being positive). The panel agreed that this is a commonly used and widely accepted method in commercial fisheries CPUE data standardization. The method is particularly useful when a certain proportion of the data is composed by zeros.

One specific comment made on the CPUE standardization was related with the distribution used. Currently the data is being modeled in catch numbers (N, discrete distribution), then transformed into a continuous variable (log (N)) to make it possible to use the lognormal distribution (continuous distribution). It was suggested, in the future, to possibly test other approaches, for example, to model the catch directly in numbers using a discrete distribution (i.e. the Negative Binomial, possibly with zero inflation if needed). Other possible alternative is the Tweedie distribution (generalization of the exponential family) that can model the mass of zeros and the continuous component for the positive sets in the same model. Those changes are unlikely to have a major impact in the CPUE series but it would be interesting to also test for those alternative approaches.

Another specific comment was made on the fact that the index from the main fishery (USDGN) had to be broken into 3 separate time series due to changes in regulations, with a period in the middle of the time series without information. The panel recognized and accepted that this had to be done because of the difficulty of modeling those changes in regulations in the GLM models, as there is no overlap of the different regulations in time and therefore the model cannot estimate parameters for those effects. However, by having to break the time series from the main fishery in 3 different sections, the overall contribution of those time series to the assessment model was also lower (except for S2 that still contributed significantly), and likely increased the variability within each section. The panel suggested that, in the future, a new attempt could be tried for the entire time series combined, trying to account for the changes in management regulations (mainly seasonal and spatial closures) as detailed spatial and seasonal effects in the GLM.

Finally, the group discussed the use of proxies for targeting variables in the models, in this case based on the rankings of swordfish catch within each year (used as categorical variables as a proxy for targeting swordfish *versus* sharks). One possible issue that was raised regarding this method is that if within specific years there is consistently the same targeting for the same species (e.g., swordfish), there will still be categorization and ranking within each year not necessarily consistent with the overall variations in the targeting of the fleet (inter-annually). This means that the targeting variable would no longer be comparable between different years. One possible suggestion by the panel to address this issue in the future would be to test and consider interactions between year and targeting effects.

3.1.4. Biological information

Biology, especially the reproductive biology, was agreed by the panel to be likely the major source of uncertainty in the stock assessment. The original stock assessment considered the hypothesis of a more productive biology based on a smaller size at maturity and annual fecundity. However, since then, there have been concerns about the original biological studies in the Pacific, with the new hypothesis that size at maturity could be larger (more similar to the one described for the Atlantic) and periodicity could be biennial.

The main issues identified with the original biological studies can be related with eventual species misidentification in threshers (between common and pelagic thresher), an issue that is now also suspected in some of the original studies in the tropical Indian Ocean. As pelagic thresher is a much smaller species, the size at maturity is also smaller and if there is misidentification this will have a great impact in the estimation of the size at maturity. There may have also been some issues with the original measurements from the observers.

It should be noted that an expert on shark biology from the Indian Ocean was contacted by e-mail during the meeting (E. Romanov) that was also involved in some of the original biological studies in that Ocean. This expert confirmed that the original studies in the tropical Indian Ocean were also likely misidentifying common and pelagic thresher, and therefore the calculation of the size at maturity is likely also incorrect.

The panel therefore fully agreed with this new hypothesis of the biology that is now posed by the SWFSC scientists of a larger size at maturity (also corroborated for the Indian Ocean) and possibly a biennial reproductive cycle. However, using this new biology created some additional convergence problems in some of the models that in general needed lower values of natural mortality (M) to converge. This issue was explored at great length during the meeting with the SWFSC modeler exploring multiple scenarios (especially combinations of M and Zfrac from the stock-recruit function) to investigate which combinations had problems of convergence, likely caused by conflicts in the data (CPUE, size data and biology). The panel agreed that the uncertainties in the reproductive biology of the common thresher shark in the Pacific are a source of major uncertainty in the stock assessment model and should be further studied.

Another minor detail noted is that the current model is using age at length data to estimate growth parameters inside the actual stock assessment model. Another option posed would be to use the parameters from an externally fitted growth model (using the same data) as fixed parameters in the SS model. The modelers explained that by allowing the stock assessment SS model to also estimate growth provided more flexibility to the biology and resulted in overall better fits. It was also noted that the parameters estimated in the SS were very similar to the externally obtained growth parameters, so this is not likely a major issue in terms of the stock assessment model.

3.1.5. Low fecundity stock-recruitment function

The stock recruitment function used in the final assessment was the one developed recently for low fecundity species like sharks. Within this function, the parameter Zfrac defines the slope of the stock-recruitment curve at the origin, i.e., the maximum recruitment rate produced when stock sizes approach very low values. This is conceptually very similar to the steepness (*h*) parameter of the Beverton-Holt stock-recruitment function, more commonly used in stock assessments.

The main issue discussed is that similarly to the steepness (*h*) parameter when using the Beverton-Holt function, there is usually also very little information in the data to actually estimate Zfrac. And, therefore, in a similar way to *h*, the values of Zfrac often have to be fixed (not estimated) and tend to be very influential in the stock assessments. This issue was explored at great length with the use of sensitivity analyses with various hypothesis and combinations of values.

In general, the use of this new low fecundity relation seems to be adequate for sharks. But it was also noted by the panel that any other form of the stock-recruitment function that have rapid declines at the origin (i.e., low stock size) should also be adequate for sharks, especially species like threshers that have very low productivity, mainly because of their very low fecundity. Some suggestions of other stock-recruitment functions with those characteristics were made, as for example a simple hockey stick with the recruitment constant over stock size until it reaches a threshold at which it declines linearly to the origin.

The panel agreed that this function and others with these same characteristics (i.e., steep decline at low stock size) would likely have produced similar results in the stock assessment results. And it should be further noted that alternative Beverton-Holt functions were used as sensitivity analysis (with the corresponding *h* value) and showed very similar results to the use of this new low fecundity stock-recruitment function. Therefore, the panel agreed that the population dynamics and stock status of the common thresher is likely robust to the function used, as long as it maintains these types of characteristics at a low stock size. However, the panel also recommended that further testing with this function should be carried out in the future.

3.1.6. Natural mortality

As mentioned previously, once the new reproductive biology was decided (based on a larger size at maturity and possible biennial cycle) the natural mortality (M) needed to be adjusted. This happened because the low productivity by year per adult female would cause the stock to collapse even without any fishing effort, if M was assumed higher than 0.14. This is a similar situation to having values of lambda (λ) lower than 1 (in a population dynamics model in this case a Leslie matrix model) that would mean a collapsing population even without any fishing mortality. This was judged unrealistic in a population dynamics perspective.

A model sensitivity run where M was allowed to be estimated (not fixed) by the model gave very low values of M of about 0.03, which corresponds to a very high maximum age. M values of 0.04, 0.06 and 0.08 mean that 1% of the stock in case of no fishing would be about 115, 77 and 58 years old, respectively. Based on the meta-analysis of M's relation to age at first maturity and to maximum age, the lower 95% confidence interval was 0.06. Runs with M equal 0.6 and 0.8 (and Zfrac varying between 0.6-0.9) made the models able to converge and not deviate much from each other in terms of model performance. The panel agreed that a maximum age of 58 years was more realistic than 77 years for this species, and therefore tentatively decided on that value for a new base run.

However, runs with M=0.08 and Zfrac=0.8 gave problems with internal consistencies of the model and data (conflicts between biology, CPUE information and size structure). Therefore, M had to be fixed at 0.04 and Zfract at 0.5 before these inconsistencies were solved. After long discussions, it was agreed to use this run as the best description of the stock dynamics and status, as the base run. This decision was reached knowing that it meant that M was outside the range indicated by the meta analysis of maximum age and age of maturity, meaning that there would be a very substantial number of very old fish in the plus group (25+). While this could be possible, at this stage it is unknown if that really is the case and where such part of the population would be located (spatially, seasonally and possibly in terms of depth habitat). Another issue was that such a low M would result in a very high maximum age of 115 years. Still, and even though there were those issues that remained to be addressed, this final scenario was regarded as the best compromise between the conflicting signals in the data and knowledge about the reproductive biology and corresponding population dynamics of this population.

3.2. ToRs item # 2

The item # 2 for the ToRs requests to "*evaluate the ability of the model, combined with available data, to assess the current status and productivity of common thresher sharks along the west coast of North America*"

It was agreed that the final base case model at the end of the meeting, that combines the currently available data and most likely hypothesis on the biology and population dynamics (larger size/age at maturity and possibly a biennial reproductive cycle), is able to currently and robustly assess the current stock status of common thresher shark. Both the review panel and modelers agreed that it would be better to use the most likely biological parameters (particularly the higher size/age at maturity that seems to be more likely) even if the model fitting was worse under those scenarios. The reasoning was that the best biological information should be used to inform as correctly as possible the population dynamics of the stock, recognizing the consequence of added uncertainties in natural mortality, maturity, gestation and reproductive cycle.

Nevertheless, both the review panel and modelers at the end were confident that the stock status determination was robust to those scenarios, and that the current stock size is above the MSY-related limits established in the US management system. All the uncertainties raised and detailed above (point 1 of the ToRs) are important, but after multiple sensitivity model runs it was determined that, in general, the model was robust in terms of the stock status determination and productivity. This means that even with the uncertainties mentioned before, the conclusions on the current stock status is consistent. The trajectories in biomass and fishing effort were very consistent in showing that stock sizes declined rapidly in the early years due to high fishing effort and catches. When the effort and catches were reduced, the stock started to recover and is currently neither overexploited nor experiencing overexploitation. The main difference in the various biological hypothesis and life history parameters was in the timing and speed of the recovery. However, several research recommendations were made for work that might further improve the model in the future, that are specified in detail below (see item 4 of the ToRs, below).

The panel cautioned that the uncertainties in life history, especially reproductive biology, and the implications for the stock-recruitment relationship are large. Therefore, projections of stock size using the current assessment and stock-recruitment model will be extrapolating beyond the data and will also be very uncertain. Therefore, and as a conclusion, while the panel is confident that the stock status is robust (i.e., stock not currently overfished nor undergoing overfishing, according to the MSY-related limits established in the US management system) the panel is also less certain about future projections and catch strategies or effort that would be required to achieve MSY related targets. If management were to pursue a policy of MSY targets, then the ability to precisely determine the strategy to achieve this would be severely limited by uncertainties in the basic biological information, as noted before. However, under current catches, the stock status seems to be robust.

3.3. ToRs item # 3

The item # 3 for the ToRs requests to "*evaluate the adequacy of sensitivity analyses to represent the main axes of uncertainty in the assessment*".

It was clear to all that the main axis of uncertainty on the final agreed base case model was the reproductive biology, and specifically the reproductive cycle/periodicity. In terms of management advice, the sensitivities were therefore mainly concentrated on this issue. It was agreed by all the participants that this approach was correct.

Currently the base case model assumes a two year reproductive cycle, and this reproductive periodicity is currently the most uncertain parameter and that is also likely contributing to most of the differences in the population dynamics of the species. Therefore, a strong recommendation to further continue work on the reproductive biology of this species was made (see item 4 of the ToRs, below). Other components that were also recommended for further testing were the stock-recruitment function and natural mortality (M).

3.4. ToRs item # 4

The item # 4 for the ToRs requests for "*recommendations for future research priorities and further improvements to the assessment model*".

There was general agreement between the review panel and stock assessment scientists on the recommendations for future research. Specific recommendations for future research were:

- Juvenile shark surveys: The survey design and protocols of the USA juvenile thresher shark survey should be reexamined and improved. Such surveys could bring important additional information to future stock assessment models. In this case, while there was data from the juvenile survey and a CPUE standardization procedure, the standardized CPUE from this survey was not actually used in the assessment. The reasons presented for this are that the location and timing of the sets were determined by the captain, with some of the initial sets used as learning sets, in a way somewhat similar to commercial fisheries operations. There were also issues with non-standardized soaking times, that was later tried to be taken into account as part of the effort in the standardization procedure. With the information and limited local knowledge I have on this specific survey, I cannot provide very specific details on how to possibly improve the survey. But the general idea, and in order for such survey to be more representative of the juvenile thresher shark abundance, it would be important to be designed in as much a fishery-independent approach as possible, with some type of randomized sampling locations, possibly depth and seasonally stratified, and using consistent operations and methods through time. The local NOAA researchers involved in such survey and familiar with the specific conditions and logistics are the ones better suited to improve the specific methods in this particular case;

- Catch and catch-at-size data: Both catch and catch-at-size estimates from USA and Mexico fisheries should be improved. The main priorities would be the Mexico fisheries and also the USA recreational fishery. The catch history of bycatch species, including most shark species, is usually one of the major uncertainty sources when conducting stock assessments. Often, this is an unknown and unaccounted source of uncertainty that is not considered, given that historical catches are usually point values given without any associated uncertainties. Even if there are now better established programs to record catch, effort and size distributions of the fisheries, the historical catches are still usually very poorly know for the bycatch species. In such cases, there is the need to reconstruct the historical catches to some degree. There are a number of ways to do this including, for example, statistical methods (e.g., GLM or GAM models to estimate past catches based on a series of covariates) or methods based on ratios of target/bycatch species. In such bycatch species with limited historical catch information, it is usually recommended to try to reconstruct the catches based on various hypotheses, and then test those within sensitivity model runs;

- Size data/samples: size samples seemed adequate from some fisheries (e.g., USDGN) but very limited in others, especially for the US recreational (USREC) and the Mexico fisheries (MXDGN and MXLL). Especially in those cases with very limited information, there was the need to assume similar size structure (i.e., similar selectivity) to some of the other fisheries with more information. This might be an important source of uncertainty in the current model and as such it was recommended for more effort to be put in collecting size data from those fisheries, preferably with sex-specific information. The improvement in the size/sex samples could be accomplished by a variety of methods, all with different characteristics and caveats that need consideration. The best way to improve data collection is specific to each fishery and fleet, and the local researchers familiar with the fleets are better suited to know which are the preferred methods. Some traditional approaches for consideration are:
    - Scientific onboard observers: This is usually the preferred method and the one most likely to capture the entire size distribution of the catches from each fleet. The drawbacks are usually high costs, and possible logistics issues of having observers in smaller vessels with limited space and conditions;
    - Port sampling: this is usually a cost-effective way to sample the size distribution of the landings. The main drawback is that it is not possible to sample discards, both in terms of discarded species and discarded sizes. Threfore, great care needs to be used when using only port-sampling information to study the species composition and size distribution of a fishery;

- Self-sampling programs: those are programs where fishing skippers and crews are trained to voluntary record the size distribution of the catch during the fishing operations. If properly established, those programs can usually provide a good coverage of the size distribution, that can include both retained and discards, at least for the main targeted species. Establishing and maintaining the quality of such programs implies a strong relation between the researchers with the fisheries sector;

- Low fecundity stock-recruitment relationship: The use of the relatively new low fecundity stock recruitment relationship seems appropriate for sharks in general, and particularly for Lamniformes as the common thresher that have some of the lowest fecundities even within sharks. However, this low fecundity stock recruitment relationship is relatively new and has not yet been fully tested, and requires further research. The stock status of common thresher seemed to be robust to this issue (as tested with sensitivity analysis), but it would be recommended to test other options (e.g., a hockey stick model or any other function that allows for rapid drops at very low stock sizes);

- Reproductive biology: The current lack of knowledge and uncertainties associated with the reproductive biology is likely the main cause of uncertainty in the stock assessment model. While most cases and sensitivities tested with the various hypotheses do not affect the stock status, in some cases there are problems of data conflicts in the model that needs further exploration. As such, it is highly recommended to continue the biological studies to further investigate the reproductive biology of this population, especially in terms of the size at maturity, age at maturity, and reproductive cycle/periodicity. It is also noted, however, that while parameters such as size/age at maturity should be relatively simple and feasible to study, the reproductive cycle (periodicity) will likely be much more difficult to fully study due to the need to have access to large number of samples (mature and pregnant females) over all seasons and with detailed reproductive data;

- CPUE standardization: While the overall CPUE standardization process seemed to follow the current practices in fisheries, especially with large pelagics, there were some issues that could be the focus for future work and research. Specifically, it was recommended to test some alternative distributions (e.g., Negative Binomial for count data or Tweedie for continuous data with a mass of zeros), consider and test the inclusion of interactions, test the possibility of modeling the USDGN as a single time series (using detailed spatial and seasonal effects to try to account for spatial/seasonal changes in management), and consider using vessel effects as a random variable to add variability associated with different vessels of the fleet.

3.5. ToRs item # 5

The item # 5 for the ToRs requests for a "*brief description on panel review proceedings highlighting pertinent discussions, issues, effectiveness, and recommendations*".

It is very important to note that the entire meeting was very productive and always carried out in a much positive atmosphere.

The SWFSC scientists, especially the modeler Steve Teo, was very supportive and skillful in providing the panel with several extra assessment model runs and plots of selected diagnostics in a speedy and very efficient way during the meeting and in the evenings between the meeting days. The panel appreciated and thanked all the support and positive atmosphere, as well as the immediate willingness of the modelers to test and consider all the alternative approaches and scenarios hypothesized.

Appendix 1: Bibliography of materials provided for review

Documents provided for review prior to the meeting

Aryafar, H., Preti, A., Dewar, H., Kohin, S. 2017. Re-examination of the reproductive biology of common thresher sharks along the west coast of North America. Fisheries Resources Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA.

Teo, S.L.H.; Rodriguez, E.G., Sosa-Nishizaki, O. 2016. Status of common thresher sharks, *Alopias vulpinus*, along the west coast of North America. NOAA-TM-NMFS-SWFSC-557.

Stock Synthesis model files and other related assessment information published in the interim that were provided by the SWFSC Project Contact (Steve Teo).

Additional documents provided during the meeting both by the review panel and stock assessment analysis

Anon. 2017. FAQs: West Coast drift gillnet (DGN) fishery & protected species. U.S. Department of Commerce, National Oceanic & Atmospheric Administration, National Marine Fisheries Service, West Coast Region.

Romanov, E. 2015. Do common thresher sharks *Alopias vulpinus* occur in the tropical Indian Ocean? IOTC Working Party on Ecosystems and Bycatch (WPEB). Olhão, Portugal.

Taylor, I.G., Gertseva, V., Methot, R.D., Maunder, M.N. 2013. A stock-recruitment relationship based on pre-recruit survival, illustrated with application to spiny dogfish shark. *Fisheries Research*, 142: 15-21.

Teo, S.L.H. 2017. Population dynamics of common thresher sharks along the West Coast of North America, assuming alternative reproductive biology and natural mortality parameters. Fisheries Resources Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA.

Independent peer review of the Common Thresher Shark (*Alopias vulpinus*) stock assessment off the west coast of North America.

conducted for

The Center of Independent Experts

by

Joseph E. Powers

Encompassing Evaluation of Research Documentation, Participation in Review Meeting at NOAA/NMFS Southwest Fisheries Science Center in La Jolla, California from 26-28, June 2017

and

Report Preparation

September 2017

Executive Summary

The current assessment of Common Thresher Shark off the west coast of North America (as amended at the Review Meeting) represents the best available data for that stock.

While the stock experienced high catches in the past, resulting in depleted stock size, recent decades of low exploitation has allowed the abundance to increase substantially. As such, in my scientific opinion, the stock abundance is larger than that which could support MSY and low recent catches (<200 t) indicate fishing intensity less than that at MSY.

There were important uncertainties in the assessment data (and subsequently the modeling), but these do not change the basic conclusions about stock status. The status is well below fishing rate limits and well above abundance limits. However, the uncertainties affect the precision of the estimates of the biological reference points.

The primary uncertainties lie with the basic life history and reproductive information: maturity, gestation, resting periods, pupping rates and spatial areas at various life stages. Research addressing these aspects should be very useful.

Background Section

The Fisheries Resources Division (FRD) of Southwest Fisheries Science Center (SWFSC) requested an independent review of the benchmark stock assessment developed for the Common Thresher Shark (*Alopias vulpinus*) stock along the west coast of North America. This was the first stock assessment of this resource that incorporated information from all fisheries exploiting the population.

In response to the FRD request, the Center for Independent Experts (CIE) was requested to complete the independent review. CIE reviewers included myself (Dr. Joseph Powers, USA), Dr. Rui Coelho (Portugal) and Dr. Henrik Sparholt (Denmark).

My role in this review was to evaluate background information including the draft stock assessment and biological research results (Appendix 1), participate in a review meeting, assist in preparing a summary report of that meeting and to provide a report of my conclusions and recommendations pertaining to the thresher assessment and research. The details of the terms of reference for my tasks are given in the Statement of Work in Appendix 2. But essentially, I was requested to provide my scientific opinion as to whether the assessment was the "best available data" and for technical comments on the factors affecting uncertainty associated with the assessment. This report represents my scientific findings on the matter.

The Stock Assessment Review was held at NOAA/NMFS Southwest Fisheries Science Center in La Jolla, California from 26-28 July 2017 to review the stock assessment. The meeting was open to the public; however, there was no public participation. Attendees at the meeting along with their affiliations are listed in Appendix 3.

The biological range of the stock spans the west coasts of Mexico, the United States of America (USA), and Canada. The common thresher shark fisheries of the USA and Mexico are managed through the Pacific Fishery Management Council (PFMC) and the Instituto Nacional de Pesca (INAPESCA), respectively. There have been no fisheries for common threshers along the west coast of Canada or in international waters that target common thresher sharks and bycatch is probably not significant.

Fisheries in both the USA and Mexico have declined substantially since the start of commercial fisheries for this stock in the late 1970s, with total removals estimated to be <200 t in 2014. The decline in catch is associated with large declines in fishing effort. For example, currently there are fewer than 10% of the vessels participating in the US drift gillnet fishery as compared to the early 1990s.

The current USA fishery management plan for this stock of common thresher sharks includes a harvest guideline of 340 t based on an unpublished analysis of USA data and is derived from the optimum yield for vulnerable species, which is defined as 0.75*MSY (or reasonable proxy). No management actions have been taken that are solely directed at threshers, but indirect effects of regulations on the fishing gear used has definitely affected fishing behavior relative to thresher exploitation.

The Stock Synthesis (SS) modeling platform was used to conduct the analysis. The model began in 1969, assuming the population was at equilibrium prior to 1969 in a near unfished state, and ended in 2014, which was the last year that data was available.

Summary of findings for the *Status of common thresher sharks, Alopias vulpinus, along the west coast of North America* for each TOR in which the weaknesses and strengths are described

TOR-1. *Evaluate the assessment model configuration, assumptions, and input parameters (e.g., natural mortality, spawner-recruit relationship, reproductive biology) to determine if the data are properly used, input parameters are reasonable, models are appropriately configured, assumptions are reasonably satisfied, and primary sources of uncertainty are accounted for.*

Catch Data

As always, some assumptions had to be made on the catch history, especially in the initial years when there were few details in species-specific catches. In general, the work that was done seems adequate to reconstruct the catch series of the fishery. There were some questions about catches from small artisanal Mexican fishing boats (about 2,000) the majority of which do not have licenses to fish for threshers, but might be still catching sharks. However, the catch estimates were derived from market sampling in addition to port-sampling. Thus, if there were significant unreported removals, then they would have had to have been discards, which is unlikely. Therefore, the catch data is the best available.

CPUE standardization

Usual (and common) CPUE standardization methods were used, i.e. GLM models using the Delta lognormal approach. It is especially used when part of the data is composed by zeros, as is the case of the CPUE datasets analyzed.

There may be alternatives in which the discrete nature of these data may be maintained through the standardization process by using a discrete distribution like a negative binomial (which allows zeros). At the assessment review meeting, a more general alternative was suggested: a Tweedie distribution (generalization of the exponential family) that can model the mass of zeros and the continuous component for the positives in the same model. I, personally, am not familiar with this (although I looked it up after the meeting). Perhaps, this can be looked at.

Perhaps the biggest difficulty with the indices was that the index from the main gillnet fishery was required to be truncated into three time blocks because of changes in regulations and a period of missing information. This means that there is more uncertainty in the large fish trends which has ramifications as noted below. Perhaps, an attempt could be made for the entire time series combined, trying to account for the changes in management regulations (mainly seasonal and spatial closures), but I am not optimistic.

Finally, the issue of targeting was considered. The targeting variable used ranking of the swordfish catches within each year. However, if there were consistent fishing strategies within a year affecting both swordfish and thresher, then this may skew the standardization. Perhaps, year-targeting interactions could be evaluated in the future.

Natural Mortality M and Reproductive Biology

There are significant uncertainties in the basic biology of this thresher stock. Natural mortality rates and reproductive biology were major sources of uncertainty in the stock assessment. In the original assessment, the size (age) of maturity was relatively small and the reproductive biology assumed four pups per year for an annual reproductive cycle (four pups per year per mature female each and every year). However, subsequent further examination of the research suggests that productivity might be lower, i.e. size at maturity is larger and perhaps a two-year reproductive cycle. This was based on comparison with Atlantic stocks and due to evaluation of the original Pacific research (perhaps misidentification of common threshers as pelagic threshers, misunderstanding of measurement units of length). I accept the new working hypothesis (larger size at maturity and possibly a biennial reproductive cycle).

This change implies a change in the perception of natural mortality rates, as expected. In order for the stock to persist under the assumed reproductive biology, natural mortality would have to be lower than M=0.14 for all ages post-recruitment. The model was unable to converge with natural mortality rates this high. Model tests with lower M's converged, but implied higher longevity. I accept that the M's are probably lower than originally specified and that longevity is larger. Ultimately, the M value specified was 0.04 (discussed further below).

Stock-Recruitment

The stock recruitment model chosen for use in the common thresher assessment was that of Taylor et al. (2013). This model is essentially a modification of a Ricker function with an additional term, β, which defines the strength of the depensation effect at larger stock sizes. Additionally, the particular parameterization allows for the use of basic reproductive information more directly in the specification of the slope of the stock-recruitment curve at the origin. The parameterization used was:

$$R_y = B_y exp\left[-z_0 + (z_0 - z_{min})\left(1 - \left(\frac{B_y}{B_0}\right)^{\beta}\right)\right]$$

where recruitment R in year y is in number of pups, B_y is the number of pups born at the beginning of the recruitment process in year y (B_0 denotes equilibrium pup production when there is no fishing and $S_0=R_0/B_0$ is the equilibrium survival when there is no fishing which is calculated using life history information: natural mortality rates at age, fecundity (number of pups) and age of maturity. Additionally,

$$z_{min} = z_0(1 - z_{frac}) = z_0 - z_0 z_{frac} \qquad z_0 = -ln(S_0) \quad z_0 - z_{min} = z_0 z_{frac}$$

and z_{frac} is a fraction ranging from 0 to 1. Hence, knowing S_0, B_0, z_{frac} and β completely defines the function. The steepness of this functional form is:

$$h = 0.2exp\left[z_0 z_{frac}(1 - 0.2^{\beta})\right]$$

although steepness is not a particularly relevant metric for this model.

The above form may be reparameterized into:

$$R_y = S_0^{1-z_{frac}} B_y exp\left[-\frac{1}{\beta}\left(\frac{B_y}{B_0}\frac{B_o}{B_{max}}\right)^{\beta}\right] = \left(\frac{R_0}{B_0}\right)^{1-z_{frac}} B_y exp\left[-\frac{1}{\beta}\left(\frac{B_y}{B_{max}}\right)^{\beta}\right]$$

where B_{max} is the number of pups at birth that produces the maximum number of surviving recruited pups. I believe this form shows the significance of the parameter choices better than the original form. Note that if β=1, then this form is a Ricker function.

The fraction z_{frac} functions similarly to the steepness parameter of more commonly used Beverton-Holt stock-recruitment models. It defines the slope of the S-R curve at the origin, i.e. the maximum recruitment rate that can be produced when stock sizes approach zero (slope at origin = $S_0^{1-z_{frac}}$). And similar to steepness specifications, there was little information in the data to determine z_{frac} and, thus, alternatives were explored in the assessment through sensitivity analyses.

There was not a strong biological hypothesis for how depensation was occurring in common thresher to support the choice of a Ricker-like form, other than it was originally applied to a shark species. Also, there was not an argument presented as to why hyper-depensation ($\beta > 1$) was occurring. Additionally, it was noted that similar to most fish stocks, the assessment model assumed that all density-dependence in common thresher over their lifespan occurred in the few months after their birth. In most fish stocks, this is a reasonable assumption. But, perhaps there are other stages in a shark's life where density-dependence can occur (nursery areas?). For example, the differential equation defining a Ricker recruitment process contains a density independent mortality rate that acts continuously during the recruitment period *and* an *instantaneous* density-dependent factor (Brooks and Powers 2007. ICES Journal of Marine Science, 64: 413–424) as compared to a Beverton-Holt process where density-dependence occurs throughout the period. So perhaps, congregation of predators in an area where pups are born might be a mechanism to induce a Ricker process. This supports the need for more basic research on reproductive biology and life history.

The final base case estimated stock recruitment model is described in Figure 1.

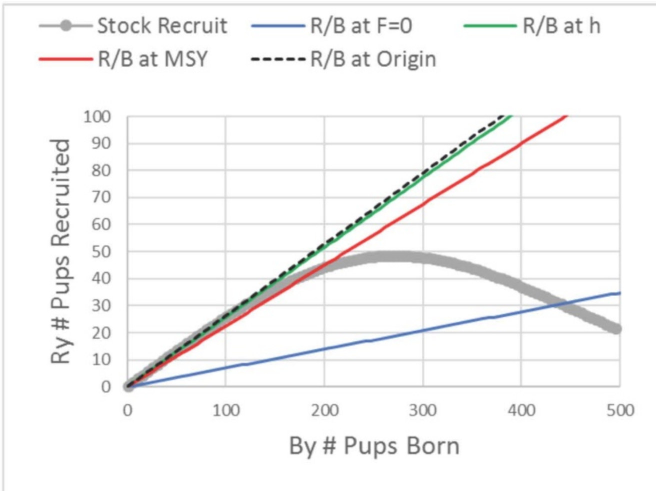

Figure 1. Final base case S-R curve with various replacement lines (*R/B's*). $S_0 = R_0/B_0 = 0.069$; β=2.53; *zfrac*=0.5; B_0=439.9; B_{msy}=203; B_{max}=271; $S_0^{1\text{-}zfrac}$ = slope at origin = 0.264; steepness h = 0.74

Other forms of the stock-recruitment function could have been explored, which would have the same effect of rapid declines when the stock size was low. One example might be a basic hockey stick model where the recruitment is constant over stock size until it reaches a threshold at which it declines linearly to the origin. A hockey-stick model is not meant to be biologically realistic, but rather it is a pragmatic test of the effects of a stock-recruitment relationship whereby declining stocks size (# pups) reaches a threshold at which recruitment declines rapidly and near-linearly to the origin. I believe that the Ricker-like form that was chosen displays these same characteristics at lower # pups produced. This model and others would likely have produced similar results. And any function with steep declines at low stock sizes would be compatible with shark life history. I believe that the resulting dynamics of common thresher stock-size over the years and basic status of the stock is relatively robust to the functional form chosen.

Interplay between M, S-R and Reproductive Biology

Note that the reproductive biology and M define the parameter $S_0 = R_0 / B_0$ of the S-R curve. And then z_{frac} is used to define the slope at the origin of the S-R curve.

Several test runs were made with M=0.08 and z_{frac}=0.8 and alternative inclusions of index data. But, removing the S4 and S5 indices from the model gave a very different stock trend over the recent years, with very low stocks sizes compared to keeping these indices in the model. M had to be reduced to 0.04 and Z_{frec} to 0.5 before these inconsistencies vanished. Ultimately, I agree that the basic uncertainties in the biology cause some inconsistencies with the data. Therefore, in order to provide the most robust management advice, the assessment model should compromise on the biology and provide the best statistical model. Implicitly, this is analogous to using a simpler regression model for use in interpolating data. However, as with simple regression, a pragmatic model is more suspect when projecting outside the range of the data. Thus, I agree with the base solution, M=0.05 and z_{frac}=0.5. But as noted, the major uncertainty is the interplay between M, reproductive biology and the S-R curve.

An implication of the stock-recruitment results and of shark life histories, in general, is that there is little surplus in recruitment to be taken as yield as the fish get older (Figure 1). While an MSY-related stock size is calculated, the results indicate that small increases in fishing mortality above that at MSY could result in rapid declines in stock size. In other words, stock size at MSY is on the declining slope on the left side of the S-R curve. This suggests caution in implementing an MSY target as an objective.

TOR-2. *Evaluate the ability of the model, combined with available data, to assess the current status and productivity of common thresher sharks along the west coast of North America.*

Stock Status

The assessment is relatively robust in showing that stock sizes declined in the early years while experiencing high catches. When catches were reduced, the stock recovered. The degree and timing of recovery are heavily dependent on uncertainties in reproductive biology and life history characteristics. The assessment choices made by the assessment team, the Review Committee including myself opted for statistical fits to the data, recognizing the apparent uncertainty in natural mortality rate, gestation, reproductive cycle. Nevertheless, I am confident that the current fishing rate is well-below MSY-related fishing limits and stock size is above limits established in the US management system.

The base-case model indicates

Number Adult Females in 2014	136,800
Number Adult Females at MSY	101,500
Number Adult Females at *MSST	97,440
Fishing Intensity (1-SPR ave 2012-14)	0.10
Fishing Intensity (1-SPR at MSY)	0.45
Catch in 2014	~160t
MSY	718t

*MSST is Minimum Stock Size Threshold = (1-M) x stock size at MSY, where natural mortality rate M is specified as 0.04. MSST is the stock size at which an overfished stock exists and a recovery plan must be implemented.

Therefore, common thresher is not overfished in that the adult female stock size is greater than that at both MSY and MSST, and the stock is not undergoing overfishing because current fishing intensity is less than that which would produce MSY.

However, uncertainties in life history, reproductive biology and the ensuing implications for the stock-recruitment relationship are large. Therefore, projections of stock size using the current assessment and stock-recruitment model will be extrapolating beyond the data and will also be very uncertain. While I am confident that the stock is not currently overfished or undergoing overfishing, there is less certainty about catch strategies that would be required to achieve MSY. If management were to pursue a policy of something close to MSY, then the ability to precisely determine the strategy to achieve this is severely limited by uncertainties in basic biological information as, noted above. But, under current catch policies, the status is robust.

The basic catch, size frequency, and CPUE index data indicate that previously there were large catches, the stock and recruitment declined and then with the large reduction in catches the stock increased. This is the common-sense conclusion drawn from the assessment. However, the adult fish CPUE index is not particularly strong, so it does not constrain the stock recruitment-M-reproductive cycle-maturity interplay very much. For example, for longer reproductive cycles, later maturity result in scenarios in which the stock recovery has been slower than the base model. Additionally, the depensation aspect of the S-R model means that as B surpasses B_{max} on its way to B_0, then recruitment declines. This also leaves a perception of a slower recovery rate.

It is also noted that MSST and MSY stock size may not be particularly precautionary for this shark species. Generally, MSST is specified to allow some flexibility if stock size declines below that at MSY before a more rigorous management response is initiated. However, the stock sizes at both MSST and MSY for common thresher are both on the declining slope of the stock-recruitment curve at lower stock size. This further suggests that if a true MSY policy were to be pursued, additional biological information is needed to be able to preciously determine that policy.

TOR-3. *Evaluate the adequacy of sensitivity analyses to represent the main axes of uncertainty in the assessment.*

The main sources of uncertainty are the result of the interplay between natural mortality rates, reproductive cycle, and life history. This manifested itself in the model in the stock-recruitment function. Several model runs were made both prior to the meeting and at the meeting itself. This primarily focused on # pups per year, M, z_{frac}, β, size of maturity and various combinations of inclusion and exclusion of indices of abundance. As noted above, while the index and size frequency data are not overly strong, they are sufficient to provide robust management advice. The weakness is in the basic biology. This was demonstrated through the sensitivity analyses.

TOR-4. *Recommendations for future research priorities and further improvements to the assessment model.*

Size samples were adequate from some fisheries but very limited in others, especially for the US recreational and Mexican commercial fisheries. The limited nature of the available data contributes to the uncertainty in (primarily) the selectivity functions estimated. Better size/sex frequency sampling could provide more precision on adult and juvenile abundance.

The survey design and protocols of the USA juvenile thresher shark survey should be re-examined and improved.

CPUE Standardization: while the standardization methods used were commonly acceptable throughout fisheries assessments, alternatives might be explored which maintain the discrete nature of the data (in numbers rather than weight). Also, issues of targeting (what criteria used for defining "targeted" thresher effort) and perhaps incorporating regulatory changes directly into the CPUE model would be useful. By doing so, the result would be indices over a longer time period with better precision.

By far the most important research direction for improving the assessment is understanding the life history and reproductive biology of these sharks. These aspects critically affect our perception of natural mortality rates and the choice and parameterization of the stock-recruitment function and the basic productivity of the population. These in turn define MSY management criteria and overfishing and overfished limits. Some issues are:

> Where do the fish go during life stages? Is all density-dependence occurring immediately after birth? Or are there nursery areas where predation may be density-dependent? What is the reproductive cycle; is there a resting period after gestation? What is the age of maturity? As such, it is highly recommended to continue the biological studies to further investigate the reproductive biology of this population, especially in terms of the size at maturity, age at maturity, and reproductive cycle/periodicity.

These results will lead directly into the stock-recruit relationship. As for the stock-recruitment functional relationship chosen, there should be further examination of biological reasons for this form (especially β). At this point in time, that choice is not critical to the scientific conclusions. But in the future, this may be important.

TOR-5. *Brief description on panel review proceedings highlighting pertinent discussions, issues, effectiveness, and recommendations.*

My review took place in three phases. First, I was provided several background documents (original assessment, update, biological research reviews). Then, I participated at the Review Meeting in La Jolla. Finally, after the meeting, I re-reviewed the available evidence and prepared a report (herein) of my findings.

The background documents were provided with adequate time to review them. They were also, understandable, i.e. the written documentation of the modeling and research were clear and concise.

The meeting itself was collegial and useful. Presentations were made to assure understanding of the process. The focus of much of the meeting was to examine diagnostics of the modeling, suggest alternative structures/sensitivities that were tested with the SS platform, then these were re-examined. Suggestions were made by both the meeting group, as well as the reviewers. The give and take provided me with adequate information to base my scientific opinion.

Subsequent to the meeting, SWFSC staff responded to further information requests rapidly. And there was adequate time to prepare the required report.

Because the background documents were available, and because SWFSC staff was available to run alternative sensitivities, the review process worked well.

I have no recommendations for improvement.

Conclusions and recommendations in accordance with the TORs

My conclusions and recommendations are essentially those expressed in the Executive Summary:

> The amended assessment is the best available data; the stock is neither overfished nor undergoing overfishing.

While these conclusions are robust, basic uncertainties remain due to limited understanding of the life history and reproductive biology. Therefore, I recommend that if improvement is desired, then research programs be continued and/or initiated to address reproductive cycle, critical life stages and maturity ogives, and how they interact with natural mortality rates and the stock-recruitment function.

Additionally, normal fisheries data: size frequencies and indices of abundance and their standardization might be improved by the combination of increased sampling of sizes, more designed resource surveys and refinements in the targeting definition for CPUE standardization.

Appendix 1: Bibliography of materials provided for review

Anon. 2017. FAQs: West Coast drift gillnet (DGN) fishery & protected species. U.S. Department of Commerce, National Oceanic & Atmospheric Administration, National Marine Fisheries Service, West Coast Region.

Aryafar, Helena; Preti, Antonella; Dewar, Heidi; and Kohin, Suzanne. 2017. Re-examination of the reproductive biology of common thresher sharks along the west coast of North America. Fisheries Resources Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA.

Romanov, Evgeny. 2015. Do common thresher sharks *Alopias vulpinus* occur in the tropical Indian Ocean? IOTC Working Party on Ecosystems and Bycatch (WPEB) Olhão, Portugal.

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Teo, Steven L. H.; Rodriguez, Emiliano Garcia; and Sosa-Nishizaki, Oscar. 2016. Status of common thresher sharks, *Alopias vulpinus*, along the west coast of North America. NOAA-TM-NMFS-SWFSC-557.

Teo, Steven L. H. 2017. Population dynamics of common thresher sharks along the West Coast of North America, assuming alternative reproductive biology and natural mortality parameters. Fisheries Resources Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA.

APPENDIX B: Re-examination of the reproductive biology of common thresher sharks along the west coast of North America

Helena Aryafar, Antonella Preti, Heidi Dewar, and Suzanne Kohin

Common thresher sharks (*Alopias vulpinus*) occur in the coastal waters of the eastern North Pacific where they support both commercial and recreational fisheries. Given their importance for local fisheries, they are actively managed by the Pacific Fishery Management Council (PFMC), and stock assessments are conducted by scientists at the NOAA Fisheries, Southwest Fisheries Science Center (SWFSC). Accurate information on reproductive parameters is critical for stock assessments, including a maturity ogive, breeding periodicity and fecundity.

Current estimates for size and age of maturity in the common thresher shark in the eastern North Pacific are based on a study by Smith et al. (2008) who used observer records on reproductive conditions for thresher sharks collected aboard commercial drift gillnet vessels from 1992 to 1997. For females, observers recorded the presence of embryos or egg capsules in the uteri, which was used as a positive index of maturity. Males were considered mature if seminal fluid was present and/or claspers were calcified. Length (fork length, FL) was recorded for all animals. During their study, 19 females, ranging in size from 142 cm FL to 253 cm FL, were documented with either fetuses or egg capsules and were considered mature. The sizes of the smallest five mature females were averaged to obtain the first quartile of the sample. Smith et al. (2008) estimated that males and females reach maturity at approximately 160 cm FL, corresponding to 4.8 years and 5.3 years, respectively.

A study on the reproductive biology of common thresher sharks, for the western North Atlantic stock, was conducted by Natanson and Gervelis (2013). In their study, females were considered mature based on changes in the relationship between ovary and uterus size with FL. Males were considered to be mature based on the relationship between clasper length to FL and clasper calcification. Using results collected for 130 males and 256 females over 33 years, they concluded that maturity occurs at much larger sizes than those reported by Smith et al. (2008). The size at first maturity was 208 cm FL in females, and the size at 50% maturity occurred at 188 cm FL in males and 216 cm FL in females (8 and 12 years, respectively; Gervelis and Natanson, 2013) (Fig. B.1).

In an additional study in the eastern North Pacific, Bedford (unpublished, 1987) examined 207 common thresher sharks, 108 females and 99 males, collected aboard commercial drift gillnet vessels between October 1980 and November 1982. For males, he measured clasper length, presence of seminal fluid, and calcification and rotation of the claspers. For females, while he made a range of measurements including ovary diameter, length of vaginal opening, and largest diameter of the oviducal gland, he concluded that only the presence of embryos and/or egg capsules were reliable for determining maturity. Of 37 females for which he provided data, ranging in size from 134 to 277 cm FL, 18 females were pregnant or contained egg capsules, and the smallest mature female was 217 cm FL (Fig. B.2). The next smallest individual recorded was 212 cm FL. Because of the relatively small sample size, it was not possible to determine the size at 50% maturity.

The dramatic differences between maturity estimates for the same species, both within and between regions, lead us to re-evaluate the results, including species identification, samples collected, and metrics used to indicate maturity. The following discussion will focus on the determination of female maturity by Smith et al. (2008). The conclusions of their study clearly hinge on accurate species ID and positive identification of embryos or egg capsules in the uteri.

Species ID

In the eastern North Pacific, there are three species of co-occurring thresher sharks that look similar: common, bigeye (*A. superciliosus*), and pelagic (*A. pelagicus*). In the studies of both Natanson and Gervelis (2013) and Bedford (unpublished, 1987), the scientists conducting the research directly examined the specimens, whereas in the study by Smith et al. (2008) fisheries observers provided the species ID and examined the reproductive tracts. A closer look at the observer data for the commercial drift gillnet fishery used for the Smith et al. (2008) study revealed that some thresher sharks collected by observers were misidentified during data collection or during the de-briefing process (or both), and only later were correctly identified by photographs or through DNA analysis. However, photos or samples for DNA analysis were not available for all of the female specimens with eggs or fetuses from the Smith et al. (2008) study. DNA analyses confirmed that 5 of them, ranging in size from 173 to 222 cm FL, were indeed common threshers, but no samples were available from the 5 smallest sharks (the first quartile, used to determine the size at maturity), thus verification of species IDs could not be made for those specimens.

Furthermore, data for 14 of the 19 specimens with fetuses or egg capsules in their uteri were collected during a single season, in 1997. The 13 smallest mature female threshers were all collected in 1997 and the sizes of the smallest 5 ranged from 142-172 cm FL. Since 1997 observers have reported only 4 additional common thresher females with egg capsules or fetuses in their uteri; all were larger than 210 cm FL. During the 1997 season there were strong El Niño conditions and an anomalously large number of pelagic thresher sharks reported. From 1990-2016 only 80 pelagic thresher sharks have been recorded in the observer database for the drift gillnet fishery (in comparison to 6707 common thresher sharks), of which 73 of these were reported during the 1997 season. Interestingly, of 58 female pelagic thresher shark reproductive tracts examined by observers in 1997, 25 were reported to have egg capsules or embryos present in their uteri. The size of those pelagic thresher sharks ranged from 147-173 cm FL, sizes consistent with the size of mature pelagic threshers in the western Pacific (50% maturity at ~167-174 cm FL; Liu et al. 1999) and overlapping with the sizes of mature common threshers reported by observers in 1997.

While we do not have evidence that any of the thresher sharks used in the Smith et al. (2008) study were misidentified, it is curious that only in 1997 do there appear to be many common thresher sharks with egg capsules or fetuses in their uteri (14 of 23 that have been reported in that condition from 1990-2016). It is also curious that of the 23 threshers reported with eggs or fetuses in their uteri, all sharks that were less than 200 cm FL (n=13) were from the 1997 season. Given that we know, based on DNA evidence and/or photos, that observers occasionally misidentify thresher sharks, and that pelagic thresher sharks are only rarely encountered in this fishery except in 1997, we suspect that some of the common thresher sharks used for the maturity estimates in the Smith et al. (2008) study may have been pelagic thresher sharks.

Presence of egg capsules or fetuses

Determination of female maturity in the Smith et al. (2008) study depended not only on proper species ID but also on reliable reporting of the presence of egg capsules or fetuses in the uteri. While Smith et al.'s (2008) conclusions relied solely on the report provided by the observers, several reproductive tracts from the 19 sharks reported as mature were collected. SWFSC biologists were able to examine reproductive tracts from 7 of the 19 specimens. Of those seven, only two were observed to have either fetuses or egg capsules present, both from females of 222 cm FL. Of the remaining five ranging in size from 155 to 196 cm FL, one was determined to be immature, and four were considered to be in a developing stage based on a number of criteria including the surface of the uterine wall, size of the ovary and/or uteri, and the presence and sizes of eggs within the ovary. Two other specimens were also available for examination but the uteri and ovary were either missing or damaged, and no egg capsules or fetuses were collected.

Gestation and breeding periodicity

It is currently assumed that gestation is approximately 9 months for eastern North Pacific common threshers based on the relationship between embryo fork length and month (Bedford, unpublished 1987) (Fig. B.3). In addition, Cailliet and Bedford (1983) reported that all mature female threshers examined in early spring were gravid, consistent with a one year breeding periodicity. In the Atlantic, Natanson and Gervelis (2013) examined the condition of the ovaries and were able to determine if the females were reproductively active or in a resting phase. Based on the proportion of sharks active versus resting, they estimated a breeding periodicity of 2 years, with the possibility of 3 years. While Bedford's data and conclusions have not been peer-reviewed or published, and our efforts to locate the raw data from his examinations have failed, his manuscript and Cailliet and Bedford (1983) do support a nine month to one year gestation period. Without further documentation about the occurrence of gravid females, which appears to be rare based on observer sampling of the drift gillnet fishery, and the potential for a resting period, it is not possible to confirm an annual breeding periodicity in the Northeast Pacific.

Conclusion

The conclusions of Smith et al. (2008) are uncertain due to: 1) potential misidentification of thresher species; and 2) the inconsistency between observers' records on the presence of egg capsules or fetuses and subsequent examination of the same specimens by SWFSC biologists. Consequently, additional research into the maturity of the common thresher shark in the eastern North Pacific is warranted. We recommend using estimates of female size at 50% maturity and breeding periodicity from Natanson and Gervelis (2013) with an alternate breeding periodicity of one year in stock assessments for this species until further sampling can be conducted in the eastern North Pacific.

Future Research

It is recommended that SWFSC conduct a new study to re-estimate the size at 50% maturity and breeding periodicity of common thresher sharks in the Eastern North Pacific Ocean. Completion of the estimation requires validating species ID, increasing sample sizes, and using more advanced approaches to determine reproductive state. Criteria for classification of maturity will be guided by findings from Natanson and Gervelis (2013). In addition to the presence of eggs and pups, measurements that can be used to indicate maturity include ovary size, uterus size, presence of urogenital sinus, and degree of vascularization of uterine walls. The goal should be to create a maturity ogive where the age at first reproduction and 50% maturity can be determined. These are more standard metrics used in stock assessments than the mean of the first quartile of gravid females. In addition, efforts should be made to differentiate between 'developing' and 'resting' classifications which requires thorough documentation of a number of qualitative characteristics while processing the reproductive tracts. This type of information is needed to determine reproductive periodicity.

The new study should take advantage of existing data and samples and newly collected specimens to fill data gaps. There are several existing datasets that can be built upon. CDFW has provided us with some of the data collected by Bedford. Additionally, there are measurements made for 30 females that were collected by observers from 1994-2002 and processed by SWFSC staff. However, not all of the 30 specimens have corresponding tissue samples to confirm species ID with DNA analysis. For the specimens collected in 1997, only those where species ID can be validated should be used. In addition, there are 18 samples collected by observers between 1991 and 2011 that have not yet been processed. Processing of these samples is currently underway and where DNA samples haven't already been taken, a piece of tissue will be collected to validate the species ID.

While the integration of these data sets increases the sample size, additional samples are needed to complete the ogive and provide conclusive information on reproductive periodicity. This will require sampling across multiple seasons, years, and various geographical areas.

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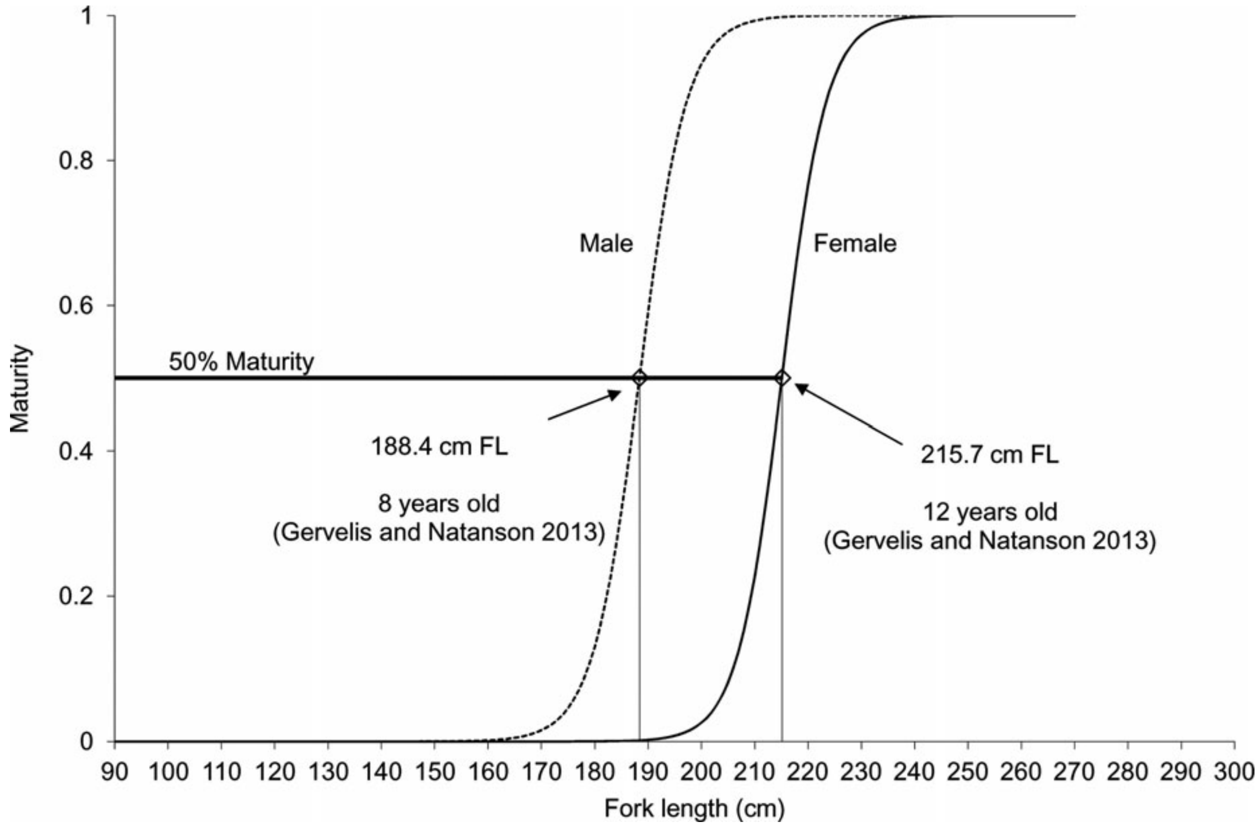
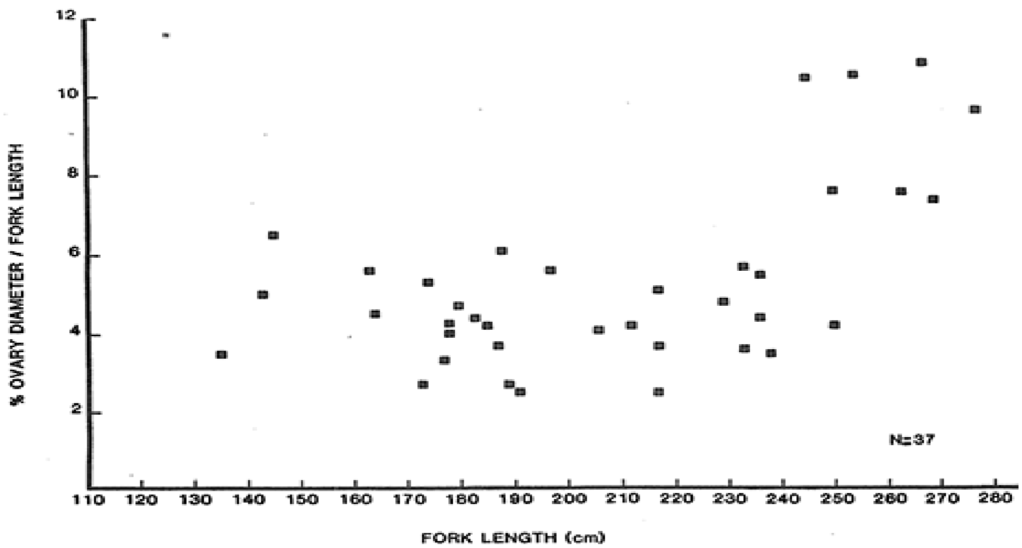
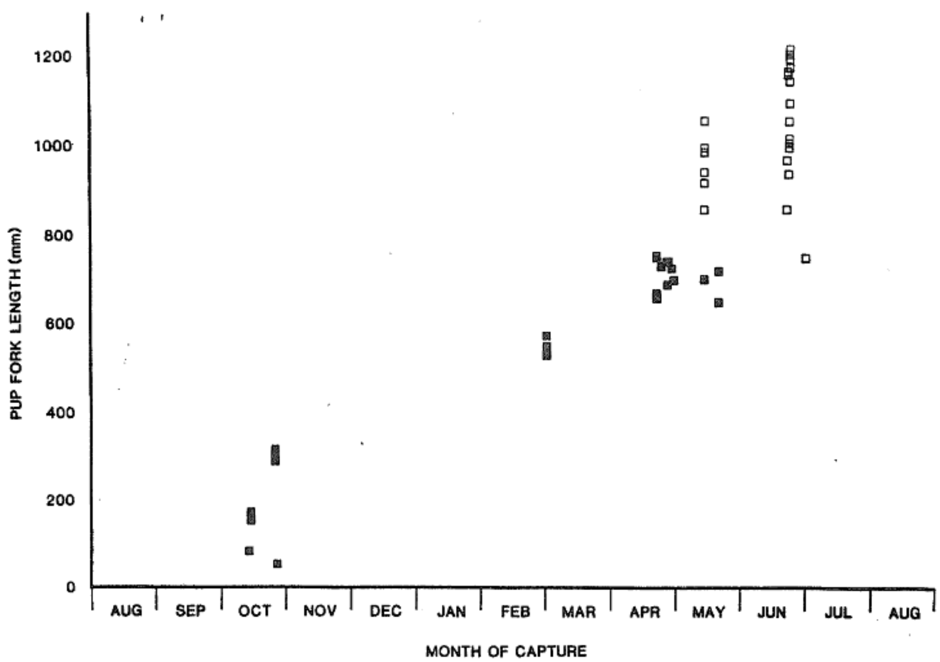


Appendix Figure B.1. Maturity ogive for male and female common thresher sharks in the western North Atlantic (from Natanson and Gervelis, 2013).



Appendix Figure B.2. Relationship between % ovary diameter (mm) to FL (mm) and FL (cm) in female common thresher sharks in the eastern North Pacific (from Bedford, unpublished 1987). Dashed line indicates the size of the smallest pregnant female (217 cm FL).



Appendix Figure B.3. The relationship between embryo fork length (solid symbols) and month of capture (from Bedford, unpublished 1987). Open symbols show the size of free swimming pups.

APPENDIX C: Population dynamics of common thresher sharks along the West Coast of North America, assuming alternative reproductive biology and natural mortality parameters

Steven L. H. Teo

Abstract

The first stock assessment of common thresher sharks, *Alopias vulpinus*, along the west coast of North America that utilized data throughout its range was conducted in 2016. Results of the assessment indicated that this stock of common thresher sharks was currently unlikely to be in an overfished condition nor experiencing overfishing, although the stock was overfished in the past. One of the key uncertainties of the assessment was the reproductive biology of the stock. In this study, the effect of using alternative reproductive biology parameters from the northwest Atlantic stock was explored in more detail, together with natural mortality (M) and a stock-recruitment parameter, z_{frac}. Four reproductive biology scenarios were examined: two options for median length at maturity (215.1 cm vs 160.7 cm) and two options for reproductive cycle (biennial versus annual). For each reproductive biology scenario, a suite of 70 models with 7 levels of M (0.06 to 0.18 y^{-1} in steps of 0.02) and 10 levels of z_{frac} (0.1 to 1.0 in steps of 0.1) were developed. The results of this study show that the conclusions of the 2016 stock assessment are robust to changes in reproductive biology, M, and z_{frac} parameters. Therefore, the common thresher shark stock along the west coast of North America is currently not likely subject to overfishing nor in an overfished condition. In addition, the current harvest guideline for US fisheries of 340 t is likely adequate to maintain fishing intensity below that corresponding to MSY. However, a single base case model may not be the best way to represent the status of this stock and the corresponding uncertainty. One way to represent the status of this stock, with its corresponding uncertainty, may be to use a model averaging approach but several questions on methodology must first be resolved.

Introduction

Teo et al. (2016) conducted the first stock assessment of common thresher sharks, *Alopias vulpinus*, along the west coast of North America that utilized data throughout its range. Results of the assessment indicated that this stock of common thresher sharks was currently unlikely to be in an overfished condition nor experiencing overfishing, although the stock was overfished in the past.

One of the key uncertainties of the assessment was the reproductive biology of the stock (Teo et al. 2016). The base case model of the 2016 assessment used biological parameters from Smith et al. (2008b) because that study was based on the same population of common thresher sharks. Smith et al. (2008b) suggested that the age of maturity (assumed to be median age of maturity in the assessment) was approximately 5 years and that female sharks exhibited an annual reproductive cycle. However, a recent study on the reproductive biology of the western North Atlantic stock demonstrated a much higher median age of maturity for female sharks (12 vs 5 y) and a longer reproductive periodicity (2 – 3 years vs 1 y) (Natanson and Gervelis 2013).

Subsequently, Aryafar et al. (2017) re-examined the reproductive biology of the common thresher sharks along the west coast of North America, and concluded that 'the conclusions of Smith et al. (2008b) are uncertain due to due to: 1) potential misidentification of thresher species; and 2) the inconsistency between observers' records on the presence of egg capsules or fetuses and subsequent examination of the same specimens by SWFSC biologists'. In addition, Aryafar et al. (2017) recommended 'using estimates of female size at 50% maturity and breeding periodicity from Natanson and Gervelis (2013) with an alternate breeding periodicity of one year in stock assessments for this species until further sampling can be conducted in the eastern North Pacific'.

Teo et al. (2016) developed sensitivity models using the reproductive biology reported by Natanson and Gervelis (2013). These sensitivity models used an age-12 median age of maturity and a biennial reproductive cycle, in both isolation and combination. However, preliminary model runs with an age-12 median age of maturity did not converge. Further exploration of these models indicated that assuming a lower rate of instantaneous natural mortality (M) than the base case model (M = 0.179 y^{-1}) allowed the models to converge. For these sensitivity models, Teo et al. (2016) assumed that the maximum age was proportional to the age of maturity (i.e., maximum age of 60 years instead of 25 years) and a corresponding M of 0.0757 y^{-1}.

These sensitivity models indicated that: 'Changing the maturity and fecundity schedules resulted in substantial differences in the trend and scale of the estimated population dynamics. Assuming a biennial reproductive cycle is identical to halving the fecundity from four to two pups per female, which resulted in an approximate doubling of the estimated number of mature females to maintain the reproductive output (i.e., number of pups produced) of the stock at about the same level. This increase in the population size also resulted in a substantial increase in the estimated MSY. Increasing the median age-of-maturity to 12 years appeared to slow the initial decline and subsequent recovery in the estimated number of mature females, even though the peak fishing intensities were highest for these runs. The slower initial decline was due to the dome-shaped selectivity of the primary commercial fisheries, which reduced the availability of mature females to these fisheries as age-of-maturity increased. However, the female sharks also took a longer time to mature, which resulted in a relatively slow recovery.' (Teo et al. 2016).

In this study, the effect of using reproductive biology parameters from Natanson and Gervelis (2013) on the estimated population dynamics was explored in more detail. In addition, the appropriate values for M were examined because model convergence was affected at the base case M value but the sensitivity models used somewhat arbitrary M values. Alternative M values were used together with alternative reproductive biology parameters in models to study their effects. Results of preliminary models indicated that the effect of M on model convergence and population dynamics was contingent on the stock-recruitment relationship in the model, in particular the z_{frac} parameter. The z_{frac} parameter is the reduction in pre-recruitment mortality as spawning depletion (i.e., reproductive output) approaches 0, and is parameterized as a fraction of z_0, the pre-recruitment mortality under virgin conditions. The effect of a range of z_{frac} values were therefore examined together with M. All other model parameters, model structure, and data remained the same as the base case model in Teo et al. (2016).

Methods

Reproductive biology

Natanson and Gervelis (2013) estimated a female median size at maturity (215.7 cm), which was converted into a median age of maturity using a growth curve for the northwest Atlantic stock (Gervelis and Natanson 2013). Given that the growth curve for the stock assessment is estimated within the stock assessment model and is slightly different to that estimated by Gervelis and Natanson (2013), the median length at maturity is used in this study instead of the median age of maturity. However, Natanson and Gervelis (2013) did not estimate the slope of the maturity ogive. In the Stock Synthesis modelling platform (Methot and Wetzel 2013), the proportion of females that are mature at length L are a function of the inflection point ($L_{50\%}$) and the slope,

$$P(maturity) = \frac{1}{1 + e^{slope*(L-L_{50\%})}}$$

In this study, observations of maturity of individual females from Natanson and Gervelis (2013) were fit to a logistic curve to estimate the $L_{50\%}$ and slope parameters. Observations from the Natanson and Gervelis (2013) study were obtained from the authors (L. Natanson, pers. comm.) and fit to the a binomial generalized linear model (GLM) with a logit link function. The $L_{50\%}$ and slope parameters were estimated to be 215.1 ± 45.8 cm FL and -0.2409 ± 0.0363 cm^{-1}, respectively (Fig. C.1).

Although Aryafar et al. (2017) considered the reproductive parameters from Smith et al. (2008b) to be uncertain, this study uses the Smith et al. (2008b) parameters for comparison and consistency with the 2016 base case model. Smith et al. (2008b) provided a length at maturity in total length (303 cm), which is approximately 160.7 cm in fork length, using the total to fork length conversion used in the assessment. However, there was no estimate of the slope of the maturity ogive. Therefore, the slope for Smith et al. (2008) was assumed to be -0.2409 cm^{-1} in this study.

An annual reproductive cycle with four pups per litter was used in the 2016 base case model because several studies had suggested that common thresher sharks had an annual reproductive cycle (Cailliet et al. 1983, Smith et al. 2008b, Castro 2009). In contrast, Natanson and Gervelis (2013) suggested that common thresher sharks had a reproductive cycle of two or more years. There is currently no definitive evidence of which reproductive cycle is more representative, but Aryafar et al (2017) suggested that the evidence from Natanson and Gervelis (2013) was more compelling. In addition, assuming a biennial reproductive cycle is more conservative because it assumes a substantially less productive shark. A biennial cycle was modeled by halving the fecundity from four pups to two pups per year.

In this study, I explored four scenarios on the reproductive biology of common thresher sharks. These four scenarios were the combination of two options for median length at maturity (215.1 vs 160.7 cm FL) and two options for reproductive cycle (biennial versus annual) (Appendix Table C.1).

Natural mortality

Teo et al. (2016) followed Smith et al. (2008a) in assuming an M of 0.179 y^{-1}, based on a maximum age of 25 y and using the empirical relationship between M and maximum age (Hoenig 1983). However, models using an M of 0.179 y^{-1} and the reproductive parameters from Natanson and Gervelis (2013) did not converge (Teo et al. 2016). Instead, Teo et al. (2016) assumed in sensitivity models that the maximum age was proportional to the age of maturity (i.e., maximum age of 60 years instead of 25 years) and a corresponding M of 0.0757 y^{-1}.

In this study, a probability distribution for M was developed by applying meta-analytical methods to empirical relationships between M and life history parameters (Hamel 2015). Two empirical relationships were examined: 1) Hoenig (1983), based on maximum age (AgeMax); and 2) Charnov and Berrigan (1990), based on age of maturity (AgeMat). The Pauly (1980) relationship between M and growth parameters was not used in this study because growth was estimated within the model and may therefore change with different model runs. In addition, the reported maximum age and median age of maturity for the northwest Atlantic stock (Natanson and Gervelis 2013, Natanson et al. 2016) were substantially higher than the northeast Pacific (Smith et al. 2008a, 2008b), and consistent with a less productive stock. However, the growth parameters were relatively similar to the northeast Pacific (Gervelis and Natanson 2013) and more consistent with a moderately productive stock. Therefore, using only maximum age and age of maturity to estimate M maintained a consistent biology of a lower productivity shark stock compared to the base case model in Teo et al. (2016).

Following Hamel (2015), log-log regressions were used for both empirical relationships (Fig. C.2), and prediction intervals were calculated for each estimated *M* using appropriate empirical data sets and life history parameters for common thresher sharks (Appendix Table C.2). Importantly, prediction intervals contain both the actual variability in the dependent variable around the regression line and estimation error in the original data (Hamel 2015). The prediction interval is therefore often wider than the actual variation in the dependent variable around the regression line and corresponding confidence interval. Both prediction and confidence intervals are imperfect representations of the uncertainty in a new *M* estimate, with the truth likely to be somewhere in the middle. However, the prediction interval was favored here because there was likely to be some bias in the original data of the empirical relationships, and the prediction interval is wide enough to compensate for that (Hamel 2015).

The AgeMax meta-analysis was updated from those in Hamel (2015) to use data from Then et al. (2015), who reviewed and updated the data used in the original Hoenig (1983) study. The AgeMat meta-analysis was performed in this study using data from three studies representing results from 78 different fish stocks or species (Beverton and Holt 1959, Beverton 1963, Gunderson 1997) (Fig. C.2). Maximum age and median age of maturity used to predict *M* were based on the northwest Atlantic stock to maintain consistency with the reproductive biology, and were considered to be 38 and 13 y, respectively (Natanson et al. 2016) (Appendix Table C.2).

Besides prediction intervals, log-normal probability distributions were also produced from the meta-analyses. These probability distributions were considered to be priors for *M*. As in Hamel (2015), the multiple priors were combined using weights based on the degree of overlap in the data sets used for the meta-analyses (data independence weights). The mean μ_c and variance σ_c^2 of the combined distribution were calculated as, $\mu_c = \sum_i(\frac{w_i\mu_i}{\sigma_i^2}) / \sum_i(\frac{w_i}{\sigma_i^2})$, and $\sigma_c^2 = 1/\sum_i(\frac{w_i}{\sigma_i^2})$, where w_i was the assigned data independence weight for prior *i*. If the priors were based on independent data sets, all weights would be 1, which would result in a combined prior with a mean equal to the inverse variance weighted mean of the means of all the priors. If *n* priors from completely overlapping data sets were combined, the weights would be $1/n$. Variances of the priors were obtained from the meta-analyses, while data independence weights were assigned based on the degrees of overlap between the data sets. The AgeMax and AgeMat meta-analyses were performed using independent data sets. Therefore, the data independence weights were set at 1 for both empirical relationships.

The resulting probability distribution of *M* in log scale was -1.967 ± 0.385 y^{-1} (Fig. C.3). In linear space, the median of the *M* distribution was 0.140 y^{-1} and the 95% prediction interval was 0.066 - 0.297 y^{-1}. In comparison, the *M* for the base case model in Teo et al. (2016) was higher at 0.179 y^{-1} but is within the *M* distribution here. For this study, I modeled the population dynamics of this stock of common thresher sharks using a range of M (0.06 – 0.18 y^{-1}) because this covered the lower end of the M distribution. It was not important to explore M values higher than 0.18 y^{-1} because models using reproductive biology parameters from Natanson and Gervelis (2013) do not converge at such M values.

Stock-recruitment relationship

The stock-recruitment relationship for the stock assessment was modeled using a functional form developed by Taylor et al. (20 13) for low fecundity fish that explicitly modeled the pre-recruit survival during the period from pupping to recruitment. Details can be found in Taylor et al. (2013).

The survival of pre-recruit sharks, S_o, was calculated as R_0/B_0, where R_0 was the recruitment at equilibrium, and B_0 was the equilibrium number of pups produced under unfished conditions, which was equal to the number of mature females multiplied by the number of pups produced per adult female.

Expected recruitment, R_y, for year y was calculated as, $R_y = S_y B_y$, where B_y was the expected number of pups produced by the number of mature female sharks in year y, and S_y was the pre-recruitment survival given by,

$$S_y = \exp\left[-z_0 + (z_0 - z_{min})\left(1 - \left(\frac{B_y}{B_0}\right)^{\beta}\right)\right]$$

where z_0 was the pre-recruitment mortality rate at equilibrium calculated as $-\log(S_0)$; z_{min} was the limit of pre-recruitment mortality as the number of mature female sharks approached 0, calculated as $z_0(1 - z_{frac})$, and z_{frac} represented the reduction in mortality as a fraction of z_0 (z_{frac} therefore ranged from 0 to 1); and β was the shape parameter of density dependence between the number of pups produced (i.e., number of mature female sharks) and pre-recruitment survival.

The z_{frac} and β parameters interact to determine the density dependence of the survival curve. As z_{frac} approaches 0, S_y approaches $\exp[-z_0]$ irrespective of β. However, for a given z_{frac}, increases in β results in a more convex survival curve. Teo et al. (2016) performed several sensitivity runs that illustrated this behavior (Fig. C.4). The β parameter was estimated inside the base case model in Teo et al. (2016) because a suite of preliminary simulations indicated that the available data were informative on β. In contrast, z_{frac} was fixed in the middle of a reasonable range for the base case model (base case: 0.6; range: 0.3 – 0.9).

In this study, the β parameter was estimated within each model while z_{frac} was fixed at levels ranging from 0.1 to 1.0, at 0.1 intervals. If the β parameter was estimated at ≥7.0, which was the upper bound of β in all models, it was assumed that the parameter was reaching unreasonable levels.

Models

The Stock Synthesis modeling platform (v3.24U) (Methot and Wetzel 2013) was used for all models in this study. Except where noted, all model structure, parameterization, and data in this study were identical to that of the base case model in Teo et al. (2016).

For each reproductive biology scenario (Appendix Table C.1), a suite of 70 models with 7 levels of M (0.06 to 0.18 y^{-1} in steps of 0.02) and 10 levels of z_{frac} (0.1 to 1.0 in steps of 0.1) were developed and run. For each model, convergence of the model was evaluated based on several criteria: 1) estimated population scale does not 'run away' and approach the parameter bounds; 2) positive definite Hessian matrix; and 3) maximum gradient <1.0E-4. Criterion #1 (a run away population scale) was the strongest indicator that a model did not converge. Criterions #2 (lack of a positive definite Hessian matrix) and #3 (maximum gradient exceeding 1.0E-4) were both suggestive of a lack of convergence but were not definitive. Although technically not an indicator of convergence, we identified models with β parameter >7.0 as models as mis-specified and labelled these models with 'possible non-convergence'.

Results and discussion

The assumed reproductive biology scenario interacted with M and z_{frac} to influence model convergence and results (Fig. C.5). Regardless of reproductive biology scenario, as M decreased, the zone with good model convergence (green in Fig. C.5 and Tables C.3 – 6) appeared to be related to declining z_{frac} values. For example, the zone with good model convergence for Scenario A at M of 0.10 y^{-1} ranged from a z_{frac} of 0.7 – 1.0. However, with an M of 0.06 y-1, the zone with good model convergence ranged from 0.4 – 0.7 (Fig. C.5). Some of the models may not have converged or were mis-specified (yellow in Fig. C.5 and Tables C.3 – 6) for a variety of diagnostics (poor gradient; non positive definite Hessian, and/or $\beta \geq 7$), while the rest of the models definitely did not converge (red in Fig. C.5 and Tables C.3 – 6) because a 'run away' estimated population was observed. Scenarios with lower productivity (i.e., Scenario A with $L_{50\%}$ of 215.1 cm and a biennial cycle) had larger zones of poor model convergence. For Scenario A, there appeared to be definite model non-convergence for models with $M \geq 0.12$ y^{-1} (Fig. C.5). In contrast, Scenario D [the scenario closest to the base case model in Teo et al. (2016)) had definite non-convergence only for models with high M and low z_{frac} values (Fig. C.5).

Importantly, all likely (green in Fig. C.5 and Tables C.3 – 6) and possibly (yellow in Fig. C.5 and Tables C.3 – 6) converged models appeared to have estimated fishing intensities (F; calculated as 1-SPR) in 2014 that were lower than F_{MSY} (i.e., $F_{2014}/F_{MSY} < 1$), irrespective of reproductive biology scenario, M and z_{frac} values (Tables C.3 – 6). Similarly, these models estimated adult female populations (spawning biomass; SB; 1000s of fish) in

2014 that were higher than SB_{MSY} (i.e., $SB_{2014}/SB_{MSY} > 1$). Therefore, the conclusions of the 2016 stock assessment (Teo et al. 2016) that the common thresher shark stock along the west coast of North America were currently not likely subject to overfishing nor in an overfished condition were robust. In addition, all estimated MSYs were larger than the current harvest guideline for US fisheries of 340 t, which suggested that the current harvest guideline is adequate to maintain fishing intensity below that corresponding to MSY. In comparison, the estimated total catch of the US and Mexico fisheries in 2014 were approximately 66.6 and 159.5 t, respectively.

However, it should be noted that although the conclusions about stock status from the 2016 assessment were robust, the estimated scale and trend was affected by the reproductive biology parameters used. For example, Teo et al. (2016) illustrated in sensitivity runs that changing the age of maturity to an older age would slow the recovery of the stock from overfishing at the start of the commercial fishery, and the estimated adult female population in 2014 relative to an unfished condition would also be lower than the base case model (Fig. C.6). Changing the reproductive cycle from an annual cycle (base case) to a biennial cycle resulted in a doubling of the estimated adult female population because twice the number of adult females are now required to produce the same number of pups (Fig. C.6).

Not surprisingly, changing M values within a reproductive biology scenario also led to changes in estimated population scale and trends (Fig. C.7). In general, as M increased, the estimated absolute and relative population also tended to increase (Fig. C.7 & Tables C.3 – 6). However, the estimated fishing intensity (F; calculated as 1-SPR) in 2014 was relatively similar because of the low levels of catch in recent years. Interestingly, model fits to the primary indices were degraded at higher M values for Scenario A (Fig. C.8). Similarly, changing z_{frac} values led to changes in the estimated absolute population scale (Fig. C.9). However, the relative population scale was not strongly affected. Therefore, the effects of M were likely to be more important than z_{frac}. In contrast to M, model fits to the primary indices improved at higher z_{frac} (Fig. C.10)

Out of the converged models, the best fitting model for each scenario was selected based on the total negative log-likelihood (Tables C.3 – 6). The best models for Scenario A was model 7 (NLL_{tot}=655.2; M=0.06; z_{frac}= 0.7); Scenario B's was model 17 (NLL_{tot}=654.8; M=0.08; z_{frac}= 0.7); Scenario C's was29 (NLL_{tot}=652.1; M=0.10; z_{frac}= 0.9); and Scenario D's was model 48 (NLL_{tot}=650.9; M=0.14; z_{frac}= 0.8). Differences in model results between the reproductive biology scenarios were similar to the sensitivity models described in Teo et al. (2016). Changing the reproductive cycle from annual to biennial led to a large increase in the estimated absolute population but minor changes in the relative population (Fig. C.11). Model fits to the primary indices of the best fitting models for each scenario was better than the base case model in Teo et al. (2016) (Fig. C.12). Model fit of the base case model

(NLL_{tot}=654.272) in Teo et al. (2016) was also poorer than the best fitting models in all reproductive biology scenarios except Scenario A. Overall, Scenario A had the poorest fitting model and poorest model convergence.

Based on the uncertainty in our current understanding of the biology of this stock and the results of this study, a single base case model may not be the best way to represent the status of this stock and the corresponding uncertainty. Aryafar et al. (2017) found several potential problems with the Smith et al. (2008b) study but there was no definitive evidence that the reported reproductive biology parameters were unrepresentative. A more recent study on the northwest Atlantic stock (Natanson and Gervelis 2013) had better methods but it is uncertain if these parameters are representative of the northeast Pacific stock. Models using the reproductive biology from the northwest Atlantic (Scenario A) had poorer model convergence and generally poorer model fits than the other scenarios. The best fitting model from Scenario A used an M of 0.06 y^{-1}, which corresponds to an expected maximum age of approximately 75 y. This expected maximum age is approximately twice that reported in the northwest Atlantic (38 y) from a study using bomb radiocarbon techniques (Natanson et al. 2016). However, using an M of 0.10 y^{-1}, which corresponds to an expected maximum age of approximately 45 y, resulted in poor overall model fits and poor fits to the primary indices. In contrast, the best fitting model from Scenario D, which used reproductive biology parameters from Smith et al. (2008b), had an M of 0.14 y^{-1} and substantially better overall model fits and better fits to the primary indices. An M of 0.14 y^{-1} appears to be more reasonable because this corresponds to an expected maximum age of approximately 33 years, and the median of the expected M distribution from a meta-analysis of empirical relationships between life history and M was 0.14 y^{-1}.

One way to represent the status of this stock, with its corresponding uncertainty, may be to use a model averaging approach (Millar et al. 2015). However, several questions must first be considered: 1) how to weight the different reproductive biology scenarios; 2) is it appropriate to use model fit (i.e., relative likelihoods because all models have the same number of parameters) for weighting, because models in Scenario D will be heavily weighted due to better model fits and better model convergence; and 3) how to estimate the overall uncertainty for all the models (e.g., simulation-based; delta method). One way to reduce the potential bias of having fewer converged models in Scenario A is to use the best fitting model from each scenario. However, it should be noted that there is approximately 4.3 log-likelihood units of difference between the model fits of the best models from Scenario A and D. Such a large difference in model fit would result in Scenario A having approximately 1% of the weight of Scenario D.

Conclusions

Most importantly, the results of this study show that the conclusions of the 2016 stock assessment (Teo et al. 2016) are robust to changes in the reproductive biology, *M*, and z_{frac} parameters. Therefore, the common thresher shark stock along the west coast of North America are currently not likely subject to overfishing nor in an overfished condition. In addition, the current harvest guideline for US fisheries of 340 t is likely adequate to maintain fishing intensity below that corresponding to MSY. In comparison, the estimated total catch of the US and Mexico fisheries in 2014 were approximately 66.6 and 159.5 t, respectively. However, a single base case model may not be the best way to represent the status of this stock and the corresponding uncertainty. One way to represent the status of this stock, with its corresponding uncertainty, may be to use a model averaging approach but several questions on methodology must first be resolved.

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Appendix Table C.1. Reproductive biology scenarios and parameters used in this study. These four scenarios are based on common thresher shark reproductive biology studies in the northwest Atlantic (Natanson and Gervelis 2013) and the northeast Pacific (Smith et al. 2008b). The base case model in Teo et al. (2016) is similar to Scenario D, except that median age at maturity (5 y) was used instead of median length at maturity.

		Median length at maturity ($L_{50\%}$)	
		Natanson and Gervelis (2013)	Smith et al. (2008b)
Reproductive cycle	Natanson and Gervelis (2013)	**Scenario A** $L_{50\%}$ at 215.1 cm Slope at -0.2409 cm^{-1} Biennial cycle (2 pups y^{-1})	**Scenario C** $L_{50\%}$ at 160.7 cm Slope at -0.2409 cm^{-1} Biennial cycle (2 pups y^{-1})
	Smith et al. (2008b)	**Scenario B** $L_{50\%}$ at 215.1 cm Slope at -0.2409 cm^{-1} Annual cycle (4 pups y^{-1})	**Scenario D** $L_{50\%}$ at 160.7 cm Slope at -0.2409 cm^{-1} Annual cycle (4 pups y^{-1})

Appendix Table Appendix C.2. Empirical relationships (method) used to estimate M along with parameter values for common thresher shark from the northwest Atlantic, and estimated prediction intervals (log M and SD of log M).

Method	**Equation**	**Regression Type**	**Log Intercept**	**Parameter Value**	**Parameter Source**	**log M**	**SD of log M**
AgeMat	M = 1.703 /AgeMat	log–log regression (fixed slope = -1)	0.5322	13	(Natanson et al. 2016)	-2.033	0.839
AgeMax	M = 5.41/AgeMax	log–log regression (fixed slope = -1)	1.6882	38	(Natanson et al. 2016)	-1.949	0.433

Appendix Table C.3. Summary of model results of Scenario A ($L_{50\%}$ 215.1 cm and 2 pups per year) at various levels of M and z_{frac}. Important quantities including, total (NLL_{tot}) and index (NLL_{idx}) negative log-likelihoods, virgin recruitment (log-scale; LN_R0); number of mature females in 2014 (SB_{2014}; 1000s of fish); fishing intensity (F; calculated as 1-SPR); maximum sustainable yield (MSY; t) are included. Overfishing is occurring if $F_{2014}/F_{MSY} > 1$; and the stock is overfished if $SB_{2014}/S_{BMSY} < 1$. Color codes for convergence are the same as Fig. C.5. Number codes for convergence are: 1=likely convergence; 2=possible non-convergence; and 3) definite non-convergence.

	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
1	0.06	0.1	7.5E-05	666.1	-43.4	7.0	5.14	1.19	479.5	674.6	0.03	1065.3	0.10	1.38	2
2	0.06	0.2	3.1E-05	663.5	-44.3	7.0	4.37	0.51	206.3	146.3	0.06	672.4	0.19	1.25	2
3	0.06	0.3	6.0E-05	660.4	-45.2	7.0	4.22	0.29	179.4	86.1	0.06	754.6	0.18	1.25	2
4	0.06	0.4	5.8E-05	658.8	-46.3	4.7	3.88	0.40	117.8	78.6	0.08	664.1	0.22	1.21	1
5	0.06	0.5	2.3E-05	657.3	-47.1	3.4	3.63	0.24	85.3	42.1	0.10	633.2	0.24	1.18	1
6	0.06	0.6	6.8E-05	656.1	-47.6	2.6	3.50	0.20	73.2	31.7	0.10	660.8	0.23	1.22	1
7	0.06	0.7	8.0E-05	655.2	-47.9	2.2	3.41	0.17	65.8	26.9	0.11	704.3	0.22	1.28	1
8	0.06	0.8	3.7E-05	654.6	-48.1	1.8	3.33	0.16	60.1	NA	0.11	754.4	0.20	1.34	2
9	0.06	0.9	5.7E-05	654.1	-48.0	1.6	3.27	0.15	57.0	NA	0.11	812.5	0.19	1.41	2
10	0.06	1.0	9.6E-05	653.8	-47.8	1.4	3.22	0.14	55.2	NA	0.11	873.5	0.18	1.48	2
11	0.08	0.1	2.9E-05	666.5	-43.2	7.0	6.56	4.07	1291.1	5513.4	0.01	3767.4	0.03	1.52	2
12	0.08	0.2	2.4E-05	664.9	-43.7	7.0	5.12	0.90	289.0	311.1	0.03	1135.2	0.10	1.41	2
13	0.08	0.3	9.5E-05	662.9	-44.2	7.0	4.55	0.44	157.3	98.5	0.05	805.8	0.16	1.32	2
14	0.08	0.4	3.9E-05	660.5	-44.6	7.0	4.41	0.28	137.5	64.5	0.05	849.5	0.16	1.32	2
15	0.08	0.5	4.4E-05	659.1	-45.2	6.0	4.32	0.49	130.0	90.1	0.05	908.4	0.15	1.41	1
16	0.08	0.6	5.5E-05	658.2	-45.9	4.3	4.01	0.35	90.1	50.5	0.07	781.5	0.19	1.37	1
17	0.08	0.7	9.5E-05	657.5	-45.8	3.4	3.83	0.27	75.3	36.1	0.08	758.4	0.20	1.42	1
18	0.08	0.8	5.1E-05	657.2	-45.5	2.7	3.72	0.23	67.4	28.7	0.09	767.3	0.20	1.49	1
19	0.08	0.9	1.9E-05	657.2	-45.2	2.2	3.65	0.20	62.3	24.7	0.09	792.9	0.19	1.55	1
20	0.08	1.0	3.3E-05	657.3	-45.1	1.7	3.61	0.20	58.8	NA	0.10	833.4	0.18	1.59	2
21	0.10	0.1	2.0E-02	666.4	-42.9	7.0	14.99	18.53	NA	NA	NA	NA	NA	NA	3
22	0.10	0.2	1.3E-05	665.4	-43.4	7.0	6.21	2.37	592.7	1500.6	0.01	2756.9	0.04	1.52	2
23	0.10	0.3	9.0E-05	664.3	-43.7	7.0	5.27	0.87	227.9	233.4	0.03	1285.2	0.09	1.46	2
24	0.10	0.4	3.4E-05	662.9	-43.9	7.0	4.80	0.47	140.5	87.5	0.04	947.3	0.13	1.40	2
25	0.10	0.5	4.4E-05	661.3	-43.6	7.0	4.61	0.31	119.0	56.7	0.05	916.6	0.14	1.41	2
26	0.10	0.6	8.2E-05	660.2	-43.2	7.0	4.63	0.24	128.5	48.6	0.04	1057.9	0.13	1.51	2
27	0.10	0.7	7.4E-05	660.1	-42.8	6.2	4.55	0.44	122.5	65.0	0.04	1091.2	0.13	1.59	1
28	0.10	0.8	8.7E-05	660.3	-42.3	5.0	4.36	0.36	102.9	46.0	0.05	1016.6	0.14	1.64	1
29	0.10	0.9	9.1E-05	660.8	-42.0	4.1	4.22	0.31	89.1	34.7	0.06	970.3	0.15	1.70	1
30	0.10	1.0	7.8E-05	661.2	-42.7	2.6	4.15	0.40	79.3	33.5	0.07	939.7	0.15	1.74	1
31	0.12	0.1	3.6E-03	666.4	-42.0	7.0	15.00	5.16	NA	NA	NA	NA	NA	NA	3
32	0.12	0.2	2.2E-03	665.8	-42.4	7.0	15.00	13.52	NA	NA	NA	NA	NA	NA	3
33	0.12	0.3	2.9E-04	665.3	-42.6	7.0	8.75	33.34	5771.3	1.9E+05	0.00	3.3E+04	0.00	1.63	2
34	0.12	0.4	1.4E-05	664.9	-42.4	7.0	6.20	2.69	455.0	1273.1	0.01	2956.8	0.04	1.60	2
35	0.12	0.5	1.0E-05	664.6	-42.0	7.0	5.50	1.15	227.3	282.7	0.02	1658.9	0.07	1.58	2
36	0.12	0.6	8.2E-05	664.4	-41.5	7.0	5.14	0.68	161.9	123.5	0.03	1309.4	0.09	1.57	2
37	0.12	0.7	3.7E-05	664.2	-40.9	7.0	4.99	0.46	141.1	76.3	0.03	1238.1	0.10	1.60	2
38	0.12	0.8	3.9E-05	664.6	-42.1	3.9	5.58	2.04	251.2	527.5	0.02	2136.1	0.06	1.72	2

	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
39	0.12	0.9	7.6E-05	664.6	-42.3	3.2	5.72	2.38	287.0	708.9	0.02	2549	0.05	1.78	2
40	0.12	1.0	3.2E-05	664.5	-42.3	2.8	5.81	2.83	315.2	923.8	0.02	2942.7	0.04	1.83	2
41	0.14	0.1	1.1E-02	668.3	-39.4	7.0	15.00	2.33	NA	NA	NA	NA	NA	NA	3
42	0.14	0.2	2.6E-04	668.1	-39.6	7.0	15.00	2.93	NA	NA	NA	NA	NA	NA	3
43	0.14	0.3	5.5E-04	667.9	-39.8	7.0	15.00	3.52	NA	NA	NA	NA	NA	NA	3
44	0.14	0.4	5.5E-03	667.9	-39.9	7.0	15.00	3.96	NA	NA	NA	NA	NA	NA	3
45	0.14	0.5	4.9E-03	667.8	-39.9	5.7	15.00	4.13	NA	NA	NA	NA	NA	NA	3
46	0.14	0.6	3.8E-04	667.8	-39.9	4.7	15.00	4.12	NA	NA	NA	NA	NA	NA	3
47	0.14	0.7	5.0E-03	667.8	-39.9	4.0	15.00	4.06	NA	NA	NA	NA	NA	NA	3
48	0.14	0.8	1.4E-02	667.7	-39.9	3.5	15.00	3.99	NA	NA	NA	NA	NA	NA	3
49	0.14	0.9	1.9E-02	667.7	-39.9	3.1	15.00	4.24	NA	NA	NA	NA	NA	NA	3
50	0.14	1.0	1.1E-03	667.7	-39.9	2.8	15.00	4.08	NA	NA	NA	NA	NA	NA	3
51	0.16	0.1	2.4E-03	673.7	-35.7	0.4	15.00	0.00	NA	NA	NA	NA	NA	NA	3
52	0.16	0.2	2.8E-03	673.7	-35.8	5.2	15.00	1.29	NA	NA	NA	NA	NA	NA	3
53	0.16	0.3	9.6E-04	673.7	-35.8	4.2	15.00	1.32	NA	NA	NA	NA	NA	NA	3
54	0.16	0.4	4.0E-03	673.7	-35.8	3.5	15.00	1.33	NA	NA	NA	NA	NA	NA	3
55	0.16	0.5	5.6E-04	673.7	-35.9	3.0	15.00	1.34	NA	NA	NA	NA	NA	NA	3
56	0.16	0.6	1.5E-02	673.7	-35.9	2.6	15.00	1.34	NA	NA	NA	NA	NA	NA	3
57	0.16	0.7	9.3E-04	673.7	-35.9	2.3	15.00	1.35	NA	NA	NA	NA	NA	NA	3
58	0.16	0.8	3.5E-03	673.6	-35.9	2.0	15.00	1.35	NA	NA	NA	NA	NA	NA	3
59	0.16	0.9	1.0E-03	673.6	-35.9	1.8	15.00	1.36	NA	NA	NA	NA	NA	NA	3
60	0.16	1.0	4.9E-03	673.6	-35.9	1.7	15.00	1.36	NA	NA	NA	NA	NA	NA	3
61	0.18	0.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
62	0.18	0.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
63	0.18	0.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
64	0.18	0.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
65	0.18	0.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
66	0.18	0.6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
67	0.18	0.7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
68	0.18	0.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
69	0.18	0.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3
70	0.18	1.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3

Appendix Table C.4. Summary of model results of Scenario B ($L_{50\%}$ 215.1 cm and 4 pups per year) at various levels of M and z_{frac}. Important quantities including, total (NLL_{tot}) and index (NLL_{idx}) negative log-likelihoods, virgin recruitment (log-scale; LN_R0); number of mature females in 2014 (SB_{2014}; 1000s of fish); fishing intensity (F; calculated as 1-SPR); maximum sustainable yield (MSY; t) are included. Overfishing is occurring if $F_{2014}/F_{MSY} > 1$; and the stock is overfished if $SB_{2014}/S_{BMSY} < 1$. Color codes for convergence are the same as Fig. C.5. Number codes for convergence are: 1=likely convergence; 2=possible non-convergence; and 3) definite non-convergence.

	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
1	0.06	0.1	2.1E-5	665.3	-43.7	7.0	4.8	0.8	335.1	346.3	0.04	854.2	0.14	1.34	2
2	0.06	0.2	4.6E-5	661.2	-44.9	7.0	4.2	0.3	163.8	89.2	0.07	668.1	0.21	1.20	2
3	0.06	0.3	7.9E-5	658.7	-46.3	4.7	3.9	0.4	117.8	78.3	0.08	667.1	0.22	1.21	1
4	0.06	0.4	6.5E-5	656.8	-47.3	3.1	3.6	0.2	80.2	37.2	0.10	641.6	0.24	1.19	1
5	0.06	0.5	4.6E-5	655.5	-47.8	2.3	3.4	0.2	67.8	28.1	0.11	691.1	0.22	1.26	1
6	0.06	0.6	6.8E-5	654.5	-48.1	1.8	3.3	0.2	60	NA	0.11	757.6	0.20	1.34	2
7	0.06	0.7	7.1E-5	653.9	-48.3	1.5	3.2	0.1	54.2	NA	0.11	828.7	0.19	1.41	2
8	0.06	0.8	6.7E-5	653.4	-48.3	1.3	3.2	0.1	49.2	NA	0.12	893.3	0.17	1.46	2
9	0.06	0.9	8.5E-5	653.1	-48.3	1.1	3.1	0.1	45	NA	0.12	940.1	0.16	1.49	2
10	0.06	1.0	5.0E-5	652.9	-48.2	1.0	3.0	0.2	41.4	NA	0.12	955.9	0.15	1.48	2
11	0.08	0.1	4.2E-5	665.8	-43.4	7.0	5.6	1.6	500.1	882	0.02	1700.9	0.06	1.46	2
12	0.08	0.2	7.8E-5	663.0	-44.1	7.0	4.6	0.5	163.9	107.4	0.05	825.9	0.15	1.33	2
13	0.08	0.3	8.5E-5	659.8	-44.8	7.0	4.5	0.3	149.7	63	0.05	951.2	0.14	1.39	2
14	0.08	0.4	7.1E-5	658.3	-45.8	4.6	4.1	0.4	95.9	57.2	0.07	803.4	0.18	1.38	1
15	0.08	0.5	6.4E-5	657.0	-46.7	3.2	3.8	0.2	62.9	30.6	0.09	720.5	0.21	1.32	1
16	0.08	0.6	2.0E-5	655.8	-47.2	2.4	3.6	0.2	49.4	20.3	0.10	724.8	0.22	1.32	1
17	0.08	0.7	3.0E-5	654.8	-47.5	2.0	3.5	0.1	42.3	16	0.11	758.7	0.21	1.36	1
18	0.08	0.8	6.7E-5	654.1	-47.7	1.6	3.4	0.1	37.5	NA	0.11	803	0.20	1.40	2
19	0.08	0.9	3.3E-5	653.5	-47.6	1.4	3.3	0.1	35	NA	0.12	854.3	0.18	1.46	2
20	0.08	1.0	5.7E-5	653.2	-47.4	1.2	3.2	0.1	33.8	NA	0.12	905.5	0.17	1.52	2
21	0.10	0.1	5.8E-5	665.8	-43.3	7.0	6.9	4.8	1191.6	NA	0.01	5194	0.02	1.55	2
22	0.10	0.2	2.9E-5	663.9	-43.8	7.0	5.1	0.7	193.2	170	0.03	1162.5	0.10	1.44	2
23	0.10	0.3	9.3E-5	661.3	-44.2	7.0	4.6	0.3	113.5	57.3	0.05	894.2	0.14	1.38	2
24	0.10	0.4	3.4E-5	659.1	-44.6	6.9	4.6	0.5	119.7	77.7	0.04	1086.3	0.12	1.49	1
25	0.10	0.5	6.9E-5	657.9	-45.4	4.8	4.2	0.3	78.4	40.4	0.06	892.1	0.16	1.47	1
26	0.10	0.6	2.4E-5	656.9	-46.0	3.6	4.0	0.2	56.9	25.7	0.07	809.3	0.19	1.46	1
27	0.10	0.7	6.0E-5	656.0	-46.5	2.8	3.8	0.2	44.7	17.1	0.09	782.5	0.20	1.46	1
28	0.10	0.8	7.7E-5	655.5	-46.2	2.3	3.7	0.2	40.2	13.6	0.09	799.3	0.19	1.55	1
29	0.10	0.9	2.8E-5	655.4	-45.9	1.8	3.6	0.1	37.1	NA	0.10	829.3	0.19	1.62	2
30	0.10	1.0	4.5E-5	655.4	-45.7	1.4	3.6	0.1	35	NA	0.10	874.3	0.17	1.65	2
31	0.12	0.1	2.1E-3	665.5	-43.1	7.0	15.0	27.6	NA	NA	NA	NA	NA	NA	3
32	0.12	0.2	8.4E-5	664.2	-43.6	7.0	5.8	1.3	271.4	NA	0.02	1917.4	0.06	1.52	2
33	0.12	0.3	6.1E-5	662.5	-43.9	7.0	5.0	0.5	123.1	78.6	0.04	1084.2	0.11	1.46	2
34	0.12	0.4	4.7E-5	660.5	-44.2	7.0	4.8	0.3	93.4	42.1	0.04	988.7	0.13	1.45	2
35	0.12	0.5	3.4E-5	658.8	-44.5	7.0	4.8	0.2	95.3	34.6	0.04	1136.7	0.12	1.53	2
36	0.12	0.6	5.8E-5	657.8	-44.8	5.3	4.5	0.4	70.5	33.4	0.05	984.8	0.14	1.54	1
37	0.12	0.7	7.7E-5	657.3	-44.5	4.2	4.3	0.3	57.8	22.6	0.06	920.4	0.16	1.60	1
38	0.12	0.8	5.5E-5	657.2	-44.1	3.4	4.1	0.2	49.7	16.7	0.07	891.8	0.17	1.67	1

	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
39	0.12	0.9	6.6E-5	657.5	-43.8	2.8	4.0	0.2	43.9	13.2	0.08	879.8	0.17	1.75	1
40	0.12	1.0	5.5E-5	657.9	-43.6	2.2	3.9	0.2	39.6	11.2	0.08	881.3	0.17	1.81	1
41	0.14	0.1	2.4E-3	665.2	-42.8	7.0	15.0	6.5	NA	NA	NA	NA	NA	NA	3
42	0.14	0.2	2.2E-5	664.2	-43.4	7.0	7.1	4.0	687.4	NA	0.01	5554.3	0.02	1.59	2
43	0.14	0.3	9.8E-5	663.1	-43.7	7.0	5.7	0.9	171.2	NA	0.02	1656.2	0.07	1.53	2
44	0.14	0.4	6.5E-5	661.8	-43.8	7.0	5.2	0.5	102.7	60	0.03	1156	0.10	1.50	2
45	0.14	0.5	5.4E-5	660.5	-43.6	7.0	4.9	0.3	85.6	36.5	0.04	1084.1	0.11	1.52	2
46	0.14	0.6	8.5E-5	659.7	-43.1	7.0	4.9	0.2	84.8	28.7	0.04	1174.5	0.11	1.59	2
47	0.14	0.7	3.9E-5	659.6	-42.6	5.9	4.7	0.4	72.2	32.5	0.04	1107.2	0.12	1.63	1
48	0.14	0.8	8.8E-5	659.7	-42.2	4.9	4.6	0.3	61	23.6	0.05	1036.1	0.14	1.68	1
49	0.14	0.9	8.9E-5	660.0	-41.9	3.9	4.4	0.3	53.1	18	0.06	986.7	0.15	1.74	1
50	0.14	1.0	3.4E-5	660.5	-41.8	3.1	4.3	0.2	47.5	14.8	0.06	959.4	0.15	1.81	1
51	0.16	0.1	9.0E-4	665.1	-42.1	7.0	15.0	3.0	NA	NA	NA	NA	NA	NA	3
52	0.16	0.2	2.9E-3	664.4	-42.5	7.0	15.0	9.1	NA	NA	NA	NA	NA	NA	3
53	0.16	0.3	1.3E-5	663.8	-42.7	7.0	7.4	5.7	765	NA	0.00	7611	0.01	1.64	2
54	0.16	0.4	3.2E-6	663.4	-42.5	7.0	6.0	1.3	191.6	NA	0.02	2162	0.05	1.60	2
55	0.16	0.5	3.4E-5	662.9	-42.2	7.0	5.5	0.7	118.1	88.7	0.03	1490.3	0.08	1.59	2
56	0.16	0.6	2.9E-5	662.6	-41.7	7.0	5.3	0.5	95.3	50.6	0.03	1322.6	0.09	1.60	2
57	0.16	0.7	3.3E-5	662.5	-41.2	7.0	5.2	0.4	89.1	37.8	0.03	1333.4	0.09	1.64	2
58	0.16	0.8	1.3E-5	662.8	-40.7	6.2	5.1	0.5	81.3	41	0.03	1302.8	0.10	1.68	1
59	0.16	0.9	7.8E-5	663.1	-41.8	3.0	5.3	1.4	93	126.9	0.03	1483.7	0.09	1.76	1
60	0.16	1.0	9.4E-5	663.2	-42.0	2.4	5.4	1.2	105.6	133.5	0.03	1729.1	0.07	1.83	1
61	0.18	0.1	5.9E-3	666.4	-40.1	7.0	15.0	1.7	NA	NA	NA	NA	NA	NA	3
62	0.18	0.2	7.1E-3	666.0	-40.5	7.0	15.0	2.6	NA	NA	NA	NA	NA	NA	3
63	0.18	0.3	8.9E-3	665.7	-40.7	7.0	15.0	4.4	NA	NA	NA	NA	NA	NA	3
64	0.18	0.4	2.8E-3	665.5	-40.8	7.0	15.0	7.5	NA	NA	NA	NA	NA	NA	3
65	0.18	0.5	2.5E-3	665.5	-40.8	6.0	15.0	9.1	NA	NA	NA	NA	NA	NA	3
66	0.18	0.6	2.4E-3	665.5	-40.8	4.7	15.0	8.0	NA	NA	NA	NA	NA	NA	3
67	0.18	0.7	1.9E-2	665.5	-40.8	3.9	15.0	6.8	NA	NA	NA	NA	NA	NA	3
68	0.18	0.8	1.3E-2	665.5	-40.8	3.3	15.0	6.8	NA	NA	NA	NA	NA	NA	3
69	0.18	0.9	5.5E-3	665.5	-40.8	2.9	15.0	7.2	NA	NA	NA	NA	NA	NA	3
70	0.18	1.0	1.2E-2	665.5	-40.8	2.6	15.0	6.5	NA	NA	NA	NA	NA	NA	3

Appendix Table C.5. Summary of model results of Scenario C ($L_{50\%}$ 160.7 cm and 2 pups per year) at various levels of M and z_{frac}. Important quantities including, total (NLL_{tot}) and index (NLL_{idx}) negative log-likelihoods, virgin recruitment (log-scale; LN_R0); number of mature females in 2014 (SB_{2014}; 1000s of fish); fishing intensity (F; calculated as 1-SPR); maximum sustainable yield (MSY; t) are included. Overfishing is occurring if F_{2014}/F_{MSY} >1; and the stock is overfished if SB_{2014}/S_{BMSY} < 1. Color codes for convergence are the same as Fig. C.5. Number codes for convergence are: 1=likely convergence; 2=possible non-convergence; and 3) definite non-convergence.

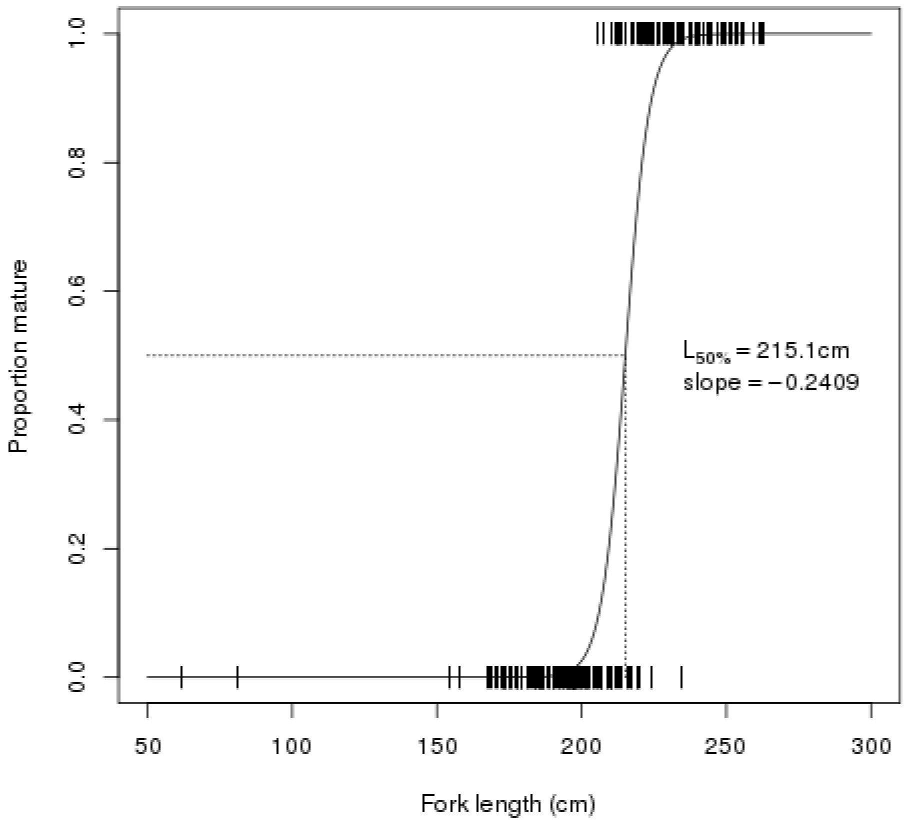
	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
1	0.06	0.1	9.1E-5	664.9	-44.2	7.0	4.8	0.6	627.5	496.9	0.04	879.6	0.13	1.48	2
2	0.06	0.2	3.7E-5	661.1	-45.3	7.0	4.1	0.2	282.5	122.3	0.07	600.9	0.23	1.41	2
3	0.06	0.3	5.0E-5	657.9	-46.5	4.9	3.7	0.1	172.1	58.8	0.10	541.4	0.29	1.34	1
4	0.06	0.4	3.5E-5	655.3	-47.2	3.6	3.4	0.1	138	37.4	0.11	555.7	0.29	1.44	1
5	0.06	0.5	9.3E-5	653.9	-47.5	2.8	3.3	0.1	119.5	29	0.12	587.3	0.28	1.57	1
6	0.06	0.6	5.6E-5	653.2	-47.5	2.1	3.2	0.1	105.7	24.2	0.13	628.5	0.27	1.69	1
7	0.06	0.7	7.0E-5	653.0	-47.3	1.7	3.1	0.1	95.4	NA	0.14	676.1	0.25	1.78	2
8	0.06	0.8	5.9E-5	653.0	-47.1	1.4	3.0	0.1	88	NA	0.15	725.7	0.23	1.84	2
9	0.06	0.9	1.9E-5	653.0	-46.9	1.1	3.0	0.2	82.7	NA	0.15	767.8	0.21	1.85	2
10	0.06	1.0	7.9E-5	653.1	-46.7	0.9	2.9	0.2	79.4	NA	0.16	787	0.20	1.78	2
11	0.08	0.1	5.6E-5	665.1	-44.0	7.0	5.4	0.9	844.6	879.8	0.02	1435.7	0.08	1.60	2
12	0.08	0.2	1.2E-5	662.0	-44.8	7.0	4.5	0.3	327.4	148.4	0.05	787	0.16	1.55	2
13	0.08	0.3	1.9E-5	659.5	-45.6	5.5	4.1	0.2	195.7	65.1	0.08	639.8	0.22	1.51	1
14	0.08	0.4	2.9E-5	657.0	-46.4	4.2	3.8	0.1	140.1	39.5	0.09	608.5	0.26	1.51	1
15	0.08	0.5	2.5E-5	654.8	-47.0	3.4	3.6	0.1	114.1	28.1	0.11	620.2	0.27	1.58	1
16	0.08	0.6	7.8E-5	653.2	-47.2	2.8	3.4	0.1	98.9	22	0.12	644.9	0.27	1.68	1
17	0.08	0.7	2.9E-5	652.2	-47.2	2.3	3.3	0.1	87.7	18.4	0.13	676.7	0.26	1.78	1
18	0.08	0.8	8.2E-5	651.7	-47.1	1.9	3.2	0.1	79.3	NA	0.14	713	0.25	1.88	2
19	0.08	0.9	4.1E-5	651.6	-46.7	1.5	3.1	0.1	74.1	NA	0.14	750.2	0.24	1.97	2
20	0.08	1.0	9.3E-5	651.8	-46.4	1.2	3.1	0.1	71	NA	0.15	789	0.22	1.99	2
21	0.10	0.1	5.3E-5	664.9	-44.0	7.0	6.1	1.4	1233.3	1958	0.01	2474.2	0.04	1.69	2
22	0.10	0.2	5.7E-5	662.2	-44.6	7.0	5.0	0.4	387.8	216.9	0.04	1055.4	0.11	1.63	2
23	0.10	0.3	1.3E-5	660.2	-45.2	6.1	4.4	0.2	221.5	77.6	0.06	773.3	0.17	1.62	1
24	0.10	0.4	1.7E-5	658.3	-45.8	4.7	4.1	0.1	152.7	42.9	0.08	677.6	0.22	1.61	1
25	0.10	0.5	9.2E-5	656.3	-46.3	3.8	3.9	0.1	119.6	29.4	0.09	659.3	0.24	1.64	1
26	0.10	0.6	5.0E-5	654.5	-46.7	3.2	3.7	0.1	100.9	22.5	0.10	669.7	0.25	1.70	1
27	0.10	0.7	7.5E-5	653.1	-46.8	2.7	3.6	0.1	89.2	18.2	0.11	690	0.25	1.79	1
28	0.10	0.8	8.1E-5	652.3	-46.4	2.3	3.5	0.1	81.4	15.6	0.12	713.1	0.25	1.91	1
29	0.10	0.9	7.9E-5	652.1	-46.0	1.9	3.4	0.1	75.6	13.9	0.12	740.1	0.24	2.03	1
30	0.10	1.0	4.0E-5	652.3	-45.7	1.6	3.3	0.1	71.8	NA	0.13	771	0.22	2.11	2
31	0.12	0.1	6.7E-5	664.6	-43.9	7.0	7.0	3.2	2402.7	NA	0.01	5547.6	0.02	1.77	2
32	0.12	0.2	2.7E-5	662.3	-44.4	7.0	5.5	0.7	502.2	399.8	0.02	1527.4	0.08	1.69	2
33	0.12	0.3	3.6E-5	660.3	-44.9	7.0	4.9	0.3	269.4	109.6	0.04	1009.3	0.13	1.70	2
34	0.12	0.4	7.2E-5	659.0	-45.4	5.2	4.4	0.2	171.5	52.1	0.06	785.6	0.17	1.68	1
35	0.12	0.5	5.9E-5	657.4	-45.8	4.2	4.2	0.1	130.1	33.4	0.07	718.5	0.21	1.69	1
36	0.12	0.6	1.1E-5	655.9	-46.1	3.6	4.0	0.1	107.6	24.4	0.08	702.1	0.22	1.73	1
37	0.12	0.7	2.5E-5	654.7	-46.0	3.1	3.9	0.1	94.7	19.7	0.09	705.7	0.23	1.81	1
38	0.12	0.8	2.8E-5	654.0	-45.7	2.7	3.8	0.1	85.5	16.7	0.10	718.3	0.23	1.91	1

	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
39	0.12	0.9	1.5E-5	653.7	-45.3	2.3	3.7	0.1	79.5	14.3	0.11	735.7	0.23	2.02	1
40	0.12	1.0	2.3E-5	653.7	-44.9	1.9	3.6	0.1	75.6	13.4	0.11	760	0.22	2.13	1
41	0.14	0.1	3.9E-2	664.2	-43.9	7.0	14.7	110.1	NA	NA	NA	NA	NA	NA	3
42	0.14	0.2	9.6E-5	662.2	-44.3	7.0	6.2	1.3	783.8	1077.1	0.01	2619.5	0.04	1.75	2
43	0.14	0.3	2.7E-5	660.3	-44.7	7.0	5.3	0.4	331.9	179.3	0.03	1340.5	0.09	1.73	2
44	0.14	0.4	9.2E-5	659.2	-45.1	6.3	4.9	0.3	209.9	78	0.04	995.2	0.13	1.73	1
45	0.14	0.5	5.3E-5	658.1	-45.4	4.9	4.5	0.2	149	42.3	0.06	826.5	0.17	1.73	1
46	0.14	0.6	6.5E-5	657.1	-45.4	4.1	4.3	0.1	121.8	30.3	0.07	769.9	0.19	1.78	1
47	0.14	0.7	7.1E-5	656.3	-45.2	3.5	4.2	0.1	104.8	23.4	0.08	746.4	0.20	1.83	1
48	0.14	0.8	7.3E-5	655.8	-44.8	3.0	4.1	0.1	94.5	19.2	0.08	744.5	0.21	1.92	1
49	0.14	0.9	3.7E-5	655.6	-44.4	2.6	4.0	0.1	87.7	16.9	0.09	752.4	0.21	2.02	1
50	0.14	1.0	6.2E-5	655.6	-44.0	2.2	3.9	0.1	83.1	16.1	0.09	769.6	0.20	2.11	1
51	0.16	0.1	5.4E-3	663.8	-43.9	7.0	15.0	6.1	NA	NA	NA	NA	NA	NA	3
52	0.16	0.2	7.6E-5	662.2	-44.2	7.0	7.5	4.6	2387.5	NA	0.00	8608.6	0.01	1.81	2
53	0.16	0.3	3.4E-5	660.5	-44.6	7.0	5.9	0.7	472.6	396.2	0.02	2027.4	0.06	1.77	2
54	0.16	0.4	6.7E-5	659.2	-44.9	7.0	5.3	0.4	274	125.1	0.03	1349.5	0.09	1.77	2
55	0.16	0.5	7.4E-5	658.5	-44.9	6.1	5.0	0.3	196.5	71.2	0.04	1085.3	0.12	1.79	1
56	0.16	0.6	3.7E-5	658.0	-44.6	4.9	4.8	0.2	151.9	45.2	0.05	933.1	0.15	1.81	1
57	0.16	0.7	8.4E-5	657.7	-44.2	4.1	4.6	0.2	128.2	33.6	0.06	865	0.16	1.87	1
58	0.16	0.8	6.6E-5	657.5	-43.7	3.5	4.5	0.2	113.3	27.2	0.06	832	0.17	1.93	1
59	0.16	0.9	7.6E-5	657.5	-43.4	3.0	4.4	0.2	104	24	0.07	821.5	0.18	2.01	1
60	0.16	1.0	2.7E-5	657.6	-43.1	2.5	4.3	0.2	98.2	23.1	0.07	827.4	0.18	2.08	1
61	0.18	0.1	7.0E-4	663.5	-43.9	7.0	15.0	2.7	NA	NA	NA	NA	NA	NA	3
62	0.18	0.2	1.7E-2	662.2	-44.1	7.0	15.0	10.0	NA	NA	NA	NA	NA	NA	3
63	0.18	0.3	2.3E-5	660.7	-44.3	7.0	7.0	2.1	1183.2	NA	0.01	5265.1	0.02	1.82	2
64	0.18	0.4	1.1E-4	659.7	-44.2	7.0	6.1	0.8	474.4	402.7	0.02	2369.2	0.05	1.81	2
65	0.18	0.5	5.2E-5	659.0	-43.9	7.0	5.6	0.5	311.8	169.9	0.02	1717.8	0.07	1.83	2
66	0.18	0.6	8.5E-5	658.9	-43.4	6.6	5.4	0.4	234.6	99.3	0.03	1409.1	0.09	1.85	1
67	0.18	0.7	8.3E-5	659.0	-43.0	5.3	5.1	0.3	186.1	69.1	0.04	1203.1	0.11	1.89	1
68	0.18	0.8	3.6E-5	659.2	-42.6	4.4	5.0	0.3	157.9	53.3	0.04	1090.7	0.12	1.94	1
69	0.18	0.9	7.3E-5	659.4	-42.3	3.7	4.8	0.3	141.9	45.5	0.05	1036.9	0.13	2.00	1
70	0.18	1.0	4.3E-5	659.6	-42.0	3.1	4.8	0.3	133.2	43.4	0.05	1021.3	0.13	2.06	1

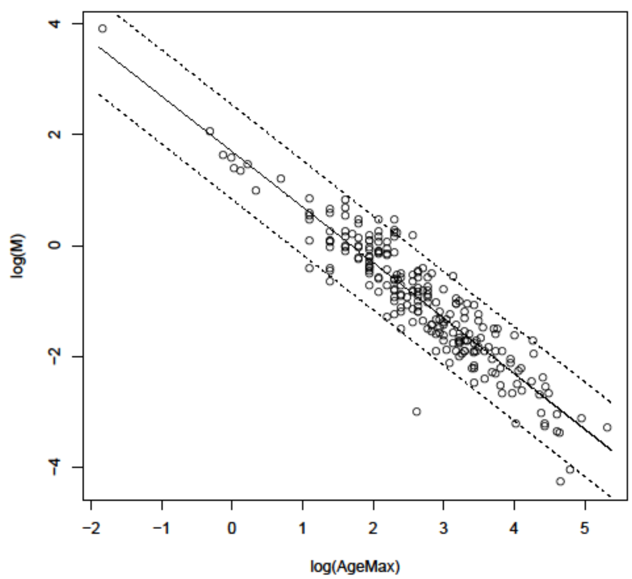
Appendix Table C.6. Summary of model results of Scenario D ($L_{50\%}$ 160.7 cm and 4 pups per year) at various levels of M and z_{frac}. Important quantities including, total (NLL_{tot}) and index (NLL_{idx}) negative log-likelihoods, virgin recruitment (log-scale; LN_R0); number of mature females in 2014 (SB_{2014}; 1000s of fish); fishing intensity (F; calculated as 1-SPR); maximum sustainable yield (MSY; t) are included. Overfishing is occurring if F_{2014}/F_{MSY} >1; and the stock is overfished if SB_{2014}/S_{BMSY} < 1. Color codes for convergence are the same as Fig. C.5. Number codes for convergence are: 1=likely convergence; 2=possible non-convergence; and 3) definite non-convergence.

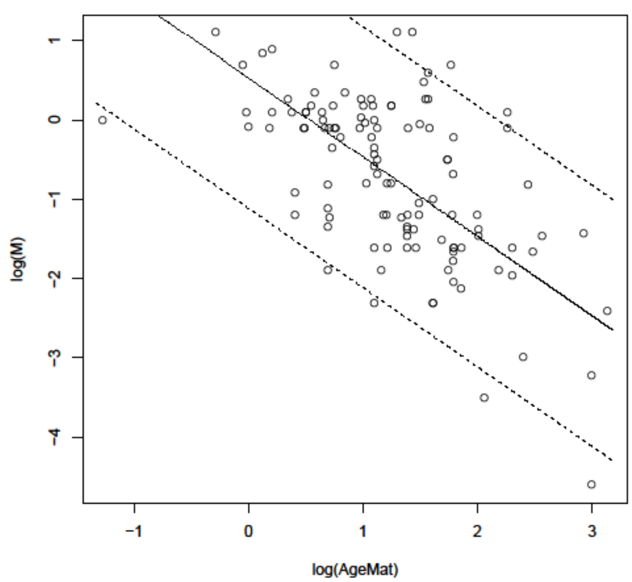
	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
1	0.06	0.1	8.8E-5	663.8	-44.5	7.0	4.6	0.4	466.6	289.0	0.05	740.6	0.16	1.45	2
2	0.06	0.2	9.0E-5	659.3	-45.9	5.8	3.8	0.2	208.9	80.2	0.09	554.5	0.26	1.36	1
3	0.06	0.3	3.8E-5	655.7	-47.1	3.8	3.5	0.1	141.8	39.4	0.11	551.7	0.29	1.41	1
4	0.06	0.4	5.7E-5	653.8	-47.5	2.7	3.3	0.1	117.7	28.4	0.12	591.7	0.28	1.58	1
5	0.06	0.5	6.7E-5	653.1	-47.5	2.0	3.1	0.1	101.3	NA	0.14	646.6	0.26	1.73	2
6	0.06	0.6	3.9E-5	653.0	-47.2	1.5	3.0	0.1	90.1	NA	0.15	709.7	0.24	1.83	2
7	0.06	0.7	4.7E-5	653.0	-46.9	1.2	3.0	0.2	83.0	NA	0.15	766.1	0.21	1.85	2
8	0.06	0.8	7.0E-5	653.1	-46.7	0.9	2.9	0.2	78.9	NA	0.16	786.3	0.19	1.75	2
9	0.06	0.9	3.2E-5	653.2	-46.6	0.7	3.0	0.2	77.1	NA	0.16	737.6	0.18	1.47	2
10	0.06	1.0	1.6E-4	653.3	-46.5	0.6	3.0	0.2	76.7	NA	0.16	639.0	0.17	1.04	2
11	0.08	0.1	8.2E-5	664.1	-44.3	7.0	5.0	0.5	549.3	389.7	0.03	1059.4	0.11	1.57	2
12	0.08	0.2	5.1E-5	660.3	-45.3	6.1	4.2	0.2	228.6	82.5	0.07	673.1	0.20	1.53	1
13	0.08	0.3	7.2E-5	657.0	-46.4	4.2	3.8	0.1	140.6	39.7	0.09	608.7	0.26	1.51	1
14	0.08	0.4	8.6E-5	654.2	-47.1	3.2	3.5	0.1	108.6	25.7	0.11	627.5	0.27	1.61	1
15	0.08	0.5	8.0E-5	652.5	-47.3	2.4	3.3	0.1	91.3	19.5	0.12	665.1	0.27	1.75	1
16	0.08	0.6	9.0E-5	651.7	-47.1	1.9	3.2	0.1	79.0	NA	0.14	713.6	0.25	1.87	2
17	0.08	0.7	3.0E-5	651.4	-46.8	1.5	3.1	0.1	70.3	NA	0.15	766.0	0.24	1.97	2
18	0.08	0.8	2.1E-5	651.4	-46.5	1.2	3.0	0.1	64.4	NA	0.15	811.8	0.22	2.00	2
19	0.08	0.9	7.3E-6	651.5	-46.2	1.0	3.0	0.2	61.0	NA	0.16	829.9	0.20	1.92	2
20	0.08	1.0	1.8E-5	651.6	-46.1	0.8	3.0	0.2	59.5	NA	0.16	792.5	0.18	1.69	2
21	0.10	0.1	4.9E-5	663.9	-44.2	7.0	5.5	0.8	654.5	589.1	0.02	1498.2	0.08	1.66	2
22	0.10	0.2	6.3E-5	660.6	-45.1	6.6	4.5	0.2	248.6	94.6	0.05	820.7	0.16	1.63	1
23	0.10	0.3	8.9E-5	657.9	-45.9	4.5	4.1	0.1	145.5	39.8	0.08	671.4	0.22	1.61	1
24	0.10	0.4	8.5E-5	655.3	-46.5	3.5	3.8	0.1	108.0	25.0	0.10	663.5	0.25	1.67	1
25	0.10	0.5	7.0E-5	653.1	-46.9	2.8	3.6	0.1	89.0	18.5	0.11	691.4	0.25	1.77	1
26	0.10	0.6	1.2E-5	651.6	-47.0	2.2	3.4	0.1	76.7	14.9	0.12	730.9	0.25	1.89	1
27	0.10	0.7	8.7E-6	650.8	-46.8	1.8	3.3	0.1	67.8	NA	0.13	777.3	0.24	2.01	2
28	0.10	0.8	2.2E-5	650.4	-46.6	1.5	3.2	0.1	61.1	NA	0.14	826.3	0.23	2.11	2
29	0.10	0.9	8.1E-5	650.3	-46.3	1.2	3.2	0.1	56.5	NA	0.15	867.9	0.22	2.16	2
30	0.10	1.0	6.6E-5	650.4	-46.1	1.0	3.2	0.2	54.6	NA	0.15	882.7	0.19	2.08	2
31	0.12	0.1	7.3E-6	663.6	-44.1	7.0	6.0	1.2	852.8	1152.3	0.01	2265.0	0.05	1.72	2
32	0.12	0.2	2.1E-5	660.4	-44.9	7.0	4.9	0.3	277.7	116.7	0.04	1027.4	0.12	1.69	2
33	0.12	0.3	1.0E-4	658.4	-45.5	4.8	4.3	0.2	151.7	42.4	0.07	749.8	0.19	1.68	1
34	0.12	0.4	4.1E-5	656.1	-46.1	3.7	4.0	0.1	109.7	25.4	0.08	703.2	0.22	1.72	1
35	0.12	0.5	7.7E-5	654.0	-46.5	3.0	3.8	0.1	89.1	18.4	0.10	714.1	0.24	1.80	1
36	0.12	0.6	2.5E-5	652.3	-46.7	2.5	3.7	0.1	76.5	14.7	0.11	745.5	0.24	1.91	1
37	0.12	0.7	6.8E-6	651.1	-46.7	2.1	3.6	0.1	67.6	12.4	0.12	786.7	0.24	2.01	1

	M	z_{frac}	Max grad.	NLL_{tot}	NLL_{idx}	Beta	LN_R0	SD LN_R0	SB_{2014}	SD SB_{2014}	F_{2014}	MSY	$\frac{F_{2014}}{F_{MSY}}$	$\frac{SB_{2014}}{SB_{MSY}}$	Conv.
38	0.12	0.8	7.0E-4	650.3	-46.6	1.7	3.5	0.1	61.1	NA	0.13	831.4	0.23	2.12	2
39	0.12	0.9	1.3E-4	650.0	-46.3	1.4	3.4	0.1	57.3	NA	0.13	870.1	0.22	2.24	2
40	0.12	1.0	7.5E-5	650.1	-46.1	1.1	3.4	0.1	55.1	NA	0.14	906.0	0.20	2.27	2
41	0.14	0.1	5.3E-5	663.1	-44.1	7.0	6.8	2.9	1458.7	NA	0.01	4408.2	0.02	1.78	2
42	0.14	0.2	8.9E-5	660.1	-44.8	7.0	5.2	0.4	310.5	156.0	0.03	1281.0	0.10	1.73	2
43	0.14	0.3	1.0E-4	658.4	-45.3	5.3	4.6	0.2	162.8	50.0	0.05	861.7	0.16	1.73	1
44	0.14	0.4	6.5E-5	656.6	-45.8	3.9	4.3	0.1	113.6	27.4	0.07	756.8	0.20	1.76	1
45	0.14	0.5	8.2E-5	654.8	-46.2	3.2	4.1	0.1	90.6	19.2	0.09	741.9	0.22	1.82	1
46	0.14	0.6	9.5E-5	653.2	-46.4	2.7	3.9	0.1	77.2	15.1	0.10	759.2	0.23	1.91	1
47	0.14	0.7	5.0E-5	651.9	-46.5	2.3	3.8	0.1	68.2	12.7	0.11	791.6	0.23	2.00	1
48	0.14	0.8	8.7E-5	650.9	-46.4	1.9	3.7	0.1	62.3	11.0	0.11	826.5	0.22	2.13	1
49	0.14	0.9	3.7E-5	650.5	-46.1	1.6	3.6	0.1	58.4	NA	0.12	864.3	0.21	2.25	2
50	0.14	1.0	3.4E-4	650.5	-45.9	1.3	3.6	0.1	55.9	0.0	0.12	905.8	0.20	2.33	2
51	0.16	0.1	1.1E-2	662.7	-44.1	7.0	13.1	237.1	NA	NA	NA	NA	NA	NA	3
52	0.16	0.2	9.5E-5	659.9	-44.7	7.0	5.6	0.5	363.8	230.7	0.02	1653.8	0.07	1.76	2
53	0.16	0.3	7.4E-5	658.3	-45.2	6.0	4.9	0.3	183.1	64.2	0.04	1035.2	0.13	1.77	1
54	0.16	0.4	2.9E-5	656.9	-45.6	4.3	4.6	0.2	120.7	31.5	0.06	835.3	0.17	1.79	1
55	0.16	0.5	6.3E-5	655.3	-45.9	3.5	4.3	0.1	94.1	20.9	0.07	783.3	0.19	1.84	1
56	0.16	0.6	6.8E-5	653.9	-46.2	2.9	4.2	0.1	79.3	16.1	0.08	779.7	0.21	1.91	1
57	0.16	0.7	1.7E-5	652.7	-46.3	2.5	4.0	0.1	69.9	13.2	0.09	796.7	0.21	2.00	1
58	0.16	0.8	1.2E-4	651.8	-46.1	2.1	3.9	0.1	64.1	11.6	0.10	821.8	0.21	2.12	1
59	0.16	0.9	4.9E-5	651.4	-45.8	1.8	3.9	0.1	60.0	10.6	0.11	854.5	0.20	2.23	1
60	0.16	1.0	2.0E-5	651.4	-45.6	1.5	3.8	0.1	57.3	NA	0.11	892.0	0.19	2.33	2
61	0.18	0.1	4.8E-3	662.4	-44.1	7.0	15.0	14.6	NA	NA	NA	NA	NA	NA	3
62	0.18	0.2	1.3E-5	659.7	-44.6	7.0	6.1	0.8	464.0	NA	0.02	2296.0	0.05	1.79	2
63	0.18	0.3	3.6E-5	658.1	-45.1	7.0	5.3	0.3	215.9	83.5	0.03	1302.6	0.10	1.80	2
64	0.18	0.4	3.7E-5	656.9	-45.4	5.0	4.9	0.2	133.6	39.4	0.05	958.9	0.14	1.81	1
65	0.18	0.5	3.0E-5	655.7	-45.7	3.9	4.6	0.1	100.5	24.3	0.06	848.5	0.17	1.85	1
66	0.18	0.6	7.0E-5	654.5	-46.0	3.2	4.4	0.1	83.1	17.7	0.07	814.9	0.19	1.90	1
67	0.18	0.7	1.7E-5	653.5	-45.9	2.7	4.3	0.1	73.4	14.5	0.08	812.5	0.20	1.99	1
68	0.18	0.8	1.1E-5	652.8	-45.7	2.3	4.2	0.1	66.8	12.5	0.09	824.7	0.20	2.09	1
69	0.18	0.9	8.7E-5	652.5	-45.4	2.0	4.1	0.1	62.3	11.4	0.09	847.3	0.19	2.20	1
70	0.18	1.0	9.0E-6	652.4	-45.2	1.6	4.0	0.1	59.3	10.9	0.10	876.9	0.19	2.30	1

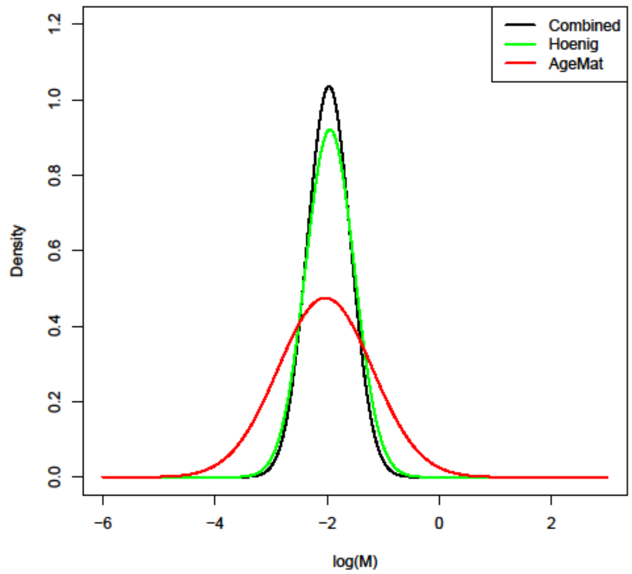


Appendix Figure C.1. Maturity ogive of female common thresher sharks in the northwest Atlantic Ocean. Data from Natanson and Gervelis (2013) (vertical lines along top and bottom of figure) were fit to a binomial GLM with a logit link function. Dotted lines indicate approximate length at which 50% of the female sharks were expected to be mature. The $L_{50\%}$ and slope were estimated to be 215.1 cm and -0.2409 cm^{-1}, respectively.

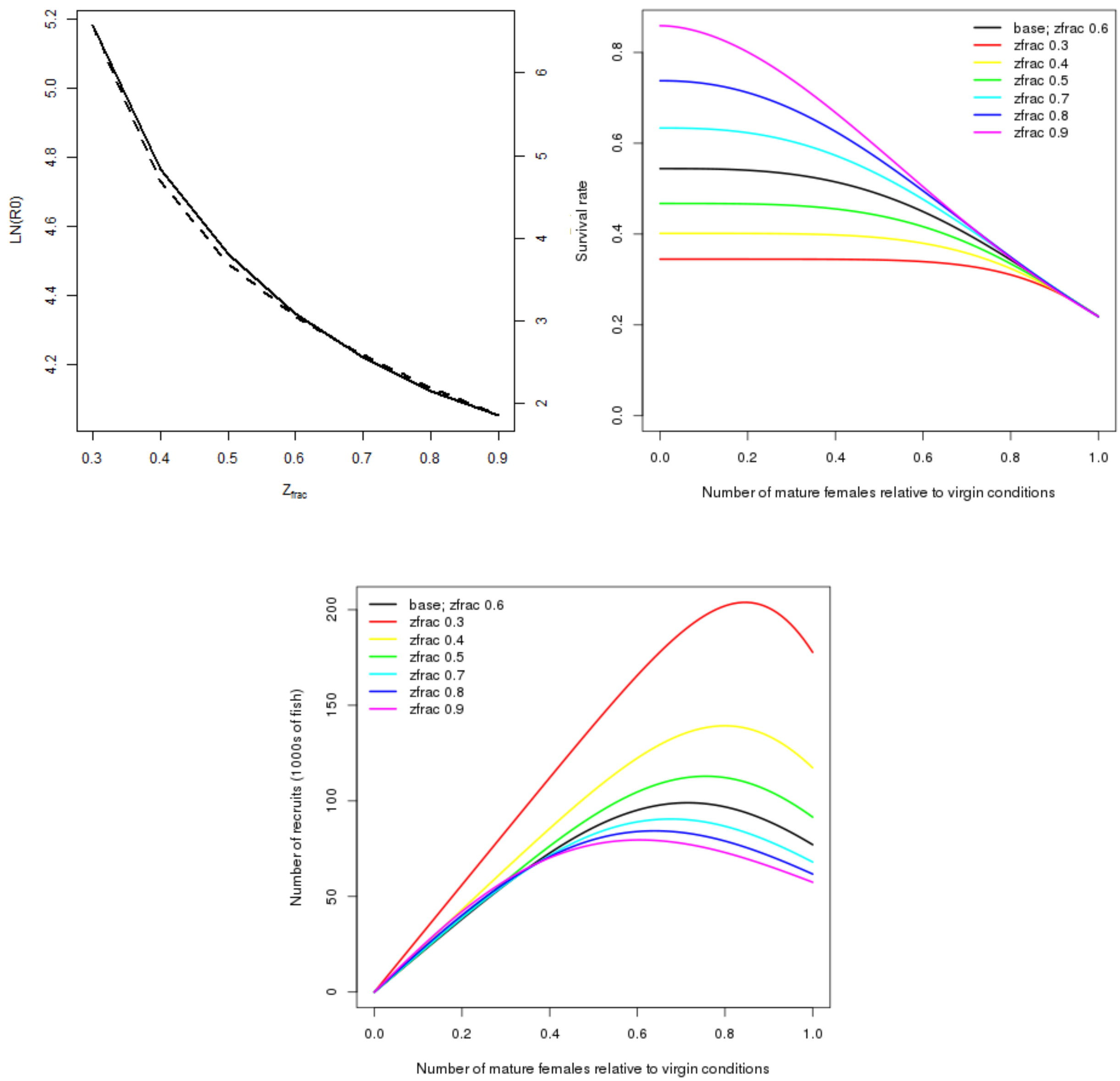




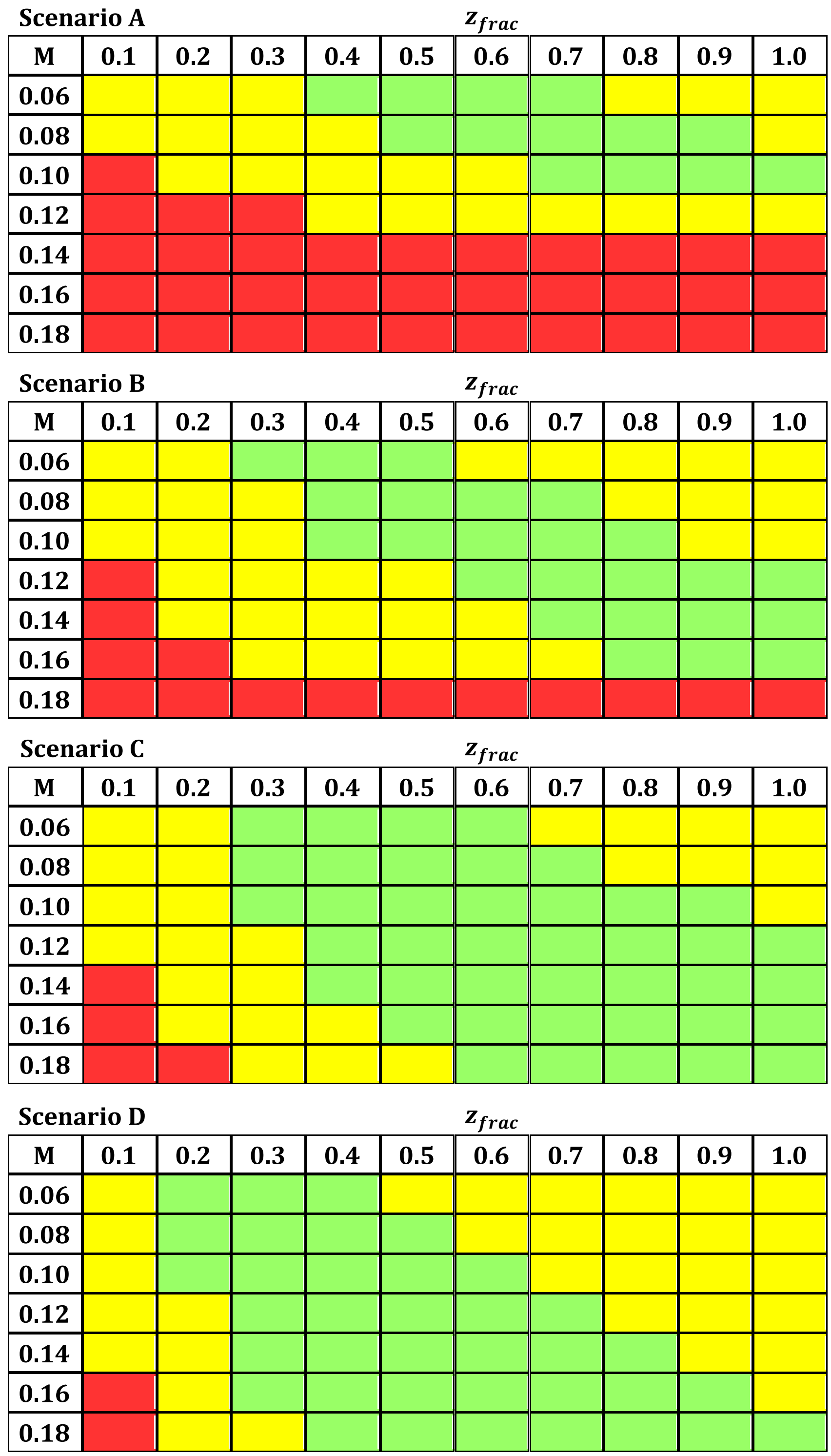
Appendix Figure C.2. Regressions of maximum age (upper panel) and age at maturity (lower panel), with natural mortality (all in log space). Dashed lines indicate 95% prediction intervals. Slopes were fixed at -1. See Table 2 for parameter estimates.



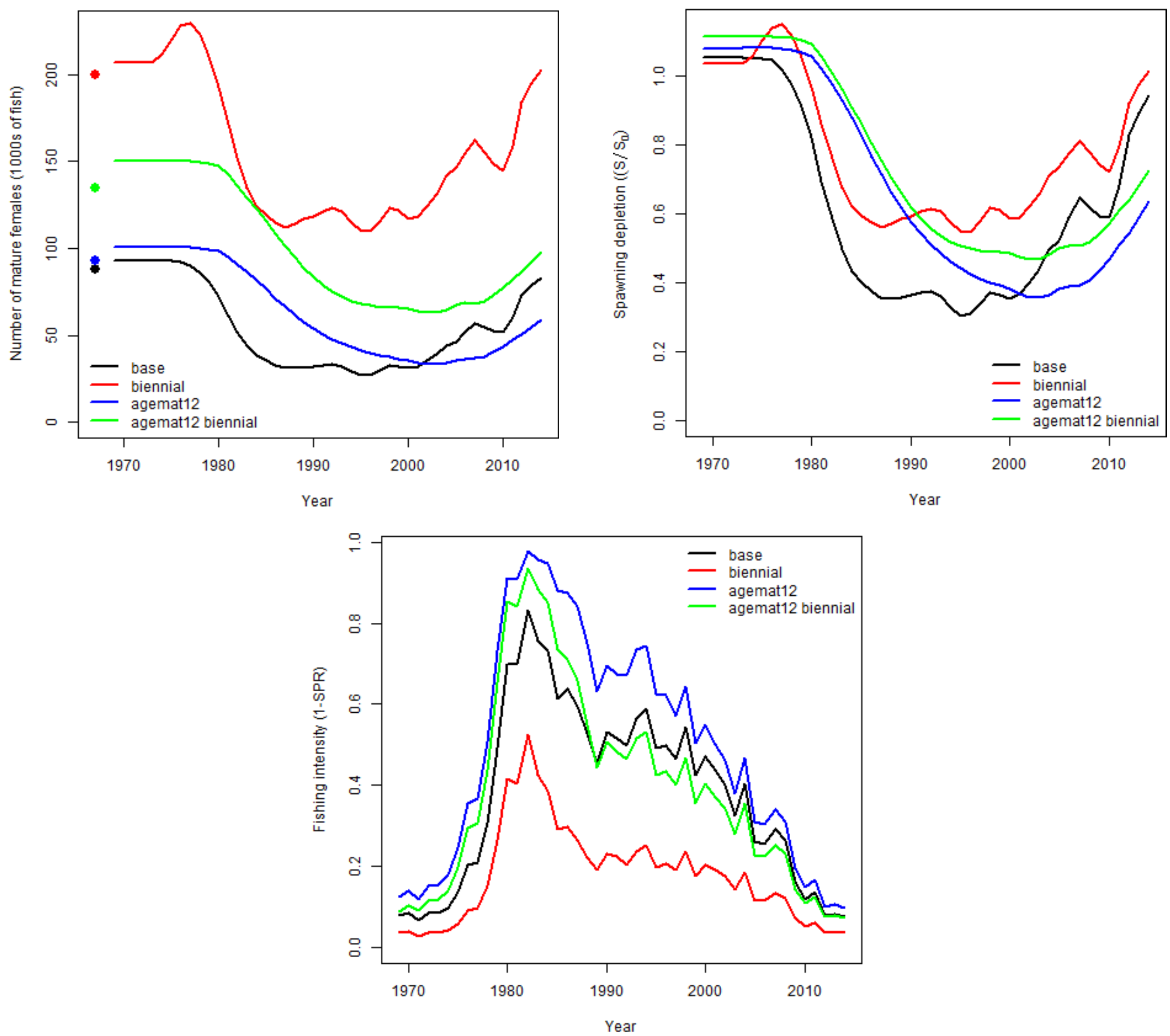
Appendix Figure C.3. Estimated M probability distributions in log space for each meta-analysis. Colored lines indicate priors from each individual meta-analysis. Black line indicates the combined prior.



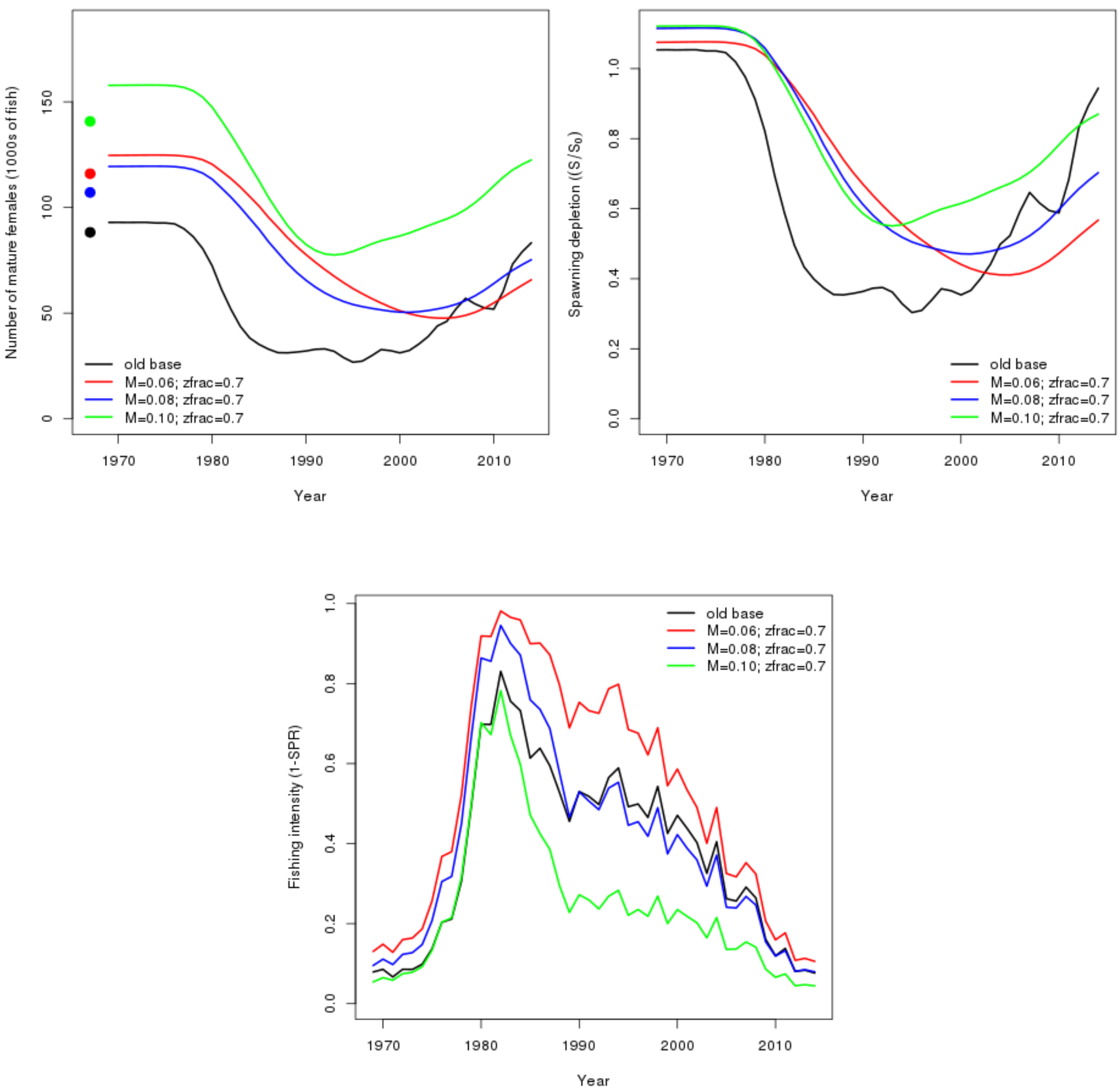
Appendix Figure C.4. Estimated stock-recruitment relationship parameters of virgin recruitment (LN($R0$): solid line) and shape parameter, (β: dashed line) (upper left) under a range of fixed z_{frac} values. Expected pup survival (upper right) and recruitment (lower left) with respect to the number of mature females relative to virgin conditions, which is equivalent to spawning depletion, under a range of fixed z_{frac} values. The base case model in Teo et al. (2016) has a fixed z_{frac} value of 0.6. Modified from Fig 6.3 in Teo et al. (2016).



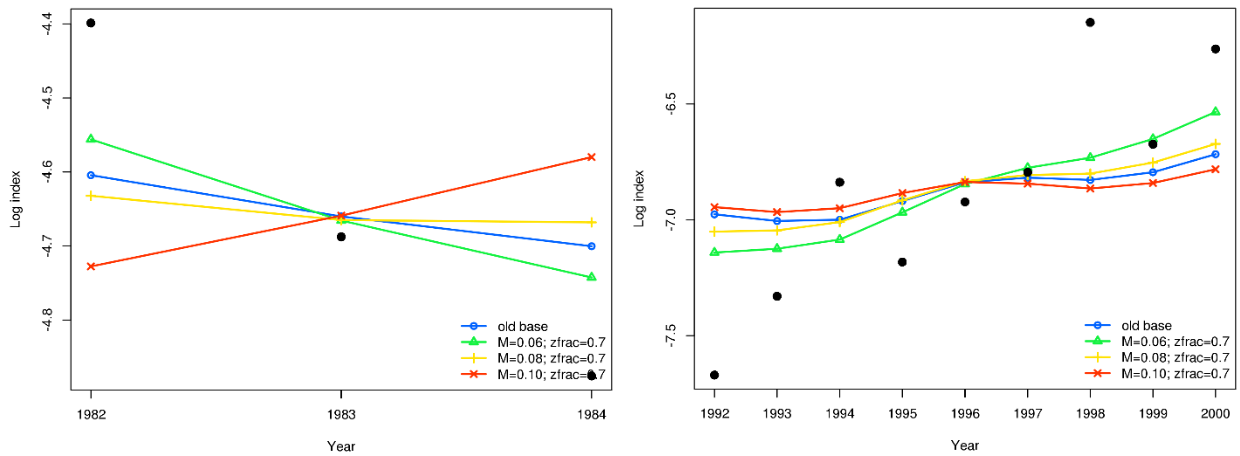
Appendix Figure C.5. Model convergence for four reproductive biology scenarios (Table C.1), and various levels of z_{frac} and *M*. Green indicates likely model convergence, while red and yellow indicate definite (e.g., ‘run away’ population scale) and possible (Hessian, gradient and/or $\beta \geq 7$) non-convergence, respectively. See Tables C.3 – 6.



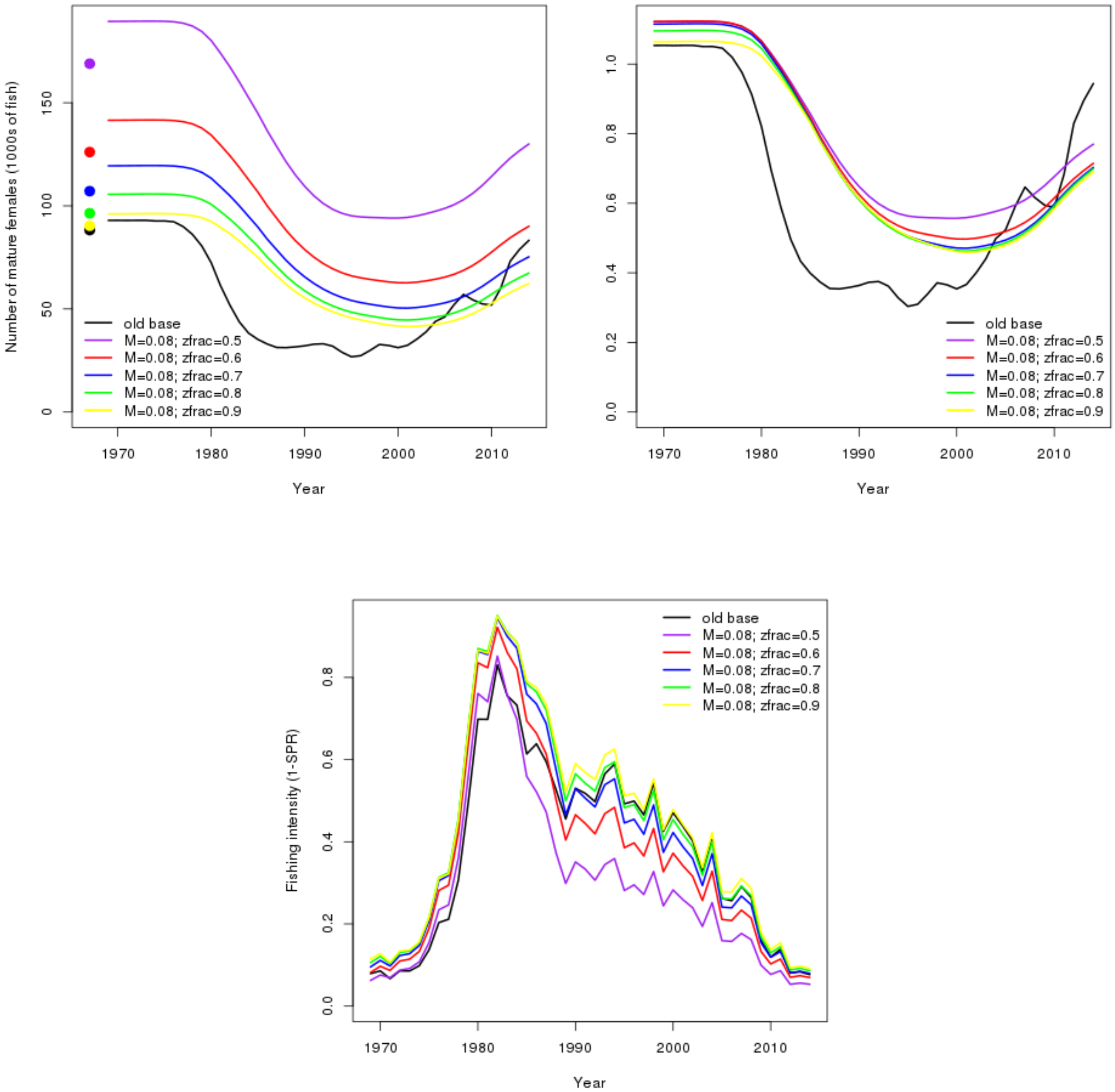
Appendix Figure C.6. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the base case model (black) and sensitivity runs assuming a median age of maturity of 12 years, a biennial reproductive cycle, and a combination of both. Figure 6.9 in Teo et al. (2016).



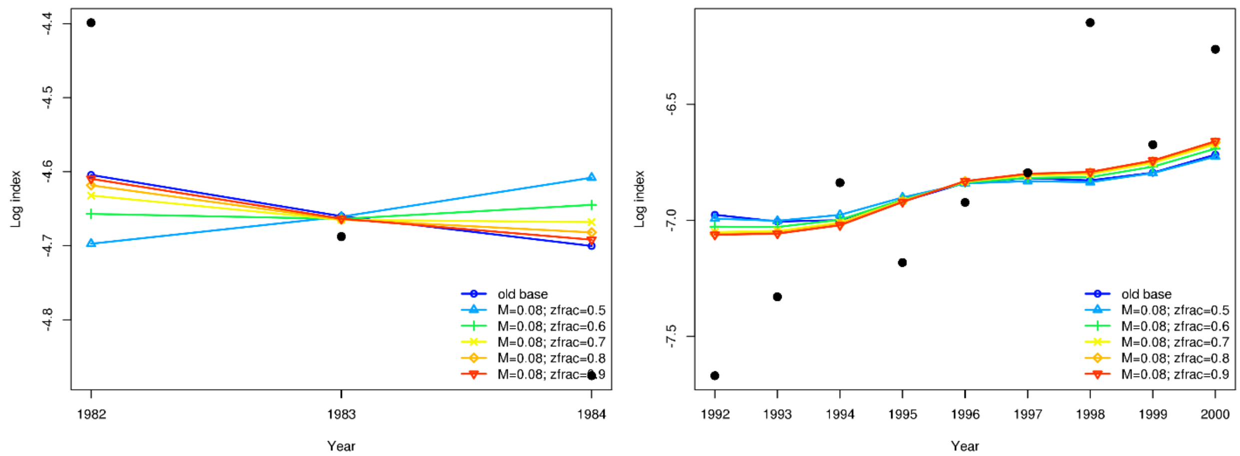
Appendix Figure C.7. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the old base case model (black) and Scenario A (median length at maturity = 215.1 cm; and biennial reproductive cycle) model runs assuming a z_{frac} of 0.7 and M ranging from 0.06 to 0.10.



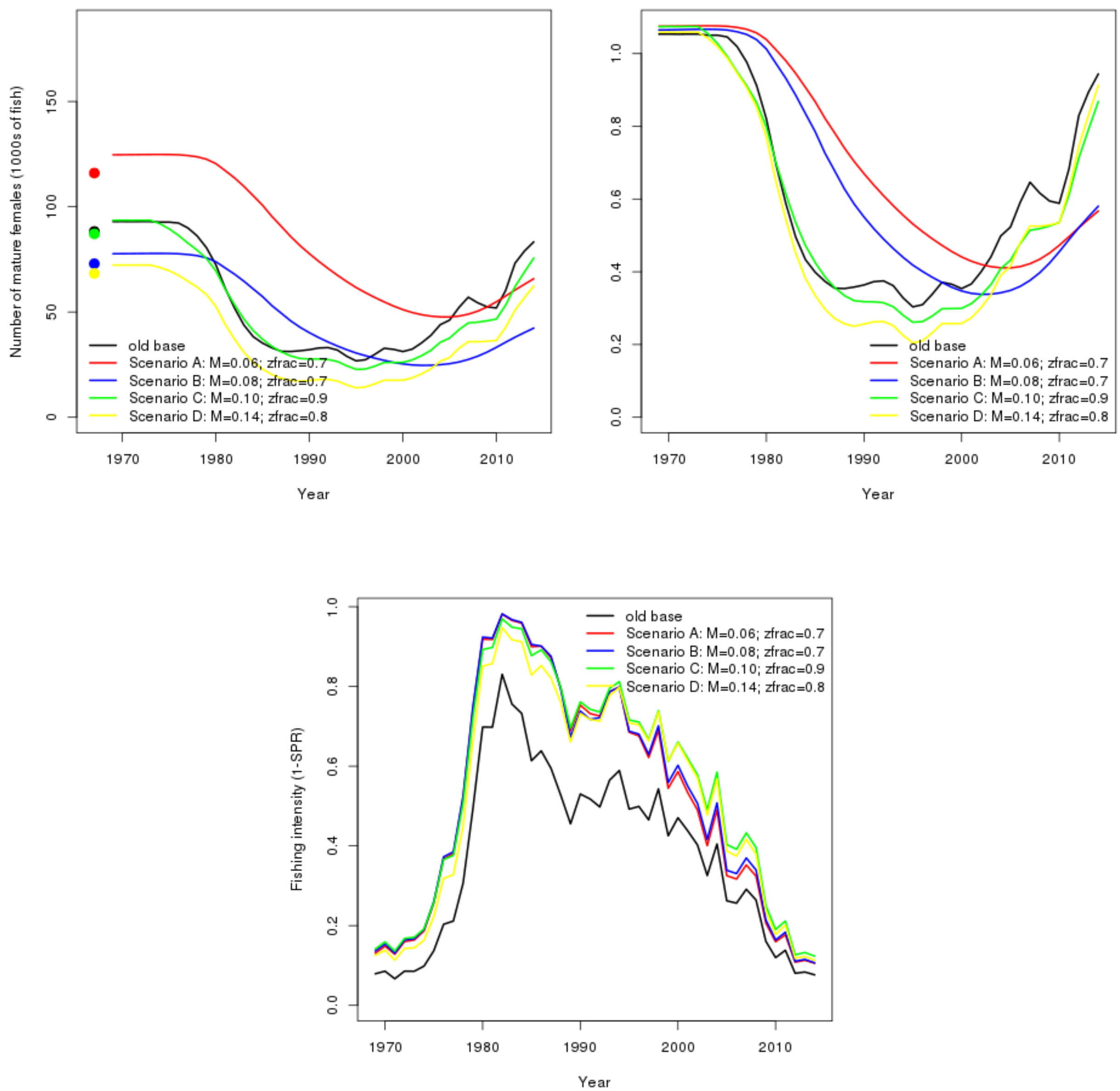
Appendix Figure C.8. Model fit to S1 (left) and S2 (right) indices, which are the primary indices in the base case model in Teo et al. (2016). Black circles indicate observations (in log scale) while colored lines indicate expectations (in log scale) of the old base case model and Scenario A (median length at maturity = 215.1 cm; and biennial reproductive cycle) model runs assuming a z_{frac} of 0.7 and M ranging from 0.06 to 0.10.



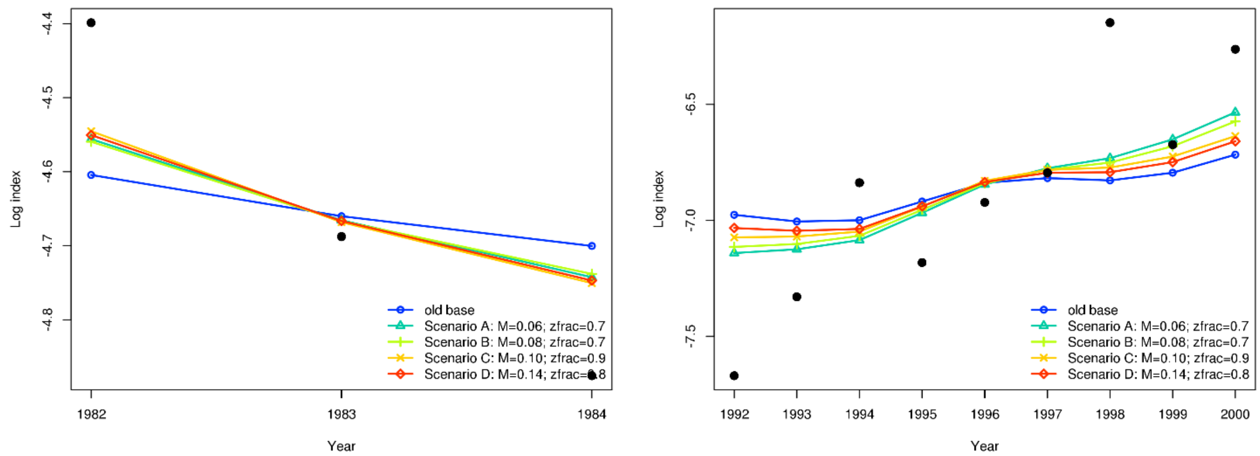
Appendix Figure C.9. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the old base case model (black) and Scenario A (median length at maturity = 215.1 cm; and biennial reproductive cycle) model runs assuming a M of 0.08, and z_{frac} ranging from 0.5 to 0.9.



Appendix Figure C.10. Model fit to S1 (left) and S2 (right) indices, which are the primary indices in the base case model in Teo et al. (2016). Black circles indicate observations (in log scale) while colored lines indicate expectations (in log scale) of the old base case model and Scenario A (median length at maturity = 215.1 cm; and biennial reproductive cycle) model runs assuming a M of 0.08, and z_{frac} ranging from 0.5 to 0.9.



Appendix Figure C.11. Estimated number of mature female sharks (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the old base case model (black) and the best fitting models from Scenario A (NLL_{tot}=655.2; M=0.06; z_{frac}= 0.7), Scenario B (NLL_{tot}=654.8; M=0.08; z_{frac}= 0.7), Scenario C (NLL_{tot}=652.1; M=0.10; z_{frac}= 0.9), and Scenario D (NLL_{tot}=650.9; M=0.14; z_{frac}= 0.8). Scenario A has a median length at maturity of 215.1 cm and a biennial reproductive cycle. Scenario B has a median length at maturity of 215.1 cm and an annual reproductive cycle. Scenario C has a median length at maturity of 160.7 cm and a biennial reproductive cycle. Scenario D has a median length at maturity of 160.7 cm and an annual reproductive cycle.



Appendix Figure C.12. Model fit to S1 (left) and S2 (right) indices, which are the primary indices in the base case model in Teo et al. (2016). Black circles indicate observations (in log scale) while colored lines indicate expectations (in log scale) for the old base case model (black) and the best fitting models from Scenario A (NLL_{tot}=655.2; M=0.06; z_{frac}= 0.7), Scenario B (NLL_{tot}=654.8; M=0.08; z_{frac}= 0.7), Scenario C (NLL_{tot}=652.1; M=0.10; z_{frac}= 0.9), and Scenario D (NLL_{tot}=650.9; M=0.14; z_{frac}= 0.8). Scenario A has a median length at maturity of 215.1 cm and a biennial reproductive cycle. Scenario B has a median length at maturity of 215.1 cm and an annual reproductive cycle. Scenario C has a median length at maturity of 160.7 cm and a biennialof reproductive cycle. Scenario D has a median length at maturity of 160.7 cm and an annual reproductive cycle.

APPENDIX D: Abundance indices for the USA swordfish/shark gillnet fishery

INTRODUCTION

The most important commercial fishery for common thresher sharks is the USA swordfish/shark drift gillnet (USDGN) fishery, which began in 1977-78 (Hanan et al. 1993). The USDGN fishery began with about 15 vessels in Southern California but the number of vessels grew rapidly (Hanan et al. 1993). Although the initial primary targets were common thresher and shortfin mako sharks, fishermen soon discovered that they could efficiently catch swordfish with the same gear, and switched to primarily targeting swordfish because of substantially higher ex-vessel prices (Hanan et al. 1993). Since those early days, the primary target of the USDGN fishery has been swordfish, with common thresher and shortfin mako sharks being secondary targets.

Fishing operations of the USDGN fishery have been heavily regulated to reduce adverse interactions with other fisheries, fishing mortality of common thresher sharks, and incidental bycatch of marine mammals and sea turtles (Hanan et al. 1993; PFMC 2003). Details of current and historical regulations have been documented by Hanan et al. (1993), PFMC (2003), and PFMC (2015) (Table 1.1 in the main document). There appeared to be three major periods for the USDGN fishery with respect to fishery operations and regulations: 1) 1977 – 1991; 2) 1992 – 2000; and 3) 2001 – 2014. The first period (1977-1991) encompassed the initial expansion of the fishery and the switch from primarily targeting pelagic sharks to swordfish. There were also early attempts at regulating the USDGN fishery, which resulted in frequent changes in regulations that included gear restrictions, swordfish catch, swordfish to shark catch ratios, seasonal closures, and time-area closures. In particular, time-area closures in California were enacted or modified in 1982, 1985, and 1989, which likely affected the CPUE of sharks for the USDGN fishery (Urbisci et al. in review). Washington and Oregon also started and closed their drift gillnet fisheries in 1983 and 1989 respectively. The time-area closures for the USDGN fishery was relatively stable during the second period (1992 – 2000), after the closure period for California was changed to May 1 through August 14 in 1992. The second period was a period of decline in the USDGN fishery, with the number of vessels landing fish declining from 119 in 1992 to 72 in 2000 (PFMC 2015). This decline continued in the third period (2001 – 2014), which was marked by the enactment of a large time-area closure in 2001 to protect leatherback turtles. The number of vessels in the USDGN fishery landing fish declined from 61 in 2001 to 18 in 2014 (PFMC 2015).

Three indices representing different regulatory and operational periods were developed for the USDGN fishery: Index 1: 1982 – 1984; Index 2: 1992 – 2000; and Index 3: 2001 – 2013. Changes in the regulations and fishery operations of this fishery have likely affected the catchability of this fishery (Urbisci et al. in review). The most important regulatory changes occurred in 1982, 1985, 1989, 1992, and 2001, when time-area closures were implemented or changed. For this assessment, we did not attempt to account for the effect of these time-area closures in our GLMs. Instead, we developed shorter time series within the periods when regulatory changes were likely less important. Logbook data for 2014 was also not available by the time that development of abundance indices was completed. An abundance index was not developed for the 1985 – 1991 period because of changing regulations and fishery operations. In addition, preliminary examination of the logbook data indicated that the CPUE of the fishery rapidly increased and decreased several fold during this period, which indicated that changing regulations and fishing operations likely resulted in the exploitation of some local areas of high thresher abundance.

Regulatory changes have affected the start of the fishing season over the years. Therefore, only data from seasons 3 and 4 (i.e., Aug – Oct and Nov – Jan) were used for the abundance indices because fishing consistently occurred during those seasons. Three bimonthly periods within the six month period were used as factors in the GLMs to account for changes in thresher CPUE due to time of year.

The annual decile rank of swordfish catch of a given drift gillnet set was included in the GLMs to account for shifts in the targeting by the fishery from pelagic sharks to swordfish. In the initial development of the fishery, the primary target of the fishery changed from pelagic sharks to swordfish because of higher market prices. However, the targeting switch was constrained by regulations restricting the total amount of monthly swordfish landings and requirements to land equal amounts of shark. Even after regulations restricting swordfish catch were removed, USDGN vessels likely switched between swordfish and pelagic sharks depending on availability and market prices. The annual decile rank of swordfish catch was determined by ranking the swordfish catch from all sets within a given year, and then splitting the ranks into deciles (e.g., 0-10%, 10-20%).

MATERIALS AND METHODS

Data

The abundance indices were developed from set-by-set logbook data submitted by skippers of vessels in the USDGN fishery after a mandatory logbook program was established in 1980, with the initial data collected in the 1981 – 1982 fishing season (Hanan et al. 1993). Data collected by the logbooks include catch (numbers of fish) by species, date, mesh size, net length, hours soaked, set number, and geographical position. Geographical positions were entered as CDFG block numbers (predominantly 10 min by 10 min squares), which were subsequently converted to latitudes and longitudes based on the center of the blocks. Coverage rate of the logbooks (proportion of landed weight reported in the logbooks) was estimated by Hanan et al. (1993) to be poor in the 1981 – 1982 fishing season (1% for thresher sharks) but was very good for all subsequent years, exceeding 100% coverage for most years. The catch and effort in the logbook data therefore appeared to be representative of the fishery, except for the 1981 – 1982 season.

Preliminary examination of the data indicated that two stages of filtering were required before the data could be used for developing abundance indices. The number of sets in the data after each filtering stage is summarized in Table D.1 and the spatial distribution of the sets and catch can be seen in Fig. D.1. The two filtering stages were:

1. Identifying swordfish/shark (large-mesh) drift gill net sets

The original data set included data from small-mesh drift gillnet and set net fisheries targeting coastal and demersal fish species but did not specifically identify sets from the swordfish/shark fishery using large-mesh drift gillnets. The logbook data were therefore filtered to select for data where gear type was identified as “drift gillnet”, and target species identified as swordfish and/or shark, and mesh size was ≥14 inches or unspecified.

2. Identifying abnormal fishing operations

The majority of fishing operations for the USDGN fishery used nets about 1,000 fathoms long and had soak times within 24 hours. However, abnormal fishing operations could result from nets being left in the water, and experimental trips using shorter nets and/or soak times. Sets with abnormal fishing operations or misreported information were identified and removed in the second filtering stage because it was considered inappropriate to use data from these abnormal fishing operations. Abnormal sets were identified based on fishery knowledge. As a result, sets that recorded missing or abnormal soak times (<3 or >17 hours), net lengths (<250 or >2000 m), mesh size (<14 or >23 inches), locations (latitude: <32 or >45°N; distance from shore: >200 km), and depth (>6201 m). In addition, only data from August through January were used for the abundance indices in order to maintain consistency with the fleet definitions used in the assessment model.

The logbook data were divided into strata based on available factors. Season was categorized as three bimonthly periods ([Aug, Sep], [Oct, Nov], [Dec, Jan]). Five areas were defined based on the latitude ([32, 34), [34, 36), [36, 38), [38, 40), and ≥40°N). Other factors included water depth (11 levels: [0, 250), [250, 500), [500, 750), [750, 1000), [1000, 1250), [1250, 1500), [1500, 1750), [1750, 2000), [2000, 3000), [3000, 4000), and ≥4000 m), distance from shore (7 levels: [0, 25), [25, 50), [50, 75), [75, 100), [100, 125), [125, 150), and ≥150 km), mesh size (3 levels: unknown, [14, 19), and ≥19 inches), and percentile rank of swordfish catch (swfrank) (10 levels: [0, 10), [10, 20), [20, 30), [30, 40), [40, 50), [50, 60), [60, 70), [70, 80), [80, 90), [90, 100]%).

Models

Delta-lognormal models (Lo et al. 1992) were used to standardize the catch per unit effort (CPUE) to obtain the abundance indices used in the stock assessment because the data set contained a large proportion of sets with zero thresher catch (Fig. D.2). Catch was defined as the sum of all kept and discarded common thresher sharks in a single set, and effort was defined as the product of the length of the net (km) and soak time (hours). Delta-lognormal models assumes that the proportion of sets with positive catch have a binomial error structure and is modeled by a GLM with a logit link function, and the catch rate of sets with positive catch has a lognormal error distribution and is modeled by a lognormal GLM. The standardized index is the product of the back-transformed marginal year effects (Searle 1980) of these two components, with a correction for the bias in the lognormal back transformation. Estimates of variance were obtained by jackknifing the data set, using a modified version of delta_glm_1-7-2 function (E. J. Dick, pers. comm.) in R (function was modified to allow for different explanatory factors for the binomial and lognormal functions).

A forward-backward stepwise model selection process, with AIC as the selection criteria, was used to determine the set of factors that explained the catch of common thresher sharks in the logbook data. The binomial and lognormal models for each time period were selected independently.

RESULTS AND DISCUSSION

Based on the stepwise model selection process, the final delta-lognormal models for each time period were:

<u>1982 – 1984</u>
Binom: logit(π) ~ year + lat + season + distance + swfrank + depth + offset[log(eff)] + ε
Lognormal: log(catch) ~ year + lat + season + distance + swfrank + depth + offset[log(eff)] + ε

<u>1992 – 2000</u>
Binom: logit(π) ~ year + lat + season + distance + swfrank + depth + mesh + offset[log(eff)] + ε
Lognormal: log(catch) ~ year + lat + distance + swfrank + depth + mesh + offset[log(eff)] + ε

<u>2001 – 2013</u>
Binom: logit(π) ~ year + lat + season + distance + swfrank + depth + mesh + offset[log(eff)] + ε
Lognormal: log(catch) ~ year + lat + season + distance + swfrank + depth + mesh + offset[log(eff)] + ε

where π was the probability of a set having positive common thresher shark catch, and the random error structures of the binomial and lognormal models were assumed to be Binom(n, π) and N(0, σ) respectively. Deviance tables for the three time periods are found in Table D.2. No first-order interactions were included in the final model selection process because abundance indices with or without first-order interactions were highly similar.

Model diagnostics indicated adequate performance of the lognormal and binomial models for all three abundance indices (Fig. D.3 – D.8). For all three time periods, the lognormal residuals were slightly skewed because the lognormal models had problems fitting sets with small numbers of fish. However, the mean predicted values of both the lognormal and binomial component models were highly representative of the observed values after aggregation into spatial and temporal bins.

In the first time period (1982 – 1984), the standardization resulted in an abundance index that was more consistently and more steeply declining than the nominal CPUE (Fig. D.9). The standardized abundance index for the second time period (1992 – 2000) indicated that the common thresher shark population was increasing rapidly during this period but there were moderate amounts of variability in the estimates (Fig. D.10). The lognormal model reduced the variability apparent in the CPUE of positive sets but the variability in the binomial component was not visibly reduced. The third period (2001 – 2013) was marked by high interannual variability in the relative abundance estimates and there were no obvious trends during this period (Fig. D.11). The jackknife procedure resulted in coefficients of variation (CVs) that were relatively high, especially for 1982 – 1984 (Table D.3 and Fig. D.12).

Appendix Table D.1. Amount of data (number of sets) in the logbook data set before and after two stages of filtering for the swordfish/shark drift gillnet fishery.

Period	**Number of sets prior to filtering**	**Number of sets after stage 1 filtering**	**Number of sets after stage 2 filtering**
1982 – 1984	83116	31173	21950
1992 – 2000	79428	28245	25305
2001 – 2013	47844	11511	9699

Appendix Table D.2. Deviance analysis of explanatory variables in delta-lognormal models for common thresher shark catch rates of USA swordfish/shark drift gillnet fishery for three time periods: 1) 1982 – 1984; 2) 1992 – 2000; and 3) 2001 – 2013.

1982 - 1984

Model factors	**Df**	**Deviance**	**Residual Df**	**Residual Deviance**	**Pr(>Chi)**
Binomial: AIC = 21735					
Null			21949	23219	
Year	2	38.18	21947	23180	5.13E-09
Latitude	4	735.70	21943	22445	<2.2E-16
Season	2	184.29	21941	22260	<2.2E-16
Distance from shore	6	374.49	21935	21886	<2.2E-16
Decile rank of swordfish catch	8	99.22	21927	21787	<2.2E-16
Depth	10	118.16	21917	21669	<2.2E-16
Lognormal: AIC = 11416					
Null			4628	4555.1	
Year	2	37.71	4626	4517.4	1.1E-12
Latitude	3	848.51	4623	3668.9	<2.2E-16
Season	2	67.36	4621	3601.6	<2.2E-16
Distance from shore	6	232.39	4615	3369.2	<2.2E-16
Decile rank of swordfish catch	8	123.23	4607	3245.9	<2.2E-16
Depth	10	98.80	4597	3147.2	<2.2E-16

Appendix Table D.2. Continued.

1992 – 2000

Model factors	**Df**	**Deviance**	**Residual Df**	**Residual Deviance**	**Pr(>Chi)**
Binomial: AIC = 18802					
Null			25304	21690	
Year	8	660.11	25296	21030	<2.2E-16
Latitude	4	230.86	25292	20799	<2.2E-16
Season	2	129.00	25290	20670	<2.2E-16
Distance from shore	6	1075.00	25284	19595	<2.2E-16
Decile rank of swordfish catch	8	508.04	25276	19087	<2.2E-16
Depth	10	358.66	25266	18728	<2.2E-16
Mesh	2	8.47	25264	18720	0.0145
Lognormal: AIC = 10043					
Null			3704	4767.4	8.0E-09
Year	8	46.75	3696	4720.7	<2.2E-16
Latitude	4	752.55	3692	3968.1	<2.2E-16
Distance from shore	6	400.48	3686	3567.7	<2.2E-16
Decile rank of swordfish catch	8	264.60	3678	3303.1	<2.2E-16
Depth	10	105.79	3668	3197.3	<2.2E-16
Mesh	2	4.33	3666	3192.9	0.0837

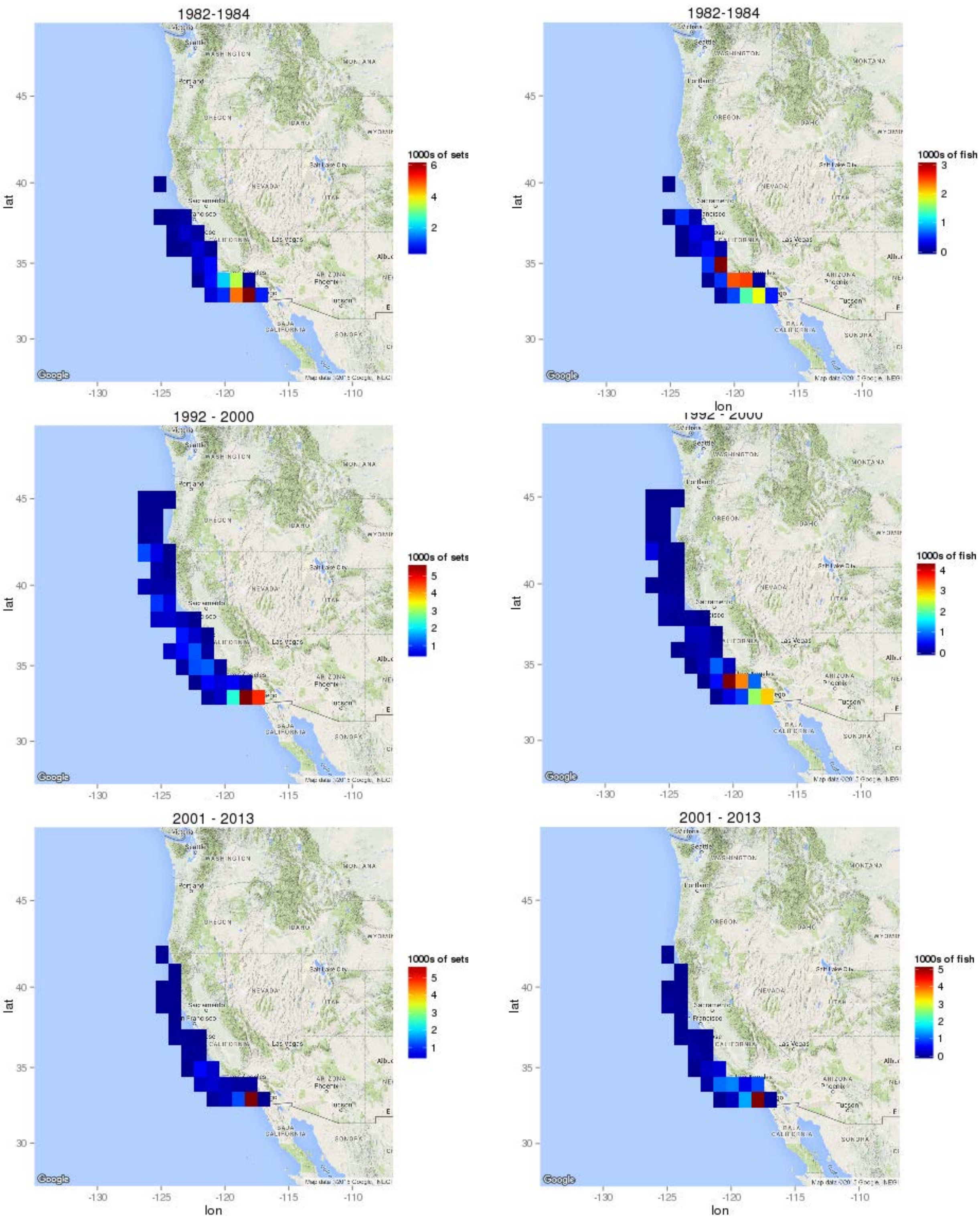
Appendix Table D.2. Continued.

2001 – 2013

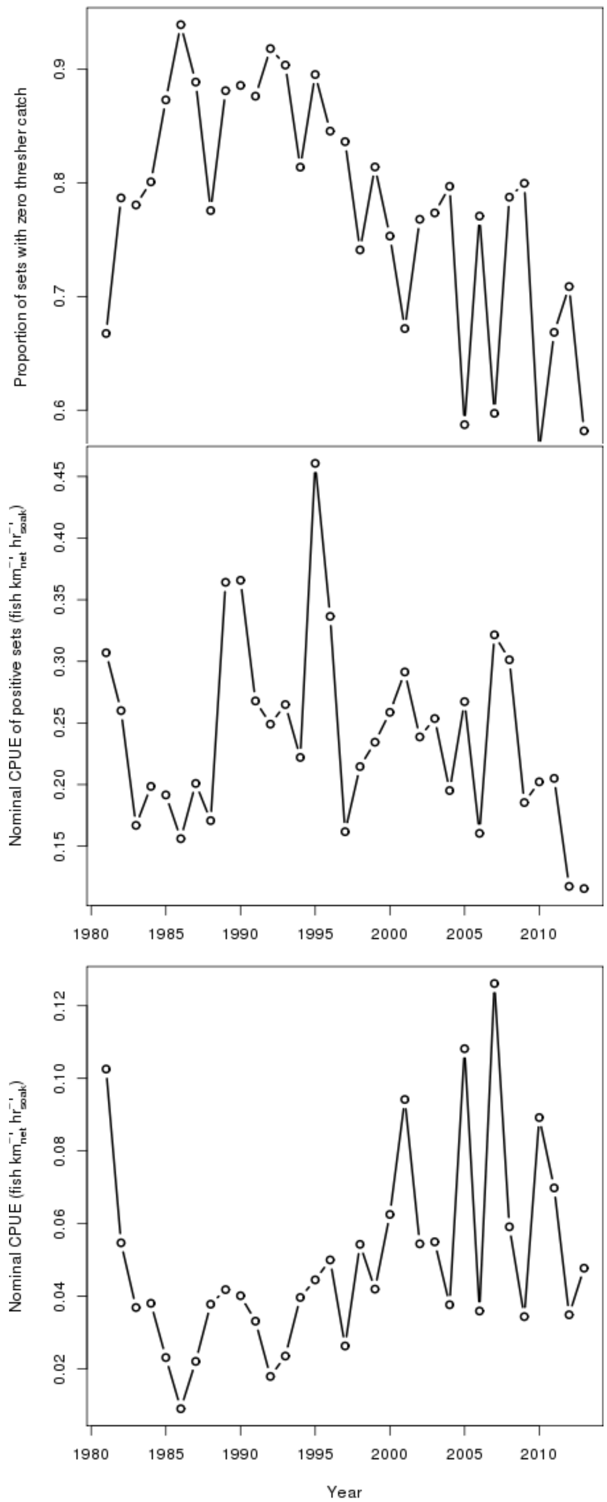
Model factors	**Df**	**Deviance**	**Residual Df**	**Residual Deviance**	**Pr(>Chi)**
Binomial: AIC = 10697					
Null			9698	11891	
Year	12	314.86	9686	11576	<2.2E-16
Latitude	4	13.00	9682	11563	0.0112
Season	2	258.04	9680	11305	<2.2E-16
Distance from shore	6	315.45	9674	10990	<2.2E-16
Decile rank of swordfish catch	9	235.57	9665	10754	<2.2E-16
Depth	10	105.03	9655	10649	<2.2E-16
Mesh	2	43.98	9653	10605	2.8E-10
Lognormal: AIC = 7342.6					
Null			2745	3149.8	
Year	12	80.12	2733	3069.7	3.3E-15
Latitude	4	44.09	2729	3025.6	9.2E-11
Season	2	12.61	2727	3013.0	5.3E-04
Distance from shore	6	461.32	2721	2551.7	<2.2E-16
Decile rank of swordfish catch	9	163.89	2712	2387.8	<2.2E-16
Depth	10	110.77	2702	2277.0	<2.2E-16
Mesh	2	24.69	2700	2252.3	3.7E-07

Table D.3. Estimated relative abundance index values, standard errors (SEs), and coefficients of variation (CVs) for three time periods: 1982 – 1984; 1992 – 2000; and 2001 – 2013 for the USA swordfish/shark drift gillnet fishery. The SEs and CVs were estimated with a jackknife procedure.

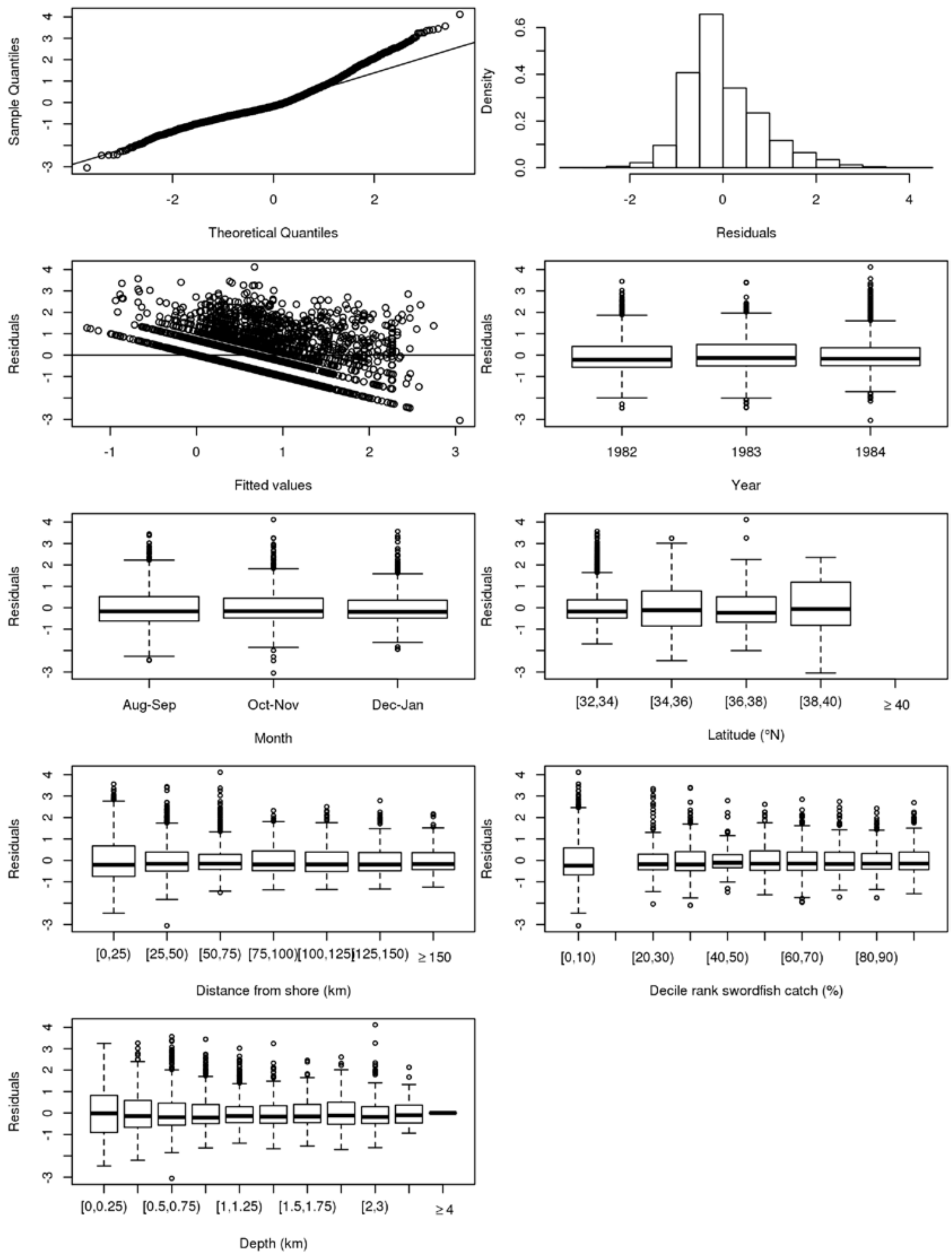
Year	Index	SE	CV
	1982 – 1984		
1982	0.01229	0.00345	0.28035
1983	0.00921	0.00256	0.27814
1984	0.00763	0.00212	0.27842
	1992 – 2000		
1992	0.00047	5.45E-05	0.11681
1993	0.00066	7.40E-05	0.11289
1994	0.00107	1.21E-04	0.11289
1995	0.00076	9.68E-05	0.12739
1996	0.00099	1.24E-04	0.12568
1997	0.00112	1.34E-04	0.11994
1998	0.00214	2.58E-04	0.12047
1999	0.00126	1.64E-04	0.12996
2000	0.00191	2.84E-04	0.14880
	2001 – 2013		
2001	0.01269	0.00250	0.19702
2002	0.00631	0.00128	0.20242
2003	0.00575	0.00122	0.21192
2004	0.00518	0.00112	0.21691
2005	0.01830	0.00372	0.20352
2006	0.00687	0.00137	0.19910
2007	0.02289	0.00451	0.19697
2008	0.00685	0.00151	0.22096
2009	0.00391	8.79E-04	0.22504
2010	0.01745	0.00403	0.23111
2011	0.01148	0.00264	0.23021
2012	0.00711	0.00162	0.22832
2013	0.01244	0.00247	0.19884



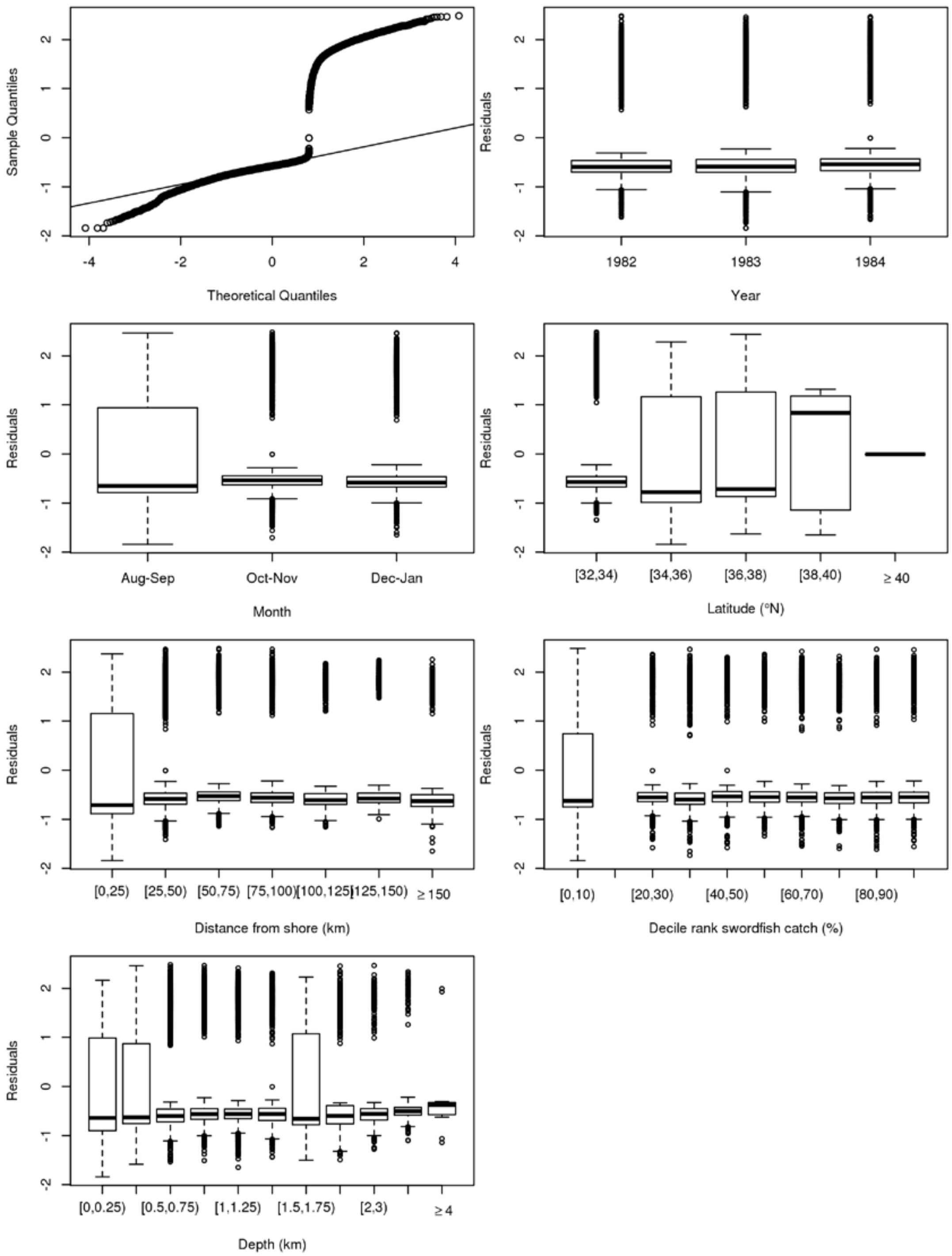
Appendix Figure D.1. Spatial distribution of sets (left) and common thresher shark catch (right) for the USA swordfish/shark drift gillnet fishery over three periods used for abundance indices.



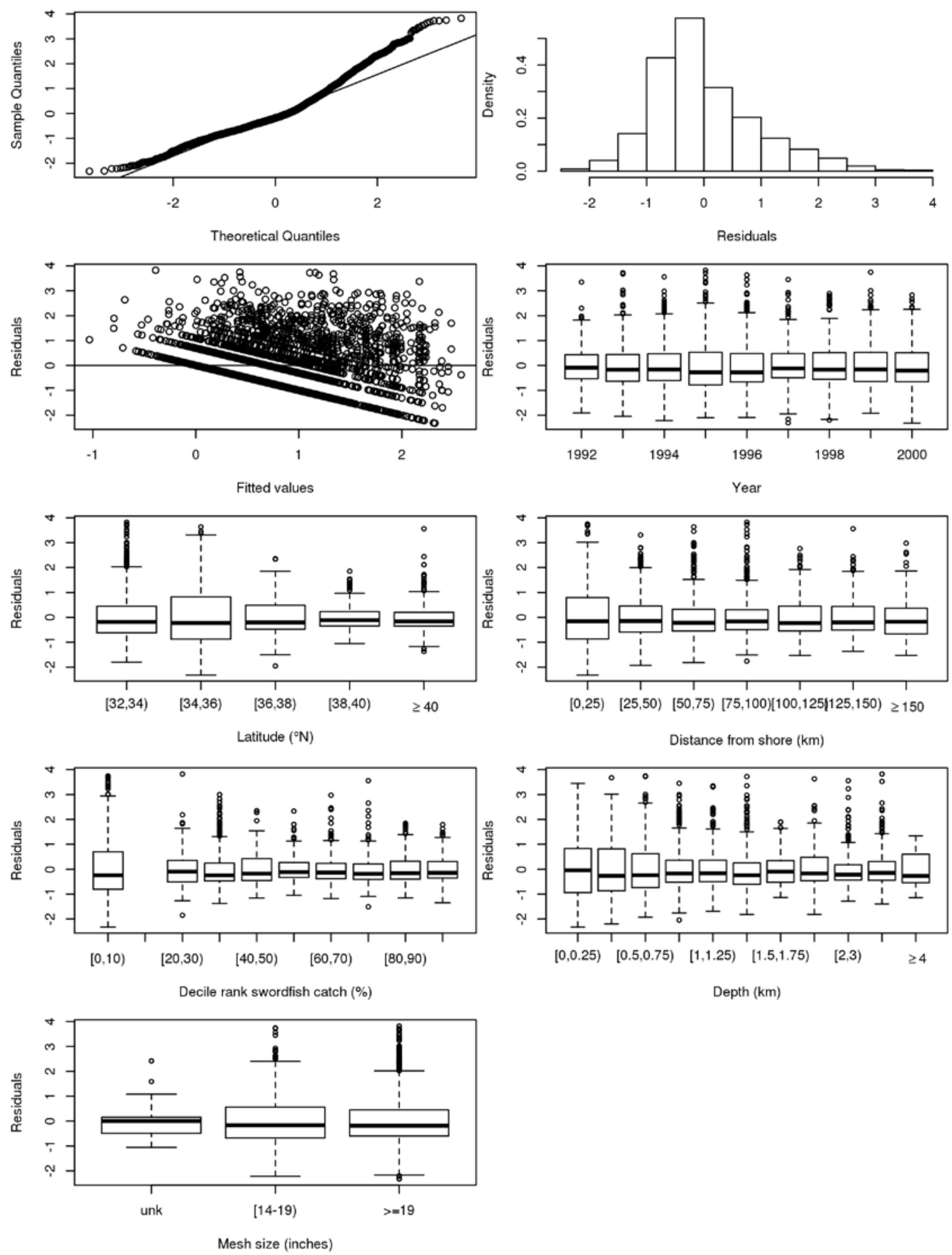
Appendix Figure D.2. Proportion of sets with zero thresher shark catch (upper), nominal catch-per-unit-effort (CPUE) of sets with positive thresher catch (middle), and overall nominal CPUE (lower) for common thresher sharks caught by the USA swordfish/shark drift gillnet fishery.



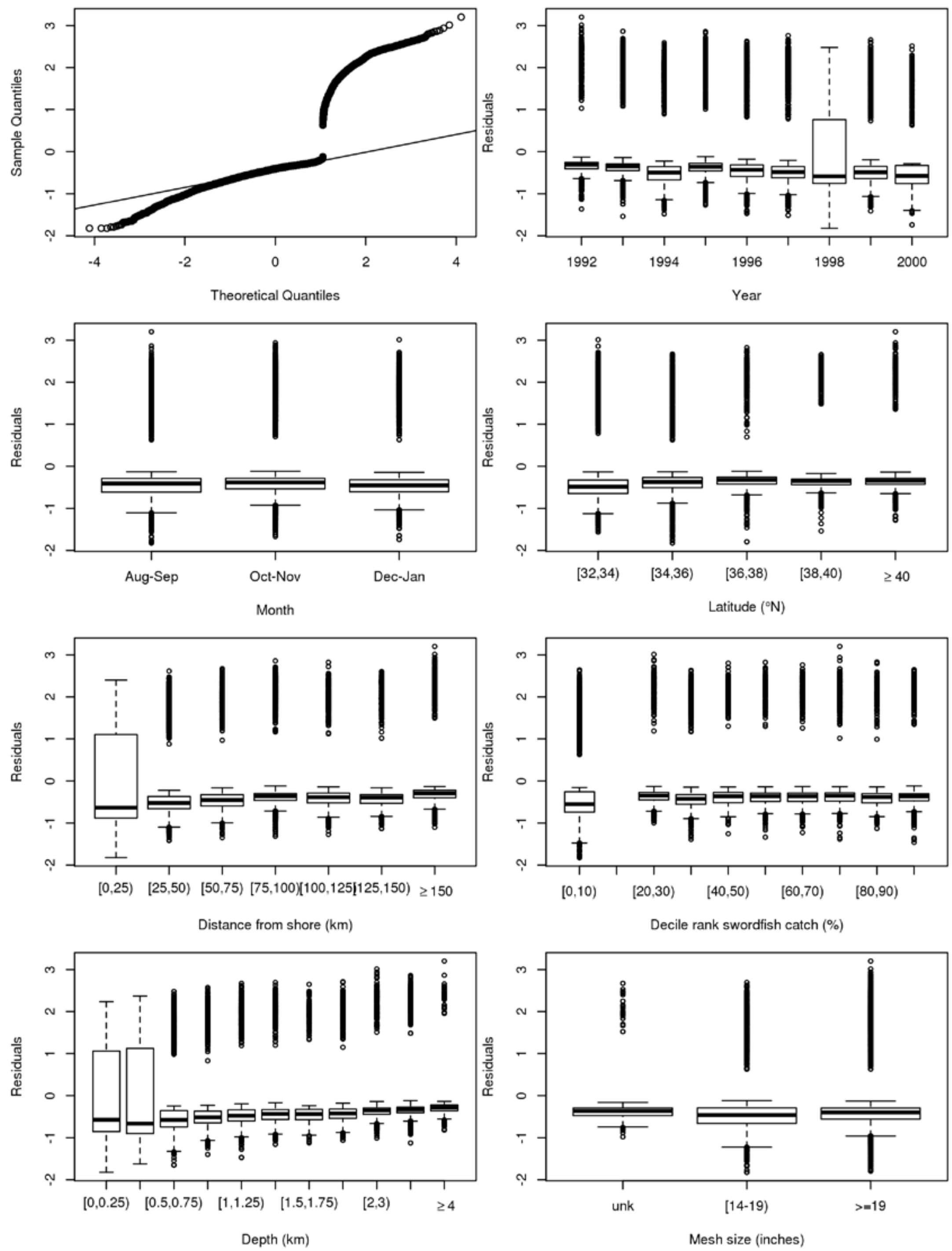
Appendix Figure D.3. Residual plots of the lognormal portion of the delta-lognormal model used to standardize the 1982 – 1984 common thresher shark abundance index for the USA swordfish/shark drift gillnet fishery.



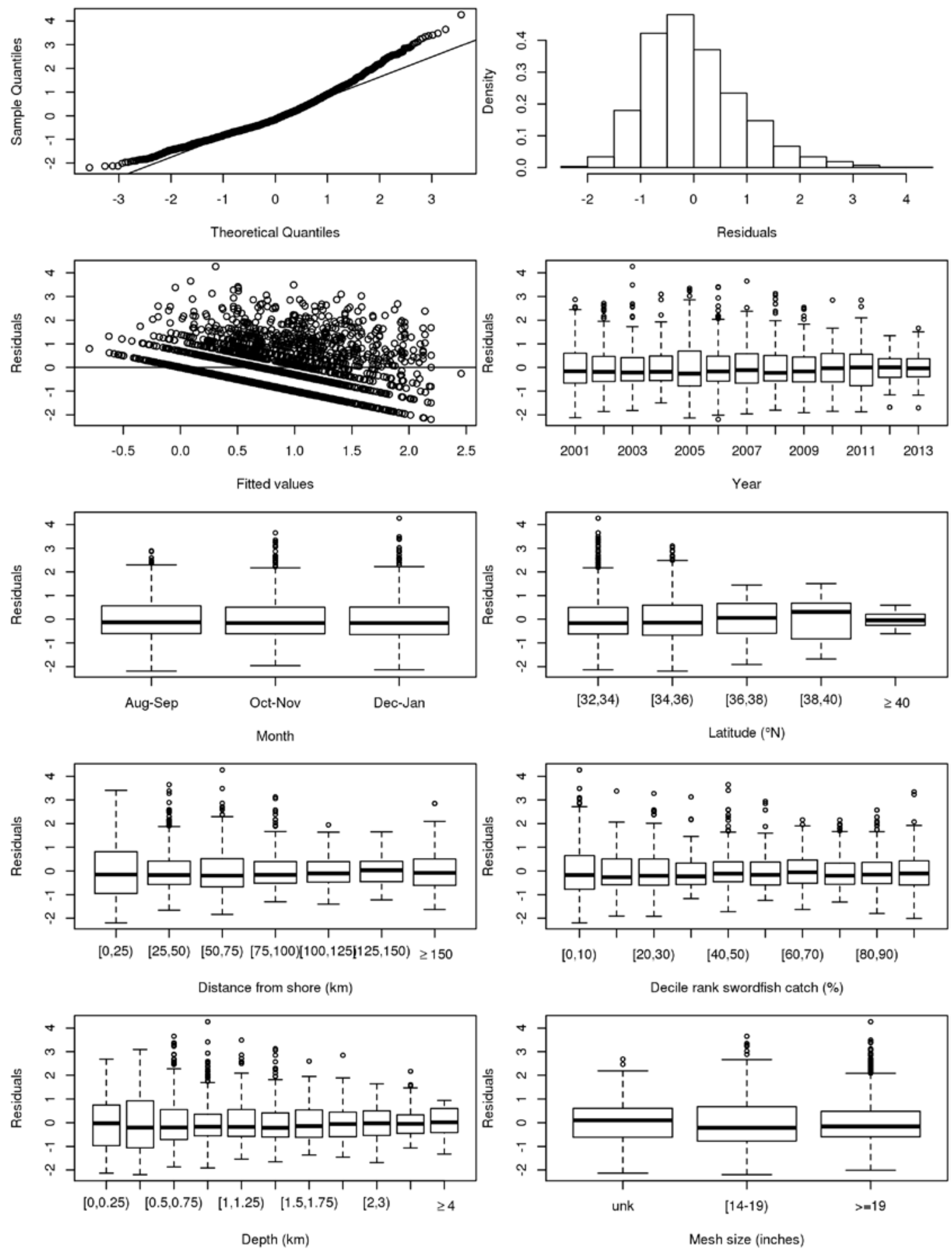
Appendix Figure D.4. Residual plots of the binomial portion of the delta-lognormal model used to standardize the 1982 – 1984 common thresher shark abundance index for the USA swordfish/shark drift gillnet fishery.



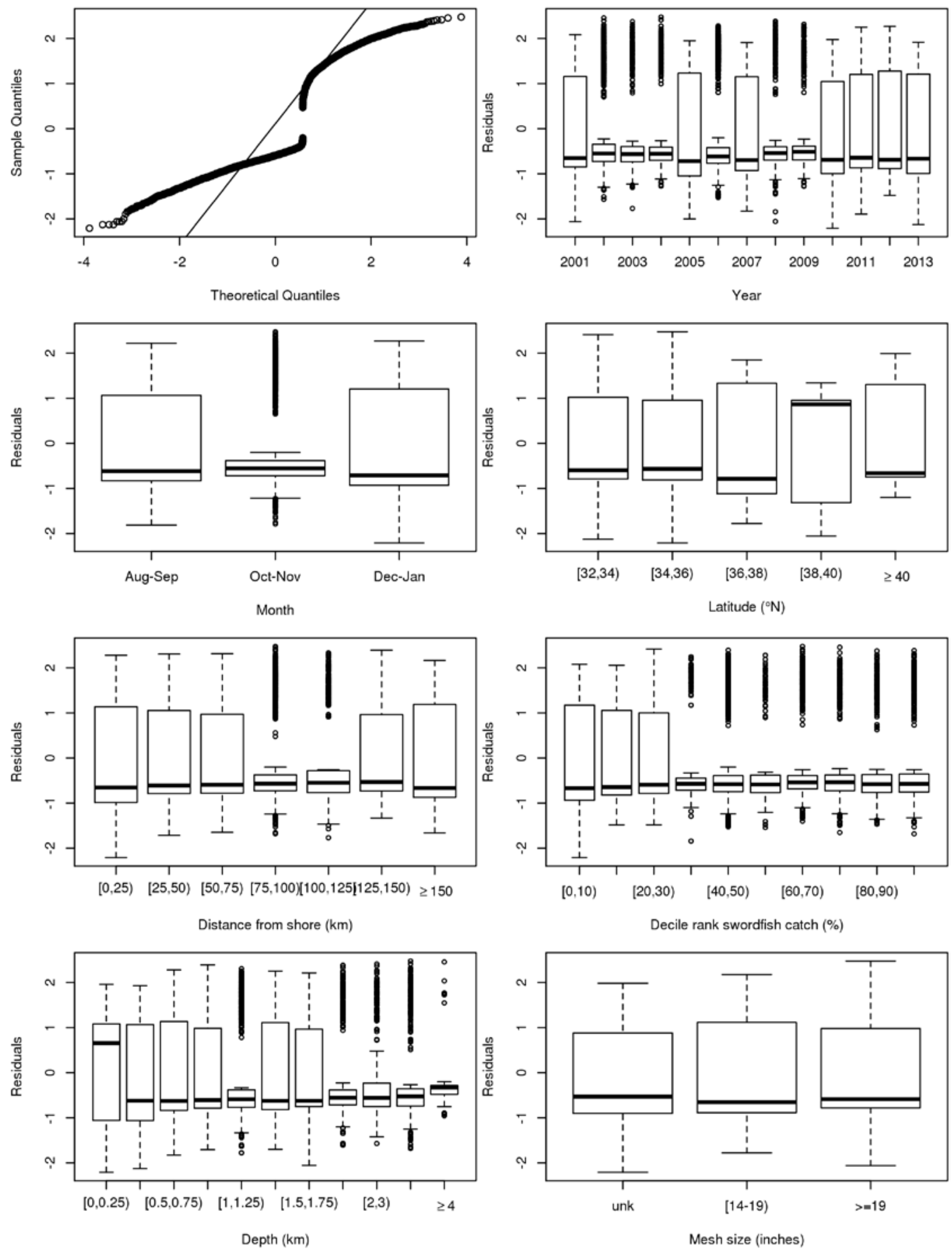
Appendix Figure D.5. Residual plots of the lognormal portion of the delta-lognormal model used to standardize the 1992 – 2000 common thresher shark abundance index for the USA swordfish/shark drift gillnet fishery.



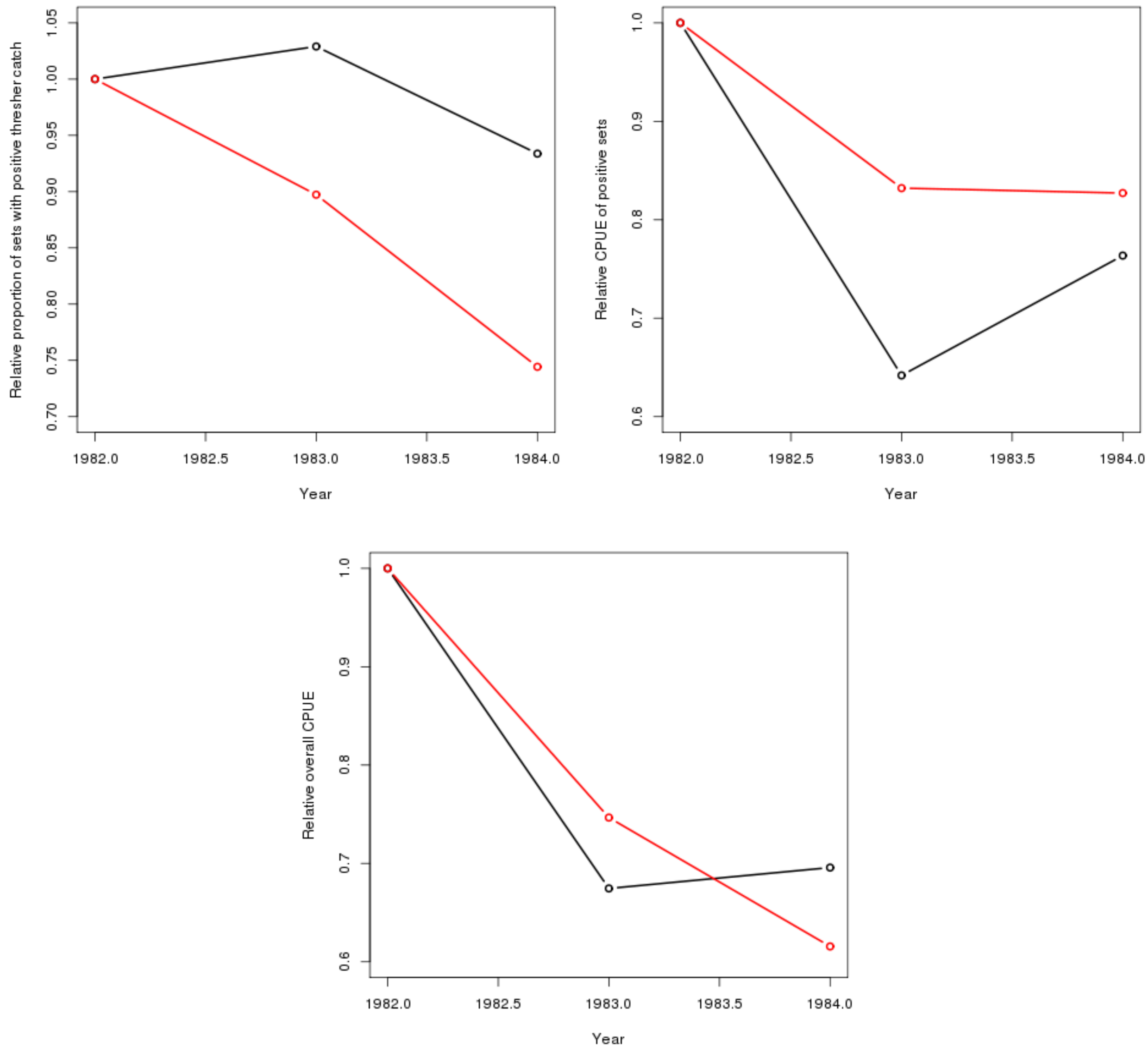
Appendix Figure D.6. Residual plots of the binomial portion of the delta-lognormal model used to standardize the 1992 – 2000 common thresher shark abundance index for the USA swordfish/shark drift gillnet fishery.



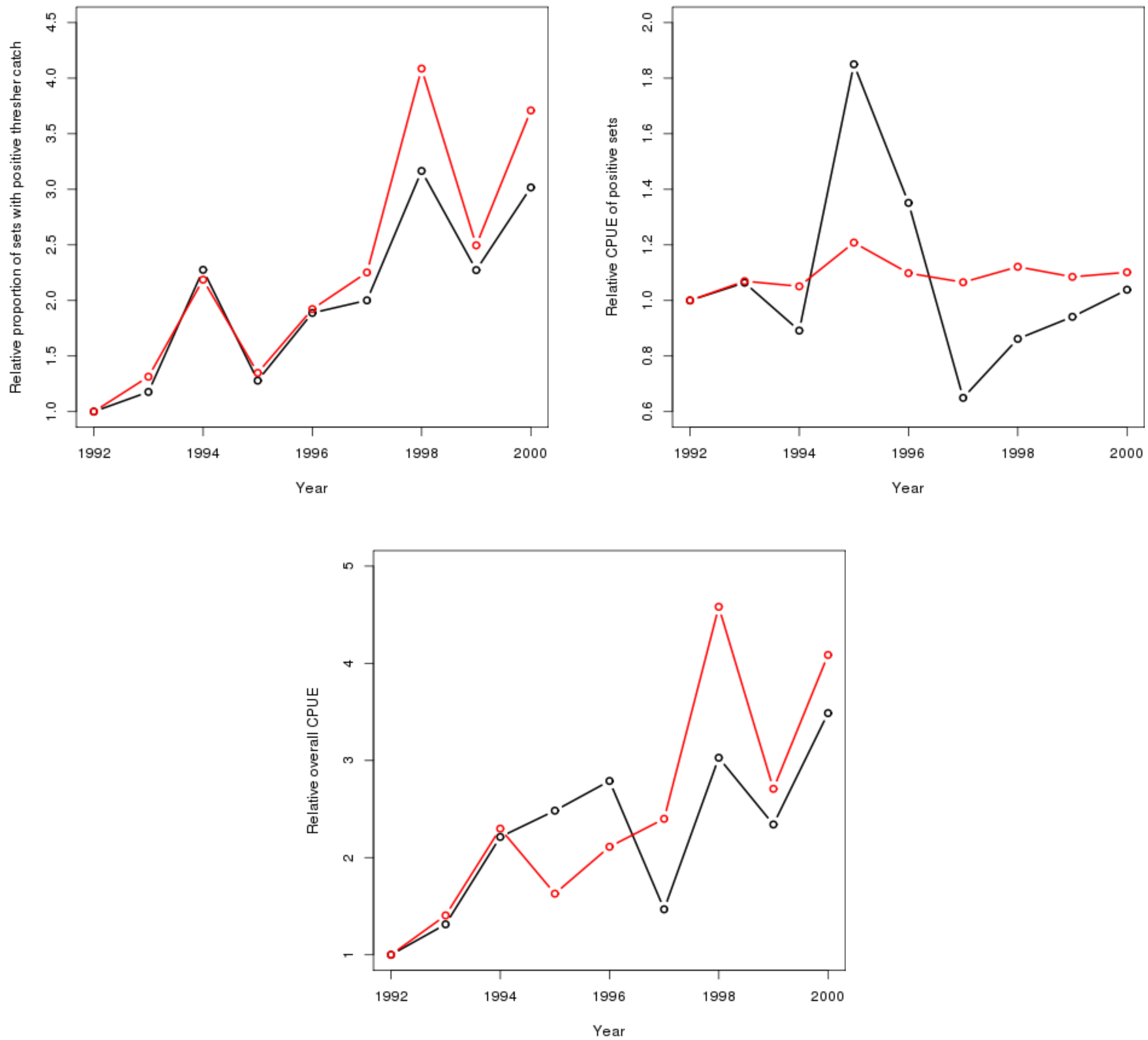
Appendix Figure D.7. Residual plots of the lognormal portion of the delta-lognormal model used to standardize the 2001 – 2013 common thresher shark abundance index for the USA swordfish/shark drift gillnet fishery.



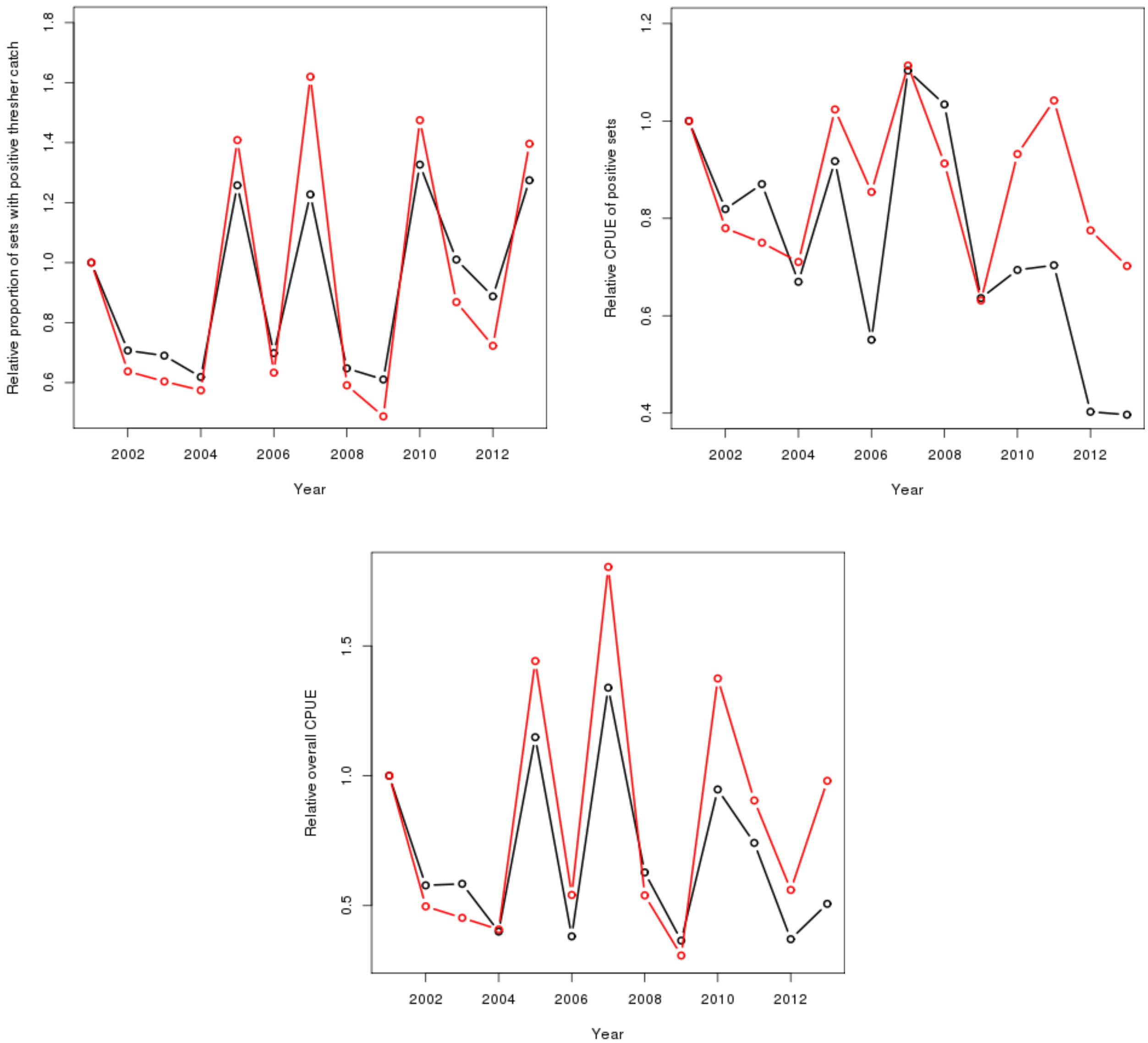
Appendix Figure D.8. Residual plots of the binomial portion of the delta-lognormal model used to standardize the 2001 – 2013 common thresher shark abundance index for the USA swordfish/shark drift gillnet fishery.



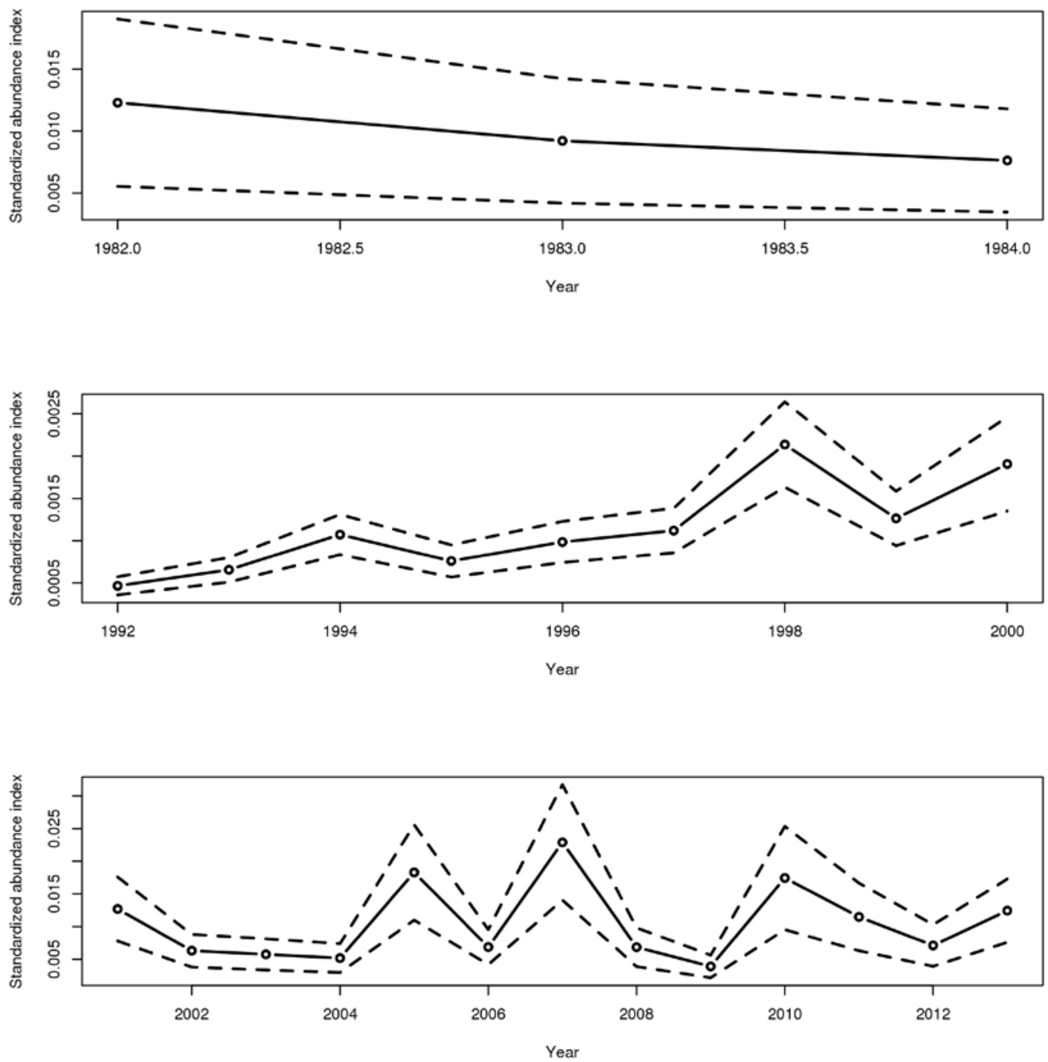
Appendix Figure D.9. Relative proportion of positive sets (upper left), CPUE of positive sets (upper right), and overall CPUE (lower) of nominal (black) and standardized (red) CPUE of the USA swordfish/shark drift gillnet fishery during 1982 – 1984. Indices are plotted relative to the value of the initial year.



Appendix Figure D.10. Relative proportion of positive sets (upper left), CPUE of positive sets (upper right), and overall CPUE (lower) of nominal (black) and standardized (red) CPUE of the USA swordfish/shark drift gillnet fishery during 1992 – 2000. Indices are plotted relative to the value of the initial year.



Appendix Figure D.11. Relative proportion of positive sets (upper left), CPUE of positive sets (upper right), and overall CPUE (lower) of nominal (black) and standardized (red) CPUE of the USA swordfish/shark drift gillnet fishery during 2001 – 2013. Indices are plotted relative to the value of the initial year.



Appendix Figure D.12. Standardized abundance indices of the USA swordfish/shark drift gillnet fishery during three periods: 1982 – 1984 (upper), 1992 – 2000 (middle), and 2001 – 2013 (lower). Dashed lines indicate 95% confidence intervals derived from jackknifing the data set.

APPENDIX E: Abundance indices for the USA nearshore set gillnet and small-mesh drift gillnet fishery

INTRODUCTION

A secondary USA commercial fishery that catches common thresher sharks is the nearshore set gillnet and small-mesh drift gillnet (USSN) fishery that target nearshore species like barracuda, white seabass, and halibut. The key differences between this fishery and the USA swordfish/shark drift gillnet (USDGN) fishery are that the USSN fishery uses nets with smaller mesh size (typically <10 inches) and operates in shallow, nearshore waters. Most of the catch and effort of the USSN fishery centers around the Southern California Bight but some parts of the fishery operates in nearshore areas as far north as around Mendocino, California (Fig. E.1).

The USSN does not target common thresher sharks but occasionally capture common thresher sharks as bycatch. The continental shelf of the Southern California Bight is a known nursery area for common thresher sharks along the USA West Coast and the USSN fishery therefore catches predominantly age-0 common thresher sharks (Cartamil et al. 2010). These abundance indices were therefore considered to be recruitment indices.

In 1994, the California Marine Resources Protection Act of 1990 began prohibiting all gillnets and trammel nets within 3 nm of the California mainland and within 1 nm (or waters <70 fathoms deep) of the Channel Islands. This resulted in the USSN fishery fishing in slightly deeper waters from 1994. In addition, data from 1981 - 1985 were not used because the USSN data were mixed with the USDGN data and could not be easily separated until after 1985, when the USDGN fishery moved out of the 75 nm zone due to regulations. Based on these changes, two indices representing different regulatory and operational periods were developed for the USSN fishery: Index 1: 1985 – 1993; and Index 2: 1994 – 2014.

Unlike the USDGN fishery, data from all four seasons were used in the indices from the USSN fishery. In addition, it was also not necessary to correct for the USSN fishery targeting swordfish instead of pelagic sharks because neither swordfish nor pelagic sharks were targets of the fishery.

MATERIALS AND METHODS

Data

The abundance indices were developed from set-by-set logbook data submitted by skippers of vessels in the USSN fishery after a mandatory logbook program was established in 1980, with the initial data collected in the 1981 – 1982 fishing season (Hanan et al. 1993). This was the same logbook program for the USDGN fishery. Data collected by the logbooks included catch (numbers of fish) by species, date, mesh size, net length, hours soaked, set number, and geographical position. Geographical positions were entered as CDFG block numbers (predominantly 10 min by 10 min squares), which were subsequently converted to latitudes and longitudes based on the center of the blocks.

Preliminary examination of the data indicated that two stages of filtering were required before the data could be used for developing abundance indices. The number of sets in the data after each filtering stage is summarized in Table E.1 and the spatial distribution of the sets and catch can be seen in Fig. E.1. The two filtering stages were:

1. Identifying USSN sets

The original data set included data from both the USSN and USDGN fisheries. The logbook data were therefore filtered to select for data where gear type was identified as “set net”, and target species were not identified as swordfish or shark, and mesh size was ≤10 inches or unspecified.

2. Identifying abnormal fishing operations

The majority of fishing operations for the USSN fishery used nets ranging from 250 to 1,000 fathoms long and had soak times of one or two days. However, abnormal fishing operations could result from nets being left in the water, and experimental trips using shorter nets and/or soak times. Sets with abnormal fishing operations or misreported information were identified and removed in the second filtering stage because it is inappropriate to use data from these abnormal fishing operations. Abnormal sets were identified based on fishery knowledge. As a result, sets that recorded missing or abnormal soak times (<6 or >48 hours), net lengths (<100 or >2000 m), mesh size (<2 or >10 inches), locations (latitude: <32 or >40°N; distance from shore: >20 km), and depth (>100 m).

The logbook data were divided into strata based on available factors. Season was categorized as four trimonthly periods ([Feb, Apr], [May, Jul], [Aug, Oct], [Nov, Dec]). Six areas were defined based on the latitude ([32, 33), [33, 34), [34, 35), [35, 36), [36,37), and [37,40] °N). Other factors included water depth (4 levels: [0, 20), [20, 40), [40, 80), and [80, 100] m), distance from shore (4 levels: [0, 5), [5, 10), [10, 15), and [15, 20] km), and mesh size (5 levels: unknown, [1, 3), [3, 6), [6, 8), and [8,10] inches).

Models

Delta-lognormal models (Lo et al. 1992) were used to standardize the catch per unit effort (CPUE) to obtain the abundance indices used in the stock assessment because the data set contained a large proportion of sets with zero thresher catch (Fig. E.2). Catch was defined as the sum of all kept and discarded common thresher sharks in a single set, and effort was defined as the product of the length of the net (km) and soak time (days). Delta-lognormal models assumes that the proportion of sets with positive catch have a binomial error structure and is modeled by a GLM with a logit link function, and the catch rate of sets with positive catch has a lognormal error distribution and is modeled by a lognormal GLM. The standardized index was the product of the back-transformed marginal year effects (Searle 1980) of these two components, with a correction for the bias in the lognormal back transformation. Estimates of variance were obtained by jackknifing the data set, using a modified version of delta_glm_1-7-2 function (E. J. Dick, pers. comm.) in R (function was modified to allow for different factors for the binomial and lognormal functions).

A forward-backward stepwise model selection process, with AIC as the selection criteria, was used to determine the set of factors that explained the catch of common thresher sharks in the logbook data. The binomial and lognormal models for each time period were selected independently.

RESULTS AND DISCUSSION

Based on the stepwise model selection process, the final delta-lognormal models for each time period were:

<u>1985 – 1993</u>
Binom: logit(π) ~ year + lat + season + distance + mesh + offset[log(eff)] + ε
Lognormal: log(catch) ~ year + lat + distance + depth + mesh + offset[log(eff)] + ε

<u>1992 – 2000</u>
Binom: logit(π) ~ year + lat + season + depth + mesh + offset[log(eff)] + ε
Lognormal: log(catch) ~ year + lat + depth + mesh + offset[log(eff)] + ε

where π was the probability of a set having positive common thresher shark catch, and the random error structures of the binomial and lognormal models were assumed to be Binom(n, π) and N(0, σ) respectively. Deviance tables for both time periods are found in Table E.2. No first-order interactions were included in the final model selection process because abundance indices with or without first-order interactions were highly similar.

Model diagnostics indicated adequate performance of the lognormal and binomial models for all three abundance indices (Fig. E.3 – E.6). For both time periods, the lognormal residuals were slightly skewed because the lognormal models had problems fitting sets with small numbers of fish. However, the mean predicted values of both the lognormal and binomial component models were highly representative of the observed values after aggregation into spatial and temporal bins.

In the first time period (1985 – 1993), a large spike in the nominal index was substantially reduced by the standardization, resulting in an index that gradually decreased to a minimum in 1989 before gradually increasing (Fig. E.7). The standardized abundance index for the second time period (1994 – 2014) indicated that the common thresher shark recruitment increased substantially during this period, albeit with substantial variability (Fig. E.8). The lognormal model reduced the variability apparent in the CPUE of positive sets but the variability in the binomial component was not visibly reduced. The jackknife procedure resulted in coefficients of variation (CVs) that were relatively high (Table E.3 and Fig. E.9).

Appendix Table E.1. Amount of data (number of sets) in the logbook data set before and after two stages of filtering for the USA nearshore set net fishery.

Period	**Number of sets prior to filtering**	**Number of sets after stage 1 filtering**	**Number of sets after stage 2 filtering**
1985 – 1993	192166	124542	68045
1994 – 2014	99174	62474	33680

Appendix Table E.2. Deviance analysis of explanatory variables in delta-lognormal models for common thresher shark catch rates of USA nearshore set net fishery for two time periods: 1) 1985 – 1993; and 2) 1994 – 2014.

1985 - 1993

Model factors	Df	Deviance	Residual Df	Residual Deviance	Pr(>Chi)
Binomial: AIC = 20812					
Null			68044	23752	
Year	8	58.98	68036	23694	7.38E-10
Latitude	5	1574.51	68031	22119	<2.2E-16
Season	3	1027.70	68028	21091	<2.2E-16
Distance from shore	3	44.72	68025	21047	1.06E-09
Mesh	4	282.50	68021	20764	<2.2E-16
Lognormal: AIC = 8113					
Null			2851	3316.0	
Year	8	113.22	2843	3202.8	<2.2E-16
Latitude	5	156.94	2838	3045.9	<2.2E-16
Distance from shore	3	71.74	2835	2974.1	1.67E-15
Depth	3	13.36	2832	2960.8	3.86E-03
Mesh	4	139.13	2828	2821.6	<2.2E-16

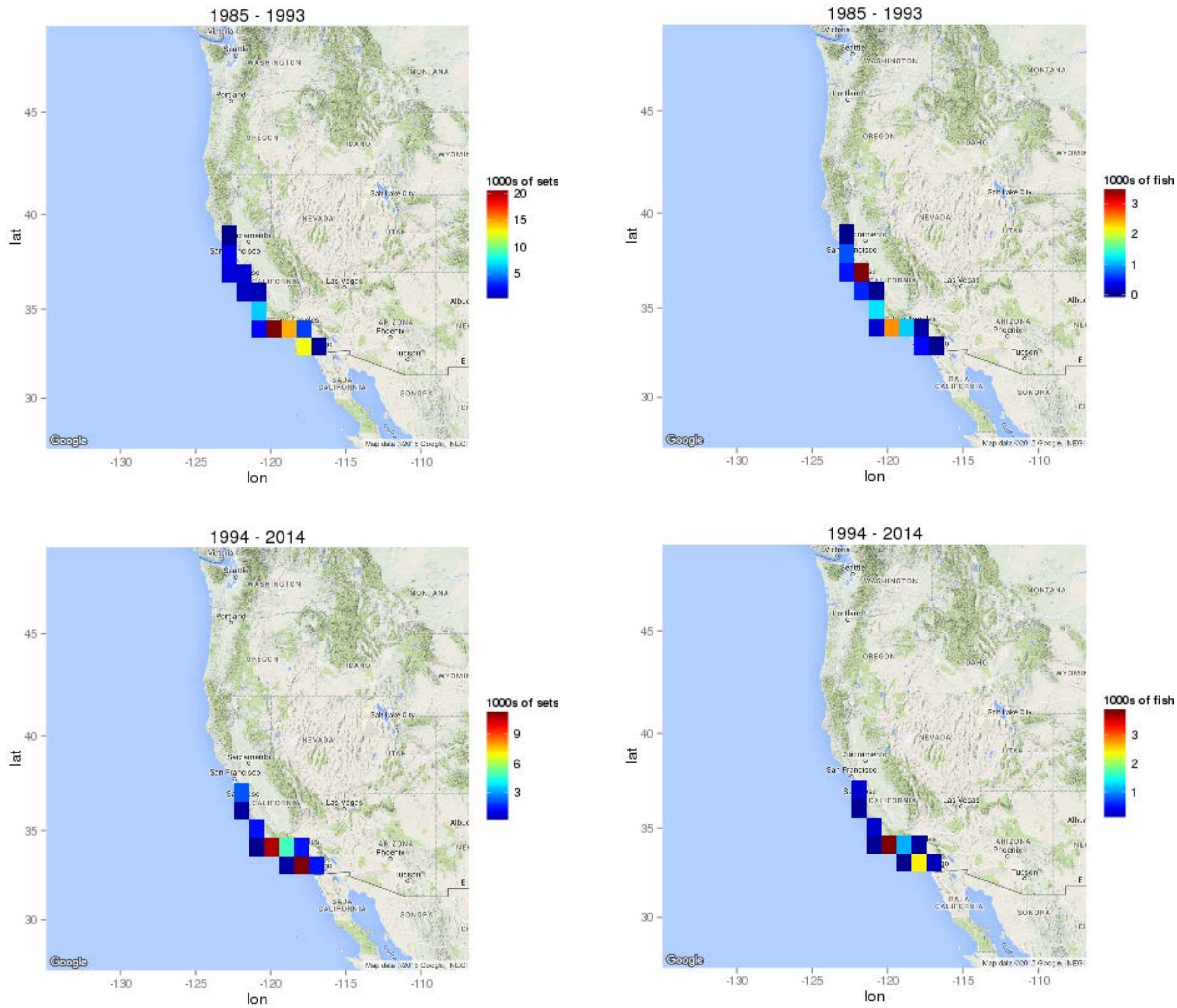
Appendix Table E.2. Continued.

1994 - 2014

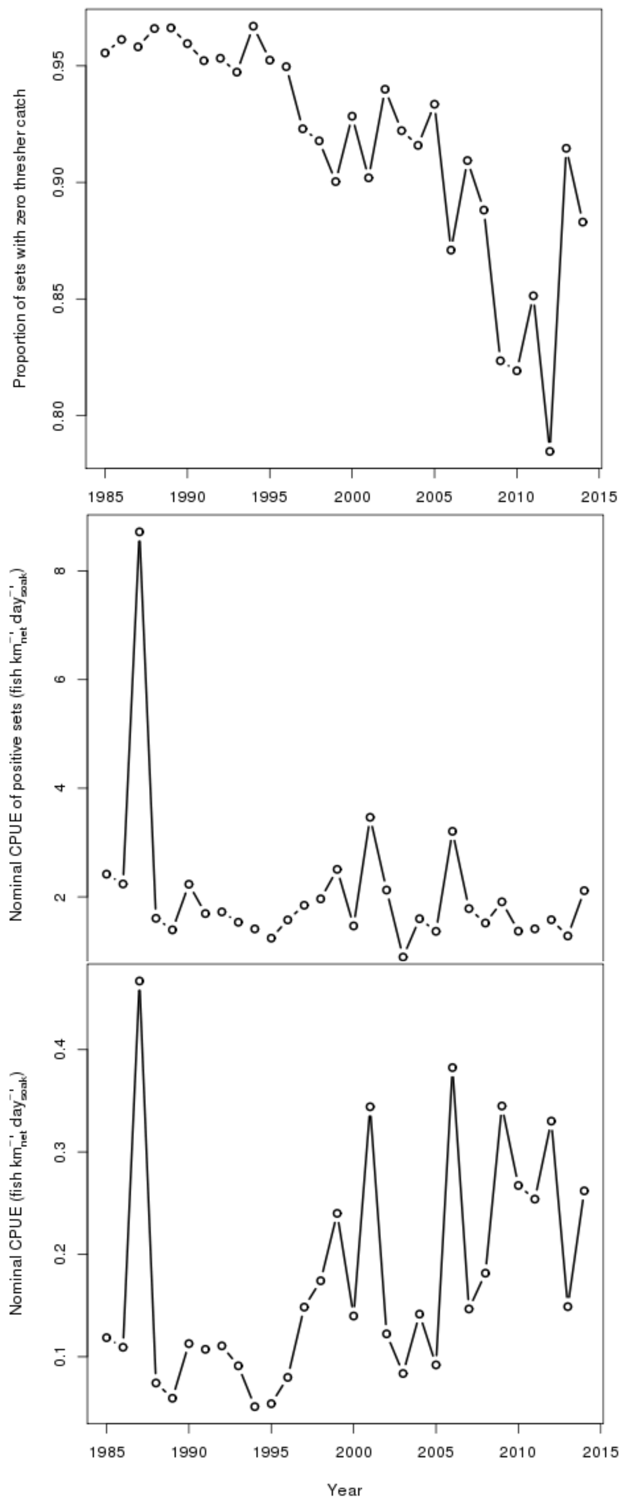
Model factors	Df	Deviance	Residual Df	Residual Deviance	Pr(>Chi)
Binomial: AIC = 18684					
Null			33679	21582	
Year	20	741.31	33659	20841	<2.2E-16
Latitude	5	464.32	33654	20377	<2.2E-16
Season	3	917.66	33651	19459	<2.2E-16
Depth	3	251.24	33648	19208	<2.2E-16
Mesh	4	595.40	33644	18612	<2.2E-16
Lognormal: AIC = 8807					
Null			3077	3850.9	
Year	20	138.38	3057	3712.6	<2.2E-16
Latitude	5	124.80	3052	3587.8	<2.2E-16
Depth	3	165.85	3049	3421.9	<2.2E-16
Mesh	3	338.23	3046	3083.7	<2.2E-16

Table E.3. Estimated relative abundance index values, standard errors (SEs), and coefficients of variation (CVs) for two time periods: 1985 – 1993; and 1994 – 2014 for the USA nearshore set net fishery. The SEs and CVs were estimated with a jackknife procedure.

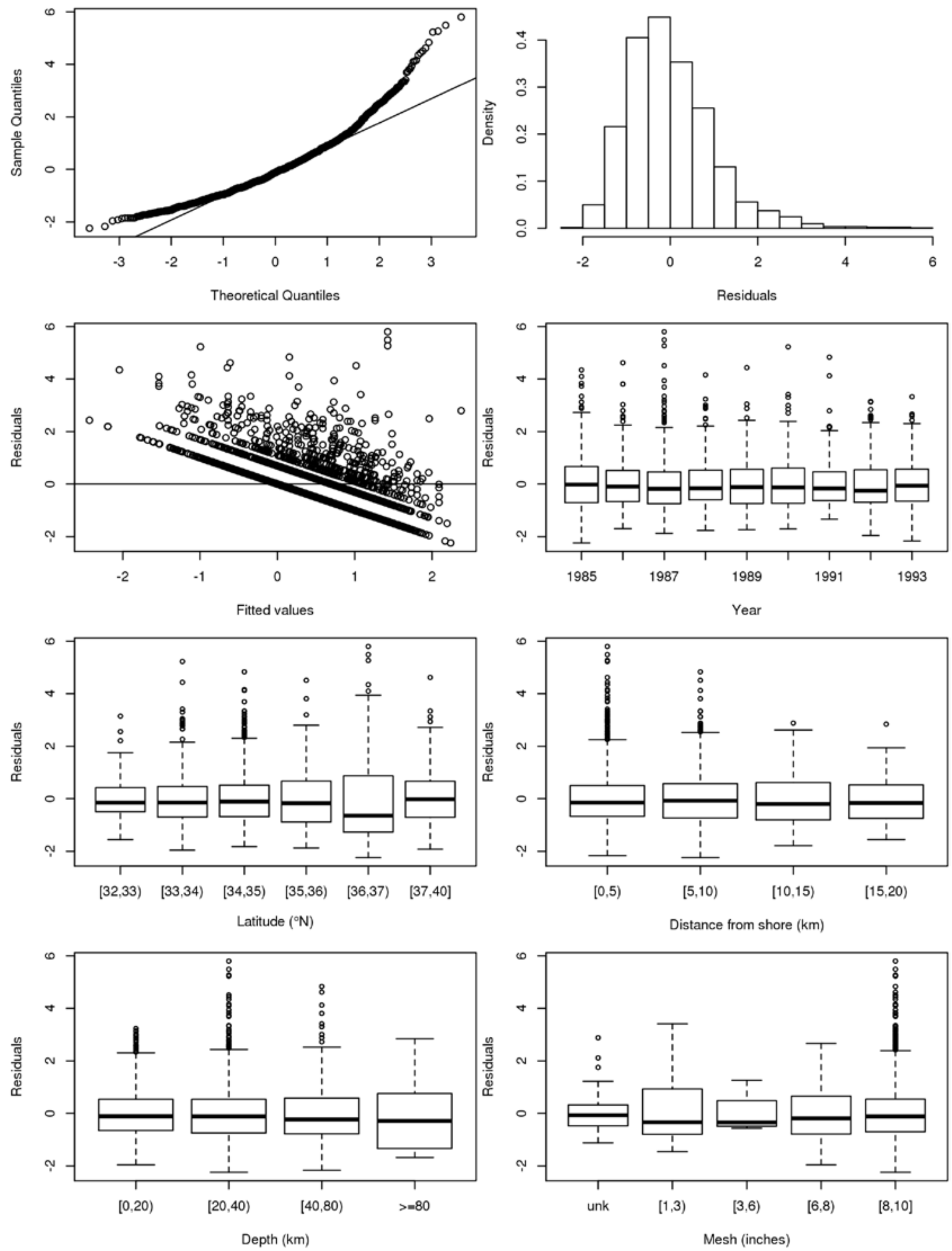
Year	Index	SE	CV
1985 – 1993			
1985	0.07149	0.01590	0.22246
1986	0.05076	0.01117	0.22000
1987	0.07998	0.01852	0.23149
1988	0.06265	0.01442	0.23024
1989	0.04039	0.00931	0.23056
1990	0.07087	0.01689	0.23840
1991	0.05103	0.01198	0.23477
1992	0.06788	0.01643	0.24198
1993	0.08320	0.01919	0.23061
1994 – 2014			
1994	0.20827	0.05303	0.25464
1995	0.20266	0.04715	0.23268
1996	0.29486	0.06484	0.21991
1997	0.45911	0.09166	0.19964
1998	0.49911	0.10357	0.20750
1999	0.55780	0.10615	0.19030
2000	0.33207	0.06748	0.20322
2001	0.69024	0.14693	0.21287
2002	0.38927	0.08773	0.22537
2003	0.22220	0.04553	0.20489
2004	0.29735	0.06158	0.20710
2005	0.24872	0.05692	0.22886
2006	1.00752	0.19371	0.19227
2007	0.69005	0.14078	0.20402
2008	0.38999	0.08275	0.21220
2009	0.69659	0.13596	0.19518
2010	0.76876	0.15233	0.19815
2011	0.51435	0.10836	0.21067
2012	0.72856	0.14386	0.19746
2013	0.21324	0.05124	0.24029
2014	0.81005	0.33390	0.41220



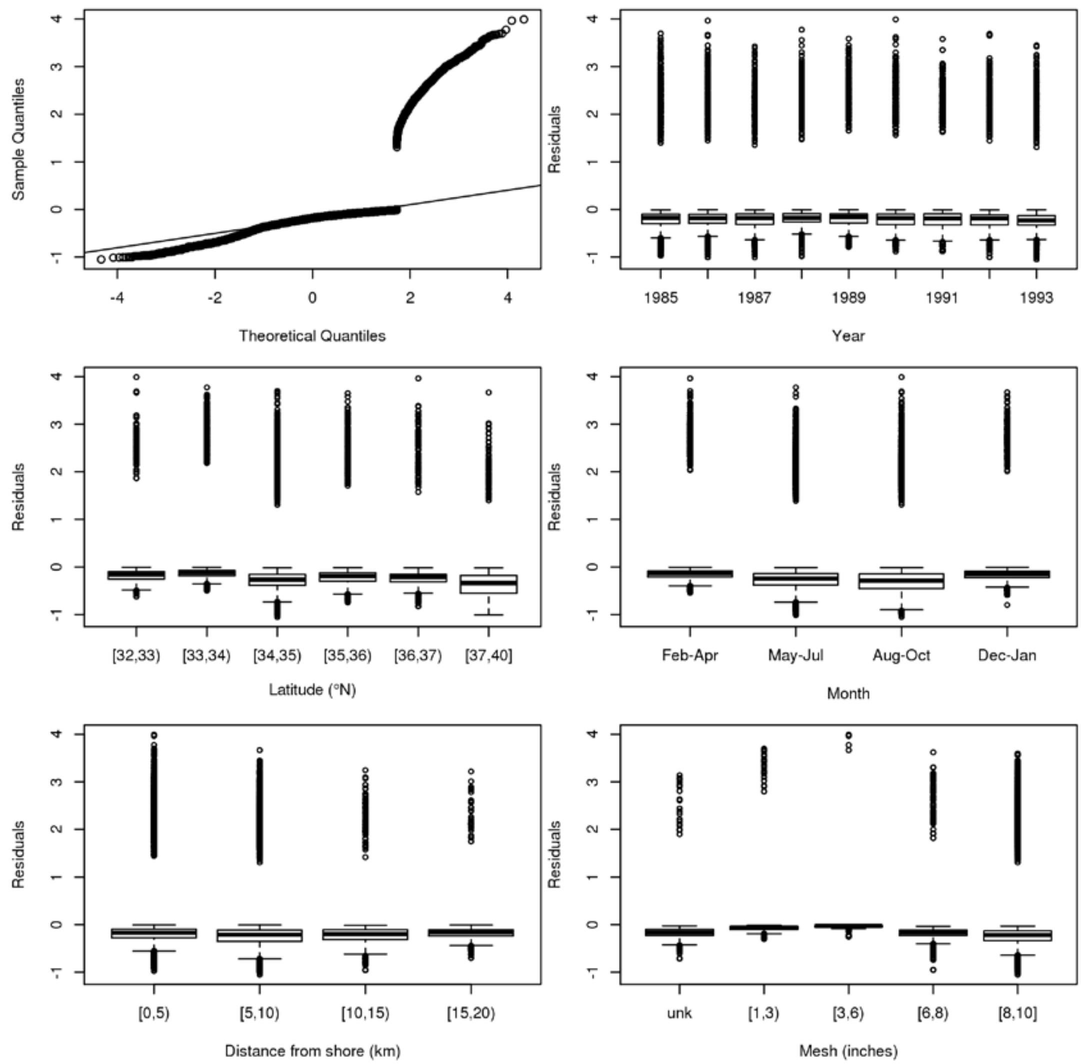
Appendix Figure E.1. Spatial distribution of sets (left) and common thresher shark catch (right) for the USSN fishery over three periods used for abundance indices.



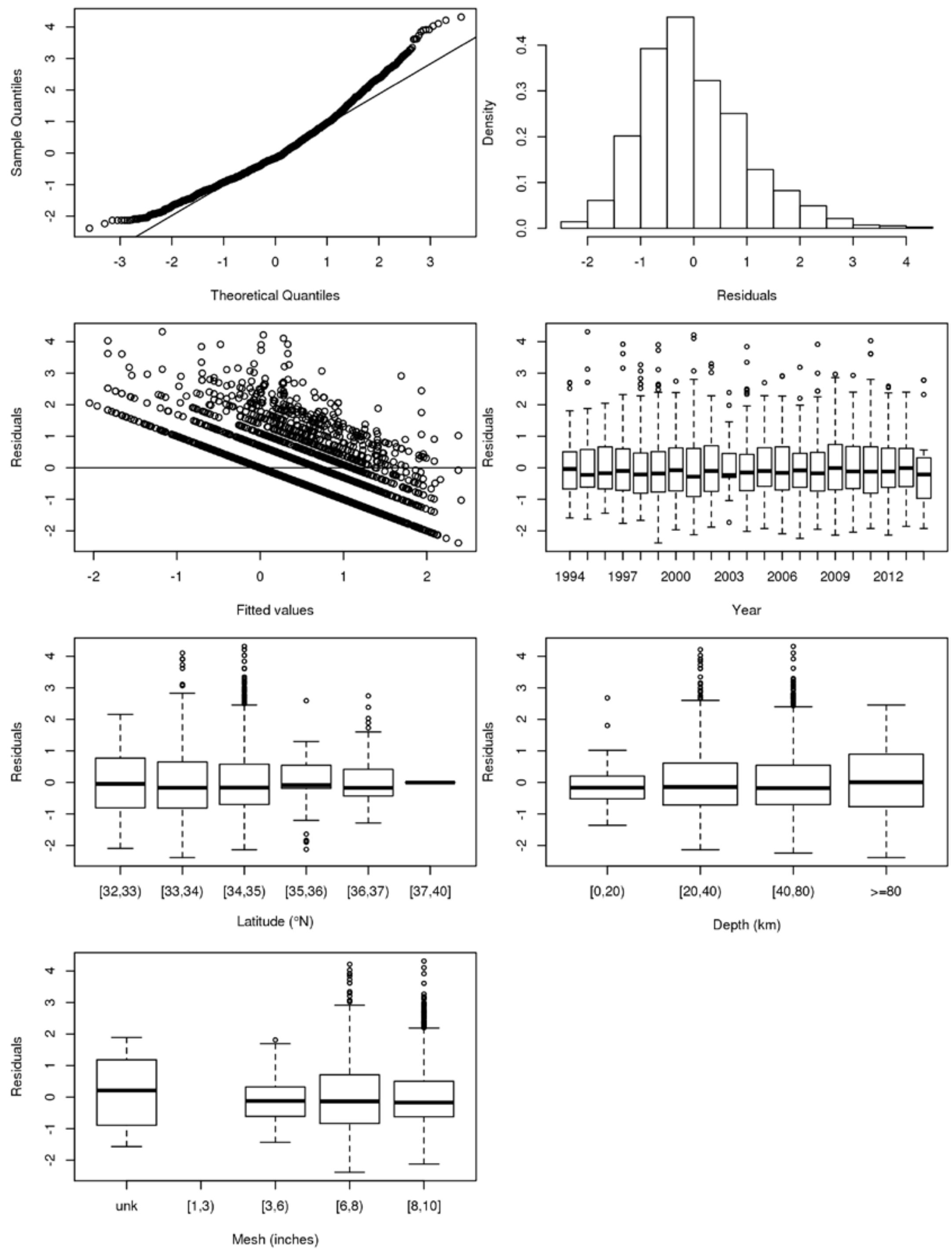
Appendix Figure E.2. Proportion of sets with zero thresher shark catch (upper), nominal catch-per-unit-effort (CPUE) of sets with positive thresher catch (middle), and overall nominal CPUE (lower) for common thresher sharks caught by the USSN fishery.



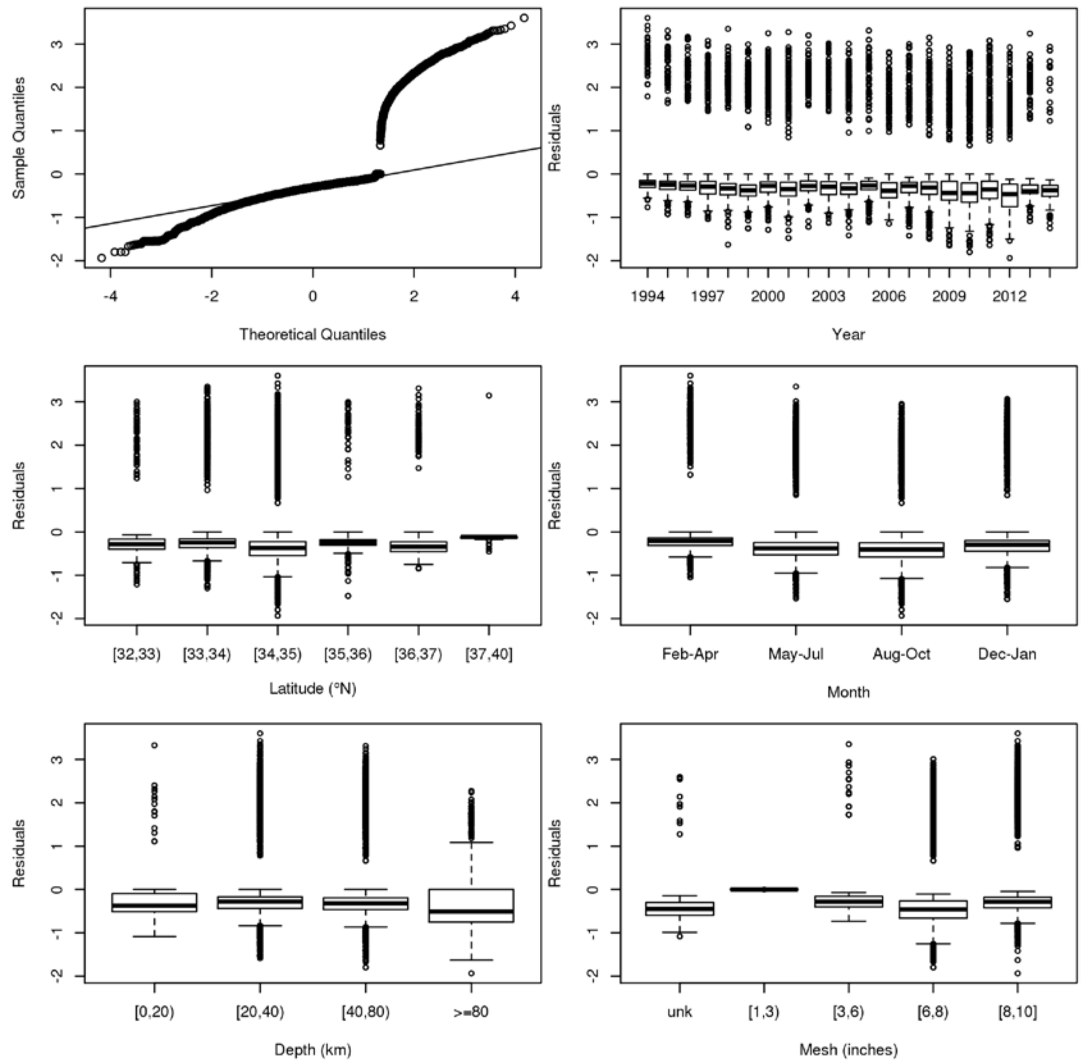
Appendix Figure E.3. Residual plots of the lognormal portion of the delta-lognormal model used to standardize the 1985 – 1993 common thresher shark abundance index for the USSN fishery.



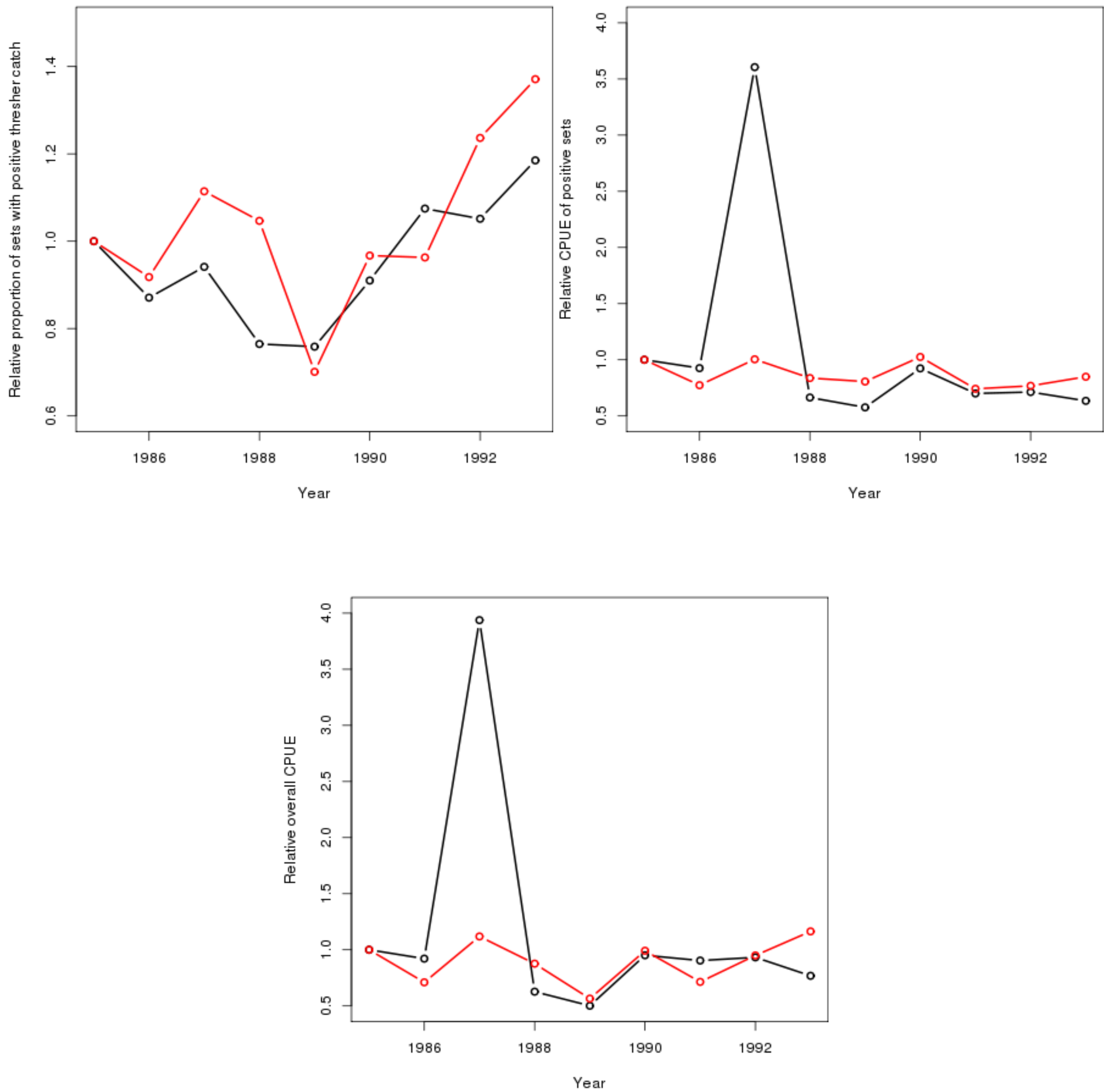
Appendix Figure E.4. Residual plots of the binomial portion of the delta-lognormal model used to standardize the 1985 – 1993 common thresher shark abundance index for the USSN fishery.



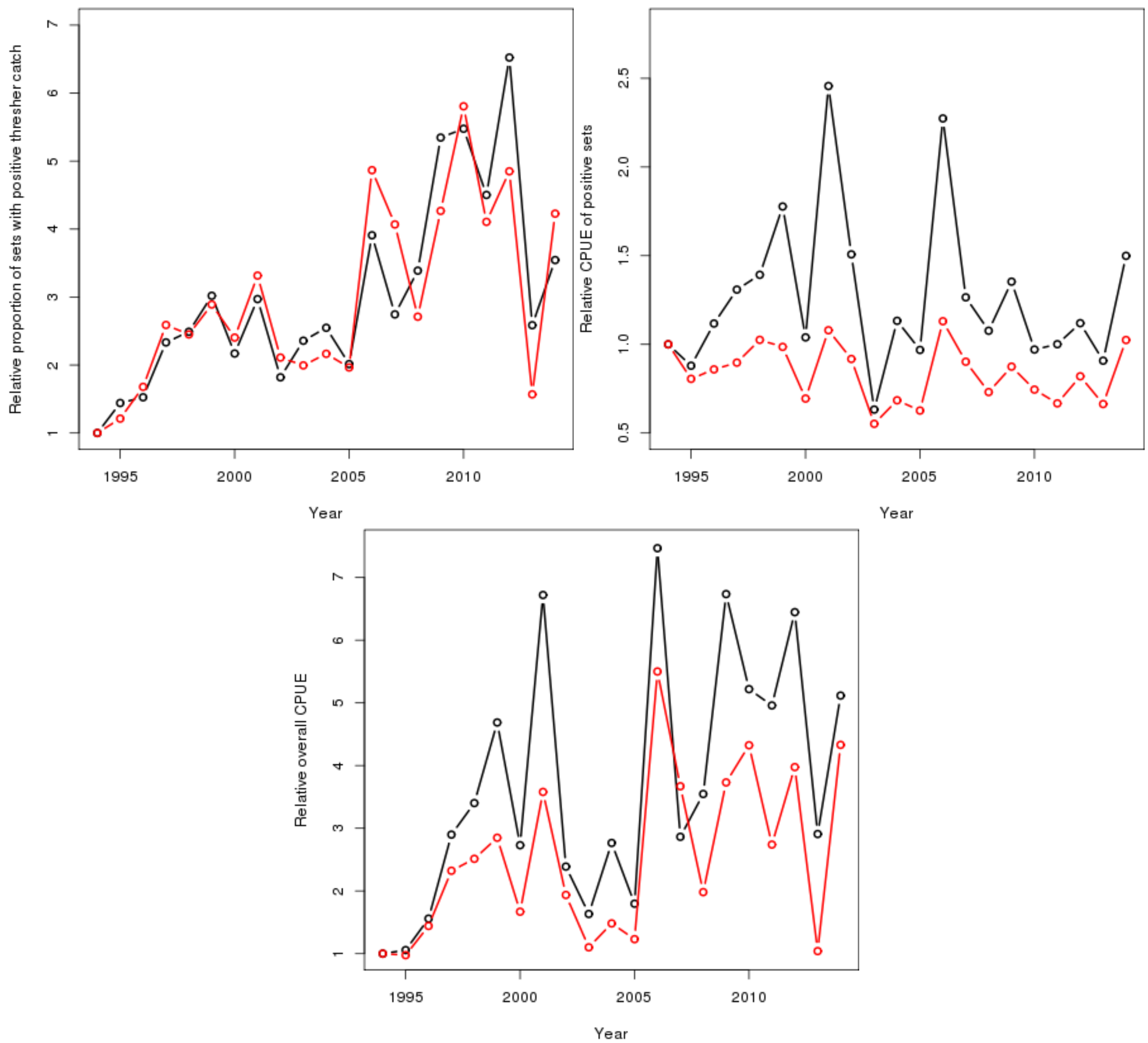
Appendix Figure E.5. Residual plots of the lognormal portion of the delta-lognormal model used to standardize the 1994 – 2014 common thresher shark abundance index for the USSN fishery.



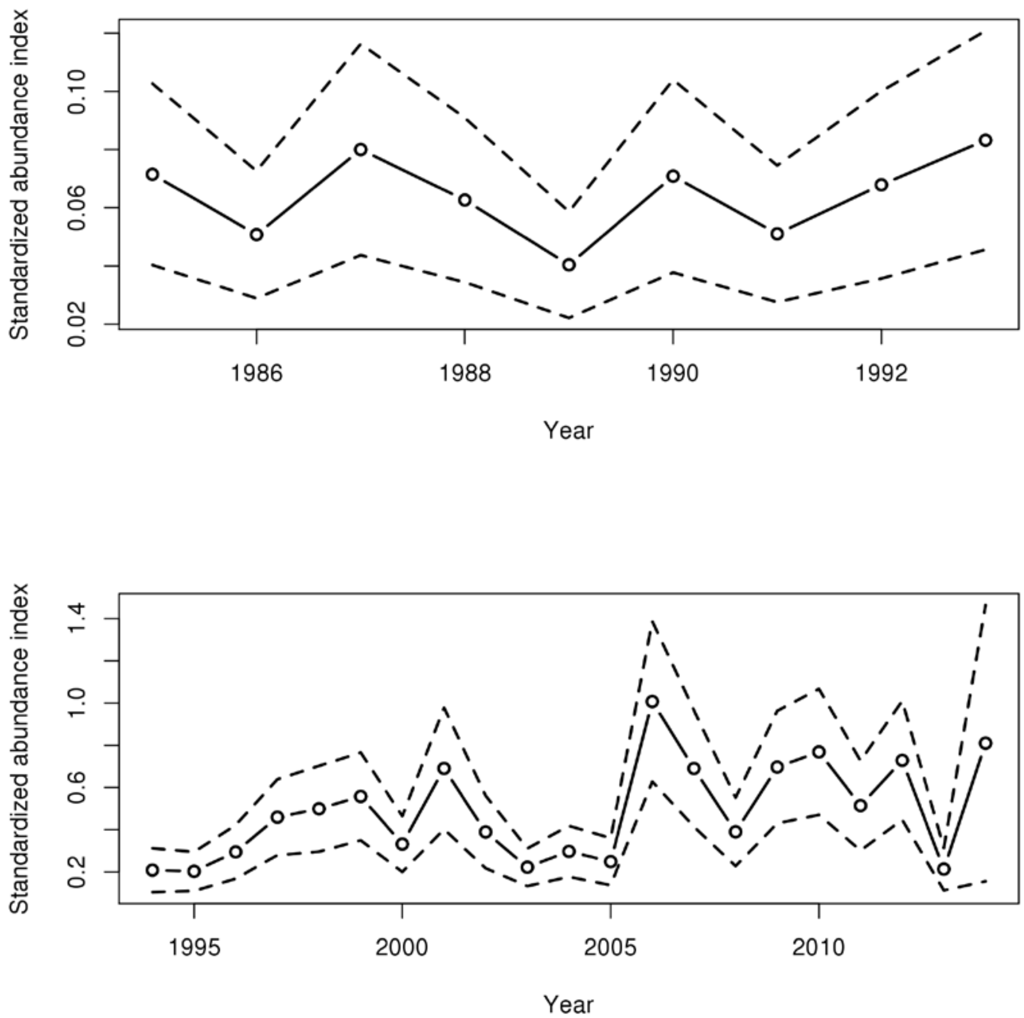
Appendix Figure E.6. Residual plots of the binomial portion of the delta-lognormal model used to standardize the 1994 – 2014 common thresher shark abundance index for the USSN fishery.



Appendix Figure E.7. Relative proportion of positive sets (upper left), CPUE of positive sets (upper right), and overall CPUE (lower) of nominal (black) and standardized (red) CPUE of the USSN fishery during 1985 – 1993. Indices are plotted relative to the value of the initial year.



Appendix Figure E.8. Relative proportion of positive sets (upper left), CPUE of positive sets (upper right), and overall CPUE (lower) of nominal (black) and standardized (red) CPUE of the USSN fishery during 1994 – 2014. Indices are plotted relative to the value of the initial year.



Appendix Figure E.9. Standardized abundance indices of the USSN fishery during two periods: 1985 – 1993 (upper), and 1994 – 2014 (lower). Dashed lines indicate 95% confidence intervals derived from jackknifing the data set.

APPENDIX F: Abundance index for the USA juvenile thresher shark survey

INTRODUCTION

The Southwest Fisheries Science Center (SWFSC) has conducted an annual juvenile thresher survey in September from 2006 through 2014. This fishery-independent survey was developed after an initial study on the nursery ground of the common thresher shark (Smith 2005). The study indicated that longline gear in nearshore waters would be successful in catching young-of-year and juvenile common thresher sharks.

The basic survey design consisted of 12 area blocks and a minimum of three longline sets were required for each block (Fig. F.1). Each longline set consisted of a one mile long pelagic monofilament longline with 100 hooks. The longline was deployed from a small commercial longline vessel and anchored at each end. The hooks were expected to fish approximately 6-8 m below the surface and were baited with primarily sardines but mackerels were sometimes used when sardines were not available. The longline sets were deployed in areas where bottom depth is <25 fathoms (~45 m). Sharks were tagged and released alive, if possible.

Several operational factors of this survey impacted how the data from this survey was utilized in this assessment. Most importantly, the location and timing of each set was determined by the captain of the vessel, within the constraints set by NOAA scientists. The sets were in effect targeted at thresher sharks and were somewhat similar to commercial longline sets, albeit with standardized fishing gear. In addition, after the initial three sets within a block were completed and there was time available, the captain was free to set again in the same area. Therefore, the first three sets in an area block could have been used as learning sets, and may have provided information on where it was more likely to encounter common thresher sharks during subsequent sets in the same block. Preliminary analysis of the catch-per-unit-effort (CPUE) indicated that sets after the initial three sets in an area had a significant positive effect on encountering non-zero thresher catch.

Another important factor was that soak times of each set were inconsistent and varied substantially (Table F.1). When relatively large numbers of sharks were caught, soak times were sometimes cut to reduce shark mortality and possible hook saturation. Occasionally on some sets in the past, if a shark was observed to be hooked, the shark would be brought aboard and released, and the hook was then rebaited and put back into the water. This practice was considered inappropriate and has since been discontinued.

Other secondary factors likely impacting the CPUE of the survey were Marine Protected Areas (MPAs) and consumption of baits by sea lions. In 2012, several areas within survey blocks became unavailable to the survey due to MPAs being implemented. Preliminary analysis indicated that sets within those areas before they became MPAs had higher CPUEs. Sea lions would also occasionally consume the baits on the longline making the longline less effective in catching fish. If the survey data indicated that baits were consumed by sea lions, the data from the set were discarded before further analysis.

MATERIALS AND METHODS

Data

The abundance index was developed using set-by-set data from 2006 through 2014. A series of criteria was used to identify sets with abnormal fishing operations: 1) sets with important missing data; 2) sets conducted outside of established area blocks; 2) sets with depth >25 fathoms; 3) sets where sea lions were observed to consume baits; 4) sets outside of September; 5) experimental sets with non-standard gear configurations (e.g., one set used only 50 hooks); and 6) sets with soak time of >4 hours. A total of 35 sets with abnormal fishing operations were identified out of 440 sets in the initial dataset. The remaining 405 sets were used to derive the abundance index, with some variability in the number of sets for each year (Table F.1).

The data were divided into strata based on available factors. Twelve areas were defined based on the experimental blocks. Other factors included water depth (5 levels: [0,10), [10,20), [20,30), [30,40), and [40,50] m), bait – percentage of sardine (4 levels: [0,25), [25,50), [50,75), and [75,100] %), first 3 sets (2 levels: 0, 1), and MPA sets (2 levels: 0, 1). We used soak time in hours as the fishing effort of each set because soak times varied substantially from set to set (Table F.1) but the number of hooks used were relatively constant (401 sets used 100 hooks but 4 sets used 104 hooks) for each set.

Models

Delta-lognormal models (Lo et al. 1992) were used to standardize the catch per unit effort (CPUE) to obtain the abundance indices used in the stock assessment because the data set contained a large proportion of sets with zero thresher catch (Fig. F.2). Catch was defined as the sum of all common thresher sharks caught in a single set, and effort was defined as the soak time (hours). A delta-lognormal model assumes that the proportion of sets with positive catch has a binomial error structure and is modeled by a GLM with a logit link function, and the catch rate of sets with positive catch has a lognormal error distribution and is modeled by a lognormal GLM. The standardized index is the product of the back-transformed marginal year effects (Searle 1980) of these two components, with a correction for the bias in the lognormal back transformation. Estimates of variance were obtained by jackknifing the data set, using a modified version of delta_glm_1-7-2 function (E. J. Dick, pers. comm.) in R (function was modified to allow for different factors for the binomial and lognormal functions).

A forward-backward stepwise model selection process, with AIC as the selection criteria, was used to determine the set of factors that explained the catch of common thresher sharks in the survey data. The binomial and lognormal models for each time period were selected independently.

RESULTS AND DISCUSSION

Based on the stepwise model selection process, the final delta-lognormal models were:

<u>2006 – 2014</u>
Binom: logit(π) ~ year + area + first3sets + offset[log(eff)] + ε
Lognormal: log(catch) ~ year + area + mpasets + offset[log(eff)] + ε

where π was the probability of a set having positive common thresher shark catch, and the random error structures of the binomial and lognormal models were assumed to be Binom(n, π) and N(0, σ) respectively. Deviance tables for both time periods are found in Table F.2. No first-order interactions were included in the final model selection process because abundance indices with or without first-order interactions were highly similar.

Model diagnostics indicated adequate performance of the lognormal and binomial models for all three abundance indices (Fig. F.3 – F.4). The lognormal residuals were relatively well represented by a normal distribution. In addition, the mean predicted values of both the lognormal and binomial component models were highly representative of the observed values after aggregation into spatial and temporal bins.

The standardized index from the USA juvenile thresher survey showed a generally increasing trend in recruitment from 2006 through 2011 but a decreasing trend in the last three years (2012 – 2014) (Fig. F.5). However, the apparent trends in the index are highly uncertain because the jackknife procedure resulted in large coefficients of variation (CVs), ranging from 0.43 to 0.55 (Table F.3 and Fig. F.6).

Appendix Table F.1. Catch and effort from the longline juvenile thresher shark survey conducted in nearshore waters of Southern California by NOAA Fisheries' Southwest Fisheries Science Center. Each longline set consists 100 hooks except for 4 sets with 104 hooks.

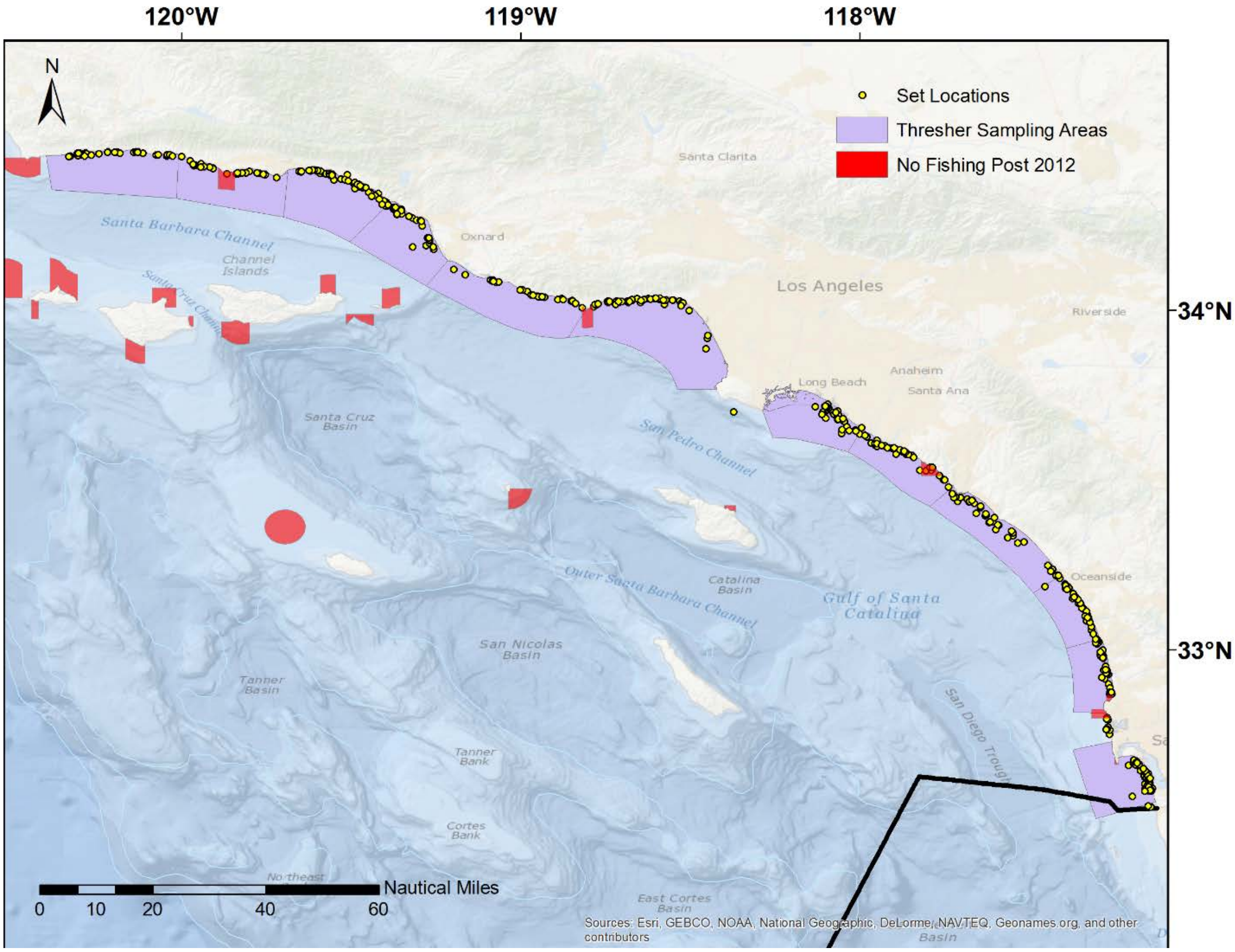
Year	Number of sets prior to filtering	Number of sets after filtering	Number of common thresher sharks	Soak time (h) Mean ± SD
2006	50	45	253	2.3 ± 0.5
2007	49	44	113	2.3 ± 0.4
2008	48	41	282	2.2 ± 0.5
2009	50	47	213	2.3 ± 0.4
2010	48	43	263	2.1 ± 0.5
2011	47	46	412	2.1 ± 0.6
2012	50	45	268	2.3 ± 0.4
2013	49	47	285	2.4 ± 0.4
2014	49	47	147	2.2 ± 0.3

Appendix Table F.2. Deviance analysis of explanatory variables in delta-lognormal models for common thresher shark catch rates of USA juvenile thresher survey for 2006 – 2014.

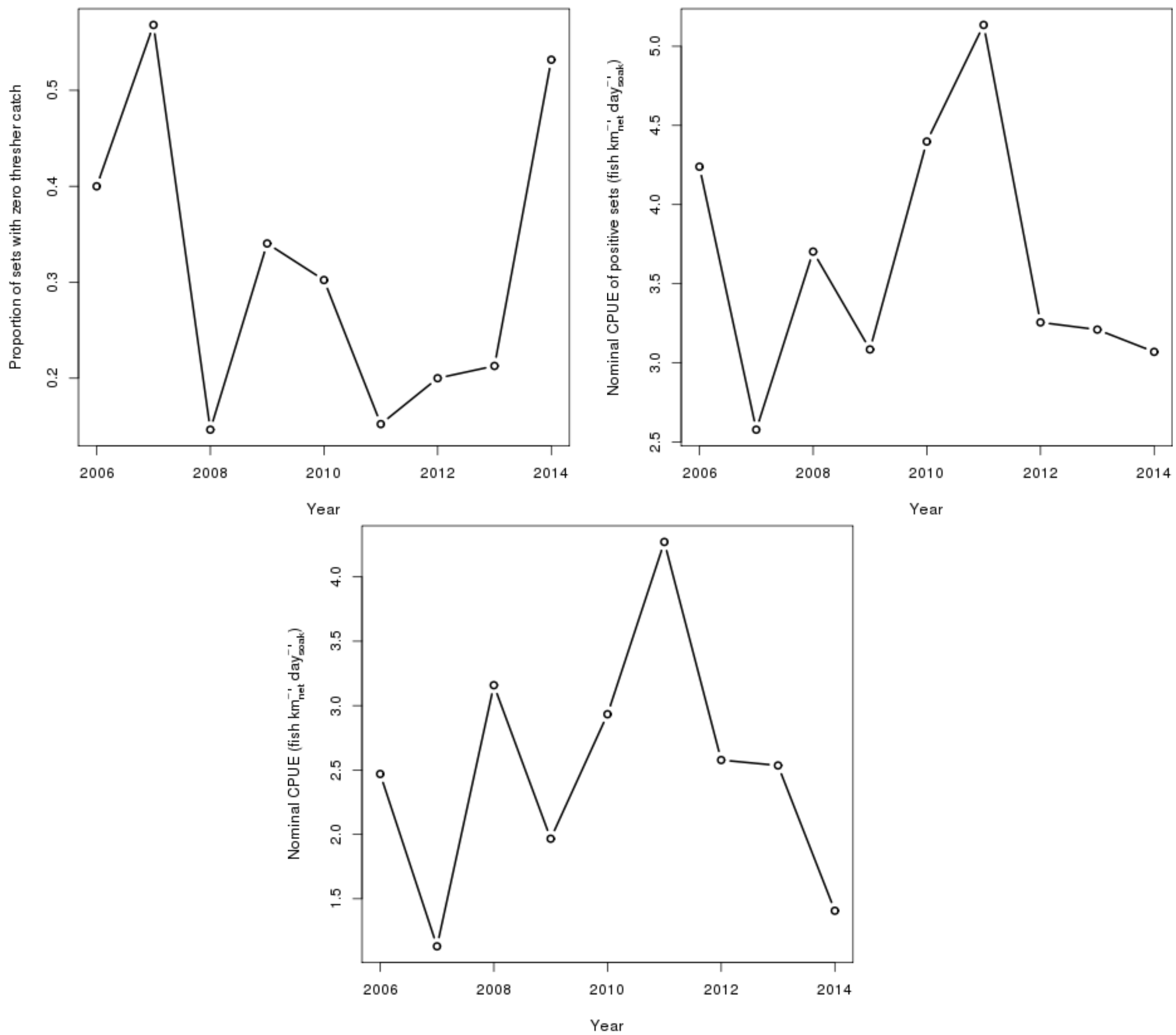
Model factors	Df	Deviance	Residual Df	Residual Deviance	Pr(>Chi)
Binomial: AIC = 464.0					
Null			404	521.95	
Year	8	43.41	396	478.54	7.35E-07
Area	11	50.11	385	428.43	5.98E-07
First 3 sets in an area block	1	6.45	384	421.99	0.0111
Lognormal: AIC = 841.7					
Null			275	336.08	
Year	8	13.14	267	322.93	0.1737
Area	11	25.76	256	297.17	0.0202
Set in MPA	1	6.37	255	290.80	0.0181

Table F.3. Estimated relative abundance index values, standard errors (SEs), and coefficients of variation (CVs) for the USA juvenile thresher survey. The SEs and CVs were estimated with a jackknife procedure.

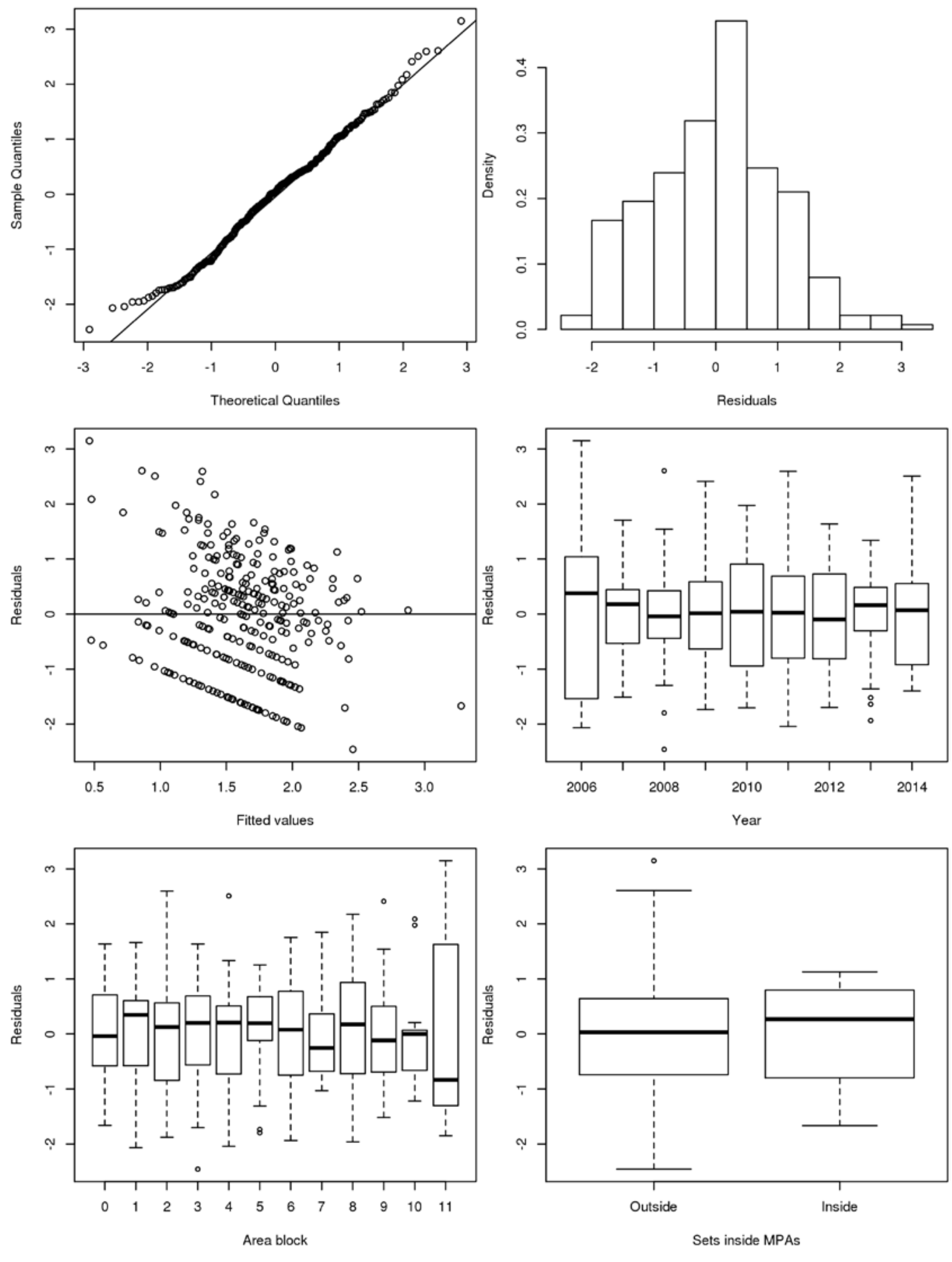
Year	Index	SE	CV
2006	3.20419	1.75810	0.54869
2007	1.70947	0.87744	0.51328
2008	7.64873	3.57938	0.46797
2009	3.04584	1.43589	0.47143
2010	5.43268	2.33678	0.43013
2011	8.82981	4.38673	0.49681
2012	4.87355	2.22676	0.45691
2013	5.18471	2.36088	0.45535
2014	1.73476	0.90736	0.52305



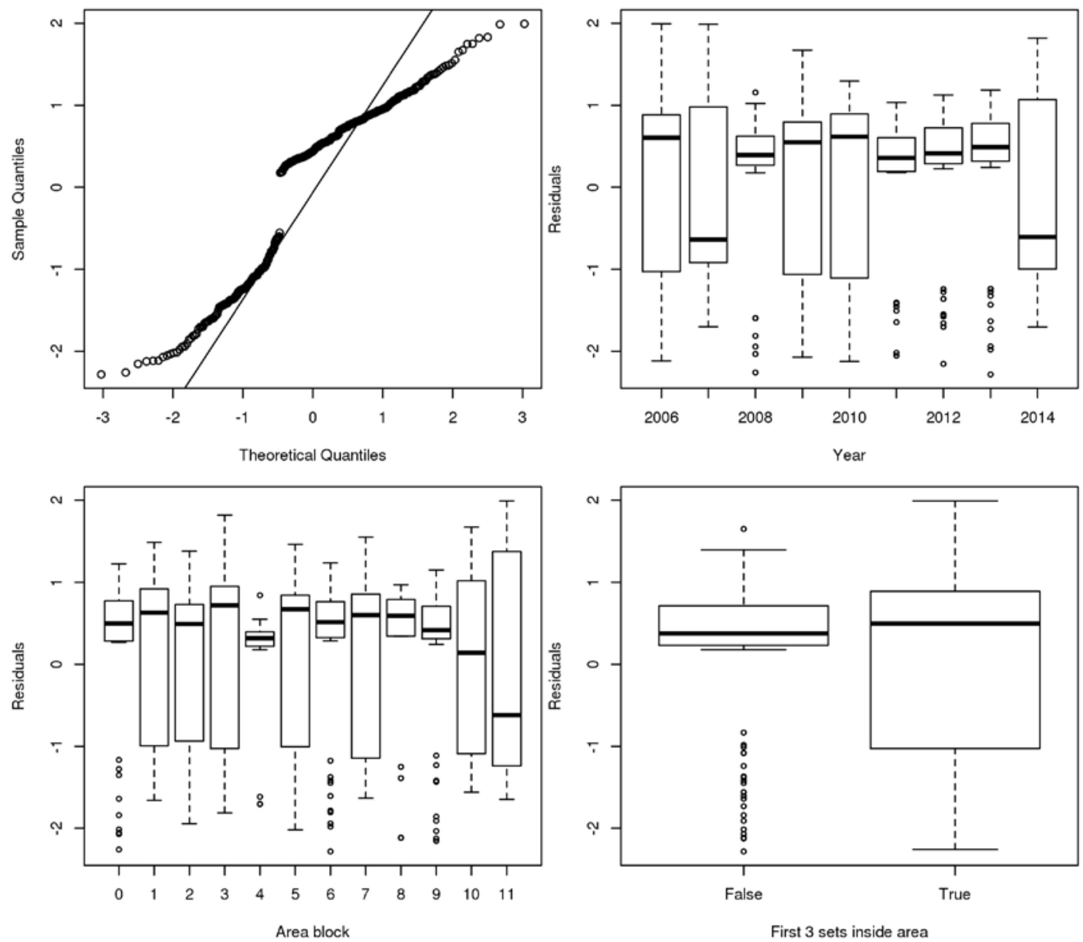
Appendix Figure F.1. Locations of 440 sets and 12 sampling areas of the U.S. juvenile thresher shark survey from 2006 through 2014. Areas where fishing was prohibited after 2012 (i.e., MPAs) are shown in red.



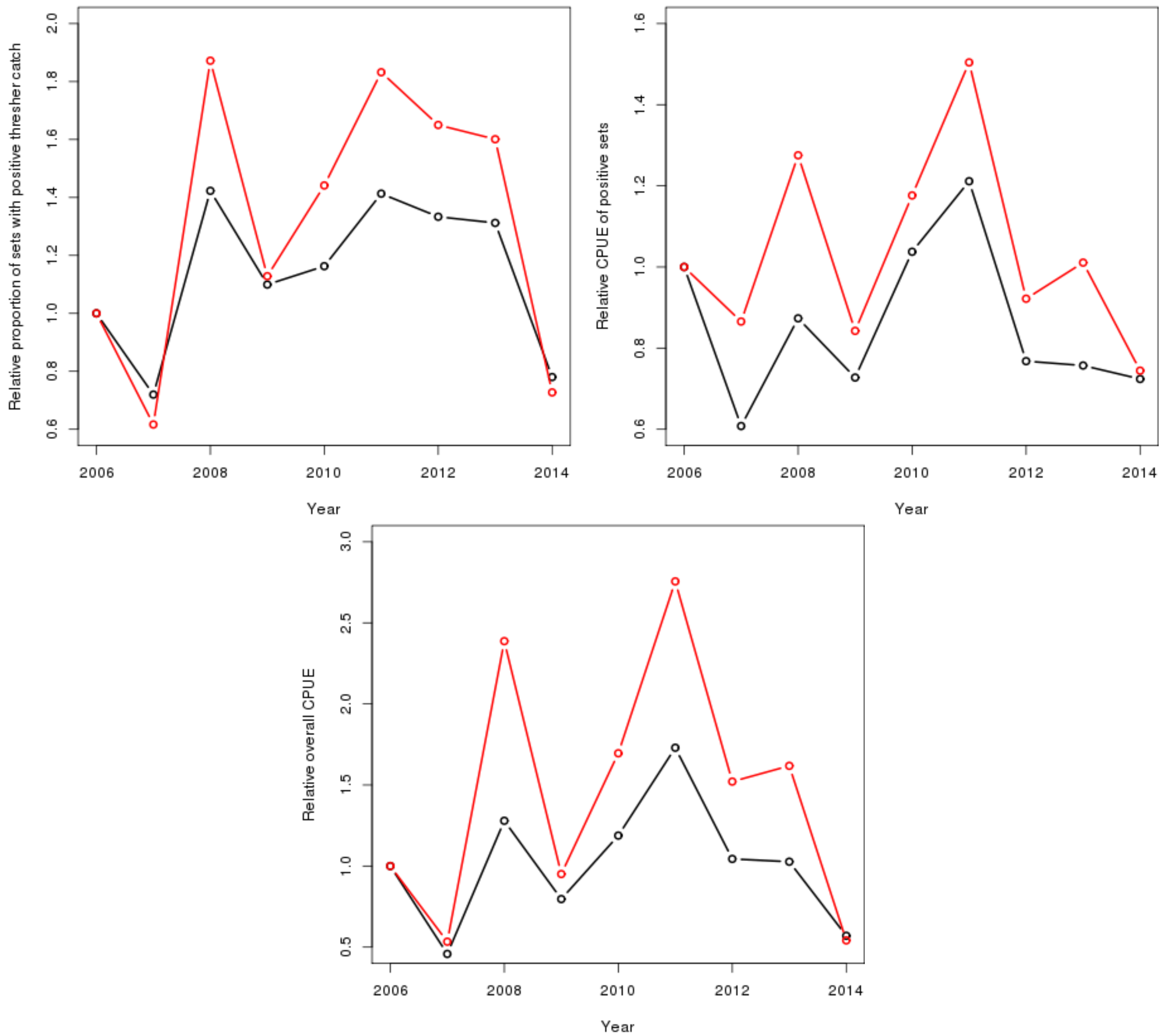
Appendix Figure F.2. Proportion of sets with zero thresher shark catch (upper), nominal catch-per-unit-effort (CPUE) of sets with positive thresher catch (middle), and overall nominal CPUE (lower) for common thresher sharks caught by the USA juvenile thresher survey.



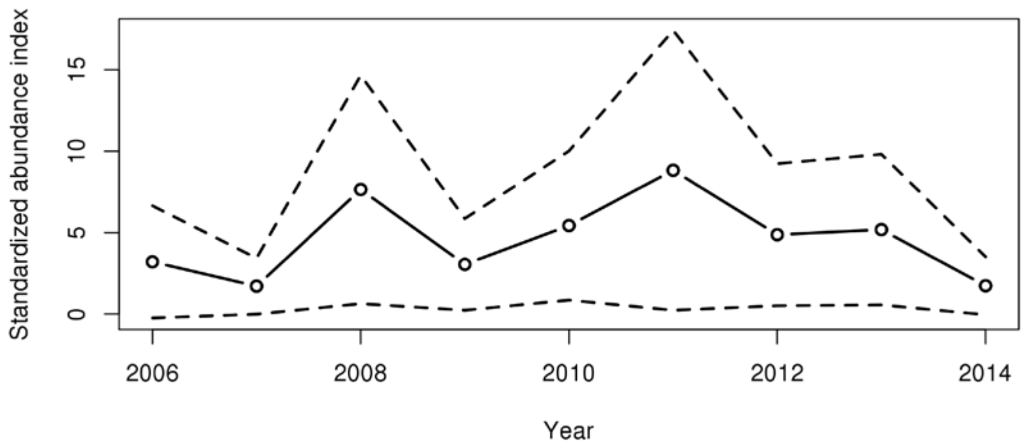
Appendix Figure F.3. Residual plots of the lognormal portion of the delta-lognormal model used to standardize the 2006 – 2014 common thresher shark abundance index for the USA juvenile thresher survey.



Appendix Figure F.4. Residual plots of the binomial portion of the delta-lognormal model used to standardize the 2006 – 2014 common thresher shark abundance index for the USA juvenile thresher survey.



Appendix Figure F.5. Relative proportion of positive sets (upper left), CPUE of positive sets (upper right), and overall CPUE (lower) of nominal (black) and standardized (red) CPUE of the USA juvenile thresher survey. Indices are plotted relative to the value of the initial year.



Appendix Figure F.6. Standardized abundance indices of the USA juvenile thresher survey. Dashed lines indicate 95% confidence intervals derived from jackknifing the data set.

APPENDIX G: Common thresher shark assessment model files

Starter file

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#V3.24U
#C 2015 thresher shark assessment
2015_THR_dat.txt
2015_THR_ctl.txt
0 # 0=use init values in control file; 1=use ss3.par
1 # run display detail (0,1,2)
1 # detailed age-structured reports in REPORT.SSO (0,1)
0 # write detailed info from first call to echoinput.sso (0,1)
0 # write parm values to ParmTrace.sso (0=no,1=good,active; 2=good,all; 3=every_iter,all_parms; 4=every,active)
1 # write to cumreport.sso (0=no,1=like&timeseries; 2=add survey fits)
0 # Include prior_like for non-estimated parameters (0,1)
1 # Use Soft Boundaries to aid convergence (0,1) (recommended)
1 # Number of datafiles to produce: 1st is input, 2nd is estimates, 3rd and higher are bootstrap
10 # Turn off estimation for parameters entering after this phase
10 # MCeval burn interval
2 # MCeval thin interval
0 # jitter initial parm value by this fraction
1967 # min yr for sdreport outputs (-1 for styr)
2014 # max yr for sdreport outputs (-1 for endyr; -2 for endyr+Nforecastyrs
0 # N individual STD years
#vector of year values

0.0001 # final convergence criteria (e.g. 1.0e-04)
0 # retrospective year relative to end year (e.g. -4)
1 # min age for calc of summary biomass
1 # Depletion basis:  denom is: 0=skip; 1=rel X*B0; 2=rel X*Bmsy; 3=rel X*B_styr
1 # Fraction (X) for Depletion denominator (e.g. 0.4)
4 # SPR_report_basis:  0=skip; 1=(1-SPR)/(1-SPR_tgt); 2=(1-SPR)/(1-SPR_MSY); 3=(1-SPR)/(1-SPR_Btarget); 4=rawSPR
1 # F_report_units: 0=skip; 1=exploitation(Bio); 2=exploitation(Num); 3=sum(Frates); 4=true F for range of ages
#COND 10 15 #_min and max age over which average F will be calculated with F_reporting=4
2 # F_report_basis: 0=raw; 1=F/Fspr; 2=F/Fmsy ; 3=F/Fbtgt
999 # check value for end of file
```

Forecast file

```
#V3.24U
#C 2015 thresher shark assessment
# for all year entries except rebuilder; enter either: actual year, -999 for styr, 0 for endyr, neg number for rel. endyr
1 # Benchmarks: 0=skip; 1=calc F_spr,F_btgt,F_msy
2 # MSY: 1= set to F(SPR); 2=calc F(MSY); 3=set to F(Btgt); 4=set to F(endyr)
0.5 # SPR target (e.g. 0.40)
0.5 # Biomass target (e.g. 0.40)
#_Bmark_years: beg_bio, end_bio, beg_selex, end_selex, beg_relF, end_relF (enter actual year, or values of 0 or -integer to be rel. endyr)
 -4 0 -4 0 -4 0
#  2010 2014 2010 2014 2010 2014 # after processing
1 #Bmark_relF_Basis: 1 = use year range; 2 = set relF same as forecast below
#
0 # Forecast: 0=none; 1=F(SPR); 2=F(MSY) 3=F(Btgt); 4=Ave F (uses first-last relF yrs); 5=input annual F scalar
0 # N forecast years
0 # F scalar (only used for Do_Forecast==5)
#_Fcast_years:  beg_selex, end_selex, beg_relF, end_relF  (enter actual year, or values of 0 or -integer to be rel. endyr)
 2010 2014 2010 2014
#  1180631114 1667592815 7631713 1936290657 # after processing
0 # Control rule method (1=catch=f(SSB) west coast; 2=F=f(SSB) )
0 # Control rule Biomass level for constant F (as frac of Bzero, e.g. 0.40); (Must be > the no F level below)
0 # Control rule Biomass level for no F (as frac of Bzero, e.g. 0.10)
0.75 # Control rule target as fraction of Flimit (e.g. 0.75)
3 #_N forecast loops (1=OFL only; 2=ABC; 3=get F from forecast ABC catch with allocations applied)
3 #_First forecast loop with stochastic recruitment
0 #_Forecast loop control #3 (reserved for future bells&whistles)
0 #_Forecast loop control #4 (reserved for future bells&whistles)
0 #_Forecast loop control #5 (reserved for future bells&whistles)
0  #FirstYear for caps and allocations (should be after years with fixed inputs)
0 # stddev of log(realized catch/target catch) in forecast (set value>0.0 to cause active impl_error)
0 # Do West Coast gfish rebuilder output (0/1)
0 # Rebuilder:  first year catch could have been set to zero (Ydecl)(-1 to set to 1999)
0 # Rebuilder:  year for current age structure (Yinit) (-1 to set to endyear+1)
1 # fleet relative F:  1=use first-last alloc year; 2=read seas(row) x fleet(col) below
# Note that fleet allocation is used directly as average F if Do_Forecast=4
0 # basis for fcast catch tuning and for fcast catch caps and allocation  (2=deadbio; 3=retainbio; 5=deadnum; 6=retainnum)
# Conditional input if relative F choice = 2
# Fleet relative F:  rows are seasons, columns are fleets
#_Fleet:  F1_US_DGN_9114 F2_US_DGN_8690 F3_US_DGN_6985 F4_US_SN_9114 F5_US_SN_6990 F6_US_OTH F7_US_REC
F8_MX_DGN F9_MX_LL F10_MX_ART
#  0 0 0 0 0 0 0 0 0 0
#  0 0 0 0 0 0 0 0 0 0
#  0 0 0 0 0 0 0 0 0 0
#  0 0 0 0 0 0 0 0 0 0
# max totalcatch by fleet (-1 to have no max) must enter value for each fleet

# max totalcatch by area (-1 to have no max); must enter value for each fleet

# fleet assignment to allocation group (enter group ID# for each fleet, 0 for not included in an alloc group)

#_Conditional on >1 allocation group
# allocation fraction for each of: 0 allocation groups
# no allocation groups
0 # Number of forecast catch levels to input (else calc catch from forecast F)
2 # code means to read fleet/time specific basis (2=dead catch; 3=retained catch; 99=F)  as below (units are from fleetunits; note new codes in
SSV3.20)
# Input fixed catch values
#Year Seas Fleet Catch(or_F) Basis
#
999 # verify end of input
```

Data file

```
#V3.24U
#_SS-V3.24U-fast;_08/29/2014;_Stock_Synthesis_by_Richard_Methot_(NOAA)_using_ADMB_11.2_Linux64_compiled_on_RHEL6.6
#_Start_time: Mon Aug 31 11:55:19 2015
#_Number_of_datafiles: 1
#C 2015 thresher shark assessment
#C FleetID    FleetID2  Description                        Shortname     Comments
#C 1          F1        US_DGN_fishery                     USDGN         Incl_US_Misc_catch
#C 2          F2        US_DGN_fishery_Seas2               USDGNs2       Incl_US_Misc_catch
#C 3          F3        US_SN_fishery                      USSN
#C 4          F4        US_Rec_Fishery                     USREC
#C 5          F5        US_Rec_Fishery_Seas2               USRECs2
#C 6          F6        MX_DGN_LL_Fishery                  MXDGNLL
#C 7          F7        MX_DGN_LL_Fishery_Seas2            MXDGNLLs2
#C 8          F8        MX_Artisanal_Fishery               MXART
#C 9          S1        US_DGN_Index_1_(1982-1984)         USDGN8284
#C 10         S2        US_DGN_Index_2_(1992-2000)         USDGN9200
#C 11         S3        US_DGN_Index_3_(2001-2013)         USDGN0113
#C 12         S4        US_SN_Index_1_(1985-1993)          USSN8593
#C 13         S5        US_SN_Index_2_(1994-2014)          USSN9414
#C 14         S6        US_Juvy_Thr_Survey_(2006-2014)     USJUV0614
#_observed data:
1969 #_styr
2014 #_endyr
4 #_nseas
 3 3 3 3 #_months/season
2 #_spawn_seas
8 #_Nfleet
6 #_Nsurveys
1 #_N_areas
F1%F2%F3%F4%F5%F6%F7%F8%S1%S2%S3%S4%S5%S6
 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 #_surveytiming_in_season
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 #_area_assignments_for_each_fishery_and_survey
 1 1 1 2 2 1 1 1 #_units of catch:  1=bio; 2=num
 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 #_se of log(catch) only used for init_eq_catch and for Fmethod 2 and 3; use -1 for discard only fleets
2 #_Ngenders
25 #_Nages
 94.08 0 0 1.16 0 0 0 23.26 #_init_equil_catch_for_each_fishery
184 #_N_lines_of_catch_to_read
#_catch_biomass(mtons):_columns_are_fisheries,year,season
 13.575 0 0.145 0.147 0 0 0 4.026 1969 1
 0 17.435 0.698 0 0.564 0 0 4.745 1969 2
 34.853 0 0.638 0.14 0 0 0 6.586 1969 3
 35.953 0 0.341 0.315 0 0 0 5.554 1969 4
 11.463 0 0.277 0.151 0 0 0 4.026 1970 1
 0 32.273 1.296 0 0.56 0 0 4.745 1970 2
 43.62 0 0.702 0.135 0 0 0 6.586 1970 3
 31.905 0 0.558 0.315 0 0 0 5.554 1970 4
 0 0 0 0.147 0 0 0 4.026 1971 1
 0 39.773 1.723 0 0.56 0 0 4.745 1971 2
 21.396 0 0.681 0.134 0 0 0 6.586 1971 3
 0 0 0 0.315 0 0 0 5.554 1971 4
 21.698 0 0.222 0.147 0 0 0 4.026 1972 1
 0 20.423 1.563 0 0.565 0 0 4.745 1972 2
 49.547 0 0.674 0.134 0 0 0 6.586 1972 3
 28.075 0 0 0.315 0 0 0 5.554 1972 4
 0 0 0 0.148 0 0 0 4.026 1973 1
 0 70.778 0.844 0 0.561 0 0 4.745 1973 2
 42.041 0 0.342 0.136 0 0 0 6.586 1973 3
 0 0 0 0.316 0 0 0 5.554 1973 4
 35.527 0 0.425 0.149 0 0 0 4.026 1974 1
 0 23.371 0.885 0 0.567 0 0 4.745 1974 2
 63.537 0 0.501 0.143 0 0 0 6.586 1974 3
 21.803 0 0.666 0.319 0 0 0 5.554 1974 4
 36.936 0 0.416 0.147 0 0 0 4.026 1975 1
 0 97.193 2.725 0 0.565 0 0 4.745 1975 2
 76.647 0 0.891 0.136 0 0 0 6.586 1975 3
 30.333 0 1.11 0.316 0 0 0 5.554 1975 4
 60.629 0 0.587 0.148 0 0 0 5.766 1976 1
```

0 133.512 3.814 0 0.576 0 0 6.795 1976 2
84.183 0 1.025 0.14 0 0 0 9.433 1976 3
119.07 0 2.267 0.316 0 0 0 7.423 1976 4
75.888 0 0.897 0.148 0 0 0 3.217 1977 1
0 166.995 5.777 0 0.56 0 0 3.792 1977 2
90.792 0 0.849 0.138 0 0 0 5.263 1977 3
79.385 0 1.409 0.316 0 0 0 4.572 1977 4
30.784 0 0.917 0.149 0 0 0 3.094 1978 1
0 254.099 20.189 0 0.564 0 0 3.647 1978 2
221.231 0 7.829 0.14 0 0 0 5.063 1978 3
70.825 0 2.985 0.315 0 0 0 4.667 1978 4
80.767 0 3.167 0.147 0 0 0 3.793 1979 1
0 380.274 28.828 0 0.56 0 0 4.469 1979 2
412.994 0 13.988 0.134 0 0 0 6.204 1979 3
251.458 0 9.542 0.315 0 0 0 6.631 1979 4
210.589 0 2.102 0.409 0 0 0 7.409 1980 1
0 486.396 12.057 0 0.004 0 0 8.732 1980 2
1057.19 0 14.466 0.006 0 0 0 12.12 1980 3
371.022 0 7.485 0.001 0 0 0 11.472 1980 4
247.716 0 6.842 0.002 0 0 0 9.988 1981 1
0 747.883 35.041 0 0.001 0 0 11.772 1981 2
495.486 0 21.525 0.002 0 0 0 16.341 1981 3
98.94 0 10.684 0.112 0 0 0 16.389 1981 4
381.602 0 17.904 0.111 0 0 0 16.261 1982 1
0 846.657 93.796 0 0.21 0 0 19.164 1982 2
449.797 0 23.516 0.195 0 0 0 26.604 1982 3
131.6 0 8.184 1.615 0 0 0 22.703 1982 4
1.37 0 0.795 0.201 0 0 0 14.428 1983 1
0 835.471 44.009 0 3.002 0 0 17.004 1983 2
307.478 0 15.879 0.086 0 0 0 23.605 1983 3
129.295 0 6.574 0.199 0 0 0 19.044 1983 4
23.275 0 2.405 0.174 0 0 0 9.473 1984 1
0 754.332 94.897 0 0.003 0 0 11.164 1984 2
267.822 0 3.868 0.437 0 0 0 15.497 1984 3
156.155 0 1.089 0 0 0.182 0 11.438 1984 4
4.121 0 0.161 0.001 0 3.042 0 2.997 1985 1
0 890.693 64.837 0 0.194 0 2.73 3.533 1985 2
205.963 0 0.827 0.208 0 2.366 0 4.904 1985 3
31.763 0 0.116 0.002 0 1.202 0 5.207 1985 4
3.087 0 0.44 1.361 0 13.145 0 5.755 1986 1
0 325.919 7.126 0 0.007 0 11.797 6.783 1986 2
516.465 0 0.916 0.004 0 10.224 0 9.415 1986 3
141.399 0 0.297 0 0 4.473 0 8.772 1986 4
3.464 0 0.326 0.002 0 44.713 0 7.341 1987 1
0 285.021 14.366 0 4.055 0 40.127 8.651 1987 2
183.88 0 0.531 0.788 0 34.777 0 12.009 1987 3
115.679 0 0.187 0.001 0 9.251 0 10.94 1987 4
7.551 0 0.339 0 0 52.416 0 8.605 1988 1
0 134.527 2.521 0 0.877 0 47.04 10.141 1988 2
252.105 0 0.756 0.009 0 40.768 0 14.078 1988 3
172.918 0 0.111 0 0 9.318 0 10.79 1988 4
4.765 0 0.54 0.001 0 35.93 0 3.932 1989 1
0 114.397 1.857 0 0.015 0 32.245 4.635 1989 2
93.76 0 0.224 0.801 0 27.946 0 6.432 1989 3
236.774 0 0.428 0.005 0 10.218 0 6.476 1989 4
4.168 0 0.366 0.007 0 88.672 0 6.469 1990 1
0 104.646 1.725 0 0.014 0 79.577 7.625 1990 2
150.221 0 1.696 0.023 0 68.967 0 10.585 1990 3
183.285 0 0.143 0 0 16.484 0 8.265 1990 4
2.083 0 0.349 0 0 72.833 0 3.416 1991 1
0 147.652 2.143 0 0 0 65.364 4.026 1991 2
224.521 0 0.226 0 0 56.648 0 5.589 1991 3
83.363 0 0.037 0 0 18.01 0 5.853 1991 4
1.657 0 0.256 0 0 134.556 0 6.311 1992 1
0 154.858 1.74 0 0 0 120.756 7.439 1992 2
98.023 0 0.415 0 0 104.655 0 10.324 1992 3
39.229 0 0.032 0 0 26.931 0 8.251 1992 4
5.601 0 0.834 0 0 142.569 0 3.901 1993 1
0 38.035 0.811 0 0.869 0 127.946 4.597 1993 2
126.071 0 0.227 1.371 0 110.887 0 6.382 1993 3

105.898 0 1.123 0.486 0 27.017 0 5.439 1993 4
21.083 0 4.555 0.225 0 125.698 0 3.44 1994 1
0 63.517 2.181 0 1.72 0 112.806 4.053 1994 2
121.692 0 1.579 1.655 0 97.765 0 5.626 1994 3
137.772 0 1.003 0 0 22.388 0 4.58 1994 4
3.865 0 1.162 1.744 0 86.897 0 2.377 1995 1
0 56.175 2.758 0 0.455 0 77.984 2.802 1995 2
91.982 0 1.606 0.455 0 67.587 0 3.889 1995 3
114.492 0 4.819 0 0 19.383 0 3.755 1995 4
1.444 0 1.721 0 0 125.359 0 3.43 1996 1
0 84.522 4.7 0 0.627 0 112.502 4.042 1996 2
158.23 0 2.497 0.076 0 97.502 0 5.611 1996 3
118.696 0 1.734 0 0 25.551 0 5.054 1996 4
10.406 0 1.142 0 0 140.54 0 3.845 1997 1
0 55.041 6.104 0 0.126 0 126.126 4.532 1997 2
124.866 0 6.244 0.126 0 109.31 0 6.291 1997 3
65.541 0 1.335 0.209 0 29.468 0 5.946 1997 4
1.266 0 1.028 0 0 166.758 0 5.16 1998 1
0 84.785 5.933 0 0.464 0 148.785 6.081 1998 2
148.729 0 3.124 0.128 0 129.037 0 8.441 1998 3
121.263 0 3.12 0.509 0 29.444 0 6.779 1998 4
1.052 0 0.501 0.366 0 92.499 0 3.293 1999 1
0 110.796 12.93 0 0.258 0 81.904 3.882 1999 2
109.953 0 3.544 0.414 0 71.099 0 5.388 1999 3
83.162 0 2.583 0 0 21.704 0 5.561 1999 4
1.643 0 1.507 0.702 0 114.586 0 5.838 2000 1
0 106.118 21.749 0 0.819 0 98.902 6.881 2000 2
71.523 0 3.369 0.819 0 86.124 0 9.55 2000 3
101.473 0 4.103 0 0 27.043 0 8.655 2000 4
2.632 0 3.214 0 0 103.206 0 6.702 2001 1
0 99.66 14.37 0 0.629 0 86.978 7.9 2001 2
125.405 0 3.32 1.574 0 75.967 0 10.966 2001 3
111.216 0 6.902 0 0 26.685 0 9.525 2001 4
12.887 0 1.641 0 0 99.354 0 6.453 2002 1
0 88.237 18.114 0 0.979 0 83.733 7.605 2002 2
115.807 0 1.336 0.665 0 73.134 0 10.557 2002 3
137.652 0 1.444 0 0 25.444 0 9.102 2002 4
11.418 0 8.666 0.167 0 92.483 0 6.006 2003 1
0 72.965 5.357 0 1.722 0 77.941 7.079 2003 2
49.835 0 0.79 0.318 0 68.076 0 9.827 2003 3
73.675 0 1.027 0 0 28.219 0 9.737 2003 4
1.293 0 1.661 0 0 145.006 0 9.418 2004 1
0 23.924 12.382 0 0.285 0 122.206 11.1 2004 2
22.867 0 1.434 0.033 0 106.736 0 15.407 2004 3
39.687 0 1.177 4.202 0 33.746 0 12.338 2004 4
2.273 0 2.77 0.027 0 90.904 0 5.904 2005 1
0 29.24 4.56 0 0.124 0 76.609 6.958 2005 2
36.926 0 1.493 0.142 0 66.912 0 9.659 2005 3
116.74 0 0.346 0.014 0 24.032 0 8.537 2005 4
3.872 0 1.01 0.032 0 94.366 0 6.128 2006 1
0 31.372 12.786 0 0.776 0 79.53 7.224 2006 2
55.864 0 1.511 0.135 0 69.462 0 10.026 2006 3
50.217 0 3.056 0 0 25.418 0 8.993 2006 4
2.909 0 2.396 0.009 0 104.078 0 6.76 2007 1
0 24.998 5.015 0 0.627 0 87.714 7.967 2007 2
63.907 0 1.632 0.862 0 76.611 0 11.059 2007 3
98.202 0 0.618 0.036 0 27.83 0 10.084 2007 4
5.992 0 1.135 0.032 0 105.688 0 7.957 2008 1
0 19.665 5.243 0 0.542 0 87.479 9.378 2008 2
65.947 0 2.669 0.512 0 76.583 0 13.018 2008 3
45.951 0 3.818 0.125 0 26.307 0 11.846 2008 4
6.775 0 2.525 0.022 0 25.146 0 9.289 2009 1
0 27.911 5.345 0 0.41 0 10.055 10.948 2009 2
17.242 0 2.504 0.714 0 10.016 0 15.197 2009 3
34.374 0 2.452 0.786 0 19.269 0 13.024 2009 4
7.694 0 5.813 0.046 0 22.756 0 8.406 2010 1
0 22.769 7.47 0 0.776 0 9.099 9.908 2010 2
14.645 0 1.55 0.295 0 9.063 0 13.753 2010 3
32.599 0 1.64 0.076 0 17.016 0 11.547 2010 4
1.229 0 1.192 1.301 0 18.641 0 6.887 2011 1

0 4.939 5.006 0 0.747 0 7.454 8.117 2011 2
7.024 0 1.938 0.342 0 7.425 0 11.266 2011 3
74.068 0 1.377 0.01 0 15.288 0 10.223 2011 4
3.333 0 0.713 0.046 0 21.526 0 7.952 2012 1
0 11.221 2.275 0 0.068 0 8.607 9.372 2012 2
10.191 0 2.807 0.243 0 8.574 0 13.01 2012 3
35.444 0 1.584 0.008 0 17.207 0 11.553 2012 4
1.219 0 0.216 0 0 22.779 0 8.415 2013 1
0 8.529 1.657 0 0.634 0 9.108 9.918 2013 2
4.182 0 0.759 0.147 0 9.073 0 13.767 2013 3
37.382 0 0.55 0.023 0 13.012 0 9.282 2013 4
0.393 0 0.807 0.002 0 20.982 0 7.751 2014 1
0 19.218 3.617 0 0.297 0 8.39 9.136 2014 2
3.094 0 0.529 0.195 0 8.357 0 12.681 2014 3
9.411 0 0.412 0 0 15.169 0 10.353 2014 4

#
64 #_N_cpue_and_surveyabundance_observations
#_Units: 0=numbers; 1=biomass; 2=F
#_Errtype: -1=normal; 0=lognormal; >0=T
#_Fleet Units Errtype
1 0 0 # F1
2 0 0 # F2
3 0 0 # F3
4 0 0 # F4
5 0 0 # F5
6 0 0 # F6
7 0 0 # F7
8 0 0 # F8
9 0 0 # S1
10 0 0 # S2
11 0 0 # S3
12 0 0 # S4
13 0 0 # S5
14 0 0 # S6
#_year seas index obs err
1982 3 9 0.0122918 0.280355 # S1
1983 3 9 0.00920862 0.278143 # S1
1984 3 9 0.00763147 0.27842 # S1
1992 3 10 0.000466618 0.11681 # S2
1993 3 10 0.000655651 0.112893 # S2
1994 3 10 0.00107238 0.112887 # S2
1995 3 10 0.000760164 0.127392 # S2
1996 3 10 0.000985173 0.12568 # S2
1997 3 10 0.00111957 0.119943 # S2
1998 3 10 0.00213771 0.120471 # S2
1999 3 10 0.00126356 0.129961 # S2
2000 3 10 0.00190646 0.148804 # S2
2001 4 11 0.0126904 0.197016 # S3
2002 4 11 0.0063087 0.202422 # S3
2003 4 11 0.00574843 0.211916 # S3
2004 4 11 0.00517914 0.21691 # S3
2005 4 11 0.0182973 0.20352 # S3
2006 4 11 0.00686545 0.1991 # S3
2007 4 11 0.0228914 0.196973 # S3
2008 4 11 0.00684689 0.220957 # S3
2009 4 11 0.00390685 0.225036 # S3
2010 4 11 0.0174454 0.231113 # S3
2011 4 11 0.0114837 0.230211 # S3
2012 4 11 0.00711149 0.22832 # S3
2013 4 11 0.0124422 0.19884 # S3
1985 2 12 0.071494 0.22246 # S4
1986 2 12 0.0507598 0.21999 # S4
1987 2 12 0.0799821 0.23149 # S4
1988 2 12 0.0626452 0.23024 # S4
1989 2 12 0.0403903 0.23055 # S4
1990 2 12 0.070865 0.23839 # S4
1991 2 12 0.0510342 0.23477 # S4
1992 2 12 0.0678798 0.24198 # S4
1993 2 12 0.0831977 0.23061 # S4

1994 2 13 0.208271 0.25464 # S5
1995 2 13 0.202657 0.232678 # S5
1996 2 13 0.29486 0.219906 # S5
1997 2 13 0.459113 0.199639 # S5
1998 2 13 0.499113 0.207498 # S5
1999 2 13 0.557804 0.190297 # S5
2000 2 13 0.332073 0.203221 # S5
2001 2 13 0.690243 0.21287 # S5
2002 2 13 0.389268 0.225373 # S5
2003 2 13 0.222197 0.204888 # S5
2004 2 13 0.297345 0.2071 # S5
2005 2 13 0.248722 0.228862 # S5
2006 2 13 1.00752 0.192267 # S5
2007 2 13 0.690049 0.204015 # S5
2008 2 13 0.389985 0.212196 # S5
2009 2 13 0.69659 0.195183 # S5
2010 2 13 0.768759 0.198151 # S5
2011 2 13 0.514355 0.210665 # S5
2012 2 13 0.728556 0.197459 # S5
2013 2 13 0.213241 0.240291 # S5
2014 2 13 0.810052 0.4122 # S5
2006 3 14 3.20419 0.548688 # S6
2007 3 14 1.70947 0.513279 # S6
2008 3 14 7.64873 0.46797 # S6
2009 3 14 3.04584 0.471428 # S6
2010 3 14 5.43268 0.430134 # S6
2011 3 14 8.82981 0.496809 # S6
2012 3 14 4.87355 0.456906 # S6
2013 3 14 5.18471 0.455354 # S6
2014 3 14 1.73476 0.523049 # S6

0 #_N_fleets_with_discard
#_discard_units (1=same_as_catchunits(bio/num); 2=fraction; 3=numbers)
#_discard_errtype: >0 for DF of T-dist(read CV below); 0 for normal with CV; -1 for normal with se; -2 for lognormal
#Fleet Disc_units err_type
0 #N discard obs
#_year seas index obs err
#
0 #_N_meanbodywt_obs
30 #_DF_for_meanbodywt_T-distribution_like

2 # length bin method: 1=use databins; 2=generate from binwidth,min,max below; 3=read vector
1 # binwidth for population size comp
40 # minimum size in the population (lower edge of first bin and size at age 0.00)
310 # maximum size in the population (lower edge of last bin)

-1 #_comp_tail_compression
0.001 #_add_to_comp
0 #_combine males into females at or below this bin number
130 #_N_LengthBins
40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100 102 104 106 108 110 112 114 116 118 120 122
124 126 128 130 132 134 136 138 140 142 144 146 148 150 152 154 156 158 160 162 164 166 168 170 172 174 176 178 180 182 184 186 188
190 192 194 196 198 200 202 204 206 208 210 212 214 216 218 220 222 224 226 228 230 232 234 236 238 240 242 244 246 248 250 252 254
256 258 260 262 264 266 268 270 272 274 276 278 280 282 284 286 288 290 292 294 296 298
58 #_N_Length_obs
#Yr Seas Flt/Svy Gender Part Nsamp datavector(female-male)
1990 3 1 3 0 7 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 0 0 0 0 0 0 0 1 1 0 0 0 1 0 1 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

26 #_N_age_bins
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
2 #_N_ageerror_definitions
-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
0.001 0.001
0.001 0.001 0.001
-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
0.175684 0.175684 0.351367 0.527051 0.702735 0.878418 1.0541 1.22979 1.40547 1.58115 1.75684 1.93252 2.1082 2.28389 2.45957 2.63525
2.81094 2.98662 3.16231 3.33799 3.51367 3.68935 3.86504 4.04072 4.2164 4.39209
152 #_N_Agecomp_obs
3 #_Lbin_method: 1=poplenbins; 2=datalenbins; 3=lengths
1 #_combine males into females at or below this bin number
#Yr Seas Flt/Svy Gender Part Ageerr Lbin_lo Lbin_hi Nsamp datavector(female-male)
1990 2 1 1 0 2 104 105 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1990 2 1 1 0 2 127 128 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 #_N_MeanSize-at-Age_obs
#Yr Seas Flt/Svy Gender Part Ageerr Ignore datavector(female-male)
samplesize(female-male)

0 #_N_environ_variables
0 #_N_environ_obs
3 # N sizefreq methods to read
38 104 31 #Sizefreq N bins per method
2 2 2 #Sizetfreq units(bio/num) per method
3 3 3 #Sizefreq scale(kg/lbs/cm/inches) per method
0.001 0.001 0.001 #Sizefreq mincomp per method
33 13 7 #Sizefreq N obs per method
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3 1986 3 3 0 0 5 8 1 1 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3 1987 2 3 0 0 9 25 3 3 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3 1987 3 3 0 0 5 11 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3 1988 2 3 0 0 6 20 2 1 3 2 0 1 0 0 0 2 0 0 1 0 0 0 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3 1989 2 3 0 0 15 51 17 8 8 6 5 1 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 # do tags (0/1)

0 # no morphcomp data

999

ENDDATA

Control file

```
#V3.24U
#C 2015 thresher shark assessment
#_data_and_control_files: 2015_THR_dat.txt // 2015_THR_ctl.txt
#_SS-V3.24U-fast;_08/29/2014;_Stock_Synthesis_by_Richard_Methot_(NOAA)_using_ADMB_11.2_Linux64_compiled_on_RHEL6.6
1  #_N_Growth_Patterns
1 #_N_Morphs_Within_GrowthPattern
#_Cond 1 #_Morph_between/within_stdev_ratio (no read if N_morphs=1)
#_Cond  1 #vector_Morphdist_(-1_in_first_val_gives_normal_approx)
#
1 #  number of recruitment assignments (overrides GP*area*seas parameter values)
0 # recruitment interaction requested
#GP seas area for each recruitment assignment
 1 2 1
#
#_Cond 0 # N_movement_definitions goes here if N_areas > 1
#_Cond 1.0 # first age that moves (real age at begin of season, not integer) also cond on do_migration>0
#_Cond 1 1 1 2 4 10 # example move definition for seas=1, morph=1, source=1 dest=2, age1=4, age2=10
#
3 #_Nblock_Patterns
 5 3 1 #_blocks_per_pattern
# begin and end years of blocks
 1982 1984 1985 1988 1989 1991 1992 2000 2001 2014
 1982 1984 1985 1988 1989 2014
 1994 2014
#
0.5 #_fracfemale
0 #_natM_type:_0=1Parm; 1=N_breakpoints;_2=Lorenzen;_3=agespecific;_4=agespec_withseasinterpolate
  #_no additional input for selected M option; read 1P per morph
1 # GrowthModel: 1=vonBert with L1&L2; 2=Richards with L1&L2; 3=age_speciific_K; 4=not implemented
0.125 #_Growth_Age_for_L1
999 #_Growth_Age_for_L2 (999 to use as Linf)
0 #_SD_add_to_LAA (set to 0.1 for SS2 V1.x compatibility)
0 #_CV_Growth_Pattern:  0 CV=f(LAA); 1 CV=F(A); 2 SD=F(LAA); 3 SD=F(A); 4 logSD=F(A)
1 #_maturity_option:  1=length logistic; 2=age logistic; 3=read age-maturity by GP; 4=read age-fecundity by GP; 5=read fec and wt from
wtatage.ss; 6=read length-maturity by GP
#_placeholder for empirical age- or length- maturity by growth pattern (female only)
5 #_First_Mature_Age
2 #_fecundity option:(1)eggs=Wt*(a+b*Wt);(2)eggs=a*L^b;(3)eggs=a*Wt^b; (4)eggs=a+b*L; (5)eggs=a+b*W
0 #_hermaphroditism option:  0=none; 1=age-specific fxn
2 #_parameter_offset_approach (1=none, 2= M, G, CV_G as offset from female-GP1, 3=like SS2 V1.x)
1 #_env/block/dev_adjust_method (1=standard; 2=logistic transform keeps in base parm bounds; 3=standard w/ no bound check)
#
#_growth_parms
#_LO HI INIT PRIOR PR_type SD PHASE env-var use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn
 0.01 0.8 0.04 -1.8488 -1 99 -1 0 0 0 0 0 0 0 # NatM_p_1_Fem_GP_1
 30 100 70.7686 85.2 -1 99 5 0 0 0 0 0 0 0 # L_at_Amin_Fem_GP_1
 200 300 245.77 246.6 -1 99 5 0 0 0 0 0 0 0 # L_at_Amax_Fem_GP_1
 0 0.2 0.135968 0.124 -1 99 5 0 0 0 0 0 0 0 # VonBert_K_Fem_GP_1
 0.001 0.3 0.08 0.1 -1 99 -5 0 0 0 0 0 0 0 # CV_young_Fem_GP_1
 0.001 0.3 0.05 0.05 -1 99 -6 0 0 0 0 0 0 0 # CV_old_Fem_GP_1
 0 0 0 0.179 -1 99 -1 0 0 0 0 0 0 0 # NatM_p_1_Mal_GP_1
 -2 2 0.0125392 74 -1 99 5 0 0 0 0 0 0 0 # L_at_Amin_Mal_GP_1
 -2 2 -0.0179372 221.6 -1 99 5 0 0 0 0 0 0 0 # L_at_Amax_Mal_GP_1
 -2 2 0.00796863 0.189 -1 99 5 0 0 0 0 0 0 0 # VonBert_K_Mal_GP_1
 0 0 0 0.1 -1 99 -5 0 0 0 0 0 0 0 # CV_young_Mal_GP_1
 0 0 0 0.05 -1 99 -6 0 0 0 0 0 0 0 # CV_old_Mal_GP_1
 0 2 0.000188 0.000188 -1 99 -3 0 0 0 0 0 0 0 # Wtlen_1_Fem
 1 4 2.5188 2.5188 -1 99 -3 0 0 0 0 0 0 0 # Wtlen_2_Fem
 100 300 215.1 5 -1 99 -3 0 0 0 0 0 0 0 # Mat50%_Fem
 -1 0 -0.2409 -3 -1 99 -3 0 0 0 0 0 0 0 # Mat_slope_Fem
 0 5 2 3 -1 99 -3 0 0 0 0 0 0 0 # Eggs_scalar_Fem
 -1 3 0 0 -1 99 -3 0 0 0 0 0 0 0 # Eggs_exp_len_Fem
 0 2 0.000188 0.000188 -1 99 -3 0 0 0 0 0 0 0 # Wtlen_1_Mal
 1 4 2.5188 2.5188 -1 99 -3 0 0 0 0 0 0 0 # Wtlen_2_Mal
 -4 4 0 0 -1 99 -3 0 0 0 0 0 0 0 # RecrDist_GP_1
 -4 4 0 0 -1 99 -3 0 0 0 0 0 0 0 # RecrDist_Area_1
 -4 4 -4 -4 -1 99 -3 0 0 0 0 0 0 0 # RecrDist_Seas_1
 -4 4 0 0 -1 99 -3 0 0 0 0 0 0 0 # RecrDist_Seas_2
```

```
 -4 4 -4 -4 -1 99 -3 0 0 0 0 0 0 0 # RecrDist_Seas_3
 -4 4 -4 -4 -1 99 -3 0 0 0 0 0 0 0 # RecrDist_Seas_4
 -4 4 1 1 -1 99 -3 0 0 0 0 0 0 0 # CohortGrowDev
#
#_Cond 0  #custom_MG-env_setup (0/1)
#_Cond -2 2 0 0 -1 99 -2 #_placeholder when no MG-environ parameters
#
#_Cond 0  #custom_MG-block_setup (0/1)
#_Cond -2 2 0 0 -1 99 -2 #_placeholder when no MG-block parameters
#_Cond No MG parm trends
#
#_seasonal_effects_on_biology_parms
 0 0 0 0 0 0 0 0 0 0 #_femwtlen1,femwtlen2,mat1,mat2,fec1,fec2,Malewtlen1,malewtlen2,L1,K
#_Cond -2 2 0 0 -1 99 -2 #_placeholder when no seasonal MG parameters
#
#_Cond -4 #_MGparm_Dev_Phase
#
#_Spawner-Recruitment
7 #_SR_function: 2=Ricker; 3=std_B-H; 4=SCAA; 5=Hockey; 6=B-H_flattop; 7=survival_3Parm; 8=Shepard_3Parm
#_LO HI INIT PRIOR PR_type SD PHASE
 1 15 3.42092 7 -1 99 1 # SR_LN(R0)
 0 1 0.5 0.5 -1 99 -7 # SR_surv_Sfrac
 0.4 7 2.53345 5 -1 99 1 # SR_surv_Beta
 0 2 0.5 0.5 -1 99 -1 # SR_sigmaR
 -5 5 0 0 -1 99 -1 # SR_envlink
 -4 4 0 0 -999 99 -1 # SR_R1_offset
 0 0 0 0 -1 99 -1 # SR_autocorr
0 #_SR_env_link
0 #_SR_env_target_0=none;1=devs;_2=R0;_3=steepness
1 #do_recdev:  0=none; 1=devvector; 2=simple deviations
1969 # first year of main recr_devs; early devs can preceed this era
2014 # last year of main recr_devs; forecast devs start in following year
1 #_recdev phase
1 # (0/1) to read 13 advanced options
 0 #_recdev_early_start (0=none; neg value makes relative to recdev_start)
 -4 #_recdev_early_phase
 0 #_forecast_recruitment phase (incl. late recr) (0 value resets to maxphase+1)
 1 #_lambda for Fcast_recr_like occurring before endyr+1
 1971.5 #_last_early_yr_nobias_adj_in_MPD
 1981.6 #_first_yr_fullbias_adj_in_MPD
 2012.6 #_last_yr_fullbias_adj_in_MPD
 2019 #_first_recent_yr_nobias_adj_in_MPD
 0.8537 #_max_bias_adj_in_MPD (-1 to override ramp and set biasadj=1.0 for all estimated recdevs)
 0 #_period of cycles in recruitment (N parms read below)
 -5 #min rec_dev
 5 #max rec_dev
 0 #_read_recdevs
#_end of advanced SR options
#
#_placeholder for full parameter lines for recruitment cycles
# read specified recr devs
#_Yr Input_value
#
# all recruitment deviations
#DisplayOnly -0.0133755 # Main_RecrDev_1969
#DisplayOnly -0.0314449 # Main_RecrDev_1970
#DisplayOnly -0.0559584 # Main_RecrDev_1971
#DisplayOnly -0.0769948 # Main_RecrDev_1972
#DisplayOnly -0.0798727 # Main_RecrDev_1973
#DisplayOnly -0.0591449 # Main_RecrDev_1974
#DisplayOnly -0.0261905 # Main_RecrDev_1975
#DisplayOnly -0.0272813 # Main_RecrDev_1976
#DisplayOnly -0.123211 # Main_RecrDev_1977
#DisplayOnly -0.127526 # Main_RecrDev_1978
#DisplayOnly 0.317263 # Main_RecrDev_1979
#DisplayOnly 0.318656 # Main_RecrDev_1980
#DisplayOnly 0.211367 # Main_RecrDev_1981
#DisplayOnly 0.0951502 # Main_RecrDev_1982
#DisplayOnly 0.330222 # Main_RecrDev_1983
#DisplayOnly -0.0346352 # Main_RecrDev_1984
```

#DisplayOnly 0.0150824 # Main_RecrDev_1985
#DisplayOnly -0.100234 # Main_RecrDev_1986
#DisplayOnly -0.115901 # Main_RecrDev_1987
#DisplayOnly -0.349577 # Main_RecrDev_1988
#DisplayOnly -0.615987 # Main_RecrDev_1989
#DisplayOnly -0.432327 # Main_RecrDev_1990
#DisplayOnly -0.370839 # Main_RecrDev_1991
#DisplayOnly -0.0915563 # Main_RecrDev_1992
#DisplayOnly -0.240137 # Main_RecrDev_1993
#DisplayOnly -0.482289 # Main_RecrDev_1994
#DisplayOnly -0.452398 # Main_RecrDev_1995
#DisplayOnly -0.0735943 # Main_RecrDev_1996
#DisplayOnly 0.103304 # Main_RecrDev_1997
#DisplayOnly 0.109601 # Main_RecrDev_1998
#DisplayOnly 0.296832 # Main_RecrDev_1999
#DisplayOnly -0.0751145 # Main_RecrDev_2000
#DisplayOnly 0.551349 # Main_RecrDev_2001
#DisplayOnly 0.037622 # Main_RecrDev_2002
#DisplayOnly -0.52096 # Main_RecrDev_2003
#DisplayOnly -0.159824 # Main_RecrDev_2004
#DisplayOnly -0.386089 # Main_RecrDev_2005
#DisplayOnly 0.731382 # Main_RecrDev_2006
#DisplayOnly 0.540008 # Main_RecrDev_2007
#DisplayOnly 0.179909 # Main_RecrDev_2008
#DisplayOnly 0.43615 # Main_RecrDev_2009
#DisplayOnly 0.476353 # Main_RecrDev_2010
#DisplayOnly 0.1488 # Main_RecrDev_2011
#DisplayOnly 0.531043 # Main_RecrDev_2012
#DisplayOnly -0.475049 # Main_RecrDev_2013
#DisplayOnly 0.167419 # Main_RecrDev_2014
#
#Fishing Mortality info
0.1 # F ballpark for annual F (=Z-M) for specified year
-2008 # F ballpark year (neg value to disable)
3 # F_Method: 1=Pope; 2=instan. F; 3=hybrid (hybrid is recommended)
4 # max F or harvest rate, depends on F_Method
no additional F input needed for Fmethod 1
if Fmethod=2; read overall start F value; overall phase; N detailed inputs to read
if Fmethod=3; read N iterations for tuning for Fmethod 3
5 # N iterations for tuning F in hybrid method (recommend 3 to 7)
#
#_initial_F_parms
#_LO HI INIT PRIOR PR_type SD PHASE
 0 3 0.0287612 0 -1 99 1 # InitF_1F1
 0 1 0 0 -1 99 -1 # InitF_2F2
 0 1 0 0 -1 99 -1 # InitF_3F3
 0 3 0.0271201 0 -1 99 1 # InitF_4F4
 0 1 0 0 -1 99 -1 # InitF_5F5
 0 1 0 0 -1 99 -1 # InitF_6F6
 0 1 0 0 -1 99 -1 # InitF_7F7
 0 3 0.0923841 0 -1 99 1 # InitF_8F8
#
#_Q_setup
 # Q_type options: <0=mirror, 0=float_nobiasadj, 1=float_biasadj, 2=parm_nobiasadj, 3=parm_w_random_dev, 4=parm_w_randwalk, 5=mean_unbiased_float_assign_to_parm
#_for_env-var:_enter_index_of_the_env-var_to_be_linked
#_Den-dep env-var extra_se Q_type
 0 0 0 0 # 1 F1
 0 0 0 0 # 2 F2
 0 0 0 0 # 3 F3
 0 0 0 0 # 4 F4
 0 0 0 0 # 5 F5
 0 0 0 0 # 6 F6
 0 0 0 0 # 7 F7
 0 0 0 0 # 8 F8
 0 0 0 0 # 9 S1
 0 0 0 0 # 10 S2
 0 0 0 0 # 11 S3
 0 0 0 0 # 12 S4
 0 0 0 0 # 13 S5

```
 0 0 0 0 # 14 S6
#
#_Cond 0 #_If q has random component, then 0=read one parm for each fleet with random q; 1=read a parm for each year of index
#_Q_parms(if_any);Qunits_are_ln(q)
#
#_size_selex_types
#discard_options:_0=none;_1=define_retention;_2=retention&mortality;_3=all_discarded_dead
#_Pattern Discard Male Special
 24 0 0 0 # 1 F1
 27 0 0 4 # 2 F2
 0 0 0 0 # 3 F3
 15 0 0 1 # 4 F4
 15 0 0 2 # 5 F5
 15 0 0 1 # 6 F6
 15 0 0 2 # 7 F7
 24 0 0 0 # 8 F8
 15 0 0 1 # 9 S1
 15 0 0 1 # 10 S2
 15 0 0 1 # 11 S3
 0 0 0 0 # 12 S4
 0 0 0 0 # 13 S5
 24 0 0 0 # 14 S6
#
#_age_selex_types
#_Pattern ___ Male Special
 11 0 0 0 # 1 F1
 11 0 0 0 # 2 F2
 14 0 0 0 # 3 F3
 11 0 0 0 # 4 F4
 11 0 0 0 # 5 F5
 11 0 0 0 # 6 F6
 11 0 0 0 # 7 F7
 11 0 0 0 # 8 F8
 11 0 0 0 # 9 S1
 11 0 0 0 # 10 S2
 11 0 0 0 # 11 S3
 15 0 0 3 # 12 S4
 15 0 0 3 # 13 S5
 11 0 0 0 # 14 S6
#_LO HI INIT PRIOR PR_type SD PHASE env-var use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn
 45 250 158.442 150 -1 99 2 0 0 0 0 0 1 2 # SizeSel_1P_1_F1
 -4 9 -4 1 -1 99 -4 0 0 0 0 0 0 0 # SizeSel_1P_2_F1
 -4 12 6.60569 3 -1 99 3 0 0 0 0 0 1 2 # SizeSel_1P_3_F1
 -4 9 6.94933 3 -1 99 3 0 0 0 0 0 1 2 # SizeSel_1P_4_F1
 -9 9 -2.10083 0 -1 99 4 0 0 0 0 0 1 2 # SizeSel_1P_5_F1
 -1000 -1000 -1000 0 -1 99 -4 0 0 0 0 0 0 0 # SizeSel_1P_6_F1
 0 2 0 150 -1 99 -99 0 0 0 0 0 0 0 # SizeSpline_Code_F2_2
 -1 1 0.0735268 1 -1 99 3 0 0 0 0 0 0 0 # SizeSpline_GradLo_F2_2
 -1 1 -0.212632 3 -1 99 3 0 0 0 0 0 0 0 # SizeSpline_GradHi_F2_2
 45 250 75 3 -1 99 -99 0 0 0 0 0 0 0 # SizeSpline_Knot_1_F2_2
 45 250 125 3 -1 99 -99 0 0 0 0 0 0 0 # SizeSpline_Knot_2_F2_2
 45 250 175 3 -1 99 -99 0 0 0 0 0 0 0 # SizeSpline_Knot_3_F2_2
 45 250 225 3 -1 99 -99 0 0 0 0 0 0 0 # SizeSpline_Knot_4_F2_2
 -9 9 -2.89269 3 -1 99 3 0 0 0 0 0 2 2 # SizeSpline_Val_1_F2_2
 -9 9 -0.387741 3 -1 99 3 0 0 0 0 0 2 2 # SizeSpline_Val_2_F2_2
 -9 9 0 3 -1 99 -3 0 0 0 0 0 0 0 # SizeSpline_Val_3_F2_2
 -9 9 -6.15183 3 -1 99 3 0 0 0 0 0 2 2 # SizeSpline_Val_4_F2_2
 45 250 78.8487 80 -1 99 2 0 0 0 0 0 0 0 # SizeSel_8P_1_F8
 -4 9 -4 0 -1 99 -4 0 0 0 0 0 0 0 # SizeSel_8P_2_F8
 -4 9 3.99715 3 -1 99 3 0 0 0 0 0 0 0 # SizeSel_8P_3_F8
 -4 9 6.66827 3 -1 99 3 0 0 0 0 0 0 0 # SizeSel_8P_4_F8
 -1000 -1000 -1000 -1000 -1 99 -2 0 0 0 0 0 0 0 # SizeSel_8P_5_F8
 -1000 -1000 -1000 -1000 -1 99 -2 0 0 0 0 0 0 0 # SizeSel_8P_6_F8
 45 250 83.2881 80 -1 99 2 0 0 0 0 0 0 0 # SizeSel_14P_1_S6
 -4 9 -4 0 -1 99 -4 0 0 0 0 0 0 0 # SizeSel_14P_2_S6
 -4 9 4.92258 3 -1 99 3 0 0 0 0 0 0 0 # SizeSel_14P_3_S6
 -4 9 7.53031 3 -1 99 3 0 0 0 0 0 0 0 # SizeSel_14P_4_S6
 -1000 -1000 -1000 -1000 -1 99 -2 0 0 0 0 0 0 0 # SizeSel_14P_5_S6
 -1000 -1000 -1000 -1000 -1 99 -2 0 0 0 0 0 0 0 # SizeSel_14P_6_S6
 0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_1P_1_F1
```

10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_1P_2_F1
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_2P_1_F2
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_2P_2_F2
-9 9 5.89827 0 -1 99 2 0 0 0 0 0 3 2 # AgeSel_3P_1_F3
-9 9 -3.64916 0 -1 99 2 0 0 0 0 0 3 2 # AgeSel_3P_2_F3
-9 9 -4.48415 0 -1 99 2 0 0 0 0 0 3 2 # AgeSel_3P_3_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_4_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_5_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_6_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_7_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_8_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_9_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_10_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_11_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_12_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_13_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_14_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_15_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_16_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_17_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_18_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_19_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_20_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_21_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_22_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_23_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_24_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_25_F3
-99 9 -99 0 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_3P_26_F3
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_4P_1_F4
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_4P_2_F4
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_5P_1_F5
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_5P_2_F5
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_6P_1_F6
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_6P_2_F6
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_7P_1_F7
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_7P_2_F7
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_8P_1_F8
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_8P_2_F8
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_9P_1_S1
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_9P_2_S1
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_10P_1_S2
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_10P_2_S2
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_11P_1_S3
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_11P_2_S3
0 10 0.1 0.1 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_14P_1_S6
10 30 25 25 -1 99 -2 0 0 0 0 0 0 0 # AgeSel_14P_2_S6
#_Cond 0 #_custom_sel-env_setup (0/1)
#_Cond -2 2 0 0 -1 99 -2 #_placeholder when no enviro fxns
1 #_custom_sel-blk_setup (0/1)
45 250 155.315 150 -1 99 5 # SizeSel_1P_1_F1_BLK1repl_1982
45 250 146.905 150 -1 99 5 # SizeSel_1P_1_F1_BLK1repl_1985
45 250 149.714 150 -1 99 5 # SizeSel_1P_1_F1_BLK1repl_1989
45 250 161.752 150 -1 99 5 # SizeSel_1P_1_F1_BLK1repl_1992
45 250 157.538 150 -1 99 5 # SizeSel_1P_1_F1_BLK1repl_2001
-4 12 6.41776 3 -1 99 5 # SizeSel_1P_3_F1_BLK1repl_1982
-4 12 7.11781 3 -1 99 5 # SizeSel_1P_3_F1_BLK1repl_1985
-4 12 8.06964 3 -1 99 5 # SizeSel_1P_3_F1_BLK1repl_1989
-4 12 6.72422 3 -1 99 5 # SizeSel_1P_3_F1_BLK1repl_1992
-4 12 6.71311 3 -1 99 5 # SizeSel_1P_3_F1_BLK1repl_2001
-9 9 6.66947 0 -1 99 6 # SizeSel_1P_4_F1_BLK1repl_1982
-9 9 6.94357 0 -1 99 6 # SizeSel_1P_4_F1_BLK1repl_1985
-9 9 6.78377 0 -1 99 6 # SizeSel_1P_4_F1_BLK1repl_1989
-9 9 6.78247 0 -1 99 6 # SizeSel_1P_4_F1_BLK1repl_1992
-9 9 6.96321 0 -1 99 6 # SizeSel_1P_4_F1_BLK1repl_2001
-9 9 -2.30122 0 -1 99 6 # SizeSel_1P_5_F1_BLK1repl_1982
-9 9 -1.7464 0 -1 99 6 # SizeSel_1P_5_F1_BLK1repl_1985
-9 9 0.335844 0 -1 99 6 # SizeSel_1P_5_F1_BLK1repl_1989
-9 9 -3.83068 0 -1 99 6 # SizeSel_1P_5_F1_BLK1repl_1992
-9 9 -3.17294 0 -1 99 6 # SizeSel_1P_5_F1_BLK1repl_2001

```
 -9 9 -2.93569 3 -1 99 6 # SizeSpline_Val_1_F2_2_BLK2repl_1982
 -9 9 -1.00025 3 -1 99 6 # SizeSpline_Val_1_F2_2_BLK2repl_1985
 -9 9 -1.48122 3 -1 99 6 # SizeSpline_Val_1_F2_2_BLK2repl_1989
 -9 9 -0.594308 3 -1 99 6 # SizeSpline_Val_2_F2_2_BLK2repl_1982
 -9 9 0.153459 3 -1 99 6 # SizeSpline_Val_2_F2_2_BLK2repl_1985
 -9 9 1.05847 3 -1 99 6 # SizeSpline_Val_2_F2_2_BLK2repl_1989
 -9 9 -5.15856 3 -1 99 6 # SizeSpline_Val_4_F2_2_BLK2repl_1982
 -9 9 -3.49927 3 -1 99 6 # SizeSpline_Val_4_F2_2_BLK2repl_1985
 -9 9 -4.70661 3 -1 99 6 # SizeSpline_Val_4_F2_2_BLK2repl_1989
 -9 9 7.02319 0 -1 99 6 # AgeSel_3P_1_F3_BLK3repl_1994
 -9 9 -5.71804 0 -1 99 6 # AgeSel_3P_2_F3_BLK3repl_1994
 -9 9 -5.38008 0 -1 99 6 # AgeSel_3P_3_F3_BLK3repl_1994
#_Cond No selex parm trends
#_Cond -4 # placeholder for selparm_Dev_Phase
1 #_env/block/dev_adjust_method (1=standard; 2=logistic trans to keep in base parm bounds; 3=standard w/ no bound check)
#
# Tag loss and Tag reporting parameters go next
0  # TG_custom:  0=no read; 1=read if tags exist
#_Cond -6 6 1 1 2 0.01 -4 0 0 0 0 0 0 0  #_placeholder if no parameters
#
1 #_Variance_adjustments_to_input_values
#_fleet: 1 2 3 4 5 6 7 8 9 10 11 12 13 14
  0 0 0 0 0 0 0 0 0 0.164573 0.333488 0 0 0 #_add_to_survey_CV
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 #_add_to_discard_stddev
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 #_add_to_bodywt_CV
  1 1 1 1 1 1 1 1 1 1 1 1 1 1 #_mult_by_lencomp_N
  1 1 1 1 1 1 1 1 1 1 1 1 1 1 #_mult_by_agecomp_N
  1 1 1 1 1 1 1 1 1 1 1 1 1 1 #_mult_by_size-at-age_N
#
10 #_maxlambdaphase
1 #_sd_offset
#
25 # number of changes to make to default Lambdas (default value is 1.0)
# Like_comp codes:  1=surv; 2=disc; 3=mnwt; 4=length; 5=age; 6=SizeFreq; 7=sizeage; 8=catch; 9=init_equ_catch;
# 10=recrdev; 11=parm_prior; 12=parm_dev; 13=CrashPen; 14=Morphcomp; 15=Tag-comp; 16=Tag-negbin; 17=F_ballpark
#like_comp fleet/survey  phase  value  sizefreq_method
 1 9 1 1 0
 1 10 1 1 0
 1 11 1 1 0
 1 12 1 1 0
 1 13 1 1 0
 1 14 1 0 0
 4 1 1 1 0
 4 2 1 1 0
 4 8 1 1 0
 4 14 1 1 0
 5 1 1 0.2 0
 5 3 1 0.2 0
 6 1 1 1 1
 6 2 1 1 1
 6 3 1 1 2
 6 3 1 1 3
 6 6 1 0 1
 9 1 1 1 0
 9 2 1 0 0
 9 3 1 0 0
 9 4 1 1 0
 9 5 1 0 0
 9 6 1 0 0
 9 7 1 0 0
 9 8 1 1 0
#
# lambdas (for info only; columns are phases)
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_1
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_2
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_3
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_4
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_5
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_6
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_7
```

```
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_8
#  1 1 1 1 1 1 1 1 1 1 #_CPUE/survey:_9
#  1 1 1 1 1 1 1 1 1 1 #_CPUE/survey:_10
#  1 1 1 1 1 1 1 1 1 1 #_CPUE/survey:_11
#  1 1 1 1 1 1 1 1 1 1 #_CPUE/survey:_12
#  1 1 1 1 1 1 1 1 1 1 #_CPUE/survey:_13
#  0 0 0 0 0 0 0 0 0 0 #_CPUE/survey:_14
#  1 1 1 1 1 1 1 1 1 1 #_lencomp:_1
#  1 1 1 1 1 1 1 1 1 1 #_lencomp:_2
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_3
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_4
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_5
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_6
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_7
#  1 1 1 1 1 1 1 1 1 1 #_lencomp:_8
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_9
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_10
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_11
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_12
#  0 0 0 0 0 0 0 0 0 0 #_lencomp:_13
#  1 1 1 1 1 1 1 1 1 1 #_lencomp:_14
#  0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 #_agecomp:_1
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_2
#  0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 #_agecomp:_3
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_4
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_5
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_6
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_7
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_8
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_9
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_10
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_11
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_12
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_13
#  0 0 0 0 0 0 0 0 0 0 #_agecomp:_14
#  1 1 1 1 1 1 1 1 1 1 #_sizefreq:_1
#  1 1 1 1 1 1 1 1 1 1 #_sizefreq:_2
#  1 1 1 1 1 1 1 1 1 1 #_sizefreq:_3
#  1 1 1 1 1 1 1 1 1 1 #_sizefreq:_4
#  0 0 0 0 0 0 0 0 0 0 #_sizefreq:_5
#  1 1 1 1 1 1 1 1 1 1 #_init_equ_catch
#  1 1 1 1 1 1 1 1 1 1 #_recruitments
#  1 1 1 1 1 1 1 1 1 1 #_parameter-priors
#  1 1 1 1 1 1 1 1 1 1 #_parameter-dev-vectors
#  1 1 1 1 1 1 1 1 1 1 #_crashPenLambda
#  0 0 0 0 0 0 0 0 0 0 # F_ballpark_lambda
0 # (0/1) read specs for more stddev reporting
 # 0 1 -1 5 1 5 1 -1 5 # placeholder for selex type, len/age, year, N selex bins, Growth pattern, N growth ages, NatAge_area(-1 for all), NatAge_yr, N Natages
 # placeholder for vector of selex bins to be reported
 # placeholder for vector of growth ages to be reported
 # placeholder for vector of NatAges ages to be reported
999
```