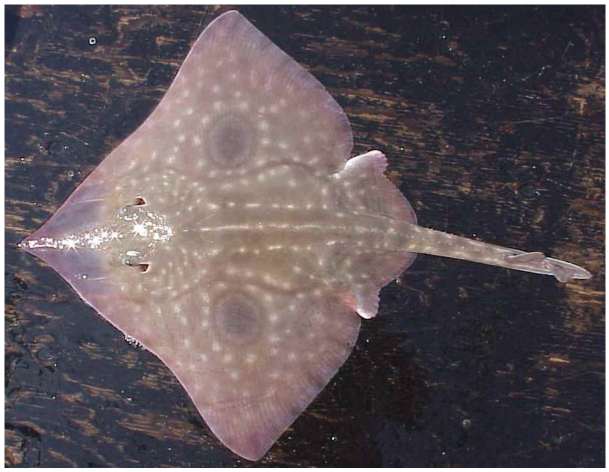
Status of Big Skate (*Beringraja binoculata*) Off the U.S. Pacific Coast in 2019



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Acronyms used in this Document

ABC	Allowable Biological Catch
ACL	Annual Catch Limit
ADFG	Alaska Department of Fish and Game
AFSC	Alaska Fisheries Science Center
A-SHOP	At-Sea Hake Observer Program
CalCOM	California Cooperative Groundfish Survey
CDFW	California Department of Fish and Wildlife
CPFV	Commercial Passenger Fishing Vessel
CRFS	California Recreational Fisheries Survey
DFO	Canada's Department of Fisheries and Oceans
IFQ	Individual Fishing Quota
IPHC	International Pacific Halibut Commission
MRFSS	Marine Recreational Fisheries Statistics Survey
NMFS	National Marine Fisheries Service
NORPAC	the North Pacific Database Program
NWFSC	Northwest Fisheries Science Center
ODFW	Oregon Department of Fish and Wildlife
OFL	Overfishing Limit
ORBS	Oregon Recreational Boat Survey
OY	Optimum Yield
PacFIN	Pacific Fisheries Information Network
PFMC	Pacific Fishery Management Council
PSMFC	Pacific States Marine Fisheries Commission
RecFIN	Recreational Fisheries Information Network
SPR	Spawning Potential Ratio
SSC	Scientific and Statistical Committee
SWFSC	Southwest Fisheries Science Center
WCGOP	West Coast Groundfish Observer Program
WDFW	Washington Department of Fish and Wildlife

Status of Big Skate (*Beringraja binoculata*) Off the U.S. Pacific Coast in 2019

Contents

Executive Summary

Stock

This assessment reports the status of the Big Skate (*Beringraja binoculata*) resource in U.S. waters off the West Coast using data through 2018.

Catches

Landings and estimated discards of Big Skate were reconstructed for this assessment from historical records of other species and from species composition data collected in the recent fishery. These reflect the fishery from 1916-1994. The current fishery started in 1995. For records from 1995-2017, Big Skate landings were estimated from species-composition samples and the landings of "Unspecified Skates". Beginning in 2017, Big Skate have been recorded in species-specific landings.

In the current fishery (since 1995), annual total landings of Big Skate have ranged between 135-528 mt, with landings in 2018 totaling 173 mt.

Table a: Recent Big Skate landings (mt)

Year	Landings
2008	366.00
2009	205.70
2010	196.20
2011	268.40
2012	269.60
2013	135.00
2014	372.40
2015	331.50
2016	411.50
2017	277.60
2018	172.60

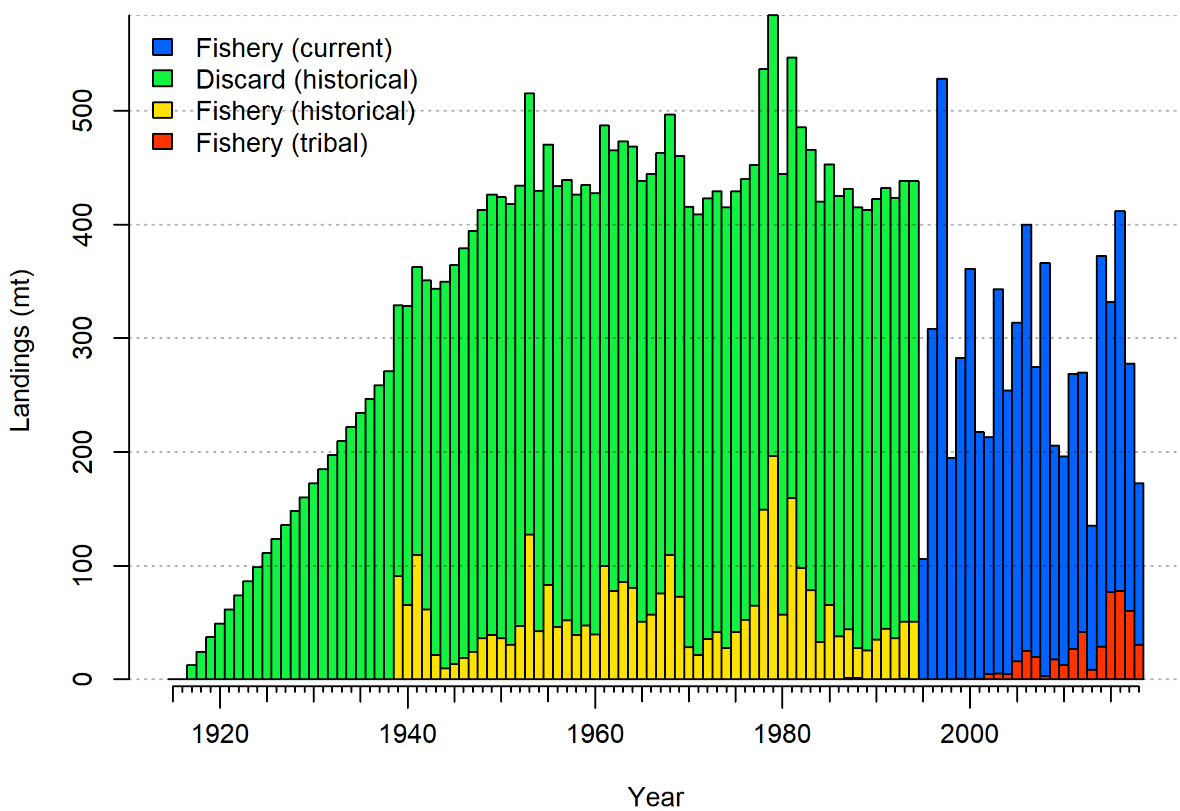

Figure a: Catch history of Big Skate in the model.

Data and Assessment

This the first full assessment for Big Skate. It is currently managed using an OFL which was based on a proxy for F_{MSY} and a 3-year recent average of survey biomass. This assessment uses the newest version of Stock Synthesis (3.30.13). The model begins in 1916, and assumes the stock was at an unfished equilibrium that year.

The assessment relies on two bottom trawl survey indices of abundance, the Triennial Survey from an index covering the period 1980–2004 was used here and the West Coast Groundifish Bottom Trawl (WCGBT) Survey, which began in 2003 and for which data is available through 2018. The triennial survey shows an increasing trend over the 25 year period it covers, which the model is not able to fit as this includes the peak period of the fishery when the stock would have been expected to be declining. The WCGBT Survey also shows an increasing trend, with the 5 most recent observations (2014–2018) all falling in the top 6 ever observed (2004 was the 5th highest observation). The most estimates an increasing trend during this period but the slope is more gradual than the trend in the survey. The misfit to these survey indices could be due to some combination of incorrect estimation of the catch history, variability in recruitment which is not modeled here, or biological or ecological changes for which data are not available.

Length composition data from the fishery is available starting in 1995 but is sparse until the past decade. Most of the ages are also from 2008 onward. This limits the ability of the model to estimate any changes composition of the population during the majority of the history of the fishery. Estimates of discard rates and mean body weight of discards are available for the years 2002 onward and discard length compositions are available starting in 2010.

The age and length data provide evidence for growth patterns and sex-specific differences in selectivity that are unusual among groundfish stocks that have been assessed within the U.S. West Coast and are not found in Longnose Skate where the data show little difference between the sexes. Growth appears to be almost linear and similar between females and males up to about age 7 or over 100 cm at which point male growth appears to stabilize while females continue to grow. However, in spite of the similar growth pattern for ages prior to 7, males are observed more frequently, with the 70–100 cm length bins often showing 60% males. Sex-specific differences in selectivity were included in the model in order to better match patterns in the sex ratios in the length composition data. The length and age data do not cover enough years or show enough evidence of distinct cohorts to reliably estimate deviations in recruitment around the stock-recruit curve.

The scale of the population is not reliably informed by the data due to the combination of surveys that show trends which can't be matched by the structure of the model and length and age data which inform growth and selectivity but provide relatively little information about changes in stock structure over time. Therefore, a prior on catchability of the WCGBT Survey (centered at 0.83) was applied in order to provide more stable results.

Although the assessment model requires numerous simplifying assumptions, it represents an improvement over the simplistic status-quo method of setting management limits, which relies on average survey biomass and an assumption about F_{MSY}. The use of an age-structured model with estimated growth, selectivity, and natural mortality likely provide a better estimate of past dynamics and the impacts of fishing in the future.

Stock Biomass

The 2018 estimated spawning biomass relative to unfished equilibrium spawning biomass is above the target of 40% of unfished spawning biomass at 72.5% (95% asymptotic interval: ± 55.2%-89.7%) (Figure c). Approximate confidence intervals based on the asymptotic variance estimates show that the uncertainty in the estimated spawning biomass is high, although even the lower range of the 95% interval for %unfished is above the 40% reference point, and all sensitivity analyses explore also show the stock to be at a high level.

Table b: Recent trend in beginning of the year spawning output and (spawning biomass relative to unfished equilibrum spawning biomass)

Year	Spawning Output (mt)	˜ 95% confidence interval	Estimated %unfished	˜ 95% confidence interval
2010	1059.250	(425.78-1692.72)	0.694	(0.552-0.837)
2011	1068.670	(434.08-1703.26)	0.700	(0.56-0.841)
2012	1073.990	(438.95-1709.03)	0.704	(0.564-0.843)
2013	1079.980	(444.55-1715.41)	0.708	(0.57-0.846)
2014	1094.970	(458.25-1731.69)	0.718	(0.583-0.852)
2015	1095.100	(458.91-1731.29)	0.718	(0.583-0.852)
2016	1097.700	(461.69-1733.71)	0.719	(0.586-0.853)
2017	1093.720	(458.52-1728.92)	0.717	(0.583-0.851)
2018	1097.080	(461.78-1732.38)	0.719	(0.586-0.852)
2019	1106.070	(504.33-1707.81)	0.725	(0.552-0.897)

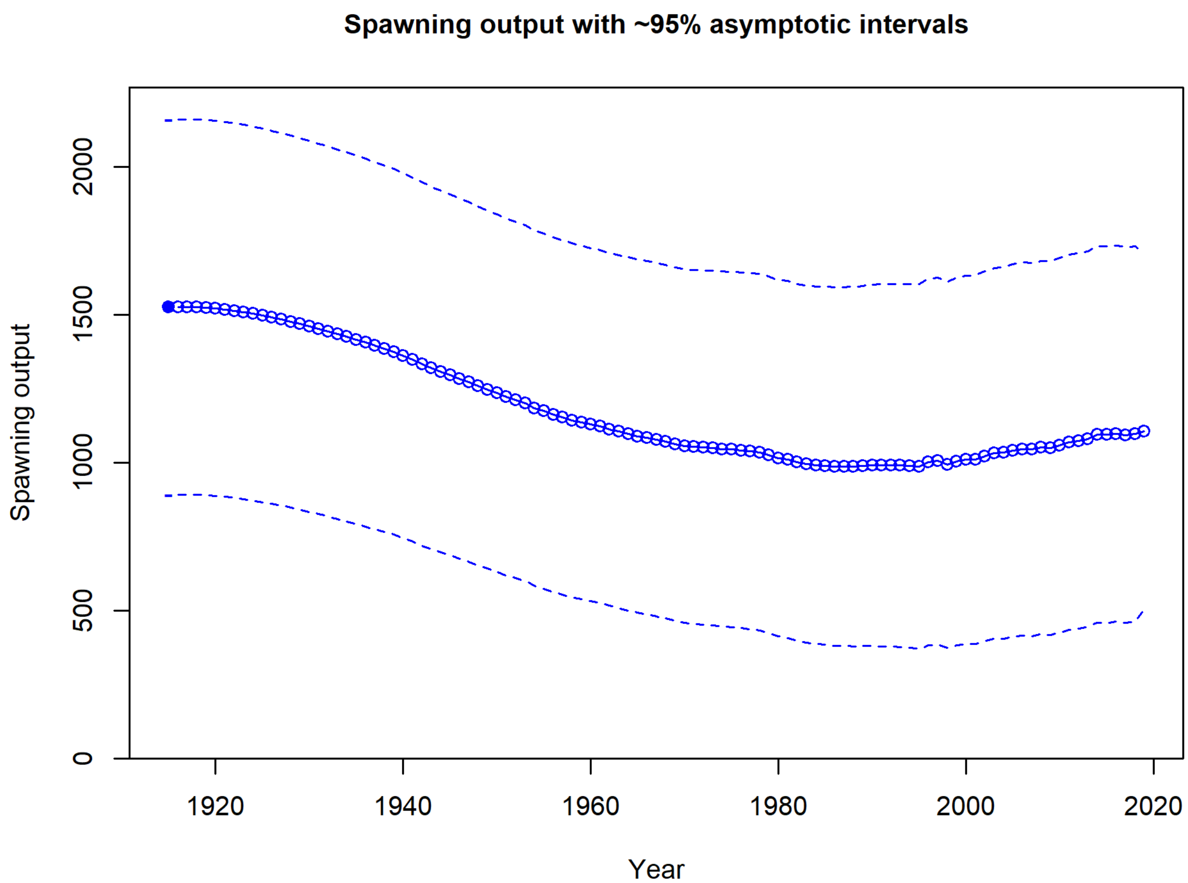

Figure b: Time series of spawning biomass trajectory (circles and line: median; light broken lines: 95% credibility intervals) for the base case assessment model.

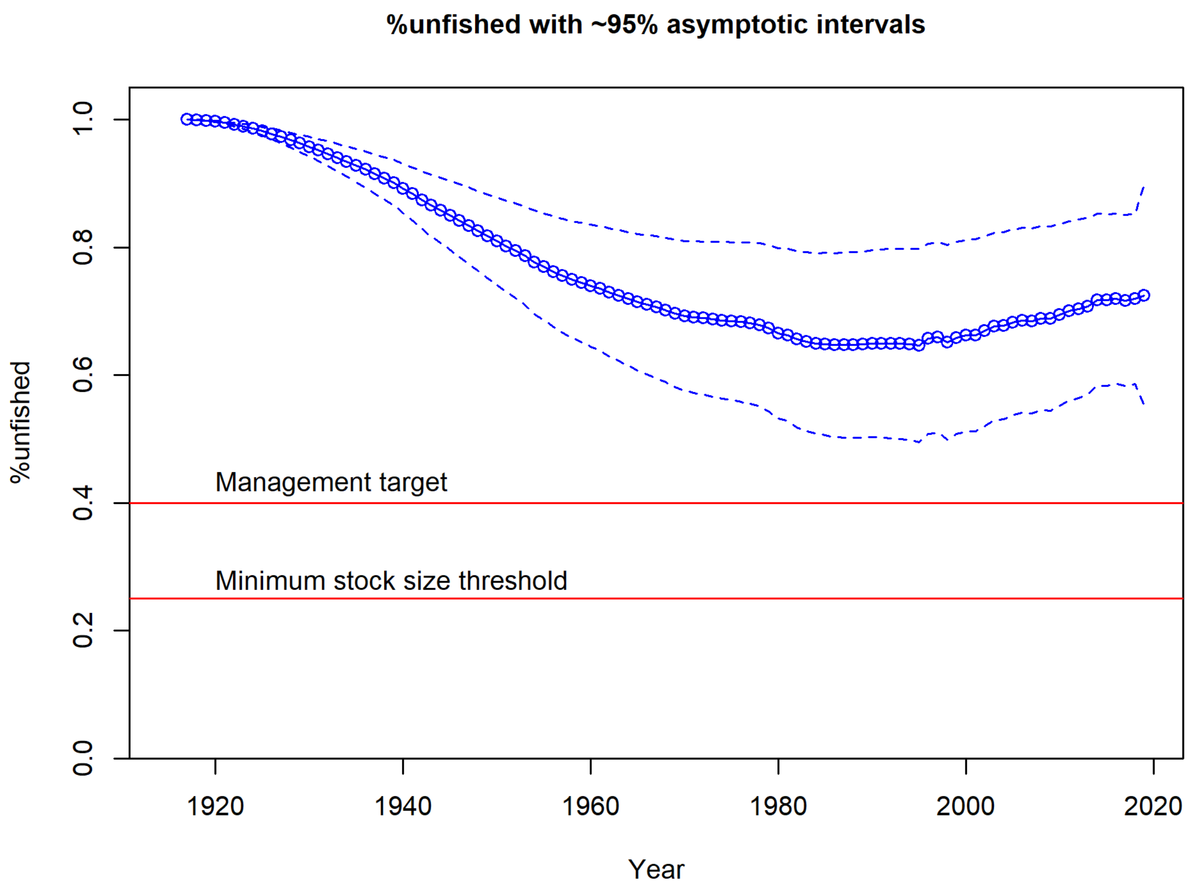

Figure c: Estimated relative %unfished with approximate 95% asymptotic confidence intervals (dashed lines) for the base case assessment model.

Recruitment

Recruitment was assumed to follow the Beverton-Holt stock recruit curve, so uncertainty in estimated recruitment is due to uncertainty in spawning biomass and the unfished equilibrium recruitment R_0 (Figure d and Table c).

Table c: Recent recruitment for the model.

Year	Estimated Recruitment (1,000s)	~ 95% confidence interval
2010	3435.91	(2128.69 - 5545.9)
2011	3450.01	(2142.11 - 5556.47)
2012	3457.92	(2149.79 - 5562.03)
2013	3466.77	(2158.45 - 5568.12)
2014	3488.68	(2179.48 - 5584.31)
2015	3488.86	(2180.18 - 5583.09)
2016	3492.63	(2184.26 - 5584.72)
2017	3486.86	(2179.33 - 5578.88)
2018	3491.73	(2184.37 - 5581.57)
2019	3504.69	(2186.12 - 5618.57)

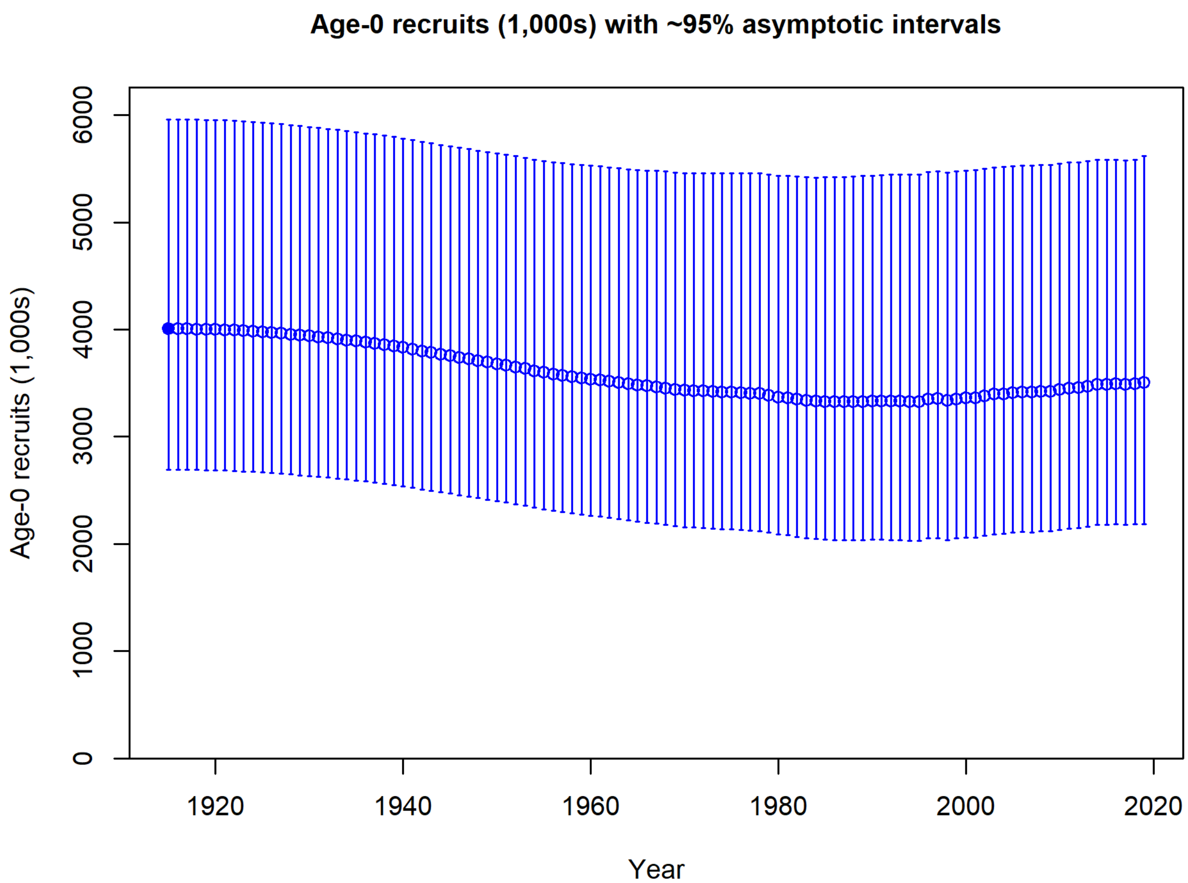

Figure d: Time series of estimated Big Skate recruitments for the base-case model with 95% confidence or credibility intervals.

Exploitation status

Harvest rates estimated by the base model indicate catch levels have been below the limits that would be associated with the SPR = 50% target (Table d and Figure e).

Table d: Recent trend in spawning potential ratio and exploitation for Big Skate in the model. Relative fishing intensity is (1-SPR) divided by 50% (the SPR target) and exploitation is catch divided by age 2+ biomass.

Year	Relative fishing intensity	˜ 95% confidence interval	Exploitation rate	˜ 95% confidence interval
2009	0.23	(0.12-0.34)	0.01	(0.01-0.02)
2010	0.22	(0.11-0.32)	0.01	(0.01-0.02)
2011	0.29	(0.15-0.42)	0.02	(0.01-0.02)
2012	0.29	(0.15-0.42)	0.02	(0.01-0.02)
2013	0.15	(0.08-0.22)	0.01	(0-0.01)
2014	0.39	(0.22-0.56)	0.02	(0.01-0.03)
2015	0.35	(0.19-0.5)	0.02	(0.01-0.03)
2016	0.43	(0.24-0.61)	0.02	(0.01-0.04)
2017	0.30	(0.16-0.44)	0.02	(0.01-0.02)
2018	0.19	(0.1-0.28)	0.01	(0.01-0.01)

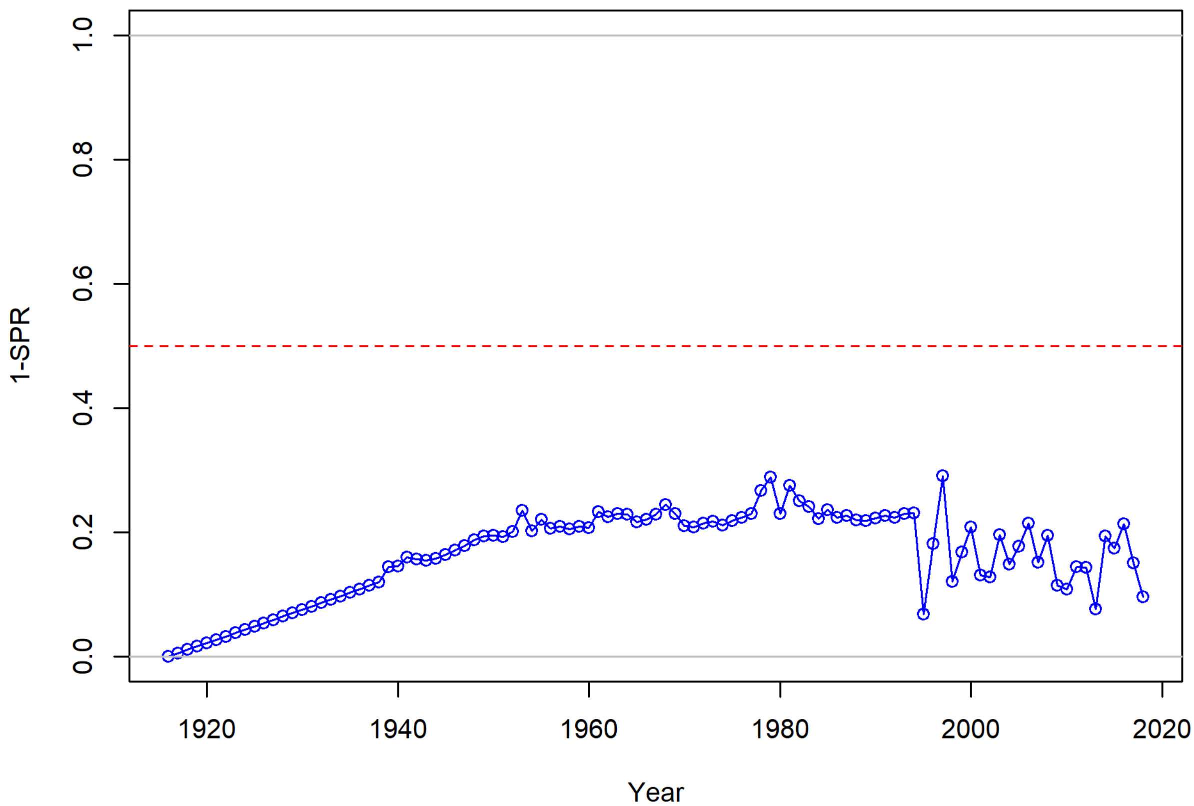

Figure e: Estimated spawning potential ratio (SPR) for the base-case model. One minus SPR is plotted so that higher exploitation rates occur on the upper portion of the y-axis. The management target is plotted as a red horizontal line and values above this reflect harvests in excess of the overfishing proxy based on the $SPR_{50\%}$ harvest rate. The last year in the time series is 2018.

Ecosystem Considerations

In this assessment, ecosystem considerations were not explicitly included in the analysis. This is primarily due to a lack of relevant data and results of analyses (conducted elsewhere) that could contribute ecosystem-related quantitative information for the assessment.

Reference Points

This stock assessment estimates that Big Skate in the model is above the biomass target ($SB_{40\%}$), and well above the minimum stock size threshold ($SB_{25\%}$). The estimated %unfished level for the base model in 2019 is 72.5% (95% asymptotic interval: ± 55.2%-89.7%, corresponding to an unfished spawning biomass of 1106.07 mt (95% asymptotic interval: 504.33-1707.81 mt) of spawning biomass in the base model (Table e). Unfished age 1+ biomass was estimated to be 2,426 mt in the base case model. The target spawning biomass ($SB_{40\%}$) is 610 mt, which corresponds with an equilibrium yield of 558 mt. Equilibrium yield at the proxy F_{MSY} harvest rate corresponding to $SPR_{50\%}$ is 466 mt (Figure f).

Table e: Summary of reference points and management quantities for the base case model.

Quantity	**Estimate**	**Low 2.5% limit**	**High 2.5% limit**
Unfished spawning output (mt)	1,526	891	2,161
Unfished age 1+ biomass (mt)	2,426	1,583	3,269
Unfished recruitment (R_0)	4,004	2,395	5,612
Spawning output(2018 mt)	1,097	462	1,732
Depletion (2018)	0.719	0.586	0.852
Reference points based on $\mathbf{SB_{40\%}}$			
Proxy spawning output ($B_{40\%}$)	610	373	848
SPR resulting in $B_{40\%}$ ($SPR_{B40\%}$)	0.625	0.625	0.625
Exploitation rate resulting in $B_{40\%}$	0.047	0.043	0.051
Yield with $SPR_{B40\%}$ at $B_{40\%}$ (mt)	558	362	754
Reference points based on SPR proxy for MSY			
Spawning output	305	187	424
SPR_{proxy}	0.5		
Exploitation rate corresponding to SPR_{proxy}	0.069	0.063	0.075
Yield with SPR_{proxy} at SB_{SPR} (mt)	466	303	629
Reference points based on estimated MSY values			
Spawning output at MSY (SB_{MSY})	578	352	804
SPR_{MSY}	0.612	0.608	0.615
Exploitation rate at MSY	0.049	0.045	0.053
Dead Catch MSY (mt)	559	363	755
Retained Catch MSY (mt)	517	337	698

Management Performance

Table f: Recent trend in total catch (mt) relative to the management guidelines. Big skate was managed in the Other Species complex in 2013 and 2014, designated an Ecosystem Component species in 2015 and 2016, and managed with stock-specific harvest specifications since 2017.

Year	OFL (mt; ABC prior to 2011)	ABC (mt)	ACL (mt; OY prior to 2011)	Estimated total catch (mt)
2009				205.70
2010				196.20
2011				268.40
2012				269.60
2013	458.00	317.90	317.90	135.00
2014	458.00	317.90	317.90	372.40
2015				331.50
2016				411.50
2017	541.00	494.00	494.00	277.60
2018	541.00	494.00	494.00	172.60
2019	541.00	494.00	494.00	
2020	541.00	494.00	494.00	

Unresolved Problems and Major Uncertainties

To be added

Decision Table

Template in Table h and associated discussion to be filled in later

Table g: Projections of landings, total mortality, OFL, and ACL values based on an SPR target of 50Category 2 Sigma which creates the buffer shown in the right-hand column.

Year	Landings (mt)	Estimated total mortality (mt)	OFL (mt)	ACL (mt)	Buffer
2019	313.16	336.35	541.00	494.00	1.00
2020	313.16	336.32	541.00	494.00	1.00
2021	1042.23	1119.74	1275.51	1119.75	0.87
2022	987.51	1062.58	1222.62	1062.58	0.86
2023	942.80	1015.91	1179.51	1015.91	0.86
2024	906.41	977.59	1145.41	977.59	0.85
2025	876.49	945.64	1118.21	945.64	0.84
2026	850.59	917.76	1095.36	917.76	0.83
2027	828.05	893.39	1075.04	893.39	0.83
2028	805.87	869.37	1056.06	869.37	0.82
2029	784.60	846.33	1037.94	846.33	0.81
2030	764.95	825.07	1020.44	825.07	0.80

Table h: Summary of 10-year projections beginning in 2020 for alternate states of nature based on an axis of uncertainty for the model. Columns range over low, mid, and high states of nature, and rows range over different assumptions of catch levels. An entry of ”–” indicates that the stock is driven to very low abundance under the particular scenario.

			States of nature					
			Low State		Base State		High State	
	Year	Catch	Spawning Output	Depletion	Spawning Output	Depletion	Spawning Output	Depletion
Default harvest, for Low State	2019	-	-	-	-	-	-	-
	2020	-	-	-	-	-	-	-
	2021	-	-	-	-	-	-	-
	2022	-	-	-	-	-	-	-
	2023	-	-	-	-	-	-	-
	2024	-	-	-	-	-	-	-
	2025	-	-	-	-	-	-	-
	2026	-	-	-	-	-	-	-
	2027	-	-	-	-	-	-	-
	2028	-	-	-	-	-	-	-
Default harvest, for Base State	2019	-	-	-	-	-	-	-
	2020	-	-	-	-	-	-	-
	2021	-	-	-	-	-	-	-
	2022	-	-	-	-	-	-	-
	2023	-	-	-	-	-	-	-
	2024	-	-	-	-	-	-	-
	2025	-	-	-	-	-	-	-
	2026	-	-	-	-	-	-	-
	2027	-	-	-	-	-	-	-
	2028	-	-	-	-	-	-	-
Default harvest, for High State	2019	-	-	-	-	-	-	-
	2020	-	-	-	-	-	-	-
	2021	-	-	-	-	-	-	-
	2022	-	-	-	-	-	-	-
	2023	-	-	-	-	-	-	-
	2024	-	-	-	-	-	-	-
	2025	-	-	-	-	-	-	-
	2026	-	-	-	-	-	-	-
	2027	-	-	-	-	-	-	-
	2028	-	-	-	-	-	-	-
Average Catch	2019	-	-	-	-	-	-	-
	2020	-	-	-	-	-	-	-
	2021	-	-	-	-	-	-	-
	2022	-	-	-	-	-	-	-
	2023	-	-	-	-	-	-	-
	2024	-	-	-	-	-	-	-
	2025	-	-	-	-	-	-	-
	2026	-	-	-	-	-	-	-
	2027	-	-	-	-	-	-	-
	2028	-	-	-	-	-	-	-

Table i: Base case results summary.

Quantity	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Landings (mt)	313.160	313.160	1042.228	987.509	942.796	906.409	876.485	850.594	828.055	805.865
Total Est. Catch (mt)	336.345	336.325	1119.745	1062.581	1015.907	977.592	945.644	917.761	893.393	869.365
OFL (mt)	541.00	541.00	1275.51	1222.62	1179.51	1145.41	1118.21	1095.36	1075.04	1056.06
ACL (mt)	494.000	494.000	1119.750	1062.580	1015.910	977.592	945.643	917.762	893.393	869.365
(1-SPR)(1-$SPR_{50\%}$)	0.22	0.29	0.29	0.15	0.39	0.35	0.43	0.30	0.19	
Exploitation rate	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.01	
Age 1+ biomass (mt)	17752.6	17914.2	18070.4	18140.7	18203.3	18389.4	18320.0	18306.6	18214.4	18273.9
Spawning Output	1059.2	1068.7	1074.0	1080.0	1095.0	1095.1	1097.7	1093.7	1097.1	1106.1
95% CI	(425.78-1692.72)	(434.08-1703.26)	(438.95-1709.03)	(444.55-1715.41)	(458.25-1731.69)	(458.91-1731.29)	(461.69-1733.71)	(458.52-1728.92)	(461.78-1732.38)	(504.33-1707.81)
Depletion	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
95% CI	(0.552-0.837)	(0.56-0.841)	(0.564-0.843)	(0.57-0.846)	(0.583-0.852)	(0.583-0.852)	(0.586-0.853)	(0.583-0.851)	(0.586-0.852)	(0.552-0.897)
Recruits	3435.91	3450.01	3457.92	3466.77	3488.68	3488.86	3492.63	3486.86	3491.73	3504.69
95% CI	(2128.69 - 5545.9)	(2142.11 - 5556.47)	(2149.79 - 5562.03)	(2158.45 - 5568.12)	(2179.48 - 5584.31)	(2180.18 - 5583.09)	(2184.26 - 5584.72)	(2179.33 - 5578.88)	(2184.37 - 5581.57)	(2186.12 - 5618.57)

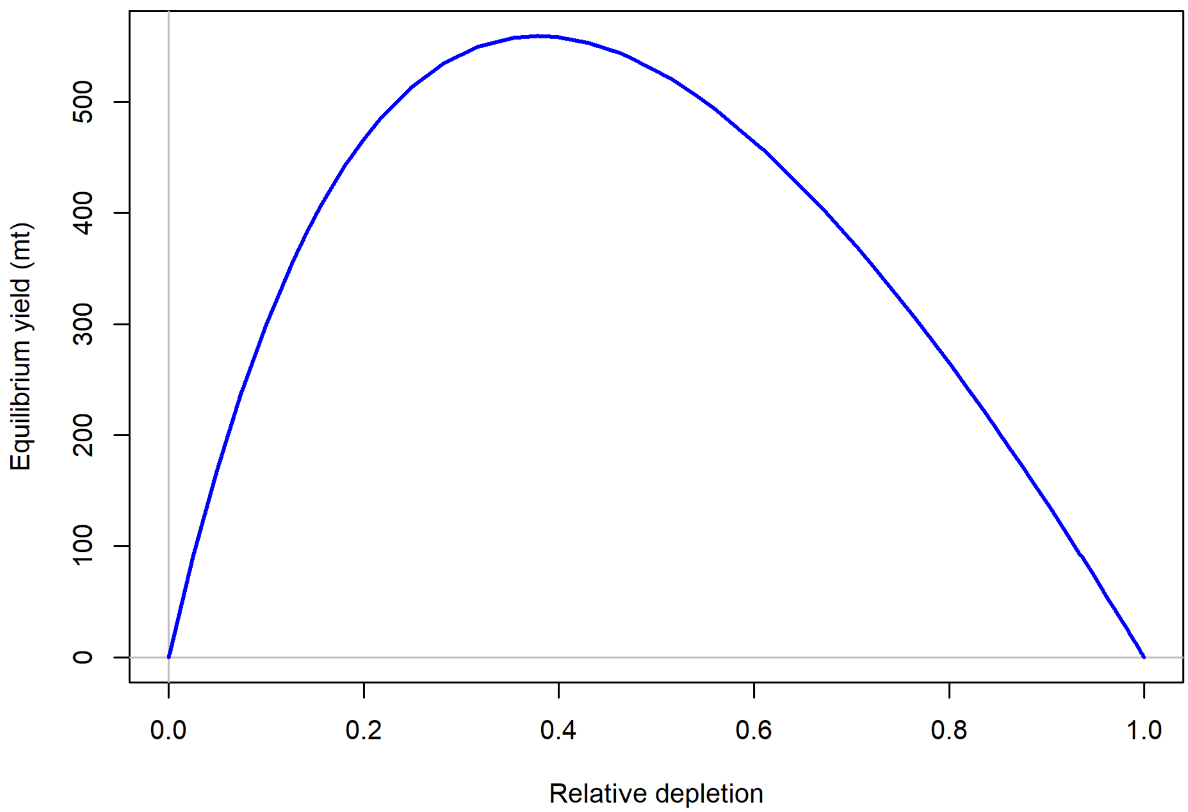

Figure f: Equilibrium yield curve for the base case model. Values are based on the 2018 fishery selectivity and with steepness fixed at 0.718.

Research and Data Needs

We recommend the following research be conducted before the next assessment:

1. **Data!**:
2. **xxxx**:
3. **xxxx**:
4. **xxxx**:
5. **xxxx**:

To be continued

1 Introduction

Skates are the largest and most widely distributed group of batoid fish with approximately 245 species ascribed to two families (Ebert and Compagno (2007), McEachran and Miyake (1990)). Skates are benthic fish that are found in all coastal waters but are most common in cold temperatures and polar waters (Ebert and Compagno 2007).

There are eleven species of skates in three genera (Amblyraja, Bathyraja, and Raja) present in the Northeast Pacific Ocean off California, Oregon and Washington (Ebert 2003). Of that number, just three species (Longnose Skate, *Raja rhina*; Big Skate, *Raja binoculata*; and Sandpaper Skate, *Bathyraja interrupta*) make up over 95 percent of West Coast Groundfish Bottom Trawl Survey (WCGBTS) catches in terms of biomass and numbers, with the Longnose Skate leading in both categories (with 62 percent of biomass and 56 percent of numbers).

Big Skate (*Raja binoculata*) is the largest of the skate species in North America with a documented maximum length of 244 cm total length and a maximum weight of 91 kg (Eschmeyer and Herald 1983). The species name "binoculata" (two-eyed) refers to the prominent ocellus at the base of each pectoral fin. Big Skates are usually seen buried in sediment with only their eyes showing.

1.1 Biology

Big Skate is oviparious, and is one of two skate species that have multiple embryos per egg case (Ebert et al. 2008). From 1–8 embryos can be contained in a single, large egg capsule, but most have 3–4 (DeLacy and Chapman 1935, Hitz 1964, Ford 1971). Eggs are deposited year-round on sand or mud substrates at depths of ˜50–150 m (Hitz 1964, Ebert and Compagno 2007). Embryos hatch from eggs after 6–20 months, with shorter developmental periods associated with warmer temperatures (Hoff, GR 2009). In captivity, Big Skate females may produce > 350 eggs/year (average of 2 embryos/egg case; Chiquillo, Kelcie L and Ebert, David A and Slager, Christina J and Crow, Karen D (2014)) from long-term sperm storage (**???**). Size at birth is 18–23 cm TL (Ebert 2003). Maximum size is 244 cm TL [Eschmeyer and Herald (1983), with females growing to larger sizes.

Size at maturity has been variably estimated for Big Skate populations off California, British Columbia, and Alaska. Off central California, Zeiner and Wolf (1993) reported sizes at first maturity of ˜129 cm TL (females) and ˜100 cm TL (males). A similar size at maturity was estimated for females from the Gulf of Alaska (first = 126 cm TL, 50% = 149 cm TL), but male estimates were considerably greater (first = 124 cm TL, 50% = 119 cm TL; Ebert et al. (2008)). Much smaller sizes at first (female = 60 cm TL, male = 50 cm TL) and 50% (female = 90 cm TL, male = 72 cm TL) maturity were generated for the Longnose Skate populations off British Columbia (McFarlane GA and King JR 2006); however, maturity evaluation criteria were flawed (subadults were considered to be mature), and these results are therefore not considered valid.

Age and growth parameters have been established from California, British Columbia, and the Gulf of Alaska. Maximum ages off central California (females = 12, males = 11; Zeiner, S.J. and P. Wolf. (1993)) and in the Gulf of Alaska (females = 14, males = 15; Gburski et al. 2007) were similar, but estimates off British Columbia were much greater (females = 26, males = 25; McFarlane and King 2006). It is important to note that age estimates are based on an unvalidated method and geographic differences in size or age may reflect differences in sampling or ageing criteria. In the Gulf of Alaska, Big Skates reach 50% maturity at 10 years and 7 years for females and males, respectively (Gburski, C.M. and Gaichas, S.K. and Kimura, D.K. (2007), Ebert et al. (2008)). Generation length estimates range from 11.5 (Zeiner, S.J. and P. Wolf. 1993) to 17 years (McFarlane GA and King JR 2006).

Table 1: Regional comparison of life history parameter estimates.

	California		British Columbia		Gulf of Alaska	
	Female	Male	Female	Male	Female	Male
1st Maturity (TL cm)	129	100	60	50	126	124
50% Maturity (TL cm)			90	72	149	119
Max Age (year)	12	11	26	25	14	15
1st Maturity (year)	12	10	6	5	7	9
50% Maturity (year)			8	10	10	7

1.2 Distribution and Life History

The Big Skate is most common in soft-sediment habitats in coastal waters of the continental shelf (Bizzarro, JJ and Broms, KM and Logsdon, MG and Ebert, DA and Yoklavich, MM and Kuhnz, LA and Summers, AP (2014), Farrugia et al. (2016)). Use of mixed substrate (e.g., mud with boulders) increases with ontogeny but hard substrates are largely avoided (Bizzarro (2015)). In the GOA, the Big Skate is the most commonly encountered skate species in continental shelf waters at 100–200 m depth, and is most abundant in the central and western areas of the GOA (Stevenson, DE and Orr, JW and Hoff, GR and McEachran, JD (2008); Bizzarro, JJ and Broms, KM and Logsdon, MG and Ebert, DA and Yoklavich, MM and Kuhnz, LA and Summers, AP (2014)). Off the U.S. Pacific Coast, the Big Skate is most densely distributed on the inner continental shelf (< 100 m; Bizzarro, JJ and Broms, KM and Logsdon, MG and Ebert, DA and Yoklavich, MM and Kuhnz, LA and Summers, AP (2014)). Eggs are mainly deposited between 70–90 m on sand or mud substrates (Hitz (1964); NMFS-NWFSC-FRAM, unpub. data). Juveniles typically occur in shallower waters than adults (Bizzarro (2015)). Core habitat regions of Big Skate off the U.S. Pacific Coast and in the Gulf of Alaska are spatially segregated from those of other species (Bizzarro, JJ and Broms, KM and Logsdon, MG and Ebert, DA and Yoklavich, MM and Kuhnz, LA and Summers, AP (2014)).

Big Skates are highly mobile and capable of long range (> 2000 km) movements (KingandMcF2010; Farrugia et al. (2016)). For example, in British Columbia, a study revealed that ˜75% of tagged individuals were recaptured within 21 km of the tagging locations, but 15 of the tagged individuals (0.1%) moved over 1,000 km (max = 2340 km; King, JR and McFarlane, GA (2010)). In the Gulf of Alaska, a year of satellite tag data showed that six of twelve tagged individuals moved over 100 km, with one skate moving > 2,000 km (Farrugia et al. 2016). Although primarily benthic, Big Skates utilize the entire water column including surface waters (Farrugia et al. (2016)). They have broad thermal tolerances 2–19º C that enable their occurrence from boreal to subtropical latitudes (Love, Milton S (2011); Farrugia et al. (2016)).

The Big Skate is broadly distributed, occurring from the southeastern Bering Sea (Mecklenburg, CW and Mecklenburg, TA and Thorsteinson, LK 2002) to southern Baja California (22.90º N, 110.03º W; (Castro-Aguirre et al. 1993)) and the Gulf of California (Castro-Aguirre and Pérez 1996). It has been reported at depths of 2–501 m (min: Miller et al. (1980); max: Farrugia et al. (2016)) but is most common on the inner continental shelf (< 100 m; (Love, Milton S 2011); (Bizzarro 2015)). Big Skates are highly mobile and capable of long range (> 2000 km) movements ((King and McFarlane 2009); (Farrugia et al. 2016)).

In 2012, the Big Skate was moved from genus *Raja* to the new genus *Beringraja* together with the Mottled Skate (*B. pulchra*) (Ishihara et al. 2012). These are the only two skates with multiple embryos per egg case, and they are very similar mophologically and genetically (Bizzarro, J. 2019).

1.3 Map

A map showing the area of the U.S. West Coast Exclusive Economic Zone covered by this stock assessment is provided in Figure **??**.

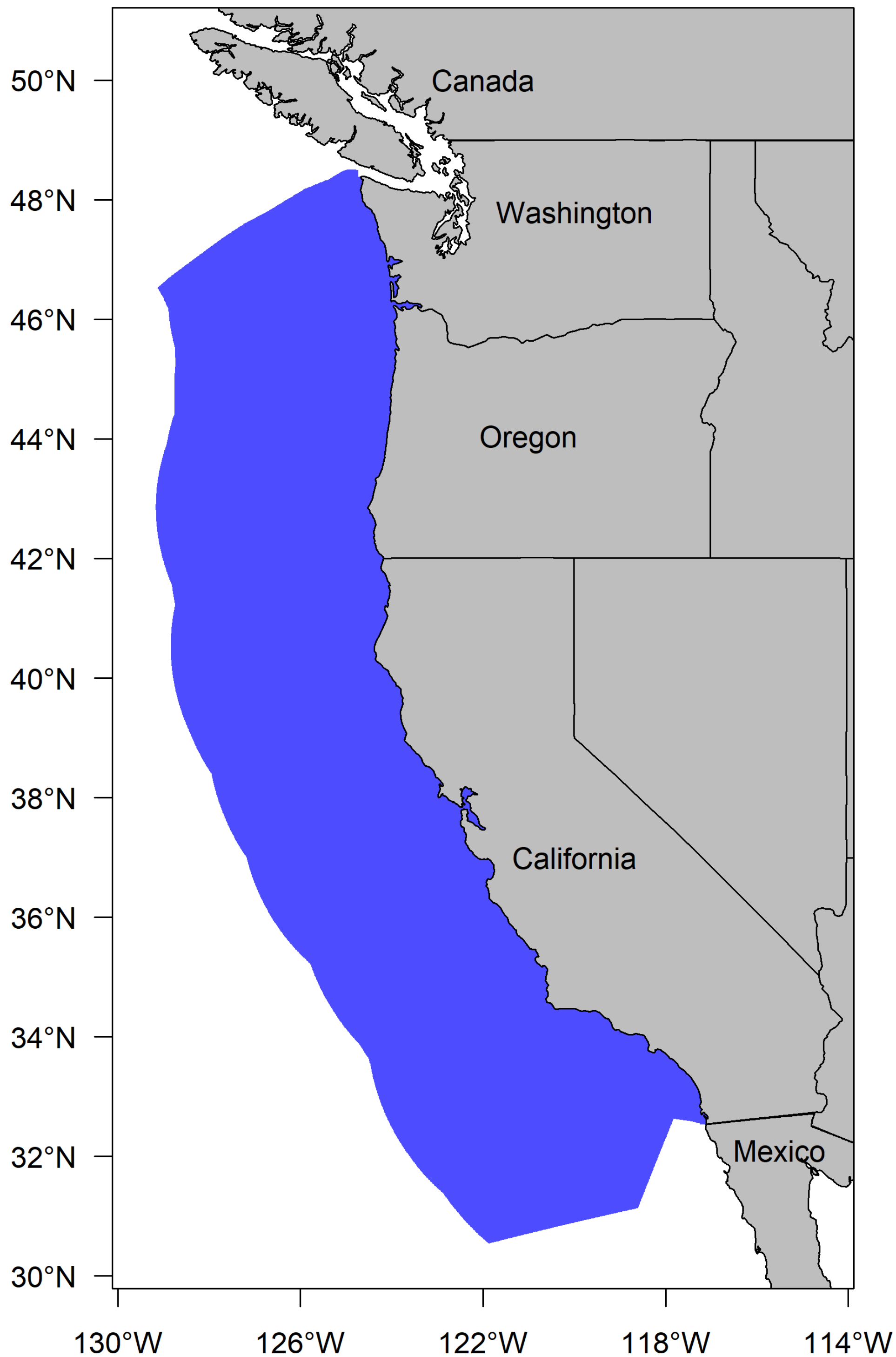

Figure 1: U.S. West Coast Exclusive Economic zone covering the area in which this stock assessment is focused.

1.4 Ecosystem Considerations

Big Skates are opportunistic, generalist mesopredators with highly variable spatio-temporal trophic roles (Ebert and Compagno (2007); Bizzarro (2015)). Off central California, diet of Big Skates is composed mainly of fishes, shrimps, and crabs (in descending order), with larger skates incorporating more fishes (Bizzarro et al. (2007)); however, in the Gulf of Alaska, Big Skate diet consists mainly of crabs (esp. Tanner Crabs) throughout ontogeny, with relatively small portions of fishes and shrimps (Bizzarro (2015)). Correspondingly, trophic level and general diet composition estimates differ significantly between California and Gulf of Alaska Big Skate populations (Bizzarro (2015)).

Big Skates and their egg cases are preyed upon by a variety of vertebrates and invertebrates. Snails and other molluscs bore holes in egg cases to feed on developing embryos and especially their protein rich yolk-sacs (Bizzarro, pers. obs; Hoff, GR (2009)). Sevengill Sharks, Brown Rockfish, and Stellar Sea Lions are known predators of juvenile and adult Big Skates (Ebert (2003), Love, Milton S (2011)). Northern Sea Lions consume free-living Big Skates and their egg cases (Ebert (2003), Love, Milton S (2011)).

In this assessment, ecosystem considerations were not explicitly included in the analysis. This is primarily due to a lack of relevant data and results of analyses (conducted elsewhere) that could contribute ecosystem-related quantitative information for the assessment.

1.5 Fishery Information

Big Skate are caught in commercial and recreational fisheries on the West Coast using line and trawl gears. There is a limited market for pectoral fins (skate wings).

The history of Big Skate is not well documented. They were used as a food source by the native Coastal and Salish Tribes (Batdorf, C 1990) long before Europeans settled in the Pacific Northwest and then as fertilizer by the settlers (Bowers, G. M. 1909). No directed fishery for Big Skate has been documented; rather, they were taken along with other skates and rays as “scrap fish” and used for fertilizer, fish meal and oil (Lippert 2019).

Skates have been regarded as a predator on desirable market species such as Dungeness crab, and were thought of as nuisance fish with no appeal as a food item save for small local markets. They had been discarded or harvested at a minimal level until their livers became valued along with those of other cartilaginous fishes for the extraction of vitamin A in the 1940s. Chapman (Chapman, W.M. 1944) recorded that “At present they are being fished heavily, in common with the other elasmobranchs of the coast, forthe vitamins in their livers. The carcasses are either thrown away at sea or made into fish meal. Little use is made of the excellent meat of the wings”.

Little information is available about the historic Washington fishery for Big Skate. In records before 2000, they are lumped together with other skates or in market categories (Lippert

2019); this necessitates considerable attention to reconstructing the fishery by observing the composition of skate catches in the modern fishery and applying those to the recently reconstructed historical records.

Very little information is known about the Big Skate historical fishery in Oregon. The information we do have is mainly from historical landing data and species composition samples starting in the mid-nineties. The bulk of the catch is from the bottom trawl and longline fisheries, with smaller amounts as by-catch in mid-water trawl and the shrimp trawl fishery. Big Skate was lumped into the nominal "Skate" category until 2015 when it was separated into its own market category. Species composition data have been vitally important in reconstructing the pre-2015 historical catch (Calavan 2019).

1.6 Stock Status and Management History

Big Skate were managed in the "Other Fish" complex until 2015 when they were designated an Ecosystem Component (EC) species. Catches of Big Skate are estimated to have averaged 95 mt from 2007–2011, along with large landings of "Unspecified Skate". Analysis of Oregon port-sampling data indicates that about 98 percent of the recent Unspecified Skate landings in Oregon were comprised of Big Skate. Such large landings indicates targeting of Big Skate has occurred and an EC designation was not warranted. Based on this evidence, Big Skate was redesignated as an actively-managed species in the fishery. Big skate have been managed with stock-specific harvest specifications since 2017.

The recent OFL of 541 mt was calculated by applying approximate MSY harvest rates to estimates of stock biomass from the Northwest Fisheries Science Center (NWFSC) West Coast Groundfish Bottom Trawl Survey. This survey-based biomass estimate is likely underestimated since Big Skate are distributed all the way to the shoreline and no West Coast trawl surveys have been conducted in water shallower than 55 meters. This introduces an extra source of uncertainty to management and suggests that increased precaution is needed to reduce the risk of overfishing the stock.

There has been consideration for managing Big Skate in a complex with Longnose Skate, the other actively-managed West Coast skate species, but the two species have disparate distributions and fishery interactions (Longnose Skate is much more deeply distributed than Big Skate) and that option was not endorsed. The Pacific Fishery Management Council has chosen to set the Annual Catch Limit (ACL) equal to the Allowable Biological Catch (ABC) with a buffer for management uncertainty (P*) of 0.45.

1.7 Fisheries Off Alaska, Canada and Mexico

1.7.1 Alaska

In Alaska, skates were primarily taken as bycatch in both longline and trawl fisheries until 2003, when a directed skate fishery developed in the Gulf of Alaska, where Longnose and Big skates comprise the majority of the skate biomass.

The Gulf of Alaska (GOA) skate complex is managed as three units. Big skates and Longnose Skates each have separate harvest specifications, with acceptable biological catches (ABCs) specified for each GOA regulatory area (western, central, and eastern). A single gulfwide overfishing level (OFL) is specified for each stock. All remaining skate species are managed as an "Other Skates" group with gulfwide harvest specifications. All GOA skates are managed as Tier 5 stocks, where OFL and ABC are based on survey biomass estimates and natural mortality rate (Alaska Fisheries Science Center 2018).

In the Bering Sea and Aleutian Islands, skates are assessed as a group rather than as separate species.

1.7.2 Canada

In Canada historic information regarding skate catches goes back to the 1950's. Prior to 1990's skates were taken mostly as bycatch and landings were reported as part of a skate complex (not by species). As with the West Coast, the trawl fishery is responsible for the largest amount of bycatch. Skate catches off British Columbia accelerated in the early 1990's, partly due to emerging Asian markets. Since 1996, longnose skate has been targeted by the B.C. trawl fishery and, as a result, catches have been more accurately reported.

Assessments of Longnose Skate and Big Skate were conducted by Canada's Division of Fisheries and Oceans in 2015(King, J.R., Surry, A.M., Garcia, S., and P.J. Starr 2015). For Big Skate, a Bayesian surplus production model failed to provide plausible results, and two data-limited approaches were investigated: Depletion-Corrected Average Catch Analysis (DCAC), and a Catch-MSY (maximum sustainable yield) Approach.

DCAC produced a range of potential yield estimates that were above the long-term average catch, with an upper bound that was three orders of magnitude larger than the long-term average catch. The Catch-MSY approach was found to be quite sensitive to assumptions and was not recommended as the sole basis of advice to managers.

The recommendation for management for both skate species was that they should be managed with harvest yields based on mean historic catch, with consideration given to survey trends and to the ranges of maximum sustainable yield estimates identified by the Catch-MSY Approach. However, the analysis found no significant trends in abundance indices for

Big Skate, and mean historical catches were below the maximum MSY estimate from the catch-MSY results.

1.7.3 Mexico

No information is available on any fishery for Big Skate in Mexican waters, where they rarely occur, however they may be taken in the artisanal fishery.

2 Fishery Data

2.1 Data

Data used in the Big Skate assessment are summarized in Figure 3. Descriptions of the data sources are in the following sections.

2.2 Fishery Landings and discards

Catch information for Big Skate is very limited, in part because the requirement to sort landings of Big Skate in the shore-based Individual Fishing Quota fishery from landings in the "Unidentified Skate" category was not implemented until June 2015. The historical catch of Big Skate therefore relies on the historical reconstruction of the landings of all skates as well as an analysis of discards of Longnose Skate. The estimated landings for each state and the tribal fishery are provided in Table 2 and shown in Figure 4.

2.2.1 Washington Commercial Skate Landings Reconstruction

Estimates of landings of Big Skate in Washington state were estimated as a fraction of total skate landings as described in (Gertseva, V. 2019). The approached relied on trawl survey estimates of depth distributions for each species, combined with logbook estimates of fishing depths in each year.

The WCGBT Survey data was used to estimate proportions of longnose and big skates by depth (aggregated into 100m bins) and year for the period of the survey (between 2003 and 2018). Big Skate were primarily found in the 0–100m and 100–200m. Trawl logbook data include information on the amount of retained catch of skate (all species combined) within each haul as well depth of catch. The proportion of Big Skate for each depth bin was assigned to the skate catch for each haul within those depth bins and summed to get a total for each year. When survey skate information was available (2003-2018), survey skate proportions were applied by depth and year to account for inter-annual variability in those proportions. Prior to 2003, average proportions from 2003-2007 within each depth bin were applied.

These estimated annual proportion of Big Skate relative to all skates from the logbook analysis was then applied to total Washington skate landings by year (provided by WDFW) to account for landings that weren't included in the available logbook data. Prior to 1987 (when no logbook data were available), the average proportion Big Skate within the combined skate category, calculated from 1987-1992 logbook data, was applied to total skate landings in Washington. Estimated Big Skate landings provided by WDFW were used for the period from 2004 forward.

2.2.2 Oregon Commercial Skate Landings Reconstruction

Oregon Department of Fish and Wildlife (ODFW) provided newly reconstructed commercial landings for all observed skate species for the 2019 assessment cycle (1978 – 2018). In addition, the methods were reviewed at a pre-assessment workshop. Historically, skates were landed as a single skate complex in Oregon. In 2009, longnose skates were separated into their own single-species landing category, and in 2014, big skates were also separated. The reconstruction methodology differed by these three time blocks in which species composition collections diverged (1978 – 2008; 2009 – 2014; 2015 – 2018).

Species compositions of skate complexes from commercial port sampling are available throughout this time period but are generally limited, which precluded the use of all strata for reconstructing landings. Quarter and port were excluded, retaining gear type, PMFC area, and market category for stratifying reconstructed landings within the three time blocks. Bottom trawl gear types include multiple bottom trawl gears, and account for greater than 98% of skate landings . Minor gear types include primarily bottom longline gear, but also include mid-water trawl, hook and line, shrimp trawl, pot gear and scallop dredge.

For bottom trawl gears, trawl logbook areas and adjusted skate catches were matched with strata-specific species compositions. In Time Block 1 (1978 – 2008), all bottom trawl gear types were aggregated due to a lack of specificity in the gear recorded on the fish tickets. However, in Time Blocks 2 and 3, individual bottom trawl gear types were retained. Some borrowing of species compositions was required (31% of strata) and when necessary, borrowed from the closest area or from the most similar gear type . Longline gear landings were reconstructed in a similar fashion as to bottom trawl and required some borrowing among strata as well (25%).

Due to insufficient species compositions, mid-water trawl landings were reconstructed using a novel depth-based approach. Available compositions indicate that the proportion by weight of big skates within a composition drops to zero at approximately 100 fathoms, and an inverse relationship is observed for longnose skate, where the proportion by weight is consistently one beyond 100 – 150 fathoms . Complex-level landings were assigned a depth from logbook entries and these species specific depth associations were used to parse out landings by species. The approach differed somewhat by time block . Landings from shrimp trawls were handled using a similar methodology. Finally, very minor landings from hook and line, pot gear and scallop dredges were assigned a single aggregated species composition, as they lack any gear-specific composition samples. Landings from within a time block were apportioned by year using the proportion of the annual ticket landings.

Results indicate that the species-specific landings from this reconstruction are very similar to those from Oregon's commercial catch reconstruction (Karnowski et al. 2014) during the overlapping years but cover a greater time period with methodology more applicable to skates in particular. ODFW intends to incorporate reconstructed skate landings into PacFIN in the future (A. Whitman, ODFW; pers. comm.).

2.2.3 California Catch Reconstruction

A reconstruction of historical skate landings from California waters was developed for the 1916–2017 time period using a combination of commercial catch data (spatially explicit block summary catches and port sample data from 2009-2017) and fishery-independent survey data (Bizzarro, J. 2019). Virtually all landings in California were of "unspecified skate" until species-composition sampling of skate market categories began in 2009.

From 2009 through 2017, catch estimates were based on these market category species-composition samples, and the average of those species-compositions was hindcast to 2002, based on the assumption that those data were representative of the era of large area closures in the post-2000 period.

For the period from 1936-1980, spatially explicit landings data (the California Department of Fisheries and Wildlife (CDFW) block summary data) were merged with survey data to provide species-specific estimates.

For years 1981-2001, a "blended" product of these two approaches was taken, in which a linear weighting scheme blended the two sets of catch estimates through that period. Landings estimates were also scaled upwards by an expansion factor for skates landed as "dressed" based on fish ticket data. Prior to 1981 these data had not been reported and skate landings were scaled by the "average" percentage landed as dressed in the 1981-1985 time period, but by the late 1980s nearly all skates were landed round.

As no spatial information on catch is available from 1916-1930, and the block summary data were very sparse in the first few years of the CDFW fish ticket program (1931–1934), spatial information from the late 1930's was used to hindcast to the 1916–1935 time period. However, since Washington and Oregon did not have catch estimates for this year period, the California estimates of catch prior to 1938 were not used as they were subsumed into an estimated of the total catch across all states increasing linearly from 1916 to 1950.

2.2.4 Tribal Catch in Washington

Tribal catch of Big Skate was provided by WDFW as all landings took place in Washington State. The landings were estimated from limited state sampling of species compositions in combined skate category. Anecdotal evidence suggest that most of the catch in tribal fishery is retained, and discard is minimal.

2.2.5 Fishery Discards

Fishery discards of Big Skate are highly uncertain. The method used to estimate discards for Longnose Skate was based on a strong correlation ($R^2 = 95.7\%$) between total mortality of that species, and total mortality of Dover Sole for the years 2009–2017 during which Longnose were landed separately from other skates. In contrast, the sorting requirement for Big Skate occurred too recently to provide an adequate range of years for this type of correlation. Furthermore, there is greater uncertainty in the total mortality for the shallow-water species with which Big Skate most often co-occurs, such as Sand Sole and Starry Flounder, than there is for Dover Sole, which has been the subject of recurring stock assessments.

Both what discard rate information is available and anecdotal information from those involved in the fishery for both skate species indicate that discarding for Big Skate and Longnose Skate in the years prior to 1995 were driven by the same market forced and the discard rates were similar. Therefore, the discard rate for Longnose Skate was used as a proxy for the discards of Big Skate in order to estimate Big Skate discards.

The reconstructed landings of Big Skate for the period 1950–1995 had a mean of 63.1 t with no significant trend (a linear model fit to the data increased from 62.8 t in 1950 to 63.5 in 1995. The estimated tribal catch prior to 1995 averaged less than 1 t and was not included in this analysis of Big Skate discards for the years prior to 1995.

The mean discard rate for LN was 92.46%, also with no significant linear trend (the linear fit decreased from 92.8% in 1950 to 92.1% in 1995). An estimate of the mean annual discard amount can therefore be calculated as from the mean discard rate and the mean landings as $\bar{L}/(1-\bar{d})$ where $\bar{L}$ is the mean landings across that time period and $\bar{d}$ is the mean discards (Figure **??**).

Two alternative methods were used to estimate the mean annual discard amount: applying the annual LN discard rates to the annual BS catch, and applying 3-year moving averages of these two quantities. The use of the annual values resulted in an implausibly high degree of annual variability among the estimates, with the most extreme being a spike of 2146.4 in 1979 compared to 1032.7 t the year before and 654.0 the year after. The use of the 3-year moving average dampened this variability and these estimates were retained for a sensitivity analysis (Figure 5).

A discard mortality rate of 50 percent was assumed for all discards, following the assumption used for the Longnose Skate assessment conducted for the U.S. West Coast in 2007 (Gertseva, V and Schrippa, MJ 2007) The same rate has been used for skates in the trawl fishery in British Columbia, based on an approximate average of these reported rates. In 2015, PFMC's Groundfish Management Team (GMT) conducted a comprehensive literature review of skate discard mortality, and concluded that the current assumption regarding Big Skate discard mortality is consistent with existing reported rates for other similar species.

Estimation of discard rates (discards amount relative to total catch) during the period of the West Coast Groundfish Observer Program (WCGOP), which began in 2002, was hindered by the landings of Big Skate primarily occurring in the "unspecified skate" category prior to 2015. Therefore, a discard rate was computed using the combination of Big Skate and unspecified skate under the assumption that the vast majority of the unspecified skates were

Big Skate. A coefficient of variation was calculated for the by bootstrapping vessels within ports because the observer program randomly chooses vessels within ports to be observed. For the years after the catch share program was implemented in 2011, the trawl fishery was subject to 100% observer coverage and discarding is assumed to be known with minimal error (CV = 0.01).

The mean body weight of discarded Big Skates, calculated from the weight and count of baskets of discarded Big Skate, was available for the years 2002–2017.

3 Fishery-Independent Data Sources

3.1 Indices of abundance

3.1.1 Alaska Fisheries Science Center (AFSC) Triennial Shelf Survey

Research surveys have been used since the 1970s to provide fishery-independent information about the abundance, distribution, and biological characteristics of Big Skate. A coast-wide survey was conducted in 1977 (Gunderson, Donald Raymond and Sample, Terrance M. 1980) by the Alaska Fisheries Science Center, and repeated every three years through 2001. The final year of this survey, 2004, was conducted by the NWFSC according to the AFSC protocol. We refer to this as the **Triennial Survey**.

The survey design used equally-spaced transects from which searches for tows in a specific depth range were initiated. The depth range and latitudinal range was not consistent across years, but all years in the period 1980-2004 included the area from 40° 10'N north to the Canadian border and a depth range that included 55-366 meters, which spans the range where the vast majority of Big Skate encountered in all trawl surveys. Therefore the index was based on this depth range. The survey as conducted in 1977 had incomplete coverage and is not believe to be comparable to the later years, and is not used in the index.

3.1.2 Northwest Fisheries Science Center West Coast Groundfish Bottom Trawl Survey

In 2003, the NWFSC took over an ongoing slope survey the AFSC had been conducting, and expanded it spatially to include the continental shelf. This survey, referred to in this document as the "WCGBT Survey" or "WCGBTS", is conducted annually. It uses a random-grid design covering the coastal waters from a depth of 55 m to 1,280 m from late-May to early-October (Bradburn, M.J. and Keller, A.A and Horness, B.H. 2011 , Keller, A.A. and Wallace, J.R. and Methot, R.D. 2017). Four chartered industry vessels are used each year (with the exception of 2013 when the U.S. federal-government shutdown curtailed the survey).

3.1.3 Index Standardization

The index standardization methods for the two bottom trawl surveys matched that used for Longnose Skate and additional detail is provided in (Gertseva, V. 2019). The data from both surveys was analyzed using a spatio-temporal delta-model (Thorson, J. T. and Shelton, A. O. and Ward, E. J. and Skaug, H. J. 2015), implemented as an R package VAST (Thorson, James T. and Barnett, Lewis A. K. 2017) and publicly available online (https://github.com/James-Thorson/VAST). Spatial and spatio-temporal variation is specifically included in both encounter probability and positive catch rates, a logit-link for encounter probability, and a log-link for positive catch rates. Vessel-year effects were included for each unique combination of vessel and year in the database for the WCGBT Survey but not the Triennial survey. Further details regarding model structure are available in the user manual (https://github.com/James-Thorson/VAST/blob/master/examples/VAST_user_manual.pdf).

Spatial patterns in the survey estimates show Big Skate widely distributed along the coast, with higher densities in the central and more northern areas and closer to shore 8.

3.1.4 Internation Pacific Halibut Commission Longline Survey

The IPHC has conducted an annual longline survey for Pacific Halibut off the coast of Oregon and Washington since 1997 (no surveys were performed in 1998 or 2000). Beginning in 1999, this has been a fixed station design, with 84 locations in this area (station locations differed in 1997, and are therefore not comparable with subsequent surveys). 400 to 800 hooks have been deployed at each station in 100-hook groups (typically called "skates" although that term will be avoided here to avoid confusion). The gear used to conduct the survey was designed to efficiently sample Pacific Halibut and used 16/0 (#3) circle hooks baited with Chum Salmon.

In some years from 2011 onward, additional stations were added to the survey to sample Yelloweye Rockfish. These stations were excluded from the analysis, as were additional stations added in 2013, 2014, and 2017, off the coast of California (south of 42 degrees latitude). Some variability in exact sampling location is practically unavoidable, and leeway is given in the IPHC methods to center the set on the target coordinates while allowing wind and currents to dictate the actual direction in which the gear is deployed. This can result in different habitats being accessed at each fixed deployment location across years. One station that was very close to the U.S. Canada border had the mid-point of the set in Canada in 2 out of the 19 years of the survey. For consistency among years, all samples from this station were included in the analysis, including those in Canada.

In most years, bycatch of non-halibut species has been recorded during this survey on the first 20 hooks of each 100-hook group, although in 2003 only 10% of the hooks were observed for bycatch, and starting in 2012, some stations had 100% of the hooks observed for bycatch. Combining these observation pattern with the number of hooks deployed each year, resulted in most stations having 80, 100, 120, 140, or 160 hooks observed, with a mean of 144 hooks and a maximum of 800 hooks observed. The depth range of the 84 stations considered was 42—530 m, thus extending beyond the range of Big Skate, but 74% of the stations were shallower than 200 m. Big Skate have been observed at 51 of the 84 the standard stations that were retained for this analysis, but no station had Big Skates observed in more than 12 out of the 19 years of survey data, and only 10% of the station/year combinations had at least one observed Big Skate (Figure X). Of those station/year combinations with at least one Big Skate observed, the Big Skates were observed on an average of 1.3% of the hooks observed. The highest proportion was 10 Big Skates out of 81 hooks observed at one station.

The IPHC longline survey catch data were standardized using a Generalized Linear Model (GLM) with binomial error structure. Catch-per-hook was modeled, rather than catch per station due to the variability in the number of hooks deployed and observed each year. The binomial error structure was considered logical, given the binary nature of capturing (or not) a Longnose Skate on each longline hook. The modeling approach is identical to that which has been applied in the past for Yelloweye Rockfish (Stewart et al. 2009), and Spiny Dogfish (Gertseva and Taylor 2011). MCMC sampling of the GLM parameters was used to estimate the variability around each index estimate. The median index estimates themselves were approximately equal to the observed mean catch rate in each year (Figure Y). In recent years, the IPHC standardization of the index of halibut abundance has included an adjustment to account for missing baits on hooks returned empty in an effort to account for reduced catchability of the gear that may result from the lost bait. This adjustment was not included in the analysis for Big Skate although it could be considered in future years.

3.2 Biological Parameters and Data

3.2.1 Measurement Details and Conversion Factors

Some size measurements were taken as either disc width or inter-spiracle width rather than total length. A conversion from disc width to total length was estimated as $L = 1.3399 * W$ based on from 95 samples from WCGBT Survey where both measurements collected (R-squared = 0.9983). Little sex difference observed, so using single relationship for both sexes (Figure 16). This estimate is similar to the conversion estimated by Ebert (2008) for Big Skate in Alaska. The inter-spiracle width to total length was converted based on estimates from Downs & Cheng (2013):

$$L = 12.111 + 9.761 * ISW \text{ (females)},$$

$$L = 3.824 + 10.927 * ISW \text{ (males)}.$$

3.2.2 Fishery dependent length and age composition data

Fishery length composition data was available from PacFIN were available for the years 1995–2018 (with the exception of 2000) as shown in Table 4. Ages were available from only 2004, 2008-2012, and 2018. These were all represented as conditioned on length in order to provide more detailed information about the relationship between age and length, to reduce any influence of size-based selectivity on the age composition, and to ensure independence from the length samples. Furthermore, the samples from Washington in 2009 were sampled using a length-stratified system, so should only be treated as conditioned on length.

Length compositions of Big Skate discarded in commercial fisheries measured by the West Coast Groundfish Observer program were available for the years 2010–2017.

The input sample sizes for the length compositions were calculated via the Stewart Method (Ian Stewart, personal communication, IPHC):

$$\text{Input N} = N_{\text{hauls}} + 0.138 * N_{\text{fish}} \text{ if } N_{\text{fish}}/N_{\text{hauls}} \text{ is} < 44,$$

$$\text{Input N} = 7.06 * N_{\text{hauls}} \text{ if } N_{\text{fish}}/N_{\text{hauls}} \text{ is} \geq 44.$$

However, no haul had greater than 44 Big Skate sampled, so only the first formula was used.

3.2.3 Survey length and age composition data

Lengths of Big Skate were only collected form the Triennial survey in 1998, 2001, and 2004, but 1998 had only 3 samples and were excluded from this analysis. Length compositions were available for all years of the WCGBT Survey. Sample sizes for both surveys are provided in Table 5. The WCGBT Survey used disc width for the years 2006 and 2007 and total length in all other years. Those samples where only disc width was measured were converted to total length using the formula above.

The length compositions from the fishery and each of the two surveys aggregated across all years is shown in Figure 10.

Ages were available from the WCGBT Survey in the years 2009, 2010, 2016, 2017, and 2018. No ages were available from the Triennial Survey.

Ageing Precision and Bias

Ages of Big Skate were all estimated based on growth band counts of sectioned vertebrae. Ageing precision and bias were estimated using double-reads of 518 Big Skate vertebrae using the approach of Punt et al. (2008). The results showed strong agreement among readers (Figure 14), with a standard deviation of the ageing error increasing from about 0.4 at age 0 to 1.6 years at age 15 (Figure 15).

Weight-Length

The mean weight as a function of length was estimated from 1159 samples from the WCGBT Survey using a linear regression on a log-log scale. Sex was not found to be a significant predictor, so a single relationship was estimated: $Weight = 0.0000074924 * Length^2.9925$ (Figure 16).

Sex Ratio, Maturity, and Fecundity

The female maturity relationship was based on visual maturity estimates from port samplers (n = 278, of which 241 were from Oregon and 37 from Washington, with 24 mature specimens) as well as 55 samples from the WCGBT Survey (of which 4 were mature). The resulting relationship was $L_{50\%} = 148.2453$ with a slope parameter of $Beta = -0.13155$ in the relationship $M = (1 + Beta(L - L_{50\%}))^{-1}$ (Figure 17).

3.2.4 Environmental or Ecosystem Data Included in the Assessment

In this assessment, neither environmental nor ecosystem considerations were explicitly included in the analysis. This is primarily due to a lack of relevant data or results of analyses that could contribute ecosystem-related quantitative information for the assessment.

4 Assessment

4.1 Previous Assessments

4.1.1 History of Modeling Approaches Used for this Stock

No previous stock assessment has been conducted for Big Skate. The current management is based on an OFL estimate calculated from a proxy for F_{MSY} and average survey biomass from the WCGBT Survey during the years 2010–2012 (Taylor IG and Cope, J and Hamel O and Thorson, J 2013). The F_{MSY} estimate was based on the product of an assumed F_{MSY}/M ratio and an M estimate of 0.162 based on the maximum age of 26 reported by McFarlane and King (McFarlane GA and King JR 2006). Values were sampled from an assumed distribution around all these quantities to develop a measure of uncertainty around the OFL estimate.

4.2 Model Description

4.2.1 Modeling Software

The STAT team used Stock Synthesis version 3.30.13 (Methot, Richard D. and Wetzel, Chantell R. (2013), Methot, RD Jr. and Wetzel, CR and Taylor, IG (2019)). The r4ss package version 1.35.1 (Taylor et al. 2019) was used to post-process the output data from Stock Synthesis.

4.2.2 Summary of Data for Fleets and Areas

Catch is divided among 4 fleets in the base model: *Fishery (current)* combines all non-tribal sources of catch for the years 1995 onward, *Discard (historical)* includes the estimated discard amount calculated from the estimated Longnose Skate discard rate as described above. The input catch for this fleet was 50% of the total estimate to account for the assumed 50% discard mortality rate. This data covers the period 1916–1994. *Fishery (historical)* includes the reconstructed landings estimates from each of the three states for 1916–1994. *Tribal* includes the estimates of catch of Big Skate by treaty tribes.

4.2.3 Other Specifications

This assessment covers the U.S. West Coast stock of Big Skate in off the coasts of Washington, Oregon and California, the area bounded by the U.S.-Canada border to the north, and the

U.S.-Mexico border to the south. The population is treated as a single coastwide stock with no net movement in or out of the area. Females and males are modeled separately as there is evidence for differences in growth based on both the age and length data, as well as patterns in the sex ratios associated with the length composition data. Natural Mortality is estimated within the model using natural mortality prior developed by Hamel (2015). A Beverton-Holt stock-recruit function is assumed with no deviations from the spawner-recruit curve estimated.

The length composition data are stratified into 37 5-cm bins, ranging between 20 and 200 cm and the age data are stratified into ages 0–15+, conditioned on the same length bin structure. The population dynamics are computed over a larger range of lengths age ages, with the 5-cm length bins extending up to 250 cm and the numbers-at-age computed up to age 20.

4.2.4 Data Weighting

The Francis (2011) data weighting method "TA1.8" as implemented in the r4ss package was used for all length and age composition data.

4.2.5 Priors

Natural mortality

A log-normal prior for natural mortality was based on a meta-analysis completed by Hamel (2015). The Hamel prior for M is lognormal(ln(5.4/max age), .438), which based on the single 15-year-old fish observed out of 1034 ages from the WCGBT Survey. This results in lognormal(log(0.36)=-1.021651, 0.438) prior.

Survey catchability

The lack of contrast in the data resulted in unstable model results under a variety of configurations. To keep biomass estimates within a plausibel range, a prior was applied to the catchability parameter (q) for the WCGBT Survey. This same prior was developed for the 2007 Longnose Skate assessment (Gertseva, V and Schrippa, MJ 2007) and is being used for the current Longnose Skate assessment (Gertseva, V. 2019). The prior for the WCGBT Survey was derived as follows.

The WCGBT Survey covers the full latitudinal range of longnose skate modeled in the assessment, and thus, the latitudinal availability factor was assumed to be one (complete latitudinal coverage). The survey coverage exceeds the maximum depth distribution of longnose skate but may not fully cover the shallow end of the skate distribution. A range of

95 to 100 percent was assumed for the depth availability. A range of 75 to 95 percent was assumed for vertical availability on the basis that longnose skate are known to bury in the mud and therefore some may be unavailable to the bottom trawl gear. The largest bounds were placed on the probability of capture, given a fish is in the net path. It is known that flatfish can be herded by trawl gear, and it is possible that this could also occur for skates. However, it is also possible that skate could avoid the trawl nets. For capture probability, a range of 75 to 150 percent was assumed. Best estimates for each factors were set at the midpoint of the range for individual factors, except for the probability of capture, which was given a value of one. The overall estimate for the survey catchability was thus estimated to be 0.83 and the consequent bounds on catch, and the best assumption are: (0.53, 1.43) and 0.83 respectively. The best estimate was equated to the median of a lognormal distribution and the bounds to 99 percent of that distribution. This resulted in a normal prior on $log(q)$, with a mean of -0.188, and standard deviation of 0.187.

4.2.6 Estimated and Fixed Parameters

A full list of all estimated and fixed parameters is provided in Tables 7.

The base model has a total of 44 estimated parameters in the following categories:

- 1 natural mortality parameter applied to both sexes,
- 6 parameters related to female growth and the variability in length age age,
- 2 parameters related to male growth relative to female growth,
- 1 stock-recruit parameter ($log(R_0)$ controlling equilibrium recruitment)
- 3 catchability parameters (1 for the WCGBT Survey and 1 each for the early and late periods of the Triennial Survey)
- 2 extra standard deviation parameters (1 for each survey), and
- 29 selectivity parameters, including 16 related to time-varying retention rate

The estimated parameters are described in greater detail below and a full list of all estimated and parameters is provided in Table 7.

Growth.

Examination of patterns of age-at-length and length-at-age indicated unusual patterns of growth for Big Skate, including almost linear growth for the early years during which both sexes appeared to have similar average size, followed by strong differences in size at older ages. This led to the choice to model growth using the “growth cessation model” recently developed by Maunder et al. (2018). The estimated growth curves are shown in Figure 18. This model provided two key advantages over the more common von Bertalanffy growth model in the case of Big Skate: it allowed essentially linear growth for the early years and it allowed growth for the earlier ages to be similar between females and males while diverging at older ages. The growth cessation model also improve the negative log likelihood by 45 units relative to the von Bertalanffy growth model.

Natural Mortality.

Male natural mortality was assumed equal to the value estimated for females. Sensitivity analyses were used to test the impact of both the the prior on natural mortality and the assumption of equal natural mortality for both sexes.

Selectivity.

A double-normal selectivity function was used for all fleets to allow consideration of both asymptotic and dome-shaped patterns. For the fishery and the Triennial survey, the difference in likelihood between dome-shaped and asymptotic patterns was very small and in the case of the Triennial survey, the dome-shape occurred at a length beyond almost all observations, indicating that this shape was likely driven by fit to other data sources, such as the index, rather than the length composition data. The WCGBT Survey was allowed to remain dome-shaped as this survey had the selectivity peak at a smaller length than the other fleets and the likelihood was improved by the dome-shape. The WCGBT Survey also has the shortest hauls, with 15 minutes or less of bottom contact, so larger skates may be better able to escape the net.

In order to fit a strong skew in the sex ratios toward males for the length bins in which the majority of the samples were found, it was necessary to estimate a sex-specific offset of selectivity. Two offset parameters were estimated for all fleets, one for the difference in length at peak selectivity and another for the maximum selectivity. The ascending slope was assumed equal in all cases, as was the descending slope for the WCGBT Survey.

Other Estimated Parameters.

Other Fixed Parameters.

Steepness was fixed at 0.4.

4.3 Model Selection and Evaluation

4.3.1 Key Assumptions and Structural Choices

To be added

4.3.2 Alternate Models Considered

To be added

4.3.3 Convergence

To be added

4.4 Response to the Current STAR Panel Requests

Request No. 1:

Rationale: xxx

STAT Response: xxx

Request No. 2:

Rationale: xxx

STAT Response: xxx

Request No. 3:

Rationale: x.

STAT Response: xxx

Request No. 4:

Rationale: xxx

STAT Response: xxx

Request No. 5:

Rationale: xxx

STAT Response: xxx

4.5 Base Case Model Results

The following description of the model results reflects a base model that incorporates all of the changes made during the STAR panel (see previous section). The base model parameter estimates and their approximate asymptotic standard errors are shown in Table 7 and the likelihood components are in Table 8. Estimates of derived reference points and approximate 95% asymptotic confidence intervals are shown in Table e. Time-series of estimated stock size over time are shown in Table 9.

4.5.1 Parameter Estimates

The additional survey variability (process error added directly to each year's input variability) for all surveys was estimated within the model.

(Figure 32).

The stock-recruit curve . . . Figure 33 with estimated recruitments also shown.

4.5.2 Fits to the Data

Model fits to the indices of abundance, fishery length composition, survey length composition, discard rates, mean body weight, and conditional age-at-length observations are all discussed below.

The observed indices show much more variability than the model expectation, with the fit to the WCGBT Survey essentially a flat line (Figure 20) and the fit to the Triennial Survey only showing a noticeable change over time due to the separate catchability parameter estimated for the early and late periods (Figure 21).

The fits to the length data are much better thanks to the combination of the growth cessation model and the sex-specific offsets to selectivity (Figures 22–23).

The conditional age-at-length data is likewise fit reasonably well, with some patterns in residuals showing variability among years, but no clear pattern that is consistent across years (Figures 24 and 25).

Sex ratio data is not included in the likelihood as such, but a part of the length composition likelihood in which the proportions of females and males are included in a single vector comapred to the model expectations in the multinomial likelihood. The patterns in sex ratio by length bin show fewer females than males for the middle range of sizes (70–120 cm), with a shift to almost 100% females for the largest size bins (over 130 cm). The use of sex-specific growth curves was adequate to fit the ratios for the largest bins, but ratio skews toward males at lengths where the mean ages are similar for females and males. The fit to this part of the sex ratio pattern required an offset is selectivity.

4.5.3 Uncertainty and Sensitivity Analyses

A number of sensitivity analyses were conducted, including:

1. Setting all selectivity curves to be asymptotic
2. Setting all selectivity curves to be dome-shaped
3. Removing the sex-specific offset on the selectivity curves
4. Removing the prior on catchability for the WCGBT Survey
5. Estimating a single catchability for all years in the Triennial Survey
6. Estimating separate natural mortality parameters for males and females
7. Removing the prior on natural mortality
8. Using the von Bertalanffy growth model
9. Using the Richards growth model
10. Tuning the sample sizes using the McAllister-Ianelli method
11. Estimating historic discards based on 3yr average of discard rates and landings
12. Changeing discard mortality from 0.5 to 0.4
13. Changeing discard mortality from 0.5 to 0.6

Results of these sensitivities are shown in Figures 35 to 37, and Tables 10 to 12.

Additional text to be added

4.5.4 Retrospective Analysis

To be added

4.5.5 Likelihood Profiles

Likelihood profiles were conducted over $log(R_0)$, stock-recruit steepness (h) and natural mortality (M).

Results of these profiles are shown in Figures 39 to 44.

Additional text to be added

4.5.6 Reference Points

Reference points were calculated using the estimated selectivities and catch distribution among fleets in the most recent year of the model, (2017). Sustainable total yield (landings plus discards) were 466 mt when using an $SPR_{50\%}$ reference harvest rate and with a 95% confidence interval of 303 mt based on estimates of uncertainty. The spawning biomass equivalent to 40% of the unfished level ($SB_{40\%}$) was 610 mt.

(Figure 30

The 2018 spawning biomass relative to unfished equilibrium spawning biomass is above/below the target of 40% of unfished levels (Figure 31). The relative fishing intensity, $(1 - SPR)/(1 - SPR_{50\%})$, has been xxx the management target for the entire time series of the model.

Table e shows the full suite of estimated reference points for the base model and Figure 45 shows the equilibrium curve based on a steepness value xxx.

5 Harvest Projections and Decision Tables

The forecasts of stock abundance and yield were developed using the final base model, with the forecasted projections of the OFL presented in Table g.

The forecasted projections of the OFL for each model are presented in Table h.

6 Regional Management Considerations

7 Research Needs

There are a number of areas of research that could improve the stock assessment for Big Skate. Below are issues identified by the STAT team and the STAR panel:

1. **Data!**:
2. **xxxx**:
3. **xxxx**:
4. **xxxx**:
5. **xxxx**:

8 Acknowledgments

The authors gratefully acknowledge the time and effort reviewers Stacey Miller, Jim Hastie and Owen Hamel put into making this a polished document.

9 Tables

9.1 Data Tables

Table 2: Landings by source. Landings are reconstructed histories 1916-1995.

Year	CA (mt)	OR (mt)	WA (mt)	Tribal (mt)	Total (mt)
1916	78.30	0.00	0.00	0.00	78.30
1917	80.10	0.00	0.00	0.00	80.10
1918	101.20	0.00	0.00	0.00	101.20
1919	75.20	0.00	0.00	0.00	75.20
1920	122.00	0.00	0.00	0.00	122.00
1921	17.80	0.00	0.00	0.00	17.80
1922	30.80	0.00	0.00	0.00	30.80
1923	34.20	0.00	0.00	0.00	34.20
1924	33.40	0.00	0.00	0.00	33.40
1925	46.70	0.00	0.00	0.00	46.70
1926	59.30	0.00	0.00	0.00	59.30
1927	67.10	0.00	0.00	0.00	67.10
1928	116.70	0.00	0.00	0.00	116.70
1929	107.50	0.00	0.00	0.00	107.50
1930	70.80	0.00	0.00	0.00	70.80
1931	43.60	0.00	0.00	0.00	43.60
1932	73.30	0.00	0.00	0.00	73.30
1933	46.50	0.00	0.00	0.00	46.50
1934	57.40	0.00	0.00	0.00	57.40
1935	70.60	0.00	0.00	0.00	70.60
1936	87.70	0.00	0.00	0.00	87.70
1937	115.40	0.00	0.00	0.00	115.40
1938	99.40	0.00	0.00	0.00	99.40
1939	90.90	0.00	0.00	0.00	90.90
1940	60.30	5.30	0.00	0.00	65.70
1941	53.10	56.40	0.00	0.00	109.40
1942	27.00	34.40	0.00	0.00	61.40
1943	20.40	0.90	0.00	0.00	21.30
1944	7.80	1.60	0.00	0.00	9.50
1945	13.30	0.30	0.00	0.00	13.50
1946	17.10	1.80	0.00	0.00	18.90
1947	24.10	0.00	0.00	0.00	24.10
1948	30.70	5.70	0.00	0.00	36.30
1949	31.90	0.00	7.20	0.00	39.10
1950	32.20	2.10	2.10	0.00	36.40
1951	21.70	4.70	3.90	0.00	30.30

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Table 2: Landings by source. Landings are reconstructed histories 1916-1995.

Year	CA (mt)	OR (mt)	WA (mt)	Tribal (mt)	Total (mt)
1952	39.10	0.10	7.80	0.00	46.90
1953	124.90	1.20	1.60	0.00	127.60
1954	38.80	2.30	1.20	0.00	42.40
1955	45.70	35.60	1.60	0.00	82.90
1956	40.40	2.60	3.10	0.00	46.10
1957	49.50	0.00	2.50	0.00	52.00
1958	38.80	0.00	0.20	0.00	38.90
1959	46.50	0.00	0.80	0.00	47.30
1960	39.20	0.00	0.70	0.00	39.80
1961	54.40	40.90	4.60	0.00	99.80
1962	44.40	27.90	5.20	0.00	77.60
1963	53.20	30.40	2.10	0.00	85.70
1964	49.90	28.30	2.70	0.00	80.90
1965	34.30	12.80	3.50	0.00	50.60
1966	36.40	20.10	0.60	0.00	57.00
1967	53.30	15.60	6.60	0.00	75.50
1968	55.30	45.40	8.80	0.00	109.50
1969	32.50	33.80	6.60	0.00	72.90
1970	16.30	11.90	0.10	0.00	28.20
1971	18.50	3.10	0.00	0.00	21.60
1972	33.50	2.00	0.10	0.00	35.60
1973	40.70	0.90	0.00	0.00	41.70
1974	21.90	5.90	0.10	0.00	27.80
1975	39.80	2.00	0.00	0.00	41.80
1976	20.70	31.30	0.20	0.00	52.20
1977	32.80	31.50	0.60	0.00	64.90
1978	67.70	77.30	4.00	0.00	149.10
1979	90.50	75.50	30.40	0.00	196.40
1980	17.60	34.10	5.20	0.00	56.90
1981	138.00	14.80	6.50	0.00	159.30
1982	78.30	5.20	14.60	0.00	98.10
1983	55.30	14.20	8.90	0.00	78.40
1984	26.20	4.90	1.60	0.00	32.70
1985	60.30	0.40	4.90	0.00	65.60
1986	27.20	1.60	8.90	0.00	37.80
1987	22.60	1.90	18.40	1.00	43.90
1988	15.30	0.30	10.90	1.20	27.60
1989	18.90	0.20	6.20	0.00	25.30
1990	25.10	0.00	9.60	0.10	34.90
1991	22.80	0.20	21.50	0.10	44.60
1992	24.60	0.30	11.20	0.00	36.10

Continued on next page

Table 2: Landings by source. Landings are reconstructed histories 1916-1995.

Year	CA (mt)	OR (mt)	WA (mt)	Tribal (mt)	Total (mt)
1993	29.00	0.20	21.00	0.60	50.70
1994	27.70	2.50	20.50	0.10	50.70
1995	43.00	41.20	21.80	0.10	106.00
1996	146.70	138.50	22.80	0.10	308.10
1997	228.40	215.40	84.00	0.20	528.00
1998	120.50	51.40	22.70	0.20	194.90
1999	109.50	131.30	41.40	0.40	282.60
2000	69.40	193.60	97.70	0.30	361.00
2001	75.30	115.10	26.70	0.40	217.50
2002	34.70	102.80	70.80	4.80	213.10
2003	48.80	223.00	65.70	5.40	342.80
2004	45.20	105.90	98.00	4.60	253.80
2005	33.40	151.30	113.10	15.70	313.40
2006	102.40	206.60	66.20	24.90	400.00
2007	35.50	190.40	29.10	19.90	274.90
2008	46.00	280.10	36.80	3.20	366.00
2009	9.60	162.00	16.50	17.50	205.70
2010	1.20	157.50	25.00	12.50	196.20
2011	0.50	231.50	10.00	26.40	268.40
2012	6.80	216.30	5.00	41.60	269.60
2013	20.90	92.30	13.00	8.80	135.00
2014	41.00	286.00	16.80	28.60	372.40
2015	35.20	218.80	1.00	76.60	331.50
2016	15.00	317.50	1.20	77.80	411.50
2017	28.00	188.00	1.40	60.20	277.60
2018	23.80	115.80	2.40	30.60	172.60

Table 3: Index inputs.

	WCGBTS		Triennial		IPHC	
Year	Obs	se_log	Obs	se_log	Obs	se_log
1980			467.83	0.53		
1983			911.85	0.30		
1986			996.75	0.29		
1989			1431.65	0.22		
1992			2426.18	0.20		
1995			497.24	0.26		
1998			2437.75	0.20		
1999					0.00	0.17
2001			1669.73	0.23	0.00	0.29
2002					0.00	0.53
2003	8170.51	0.20			0.00	0.43
2004	14349.00	0.18	3674.14	0.19	0.00	0.20
2005	12122.52	0.16			0.00	0.18
2006	9273.79	0.18			0.00	0.64
2007	8137.47	0.18			0.00	0.34
2008	5494.76	0.21			0.00	0.81
2009	10721.30	0.17			0.00	0.48
2010	11475.29	0.14			0.00	0.24
2011	8029.69	0.16			0.00	0.20
2012	11593.79	0.16			0.00	0.61
2013	11521.85	0.17			0.00	0.20
2014	19855.79	0.13			0.00	0.19
2015	19251.41	0.13			0.00	0.16
2016	17141.95	0.15			0.00	0.17
2017	13237.37	0.14			0.00	0.18
2018	14568.79	0.14			0.00	0.26

Table 4: PacFIN Samples.

	CA		OR		WA		All Landings		Discards	
Year	Ntows	Nfish	Ntows	Nfish	Ntows	Nfish	Ntows	Nfish	Ntows	Nfish
Lengths										
1995			6	55			6	55		
1996			3	8			3	8		
1997			1	14			1	14		
1998			1	2			1	2		
1999			1	8			1	8		
2000										
2001			3	43			3	43		
2002			6	199			6	199		
2003			9	202			9	202		
2004			2	27	2	12	4	39		
2005			7	123	6	87	13	210		
2006			13	310	15	191	28	501		
2007	1	1	10	128	9	172	20	301		
2008			10	94	8	94	18	188		
2009	8	32	17	234	1	18	26	284		
2010	2	8	15	186			17	194	149	349
2011	2	2	29	418	4	9	35	429	554	1518
2012	3	43	24	477	3	38	30	558	544	1405
2013	11	201	11	252	8	168	30	621	443	987
2014	15	217	11	237	5	249	31	703	676	1625
2015	25	237	21	411	2	5	48	653	688	1557
2016	14	181	34	444	7	98	55	723	652	1456
2017	14	239	50	668	12	47	76	954	508	1248
2018	15	133	46	552	14	98	75	783		
Ages										
2004					2	11	2	11		
2008			8	80			8	80		
2009			10	87	8	65	18	152		
2010			10	102			10	102		
2011			21	202			21	202		
2012			12	120			12	120		
2018			6	39	13	93	19	132		

Table 5: Samples from the surveys.

	Triennial		WCGBTS		IPHC	
NA.	Triennial	NA..1	WCGBTS	NA..2	IPHC	NA..3
Year	Ntows	Nfish	Ntows	Nfish	Nsets	Nfish
Lengths						
2001	41	81				
2003			60	197		
2004	39	100	81	262		
2005			99	328		
2006			67	154		
2007			76	192		
2008			53	159		
2009			82	305		
2010			130	466		
2011			99	360		
2012			104	395		
2013			84	316		
2014			149	552	14	54
2015			134	546		
2016			105	422		
2017			125	496		
2018			123	331		
Ages						
2009			77	230		
2010			124	333		
2016			100	138		
2017			110	164		
2018			118	169		

9.2 Model Results Tables

Table 6: Results from 100 jitters from the base case model.

Description	Value	NA	NA
Returned to base case	-	-	-
Found local minimum	-	-	-
Found better solution	-	-	-
Error in likelihood	-	-	-
Total	100	100	100

Table 7: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values indicate not estimated), status (indicates if parameters are near bounds, and prior type information (mean, SD).

No.	Parameter	Value	Phase	Bounds	Status	SD	Prior (Exp.Val, SD)
1	NatM_p_1_Fem_GP_1	0.384	1	(0.01, 0.8)	OK	0.014	Log_Norm (-1.02165, 0.0438)
2	L_at_Amin_Fem_GP_1	20.393	2	(10, 40)	OK	1.020	None
3	Linf_Fem_GP_1	176.000	2	(100, 300)	OK	3.927	None
4	VonBert_K_Fem_GP_1	11.994	1	(0.005, 30)	OK	0.312	None
5	Cessation_Fem_GP_1	3.877	3	(0.1, 5)	OK	6.181	None
6	SD_young_Fem_GP_1	5.683	5	(1, 20)	OK	0.916	None
7	SD_old_Fem_GP_1	7.378	5	(1, 20)	OK	0.886	None
8	Wtlen_1_Fem_GP_1	0.000	-3	(0, 3)			None
9	Wtlen_2_Fem_GP_1	2.993	-3	(2, 4)			None
10	Mat50%_Fem_GP_1	148.245	-3	(10, 140)			None
11	Mat_slope_Fem_GP_1	-0.132	-3	(-0.09, -0.05)			None
12	Eggs/kg_inter_Fem_GP_1	0.500	-3	(-3, 3)			None
13	Eggs/kg_slope_wt_Fem_GP_1	0.000	-3	(-3, 3)			None
14	NatM_p_1_Mal_GP_1	0.000	-2	(-3, 3)			None
15	L_at_Amin_Mal_GP_1	0.000	-2	(-1, 1)			None
16	Linf_Mal_GP_1	-0.381	2	(-1, 1)	OK	0.025	None
17	VonBert_K_Mal_GP_1	0.109	3	(-10, 20)	OK	0.032	None
18	Cessation_Mal_GP_1	0.200	-3	(-3, 3)			None
19	SD_young_Mal_GP_1	0.000	-5	(-1, 1)			None
20	SD_old_Mal_GP_1	0.000	-5	(-1, 1)			None
21	Wtlen_1_Mal_GP_1	0.000	-3	(0, 3)			None
22	Wtlen_2_Mal_GP_1	2.993	-3	(2, 4)			None
23	CohortGrowDev	1.000	-5	(0, 2)			None
24	FracFemale_GP_1	0.500	-99	(0.001, 0.999)			None
25	SR_LN(R0)	8.295	1	(5, 15)	OK	0.205	None
26	SR_BH_steep	0.400	-3	(0.2, 1)			None

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Table 7: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values indicate not estimated), status (indicates if parameters are near bounds, and prior type information (mean, SD).

No.	Parameter	Value	Phase	Bounds	Status	SD	Prior (Exp.Val, SD)
27	SR_sigmaR	0.300	-2	(0, 0.4)			None
28	SR_regime	0.000	-1	(-2, 2)			None
29	SR_autocorr	0.000	-99	(0, 0)			None
78	LnQ_base_WCGBTS(5)	-0.144	1	(-2, 2)	OK	0.187	Normal (-0.188, 0.187)
79	Q_extraSD_WCGBTS(5)	0.161	5	(0, 2)	OK	0.057	None
80	LnQ_base_Triennial(6)	-1.382	1	(-10, 2)	OK	0.559	None
81	Q_extraSD_Triennial(6)	0.365	5	(0, 2)	OK	0.146	None
82	LnQ_base_Triennial(6)__1995	-1.065	1	(-7, 0)	OK	0.559	None
83	Size_DblN_peak_(1)	86.826	4	(80, 150)	OK	4.112	None
84	Size_DblN_top_logit_(1)	-15.000	-5	(-15, 4)			None
85	Size_DblN_ascend_se_(1)	7.064	4	(-1, 9)	OK	0.126	None
86	Size_DblN_descend_se_(1)	20.000	-5	(-1, 20)			None
87	Size_DblN_start_logit_(1)	-999.000	-4	(-999, 9)			None
88	Size_DblN_end_logit_(1)	-999.000	-5	(-999, 9)			None
89	Retain_L_infl_(1)	66.645	2	(15, 150)	OK	0.629	None
90	Retain_L_width_(1)	4.962	2	(0.1, 10)	OK	0.350	None
91	Retain_L_asymptote_logit_(1)	2.111	3	(-10, 20)	OK	0.352	None
92	Retain_L_maleoffset_(1)	0.000	-3	(0, 0)			None
93	DiscMort_L_infl_(1)	5.000	-4	(5, 15)			None
94	DiscMort_L_width_(1)	0.000	-4	(0.001, 10)			None
95	DiscMort_L_level_old_(1)	0.500	-5	(0, 1)			None
96	DiscMort_L_male_offset_(1)	0.000	-5	(0, 0)			None
97	SzSel_Fem_Peak_(1)	-4.986	4	(-50, 50)	OK	2.038	None
98	SzSel_Fem_Ascend_(1)	0.000	-4	(-5, 5)			None
99	SzSel_Fem_Descend_(1)	0.000	-4	(-5, 5)			None
100	SzSel_Fem_Final_(1)	0.000	-4	(-5, 5)			None
101	SzSel_Fem_Scale_(1)	0.774	4	(0.5, 1.5)	OK	0.083	None

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Table 7: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values indicate not estimated), status (indicates if parameters are near bounds, and prior type information (mean, SD).

No.	Parameter	Value	Phase	Bounds	Status	SD	Prior (Exp.Val, SD)
102	Size_DblN_peak_WCGBTS(5)	72.392	4	(50, 150)	OK	5.639	None
103	Size_DblN_top_logit_WCGBTS(5)	-15.000	-5	(-15, 4)			None
104	Size_DblN_ascend_se_WCGBTS(5)	6.440	4	(-1, 9)	OK	0.371	None
105	Size_DblN_descend_se_WCGBTS(5)	10.061	5	(-1, 20)	OK	1.621	None
106	Size_DblN_start_logit_WCGBTS(5)	-5.000	-4	(-999, 9)			None
107	Size_DblN_end_logit_WCGBTS(5)	-999.000	-5	(-999, 9)			None
108	SzSel_Fem_Peak_WCGBTS(5)	-7.134	4	(-50, 50)	OK	3.982	None
109	SzSel_Fem_Ascend_WCGBTS(5)	0.000	-4	(-5, 5)			None
110	SzSel_Fem_Descend_WCGBTS(5)	0.000	-4	(-5, 5)			None
111	SzSel_Fem_Final_WCGBTS(5)	0.000	-4	(-5, 5)			None
112	SzSel_Fem_Scale_WCGBTS(5)	0.743	4	(0.5, 1.5)	OK	0.121	None
113	Size_DblN_peak_Triennial(6)	176.755	4	(50, 180)	OK	26.076	None
114	Size_DblN_top_logit_Triennial(6)	-15.000	-5	(-15, 4)			None
115	Size_DblN_ascend_se_Triennial(6)	8.481	4	(-1, 9)	OK	0.381	None
116	Size_DblN_descend_se_Triennial(6)	20.000	-5	(-1, 20)			None
117	Size_DblN_start_logit_Triennial(6)	-4.025	4	(-15, 9)	OK	0.527	None
118	Size_DblN_end_logit_Triennial(6)	-999.000	-5	(-999, 9)			None
119	SzSel_Fem_Peak_Triennial(6)	0.000	-4	(-50, 50)			None
120	SzSel_Fem_Ascend_Triennial(6)	0.000	-4	(-5, 5)			None
121	SzSel_Fem_Descend_Triennial(6)	0.000	-4	(-5, 5)			None
122	SzSel_Fem_Final_Triennial(6)	0.000	-4	(-5, 5)			None
123	SzSel_Fem_Scale_Triennial(6)	0.600	4	(0.5, 1.5)	OK	0.128	None
124	Retain_L_asymptote_logit__2005	2.325	4	(-10, 20)	OK	0.562	None
125	Retain_L_asymptote_logit__2006	3.330	4	(-10, 20)	OK	1.315	None
126	Retain_L_asymptote_logit__2007	4.000	4	(-10, 20)	OK	2.027	None
127	Retain_L_asymptote_logit__2008	11.158	4	(-10, 20)	OK	111.095	None

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Table 7: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values indicate not estimated), status (indicates if parameters are near bounds, and prior type information (mean, SD).

No.	Parameter	Value	Phase	Bounds	Status	SD	Prior (Exp.Val, SD)
128	Retain_L_asymptote_logit__2009	4.991	4	(-10, 20)	OK	3.975	None
129	Retain_L_asymptote_logit__2010	13.248	4	(-10, 20)	OK	88.075	None
130	Retain_L_asymptote_logit__2011	14.665	4	(-10, 20)	OK	73.786	None
131	Retain_L_asymptote_logit__2012	13.918	4	(-10, 20)	OK	81.260	None
132	Retain_L_asymptote_logit__2013	3.475	4	(-10, 20)	OK	0.337	None
133	Retain_L_asymptote_logit__2014	3.653	4	(-10, 20)	OK	0.279	None
134	Retain_L_asymptote_logit__2015	3.430	4	(-10, 20)	OK	0.263	None
135	Retain_L_asymptote_logit__2016	2.901	4	(-10, 20)	OK	0.193	None
136	Retain_L_asymptote_logit__2017	2.822	4	(-10, 20)	OK	0.192	None

Table 8: Likelihood components from the base model.

Likelihood component	Value
TOTAL	1097.30
Catch	0.00
Survey	-98.12
Length composition	763.02
Age composition	421.52
Recruitment	10.88
Forecast recruitment	0.00
Parameter priors	0.00
Parmeter soft bounds	0.01

Table 9: Time-series of population estimates from the base-case model. Relative exploitation rate is $(1 - SPR)/(1 - SPR_{50\%})$.

Year	Total biomass (mt)	Spawning biomass (mt)	Depletion	Age-0 recruits	Total catch (mt)	Relative exploitation rate	SPR
1916	24263	1526	0.000	4004	0	0.00	1.00
1917	24263	1526	0.000	4004	12	0.00	0.99
1918	24251	1525	0.999	4003	25	0.00	0.99
1919	24228	1524	0.998	4001	37	0.00	0.98
1920	24196	1521	0.997	3999	49	0.00	0.98
1921	24156	1518	0.995	3996	62	0.00	0.97
1922	24108	1514	0.992	3992	74	0.00	0.97
1923	24054	1510	0.989	3987	86	0.00	0.96
1924	23994	1504	0.986	3982	99	0.00	0.96
1925	23928	1498	0.982	3976	111	0.00	0.95
1926	23857	1492	0.977	3969	123	0.01	0.95
1927	23780	1485	0.973	3962	136	0.01	0.94
1928	23699	1477	0.968	3954	148	0.01	0.94
1929	23614	1469	0.963	3946	160	0.01	0.93
1930	23524	1461	0.957	3938	172	0.01	0.92
1931	23430	1453	0.952	3929	185	0.01	0.92
1932	23332	1444	0.946	3920	197	0.01	0.91
1933	23231	1435	0.940	3911	210	0.01	0.91
1934	23126	1426	0.934	3901	222	0.01	0.90
1935	23018	1416	0.928	3890	234	0.01	0.90
1936	22907	1406	0.921	3880	246	0.01	0.89
1937	22794	1396	0.915	3868	259	0.01	0.89
1938	22677	1386	0.908	3857	271	0.01	0.88
1939	22558	1375	0.901	3845	329	0.02	0.86
1940	22393	1361	0.892	3830	329	0.02	0.86
1941	22242	1348	0.884	3815	363	0.02	0.84
1942	22069	1334	0.874	3798	351	0.02	0.84
1943	21922	1320	0.865	3783	343	0.02	0.85
1944	21794	1308	0.857	3769	350	0.02	0.84
1945	21669	1296	0.850	3754	364	0.02	0.84
1946	21539	1284	0.842	3740	379	0.02	0.83
1947	21402	1272	0.834	3725	394	0.02	0.82
1948	21258	1260	0.826	3710	412	0.02	0.81
1949	21106	1248	0.818	3694	426	0.02	0.81
1950	20951	1235	0.809	3679	424	0.02	0.81
1951	20808	1223	0.802	3664	418	0.02	0.81
1952	20681	1212	0.794	3650	434	0.02	0.80

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Table 9: Time-series of population estimates from the base-case model. Relative exploitation rate is $(1 - SPR)/(1 - SPR_{50\%})$.

Year	Total biomass (mt)	Spawning biomass (mt)	Depletion	Age-0 recruits	Total catch (mt)	Relative exploitation rate	SPR
1953	20546	1201	0.787	3634	515	0.03	0.76
1954	20341	1185	0.776	3613	430	0.02	0.80
1955	20232	1174	0.770	3599	470	0.02	0.78
1956	20090	1162	0.762	3583	434	0.02	0.79
1957	19992	1153	0.755	3570	439	0.02	0.79
1958	19892	1144	0.750	3558	426	0.02	0.80
1959	19809	1136	0.745	3547	435	0.02	0.79
1960	19720	1129	0.740	3537	427	0.02	0.79
1961	19641	1122	0.735	3528	487	0.03	0.77
1962	19506	1113	0.729	3515	465	0.03	0.77
1963	19401	1105	0.724	3504	473	0.03	0.77
1964	19293	1097	0.719	3492	468	0.03	0.77
1965	19197	1090	0.714	3481	438	0.02	0.78
1966	19136	1084	0.710	3473	444	0.02	0.78
1967	19071	1078	0.706	3464	463	0.03	0.77
1968	18991	1071	0.702	3453	497	0.03	0.76
1969	18881	1062	0.696	3440	460	0.03	0.77
1970	18812	1056	0.692	3432	416	0.02	0.79
1971	18788	1054	0.690	3427	409	0.02	0.79
1972	18770	1052	0.689	3424	423	0.02	0.79
1973	18737	1049	0.687	3420	429	0.02	0.78
1974	18697	1046	0.686	3416	415	0.02	0.79
1975	18671	1045	0.684	3414	429	0.02	0.78
1976	18631	1042	0.683	3410	440	0.02	0.78
1977	18584	1039	0.681	3406	452	0.03	0.77
1978	18527	1036	0.679	3400	536	0.03	0.73
1979	18393	1027	0.673	3387	584	0.03	0.71
1980	18224	1015	0.665	3368	444	0.03	0.77
1981	18202	1011	0.663	3362	547	0.03	0.72
1982	18083	1001	0.656	3346	486	0.03	0.75
1983	18030	995	0.652	3336	466	0.03	0.76
1984	17998	991	0.649	3329	420	0.02	0.78
1985	18008	989	0.648	3327	453	0.03	0.76
1986	17981	987	0.647	3323	425	0.03	0.78
1987	17977	987	0.647	3323	431	0.03	0.77
1988	17965	987	0.647	3324	415	0.02	0.78
1989	17965	989	0.648	3326	413	0.02	0.78

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Table 9: Time-series of population estimates from the base-case model. Relative exploitation rate is $(1 - SPR)/(1 - SPR_{50\%})$.

Year	Total biomass (mt)	Spawning biomass (mt)	Depletion	Age-0 recruits	Total catch (mt)	Relative exploitation rate	SPR
1990	17967	991	0.649	3329	422	0.02	0.78
1991	17960	991	0.650	3330	432	0.03	0.77
1992	17944	991	0.649	3329	424	0.02	0.78
1993	17938	990	0.649	3329	438	0.03	0.77
1994	17921	989	0.648	3326	438	0.03	0.77
1995	17905	987	0.647	3323	119	0.01	0.93
1996	18199	1003	0.657	3348	347	0.02	0.82
1997	18257	1006	0.659	3353	594	0.03	0.71
1998	18075	994	0.651	3334	219	0.01	0.88
1999	18268	1004	0.658	3351	318	0.02	0.83
2000	18354	1010	0.662	3360	406	0.02	0.79
2001	18349	1010	0.662	3361	245	0.01	0.87
2002	18500	1021	0.669	3377	239	0.01	0.87
2003	18643	1032	0.676	3394	385	0.02	0.80
2004	18635	1034	0.677	3397	285	0.02	0.85
2005	18723	1042	0.683	3409	347	0.02	0.82
2006	18747	1046	0.685	3416	429	0.02	0.79
2007	18697	1045	0.685	3414	292	0.02	0.85
2008	18786	1051	0.689	3423	387	0.02	0.81
2009	18783	1050	0.688	3422	217	0.01	0.89
2010	18946	1059	0.694	3436	207	0.01	0.89
2011	19107	1069	0.700	3450	282	0.02	0.86
2012	19180	1074	0.704	3458	282	0.02	0.86
2013	19245	1080	0.708	3467	144	0.01	0.92
2014	19436	1095	0.718	3489	397	0.02	0.81
2015	19370	1095	0.718	3489	351	0.02	0.83
2016	19357	1098	0.719	3493	441	0.02	0.79
2017	19265	1094	0.717	3487	297	0.02	0.85
2018	19324	1097	0.719	3492	185	0.01	0.90
2019	19491	1106	0.725	3505			

Table 10: Sensitivity of the base model to assumptions about selectivity and catchability.

Label	Base model	Sel all asymptotic	Sel all domed	Sel no sex offset	Q no prior on WCGBTS	Q no offset on triennial
TOTAL likelihood	441.63	441.41	441.63	441.63	441.13	444.19
Survey likelihood	-9.78	-9.78	-9.78	-9.78	-10.06	-8.37
Length comp likelihood	366.25	366.14	366.25	366.25	366.93	366.81
Age comp likelihood	110.51	110.44	110.51	110.51	110.12	110.30
Discard likelihood	-21.79	-21.79	-21.79	-21.79	-22.06	-22.09
Mean body wt likelihood	-4.69	-4.69	-4.69	-4.69	-4.47	-4.46
Parm priors likelihood	1.12	1.09	1.12	1.12	0.66	1.99
Recr Virgin millions	4.00	3.95	4.00	4.00	2.81	3.33
log(R0)	8.29	8.28	8.29	8.29	7.94	8.11
NatM Female	0.38	0.38	0.38	0.38	0.38	0.39
NatM Male	0.38	0.38	0.38	0.38	0.38	0.39
Linf Female	176.00	175.90	176.00	176.00	175.97	176.05
Linf Male	120.24	120.20	120.24	120.24	120.38	120.21
Q WCGBTS	0.87	0.87	0.87	0.87	1.48	1.03
SSB Virgin thousand mt	3.05	3.04	3.05	3.05	2.31	2.44
SSB 2019 thousand mt	2.21	2.19	2.21	2.21	1.30	1.55
Bratio 2019	0.72	0.72	0.72	0.72	0.56	0.64
SPRratio 2018	0.19	0.19	0.19	0.19	0.31	0.25
Retained Catch MSY	517.38	513.46	517.39	517.38	381.02	425.06
Dead Catch MSY	559.36	555.10	559.36	559.36	410.67	458.77
Totbio unfished	24263.70	24029.90	24263.70	24263.70	17726.60	19826.60
OFLCatch 2021	1275.53	1263.01	1275.53	1275.53	783.06	953.04

Table 11: Sensitivity of the base model to assumptions about catches.

Label	Base model	Discards based on 3yr averages	Discard mortality 0 4	Discard mortality 0 6
TOTAL likelihood	441.63	440.89	441.18	442.05
Survey likelihood	-9.78	-10.00	-10.08	-9.50
Length comp likelihood	366.25	365.86	366.41	366.12
Age comp likelihood	110.51	110.53	110.46	110.54
Parm priors likelihood	1.12	1.13	1.06	1.17
Size at age likelihood	0.00	0.00	0.00	0.00
Recr Virgin millions	4.00	3.91	4.02	4.01
log(R0)	8.29	8.27	8.30	8.30
NatM Female	0.38	0.38	0.38	0.38
NatM Male	0.38	0.38	0.38	0.38
Linf Female	176.00	176.08	176.04	175.95
Linf Male	120.24	120.24	120.25	120.24
Q WCGBTS	0.87	0.90	0.88	0.85
SSB Virgin thousand mt	3.05	2.99	3.10	3.03
SSB 2019 thousand mt	2.21	2.06	2.17	2.26
Bratio 2019	0.72	0.69	0.70	0.75
SPRratio 2018	0.19	0.20	0.19	0.19
Retained Catch MSY	517.38	505.20	533.01	506.38
Dead Catch MSY	559.36	545.84	567.42	555.91
Totbio unfished	24263.70	23754.50	24522.60	24192.50
OFLCatch 2021	1275.53	1205.43	1265.56	1291.27

Table 12: Sensitivity of the base model to assumptions about biology and misc.

Label	Base model	Bio separate M by sex	Bio no M prior	Bio von Bertalanffy growth	Bio Richards growth	Misc McAllister Ianelli tuning
TOTAL likelihood	441.63	441.14	437.95	486.39	567.21	1132.64
Survey likelihood	-9.78	-9.86	-9.71	-9.80	-5.27	-9.76
Length comp likelihood	366.25	364.91	365.51	404.62	472.34	572.70
Age comp likelihood	110.51	111.02	108.63	117.88	124.25	594.48
Parm priors likelihood	1.12	1.45	0.01	0.04	0.33	4.59
Size at age likelihood	0.00	0.00	0.00	0.00	0.00	0.00
Recr Virgin millions	4.00	3.47	6.29	3.26	3.23	4.82
log(R0)	8.29	8.15	8.75	8.09	8.08	8.48
NatM Female	0.38	0.39	0.45	0.36	0.36	0.41
NatM Male	0.38	0.36	0.45	0.36	0.36	0.41
Linf Female	176.00	176.07	175.91	340.86	1563.81	177.98
Linf Male	120.24	119.90	120.98	153.33	174.21	120.30
Q WCGBTS	0.87	0.88	0.81	0.83	0.95	0.87
SSB Virgin thousand mt	3.05	2.57	2.23	2.74	4.29	2.85
SSB 2019 thousand mt	2.21	1.72	1.68	1.79	3.03	2.09
Bratio 2019	0.72	0.67	0.75	0.65	0.71	0.73
SPRratio 2018	0.19	0.23	0.17	0.24	0.20	0.19
Retained Catch MSY	517.38	456.14	564.78	446.71	486.58	530.92
Dead Catch MSY	559.36	492.51	610.60	482.17	527.60	573.75
Totbio unfished	24263.70	22766.70	25468.10	24181.20	26813.50	24157.50
OFLCatch 2021	1275.53	1055.25	1410.51	1017.39	1214.28	1314.46

Table 13: Summaries of key assessment outputs and likelihood values from the retrospective analysis. Note that male growth parameters are exponential offsets from female parameters, and depletion and SPR ratio are for the year of 2017. The base model includes all of the data. Retro1 removes the last year of data (2016), Retro2 removes the last two years of data, Retro3 removes three years and Retro4 removes four years.

Label	Base	Retro1	Retro2	Retro3	Retro4
Female natural mortality	0.26	0.26	0.26	0.26	0.26
Steepness	0.72	0.72	0.72	0.72	0.72
lnR0	8.16	8.09	8.07	8.04	8.08
Total Biomass (mt)	2796.86	2593.78	2568.77	2498.07	2650.36
Depletion	57.41	53.57	50.74	50.72	54.78
SPR ratio	0.72	0.76	0.79	0.80	0.74
Female Lmin	12.43	12.45	12.90	12.63	13.03
Female Lmax	33.31	33.50	33.39	33.37	33.46
Female K	0.25	0.24	0.24	0.25	0.23
Male Lmin (offset)	0.00	0.00	0.00	0.00	0.00
Male Lmax (offset)	-0.16	-0.16	-0.15	-0.16	-0.15
Male K (offset)	-0.29	-0.30	-0.43	-0.41	-0.56
Negative log-likelihood	1097.30	1047.56	1009.37	961.81	897.04
No. parameters	0.00	0.00	0.00	0.00	0.00
TOTAL	0.00	0.00	0.00	0.00	0.00
Equililibrium catch	-98.12	-92.00	-89.12	-81.75	-80.59
Survey	763.02	739.90	720.39	700.10	670.66
Length composition	421.52	390.56	369.97	336.26	299.84
Age composition	10.88	9.09	8.12	7.20	7.12
Recruitment	0.00	0.00	0.00	0.00	0.00
Forecast Recruitment	0.00	0.00	0.00	0.00	0.00
Parameter priors	0.01	0.01	0.01	0.01	0.01

Table 14: Summaries of key assessment outputs and likelihood values from selected likelihood profile runs on virgin recruitment (lnR0) and steepness. Note that male growth parameters are exponential offsets from female parameters, and depletion and SPR ratio are for the year of 2017.

Label	R07400	R07800	R08200	R08600	R09000	h0410	h0570	h0710	h0870	h0990
Female M	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Steepness	0.72	0.72	0.72	0.72	0.72	0.41	0.57	0.71	0.87	0.99
lnR0	7.40	7.80	8.20	8.60	9.00	8.34	8.21	8.16	8.13	8.11
Total biomass (m)	1623.19	2113.03	2894.72	4173.95	6142.97	3313.42	2943.85	2802.69	2712.12	2667.97
Depletion (%)	46.83	49.83	58.31	66.23	71.80	51.20	55.27	57.32	58.81	59.60
SPR ratio	1.05	0.91	0.70	0.49	0.34	0.68	0.71	0.72	0.72	0.73
Female Lmin	12.16	12.41	12.43	12.39	12.36	12.43	12.44	12.43	12.43	12.43
Female Lmax	34.29	33.83	33.26	32.76	32.42	33.19	33.28	33.31	33.33	33.34
Female K	0.24	0.25	0.25	0.26	0.26	0.25	0.25	0.25	0.25	0.25
Male Lmin (offset)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Male Lmax (offset)	-0.18	-0.17	-0.16	-0.15	-0.15	-0.16	-0.16	-0.16	-0.16	-0.16
Male K (offset)	-0.22	-0.31	-0.29	-0.24	-0.21	-0.27	-0.29	-0.29	-0.30	-0.30
Negative log-likelihood										
TOTAL	1117.15	1101.02	1097.33	1099.69	1102.95	1101.35	1098.58	1097.35	1096.72	1100.21
Catch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Equil_catch	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Survey	-100.10	-99.20	-97.99	-97.00	-96.37	-98.27	-98.18	-98.12	-98.06	-98.03
Length_comp	761.18	760.12	763.44	767.61	770.76	765.11	763.69	763.05	762.58	762.33
Age_comp	437.32	427.37	421.09	418.57	417.98	420.58	421.24	421.51	421.68	421.77
Recruitment	18.74	12.72	10.80	10.50	10.58	12.55	11.40	10.90	10.56	10.38
Forecast_Recruitment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Parm_priors	0.00	0.00	0.00	0.00	0.00	1.38	0.42	0.01	-0.04	3.76
Parm_softbounds	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Parm_devs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Crash_Pen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 15: Summaries of key assessment outputs and likelihood values from selected likelihood profile runs on female natural mortality. Note that male growth parameters are exponential offsets from female parameters, and depletion and SPR ratio are for the year of 2017.

Label	M0220	M0260	M0300	M0350	M0400
Female M	0.22	0.26	0.30	0.35	0.40
Steepness	0.72	0.72	0.72	0.72	0.72
lnR0	7.67	8.20	8.95	12.21	31.00
Total biomass (m)	2259.39	2861.79	4632.81	89473.50	9753570000000.00
Depletion (%)	47.72	58.15	68.08	79.27	79.74
SPR ratio	0.97	0.70	0.41	0.02	0.00
Female Lmin	12.39	12.44	12.43	12.39	12.24
Female Lmax	33.23	33.31	33.31	33.25	33.73
Female K	0.25	0.25	0.25	0.25	0.24
Male Lmin (offset)	0.00	0.00	0.00	0.00	0.00
Male Lmax (offset)	-0.16	-0.16	-0.15	-0.15	-0.15
Male K (offset)	-0.27	-0.30	-0.31	-0.32	-0.36
Negative log-likelihood					
TOTAL	1102.66	1096.96	1092.96	1089.92	1091.52
Catch	0.00	0.00	0.00	0.00	0.00
Equil_catch	0.00	0.00	0.00	0.00	0.00
Survey	-97.79	-98.14	-98.33	-98.33	-98.95
Length_comp	765.50	762.85	760.88	759.19	755.26
Age_comp	422.97	421.41	420.05	418.75	425.16
Recruitment	11.91	10.82	10.30	10.05	9.54
Forecast_Recruitment	0.00	0.00	0.00	0.00	0.00
Parm_priors	0.06	0.00	0.06	0.25	0.51
Parm_softbounds	0.01	0.01	0.01	0.00	0.00
Parm_devs	0.00	0.00	0.00	0.00	0.00
Crash_Pen	0.00	0.00	0.00	0.00	0.00

Table 16: Projection of potential OFL, spawning biomass, and depletion for the base case model.

Yr	OFL contribution (mt)	ACL landings (mt)	Age 5+ biomass (mt)	Spawning Biomass (mt)	Depletion
2019	1274.290	1185.906	18438.000	1106.070	0.725
2020	1211.220	1125.230	17564.900	1048.210	0.687
2021	1159.120	1074.895	16847.100	993.337	0.651
2022	1117.470	1034.993	16248.300	941.818	0.617
2023	1083.860	1003.371	15744.500	893.809	0.586
2024	1055.150	976.699	15309.700	849.368	0.557
2025	1029.120	952.644	14919.700	808.738	0.530
2026	1004.390	929.838	14555.100	772.649	0.506
2027	980.334	907.640	14202.800	742.174	0.486
2028	956.747	885.819	13859.300	717.965	0.470
2029	933.761	864.469	13527.100	699.544	0.458
2030	911.621	843.793	13209.600	684.888	0.449

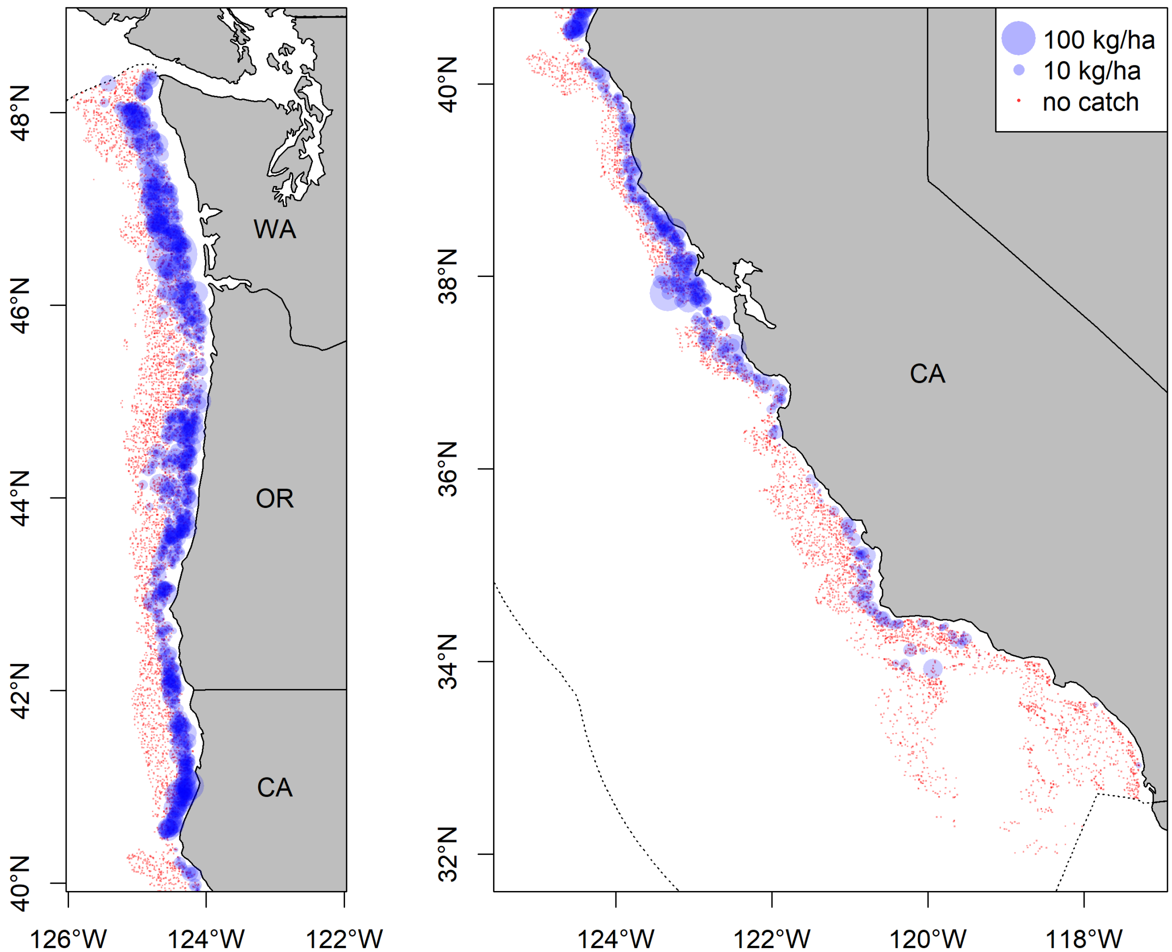

Figure 2: Map showing the distribution of Big Skate within the area covered by the West Coast Groundfish Bottom Trawl Survey aggregated over the years 2003–2018.

940 # 10 Figures

941 ## 10.1 Data Figures

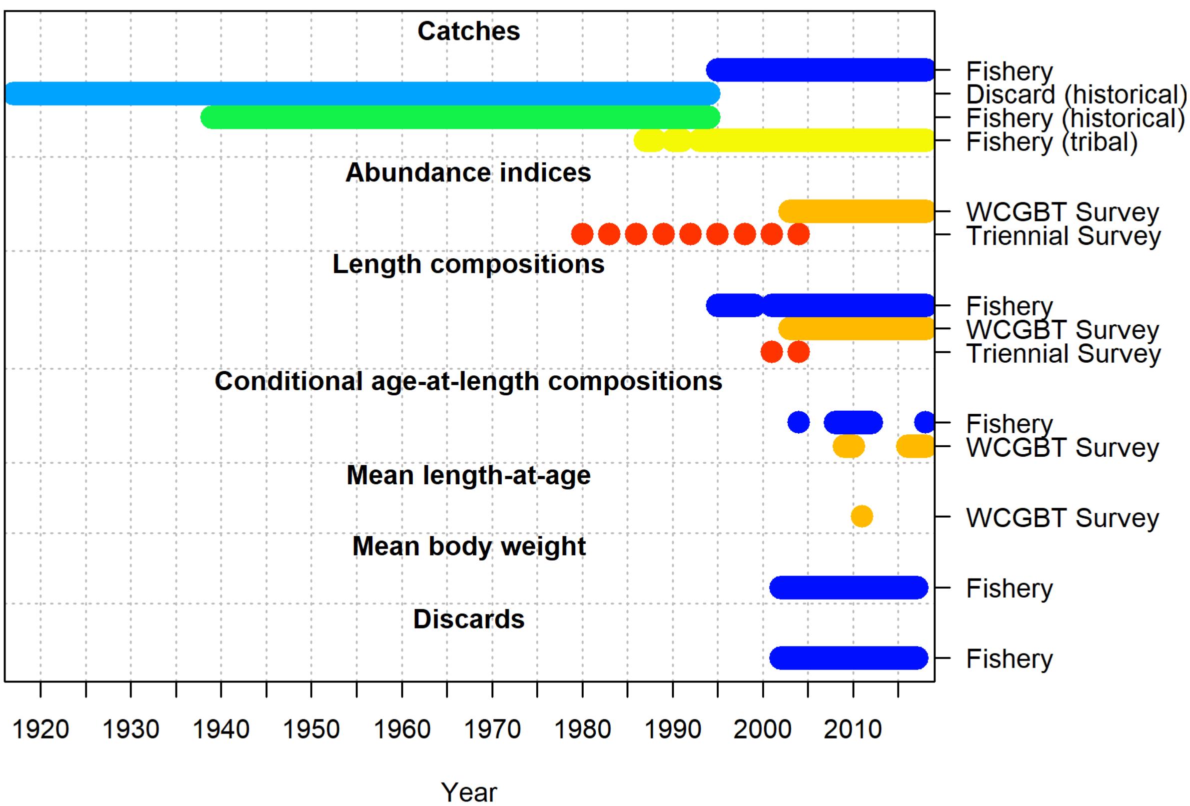

Figure 3: Summary of data sources used in the model.

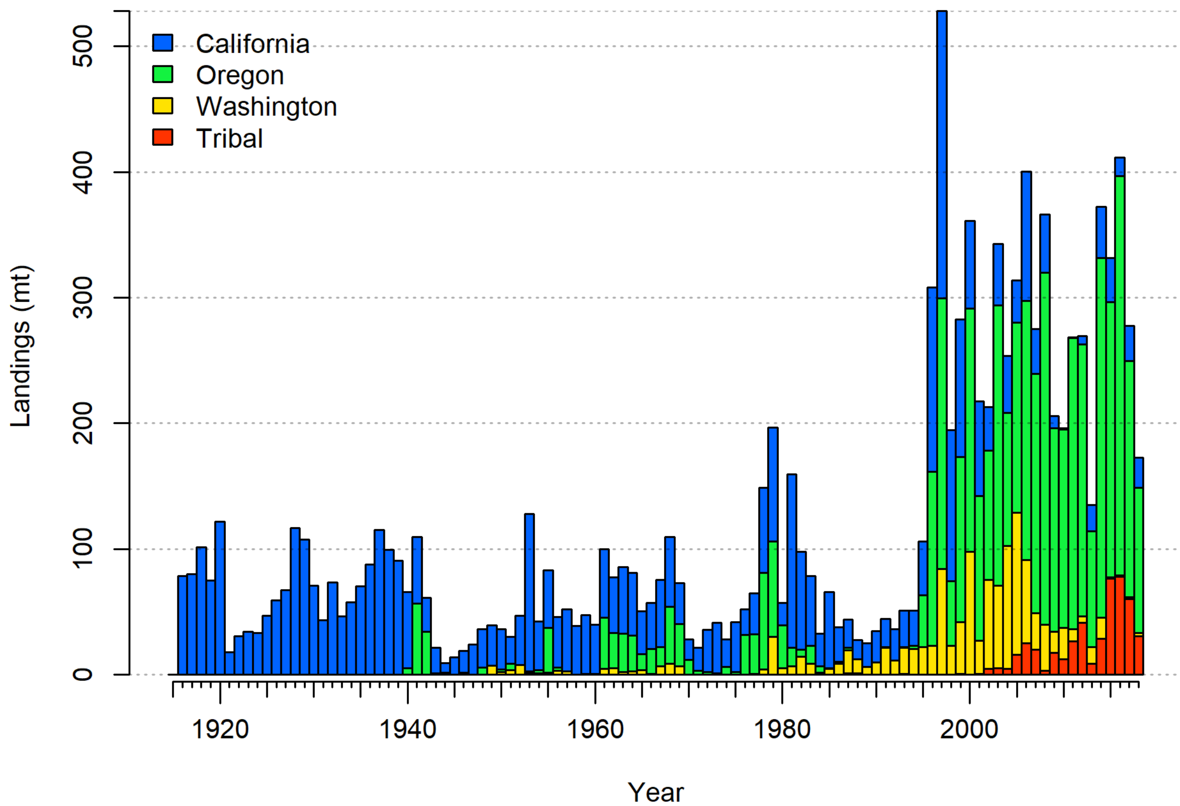

Figure 4: Reconstructed landings by area. Tribal catch was all landed in Washington.

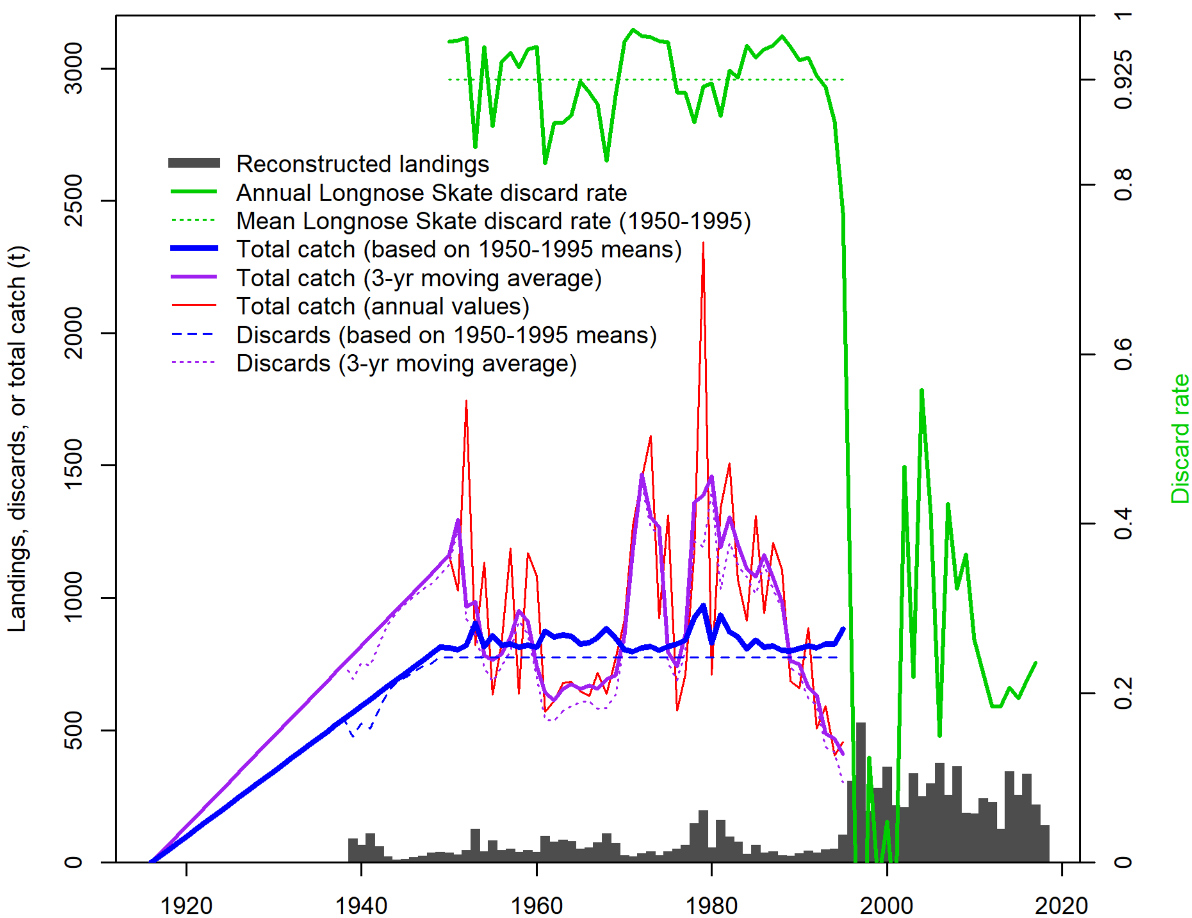

Figure 5: Estimated total catch using different assumptions for discards. The discard rates shown in green lines are relative to the right-hand axis while all other values are relative to the left-hand axis.

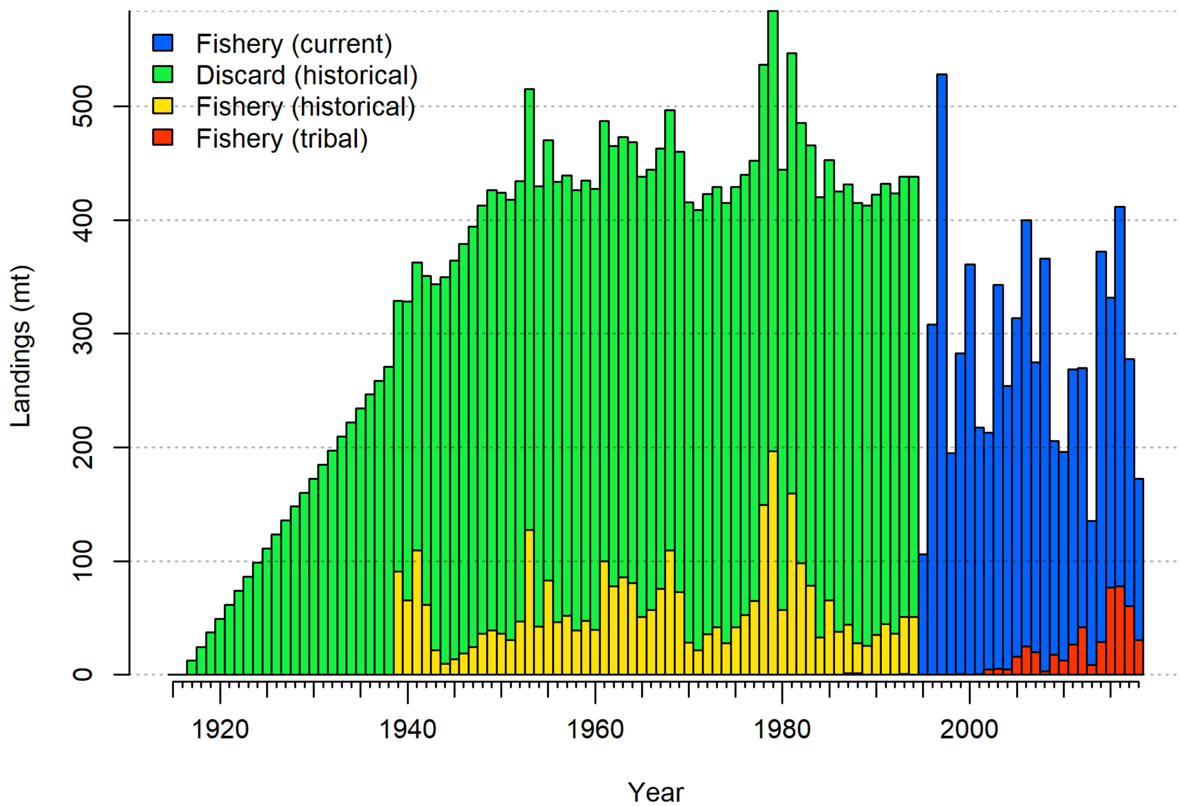

Figure 6: Catch data input to the model under assumed fleet structure. The historical discards shown in green have been scaled to account for an assumed 50% discard mortality. Discards during the period from 1995 onward are not represented here as they are estimated within the model.

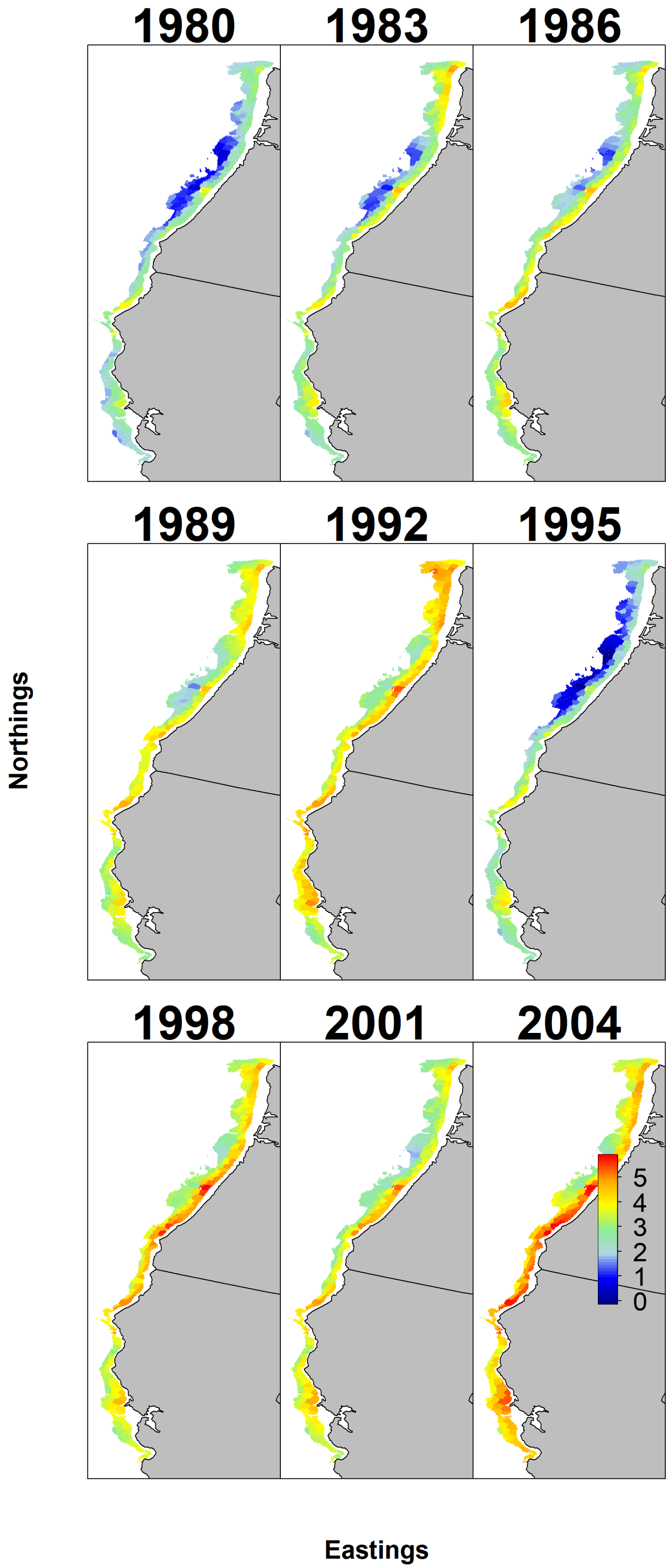

Figure 7: Map of estimated density by year for Big Skate in the Triennial survey.

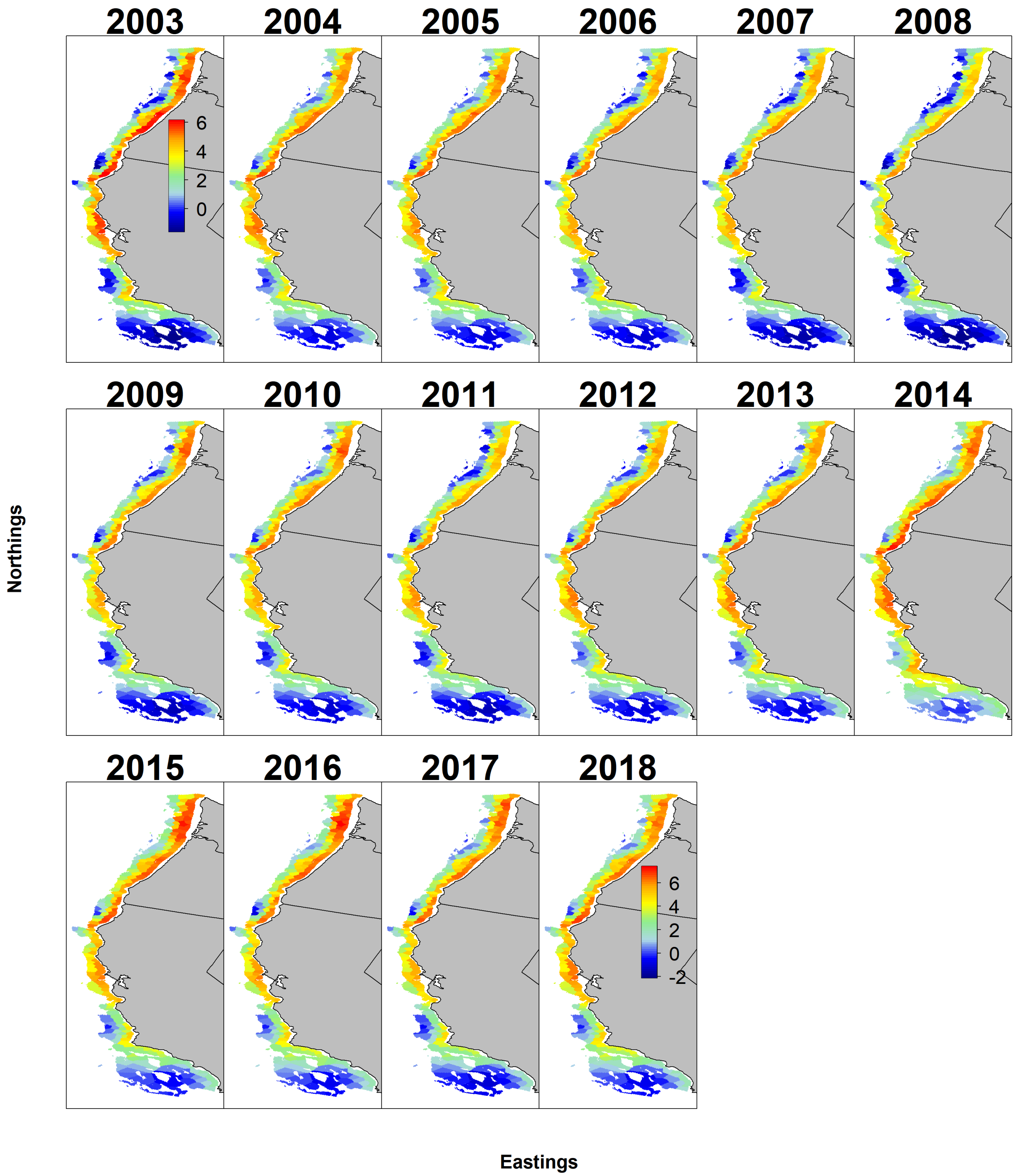

Figure 8: Map of estimated density by year for Big Skate in the WCGBT Survey.

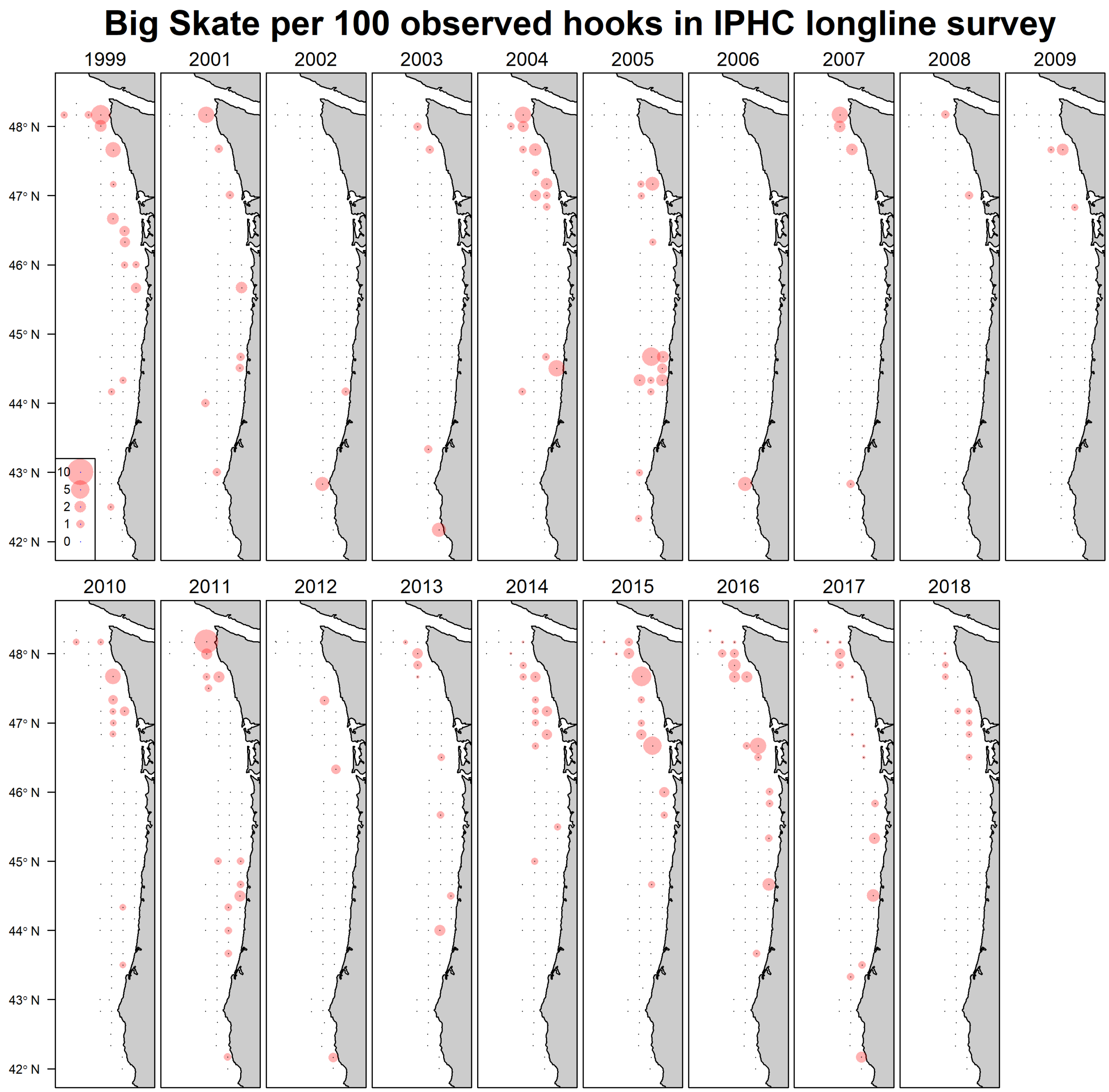

Figure 9: Map of catch rates by year for Big Skate in the International Pacific Halibut Commission longline survey.

10.2 Biology Figures

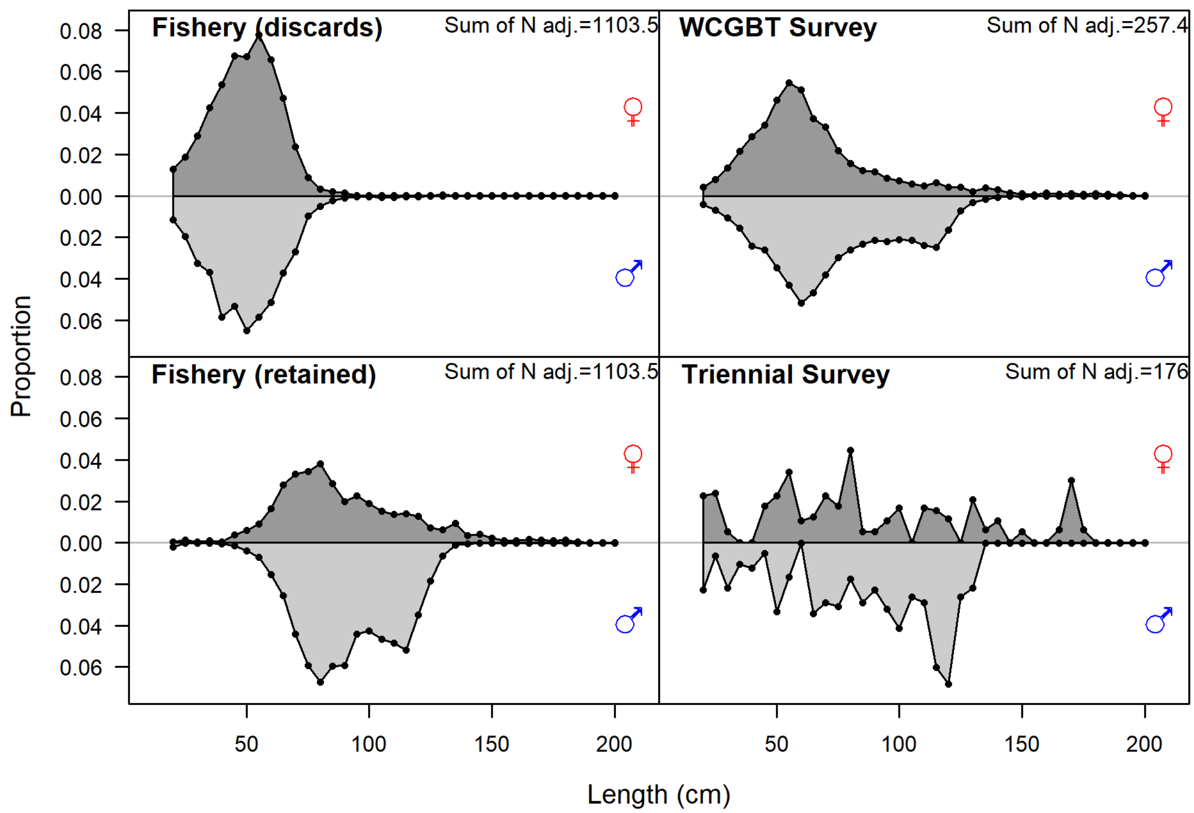

Figure 10: Length comp data, aggregated across time by fleet.

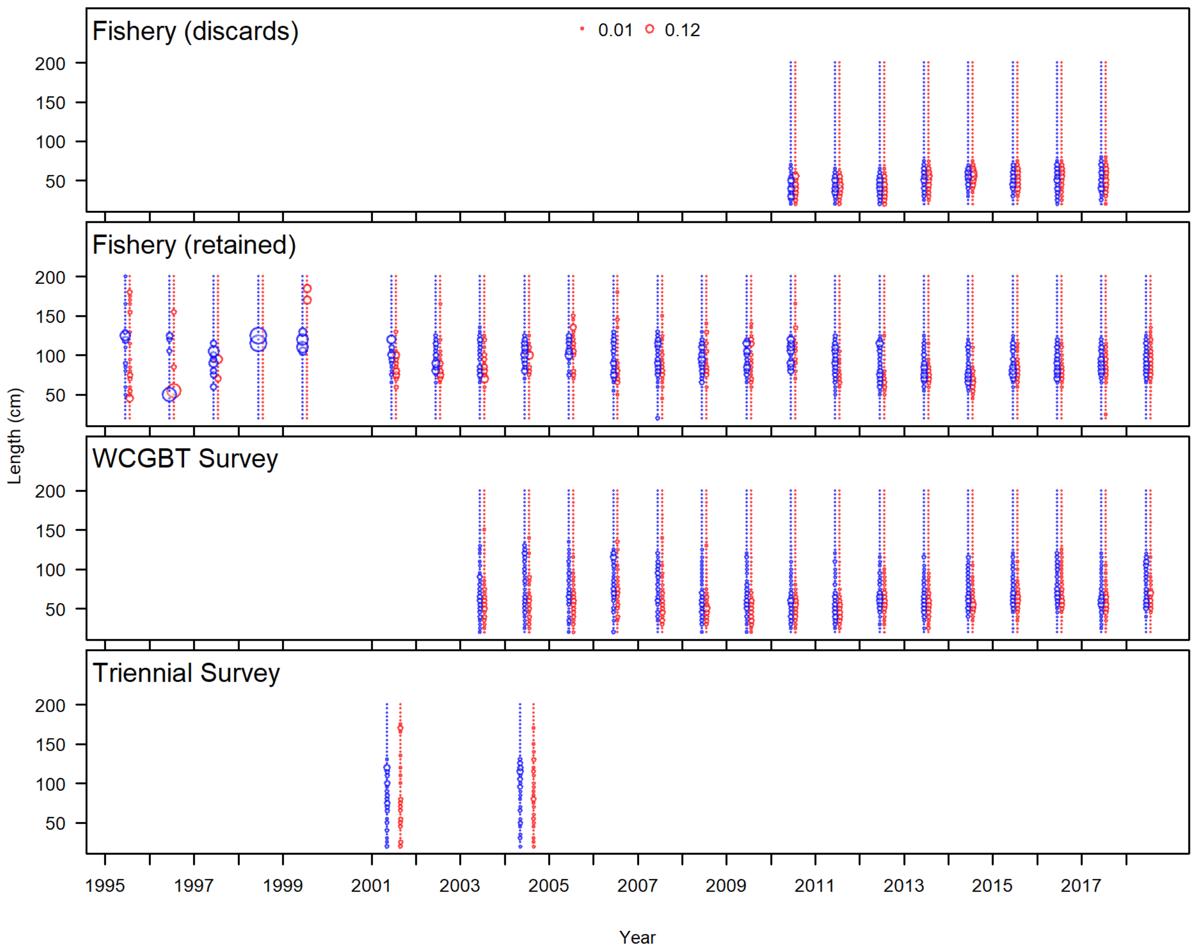

Figure 11: Length comp data for all years and fleets. Bubble size indicates the observed proportions, with females in red and males in blue.

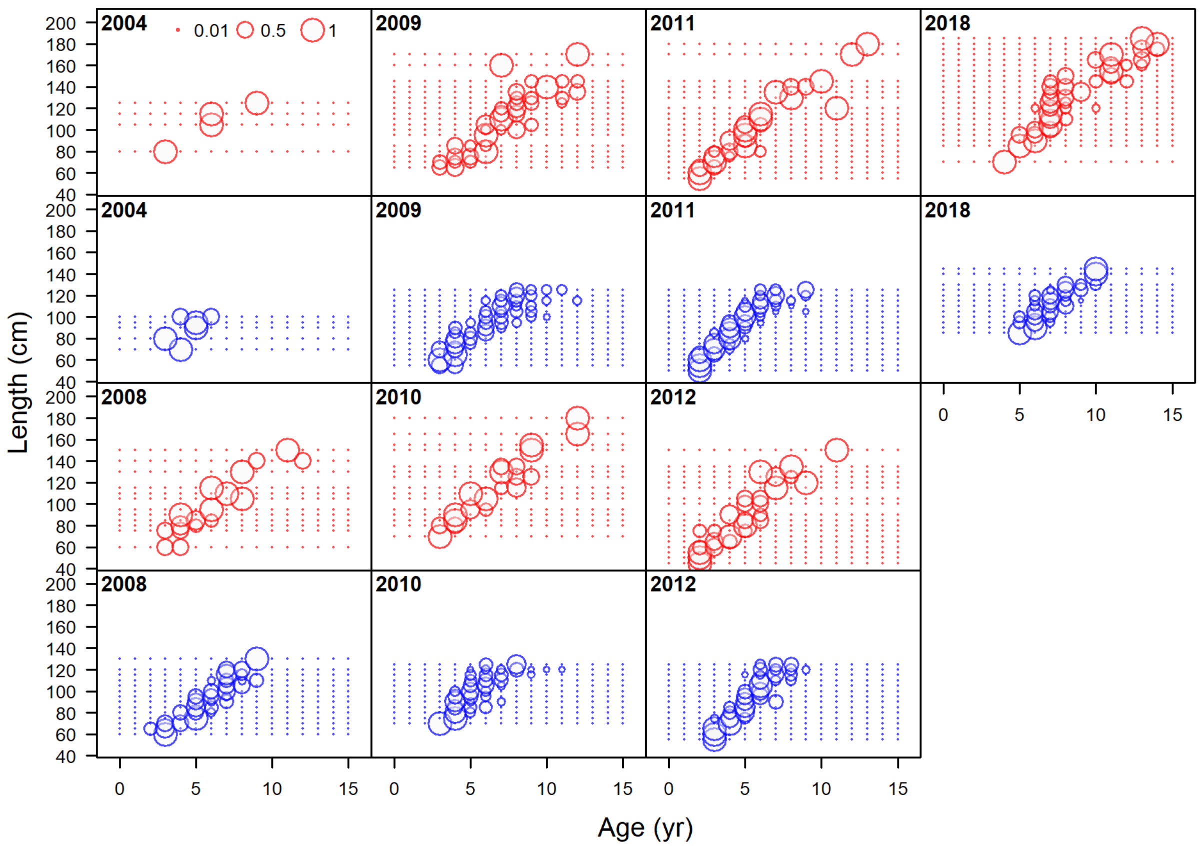

Figure 12: Conditional age-at-length data from the fishery.

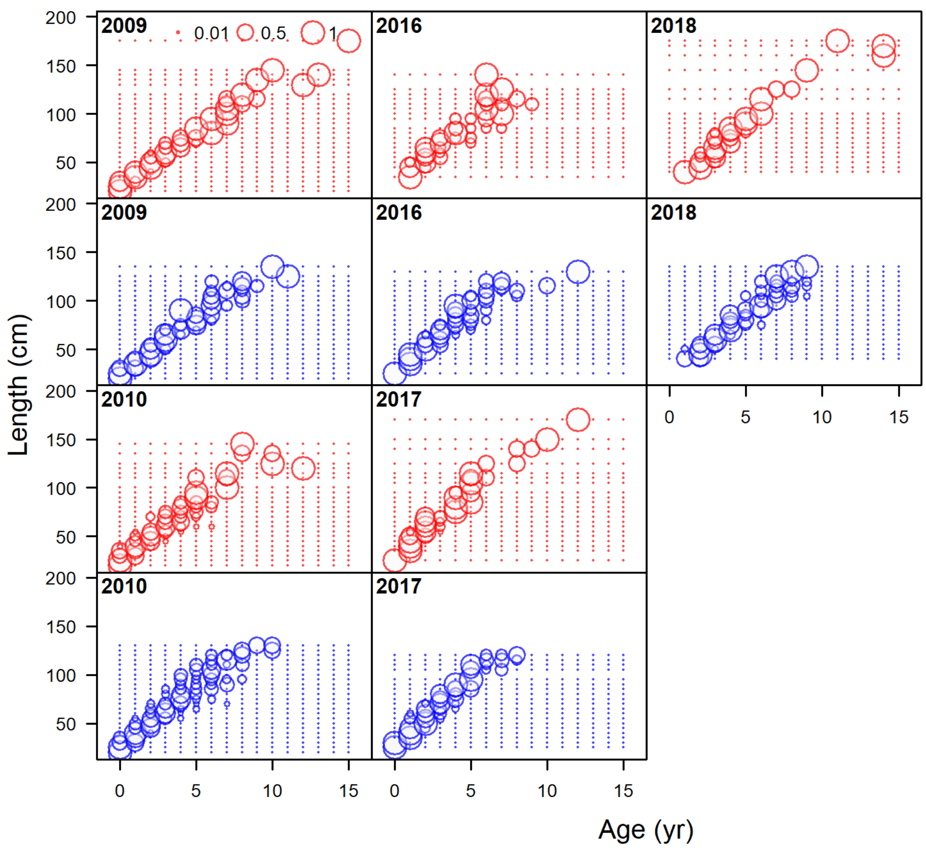

Figure 13: Conditional age-at-length data from the WCGBT Survey.

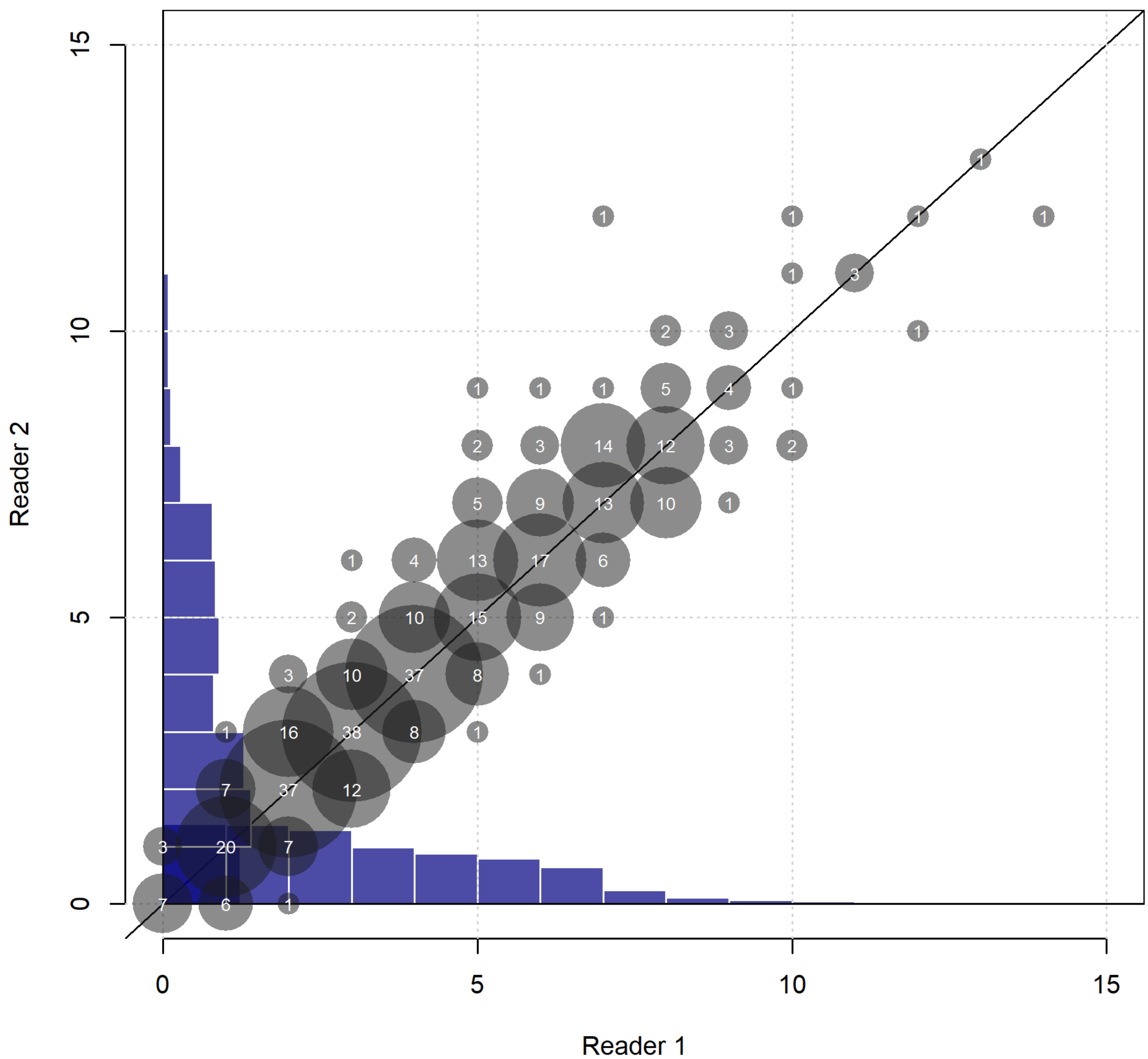

Figure 14: Comparison of reads from each of two age readers for Big Skate. Sample sizes associated with each combination of ages are shown by the size circles and the within them. The blue histograms show the distribution of ages estimated by each reader.

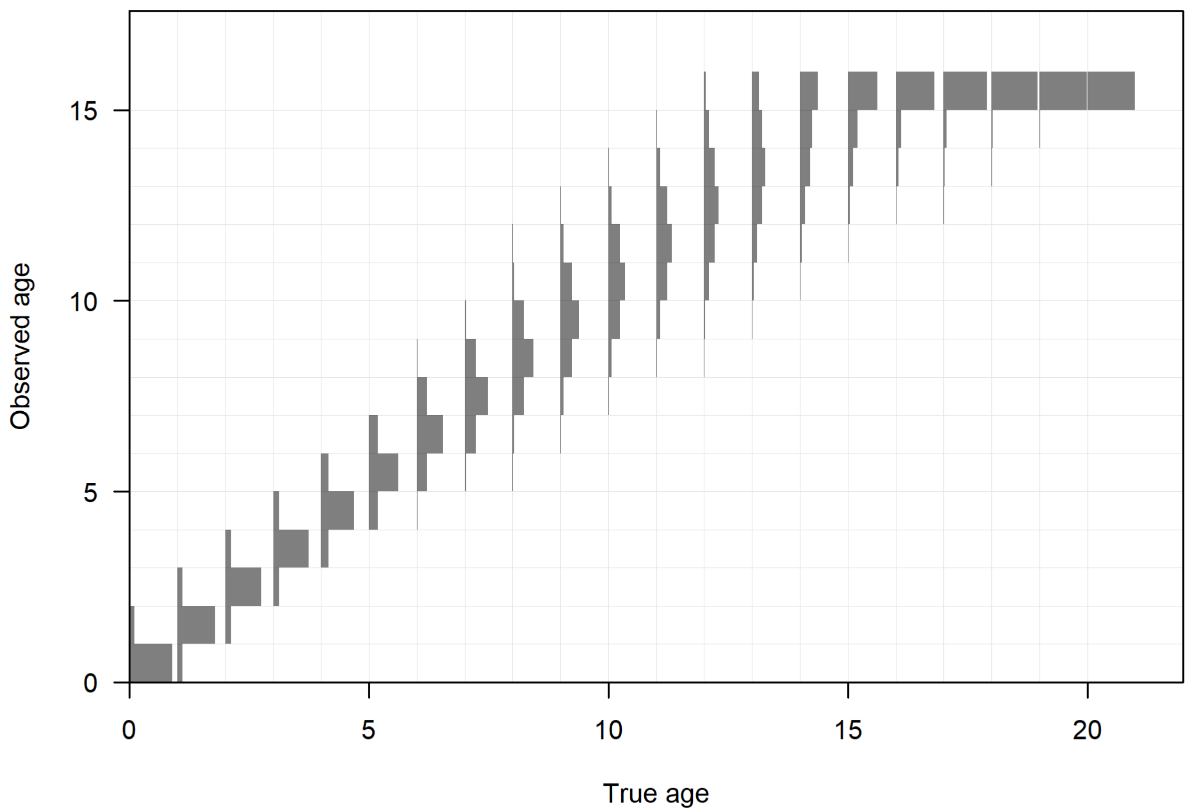

Figure 15: Estimated ageing imprecision.

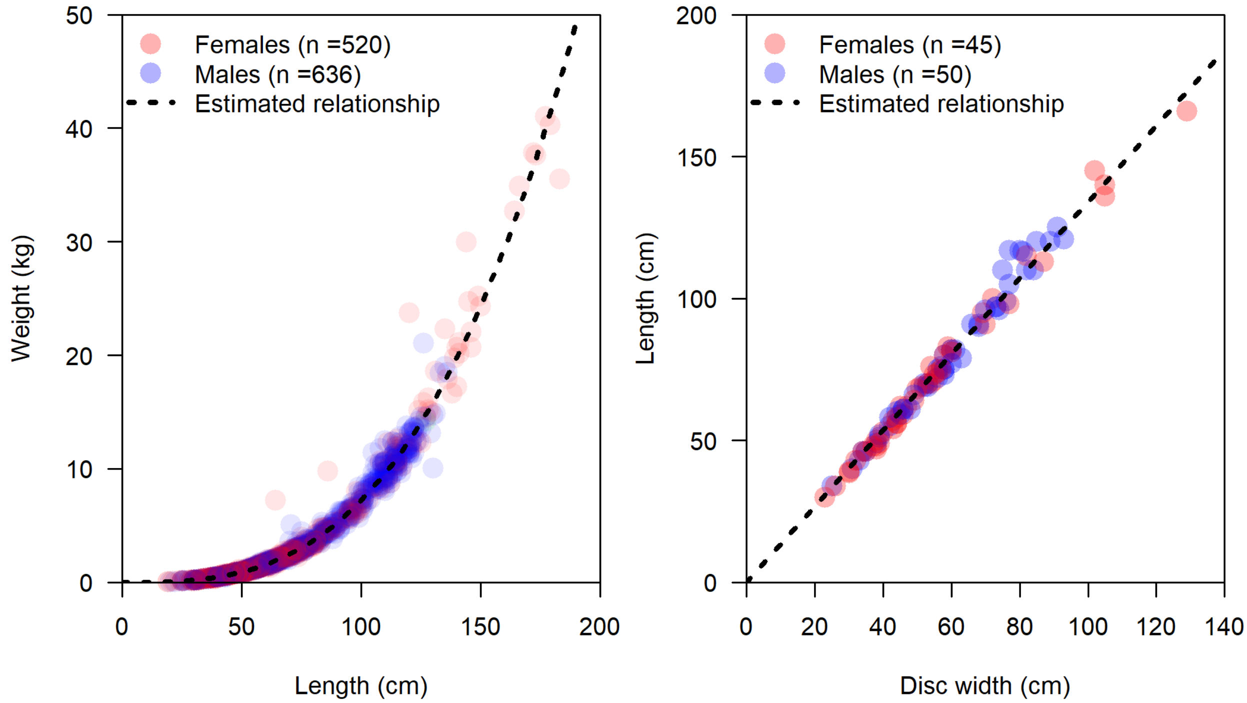

Figure 16: Estimated relationship between length and weight (left) and disc-width and length (right) for Big Skate. Colored points show observed values and the black line indicates the estimated relationship $W = 0.0000074924L^{2.9925}$.

943 ## 10.3 Model Results Figures

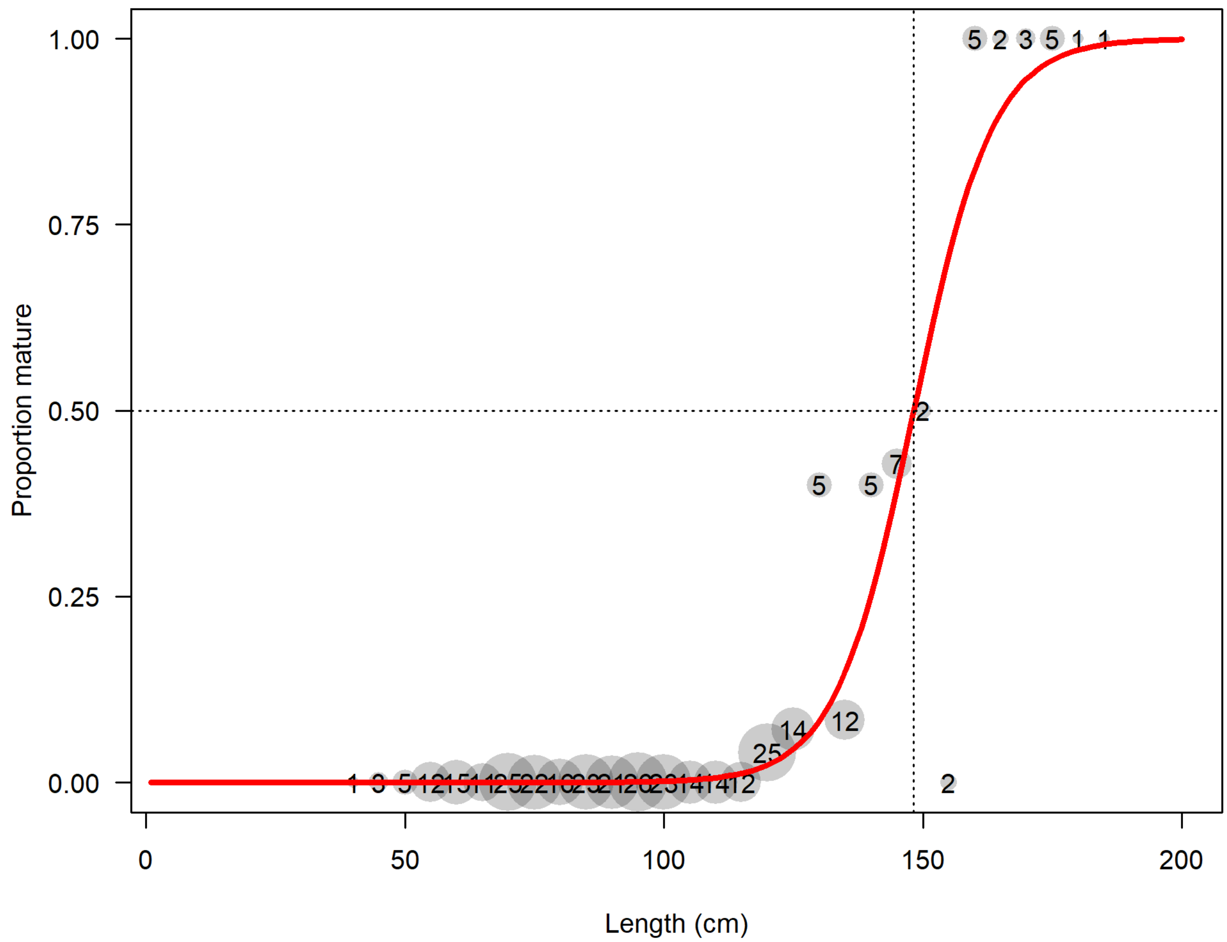

Figure 17: Estimated maturity relationship for female Big Skate. Gray points indicate average observed functional maturity within each length bin with point size proportional to the number of samples (indicated by text within each point).

10.3.1 Growth and Selectivity

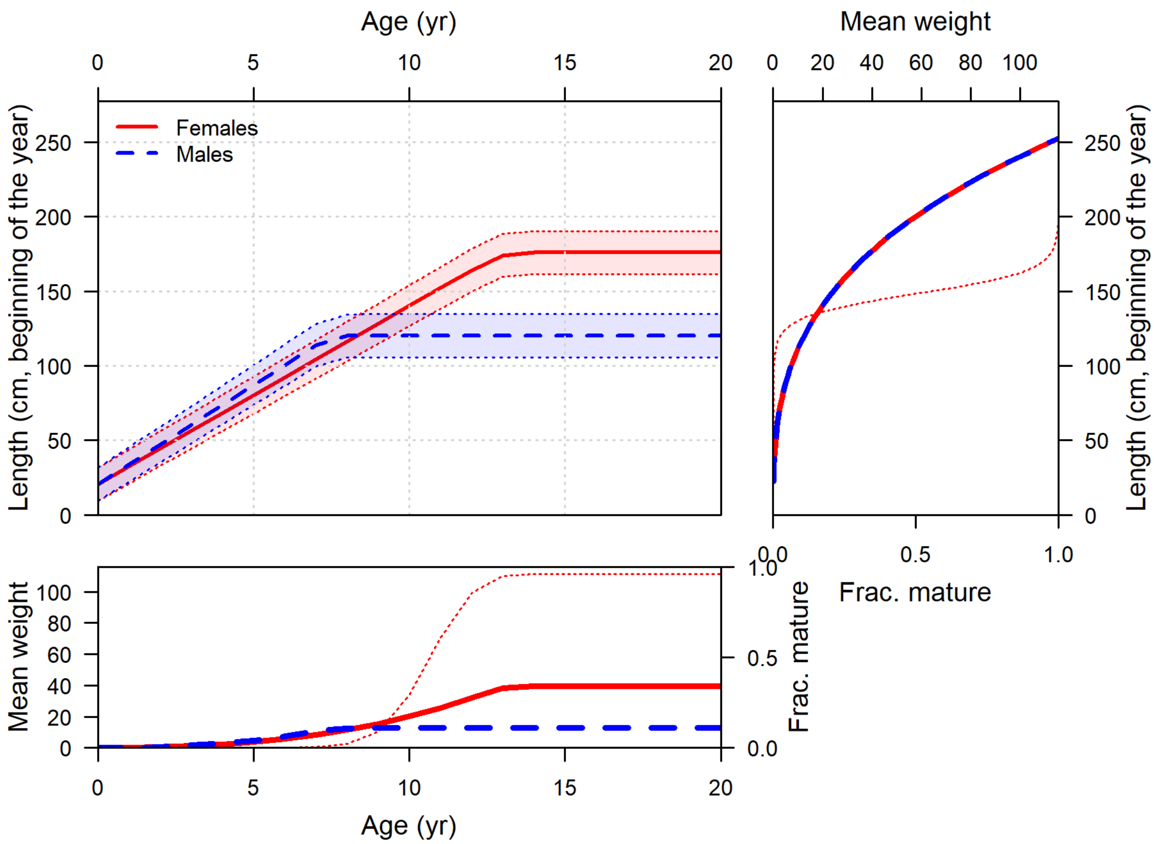

Figure 18: Estimated length-at-age for female and male Big Skate (top left panel). Shaded areas indicate 95% intervals for distribution of lengths at each age. Values represent beginning-of-year growth. Weight (thick line) and maturity (thin line) are shown in the top-right and lower-left panels as a function of length and age, respectively, where the values-at-age are calculated by mapping the length-based relationships through the estimated distribution of length at each age.

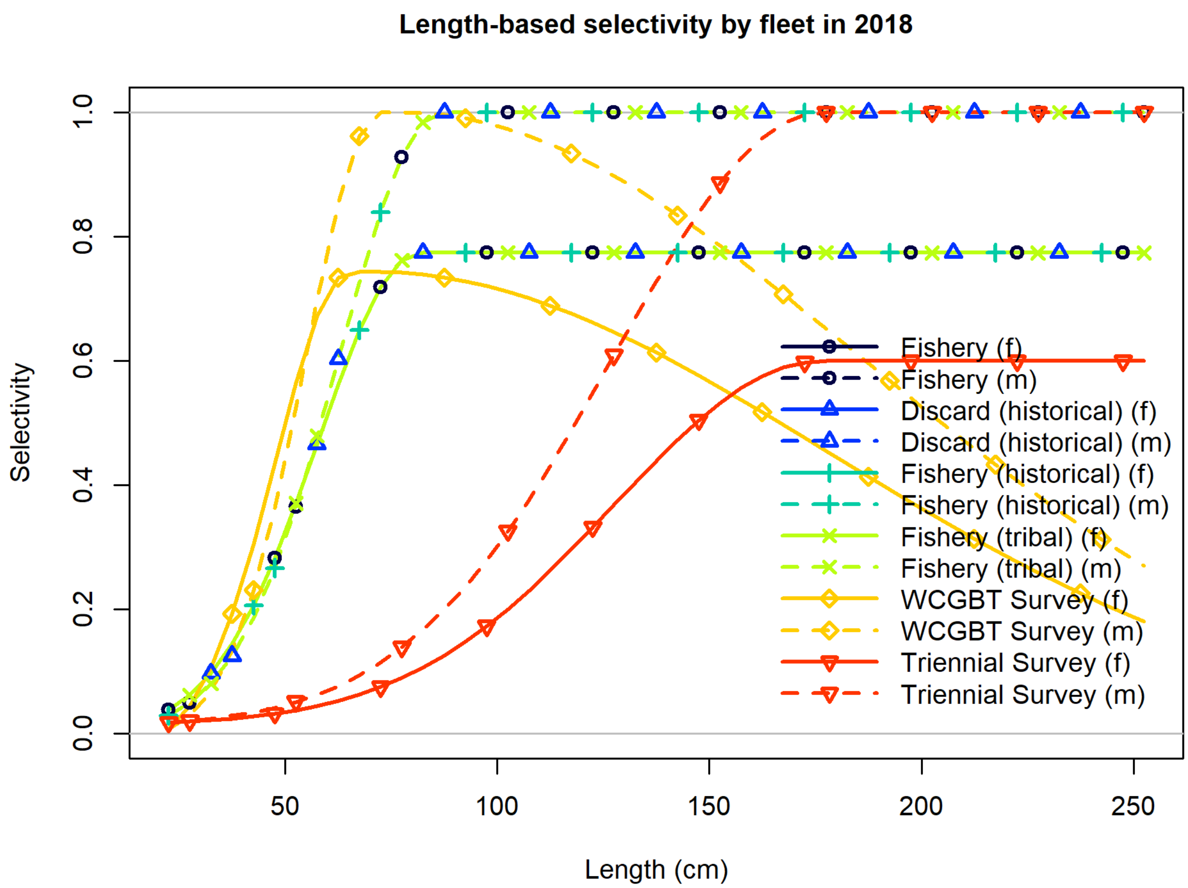

Figure 19: Selectivity at length for all of the fleets in the base model.

10.3.2 Fits to the Data

10.3.3 Time Series Figures

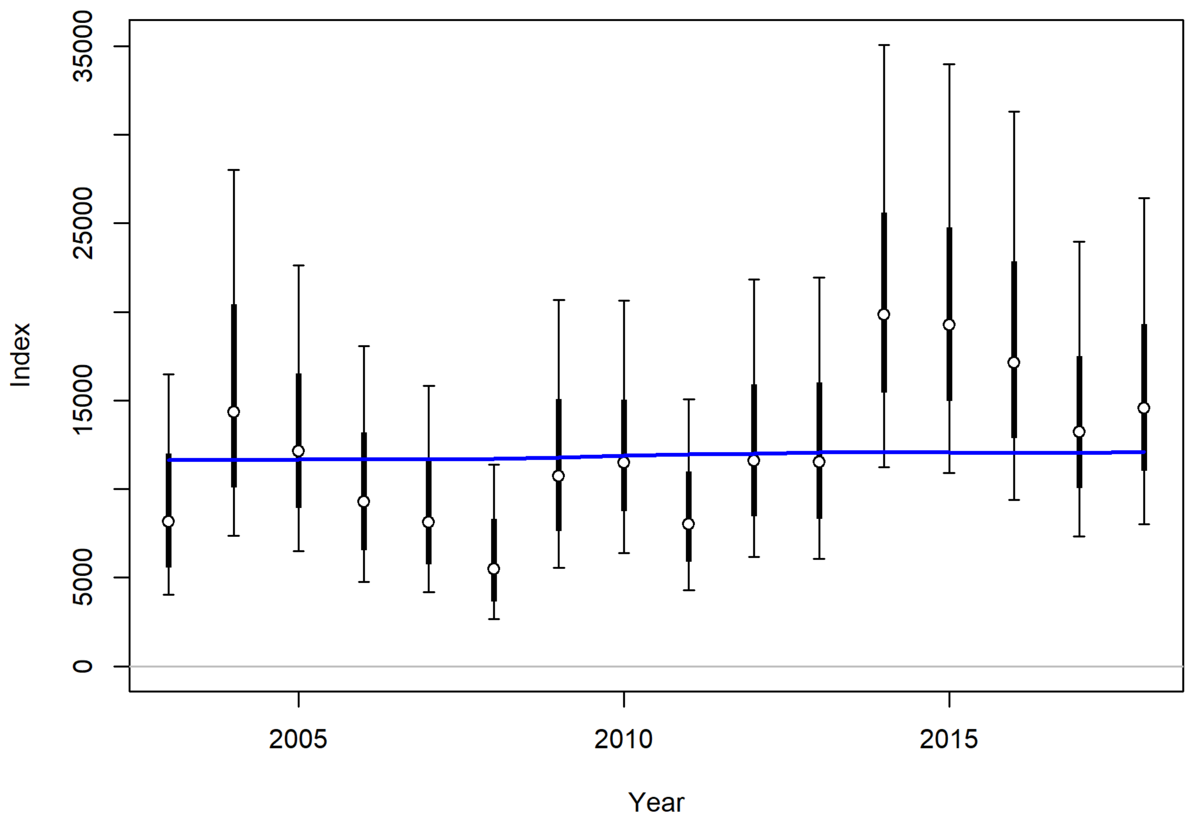

Figure 20: Fit to index data for WCGBT Survey. Lines indicate 95% uncertainty interval around index values. Thicker lines indicate input uncertainty before addition of estimated additional uncertainty parameter. The blue line indicates the model estimate.

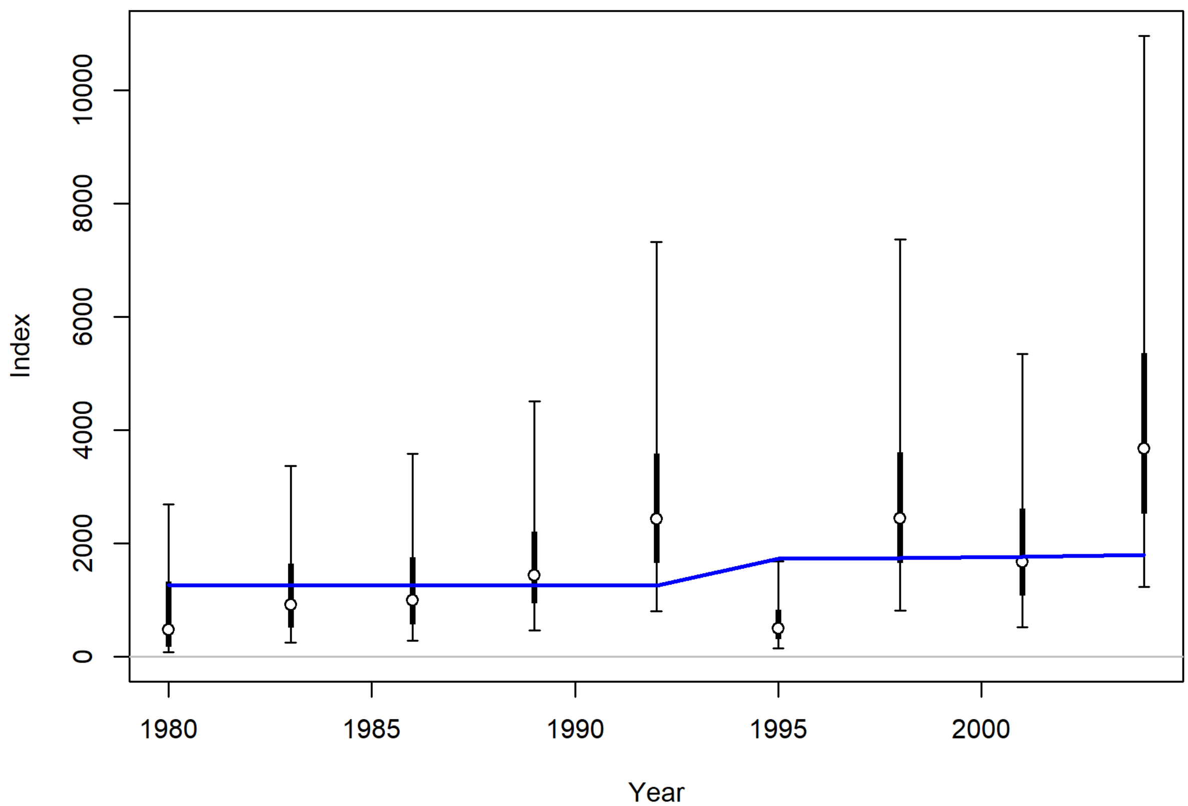

Figure 21: Fit to index data for Triennial Survey. Lines indicate 95% uncertainty interval around index values. Thicker lines indicate input uncertainty before addition of estimated additional uncertainty parameter. The blue line indicates the model estimate with a change between 1992 and 1995 associated with the estimated change in catchability.

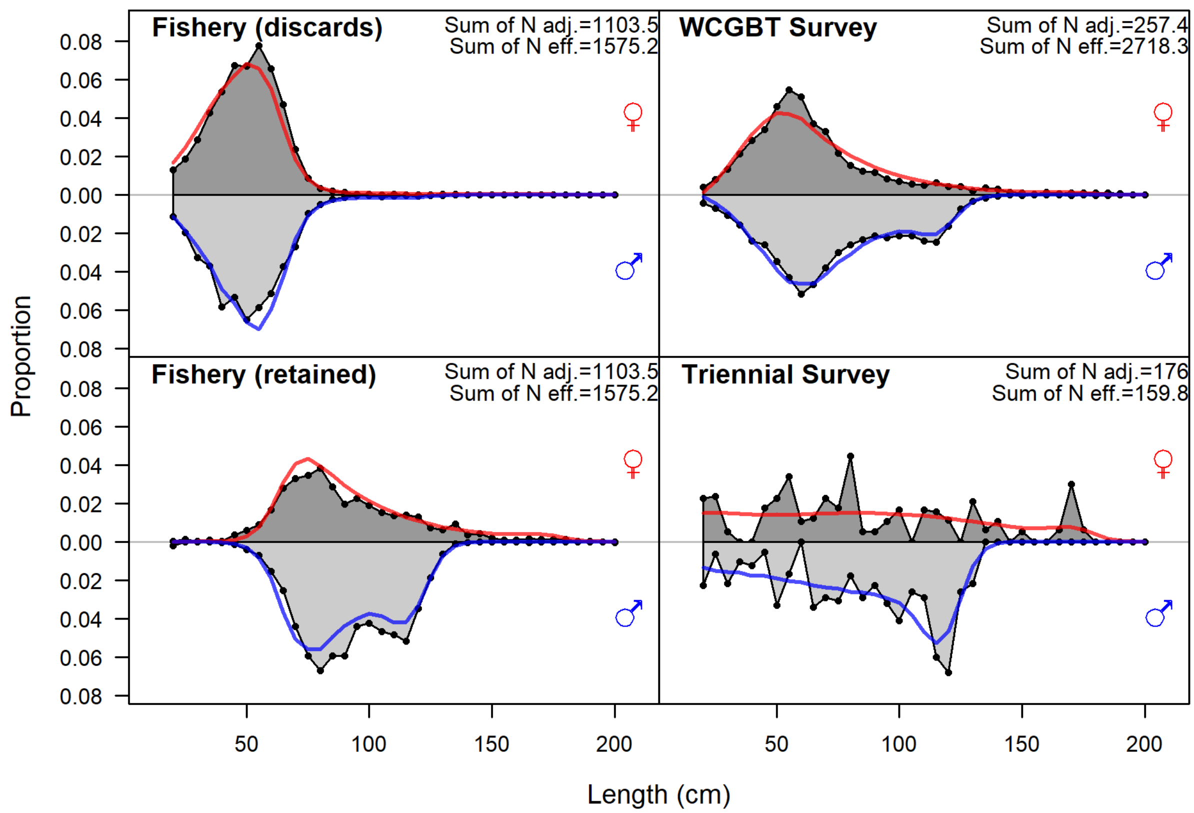

Figure 22: Fits to length comp data, aggregated across time by fleet.

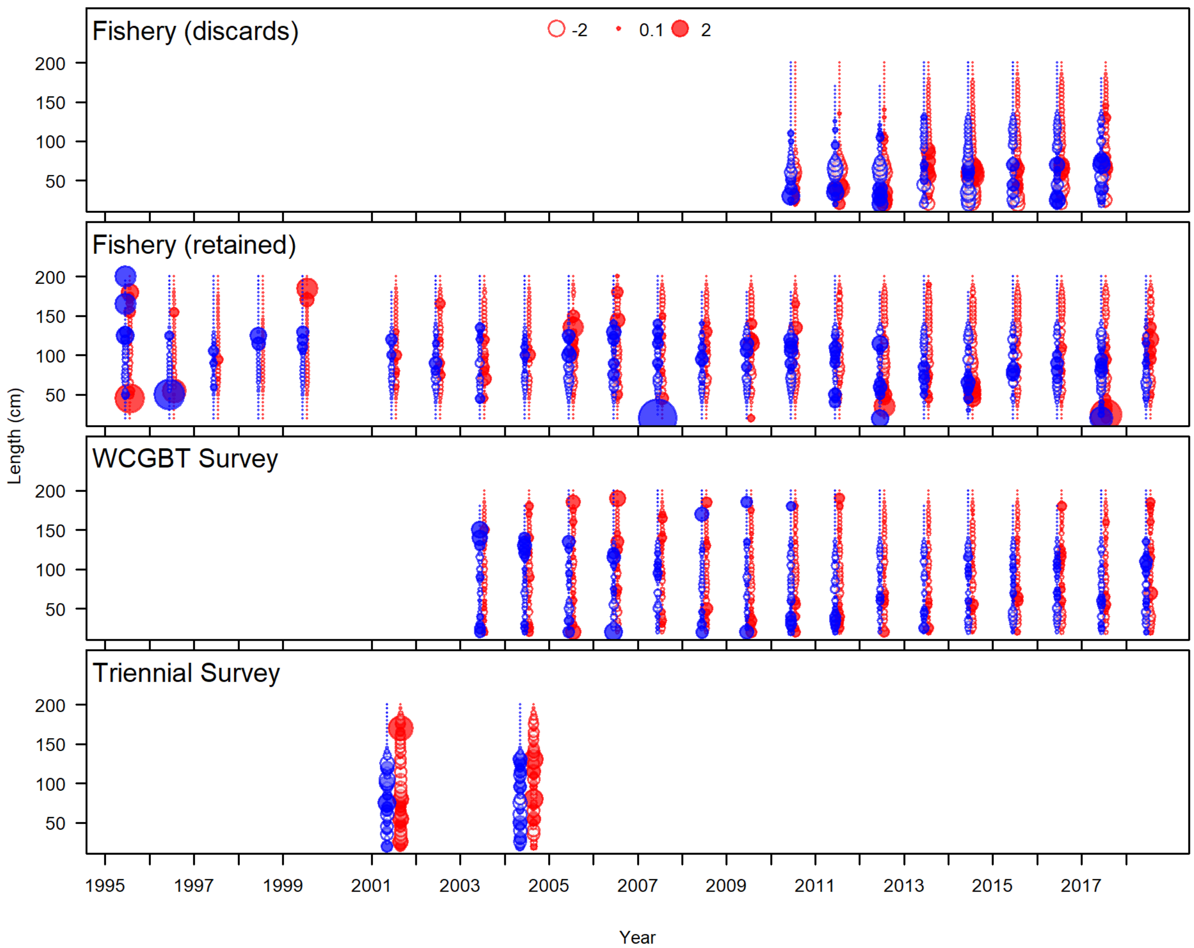

Figure 23: Pearson residuals for length comp data for all years and fleets, with females in red and males in blue.

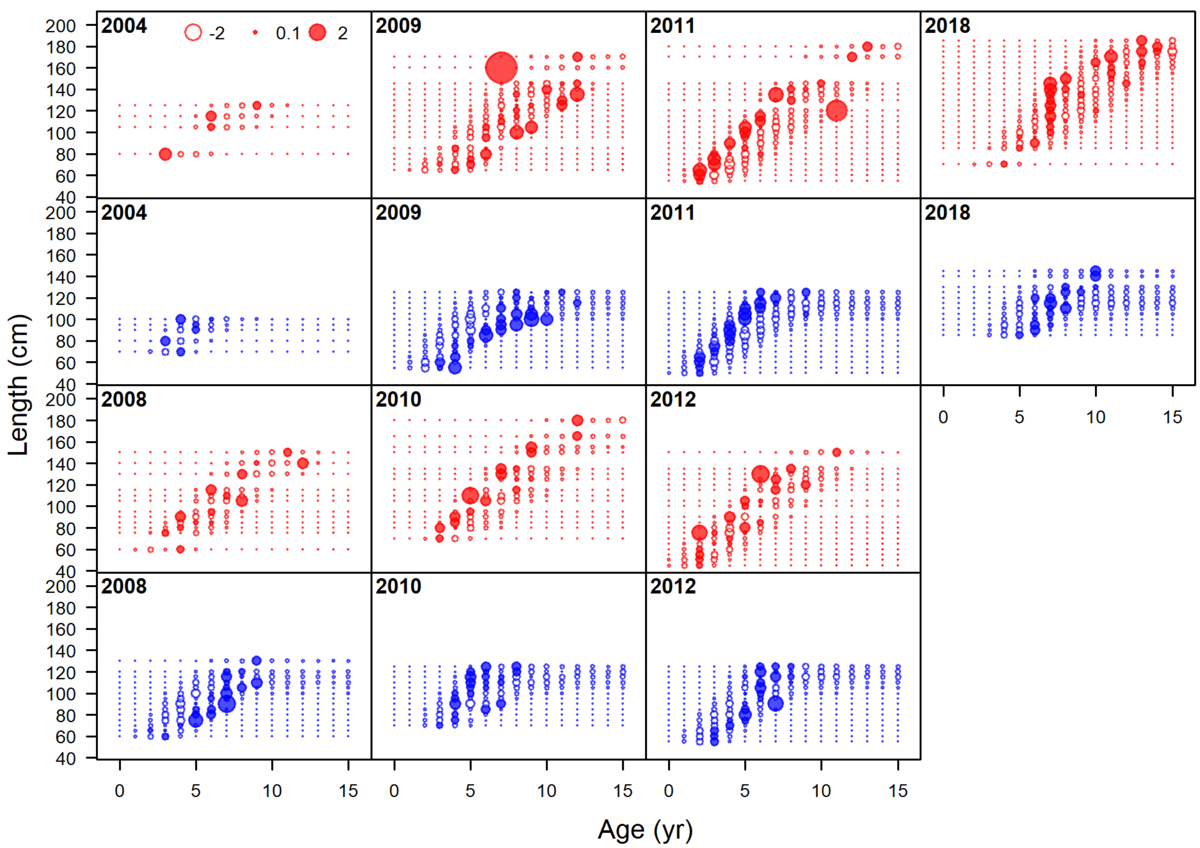

Figure 24: Pearson residuals for the fit to conditional age-at-length data from the fishery.

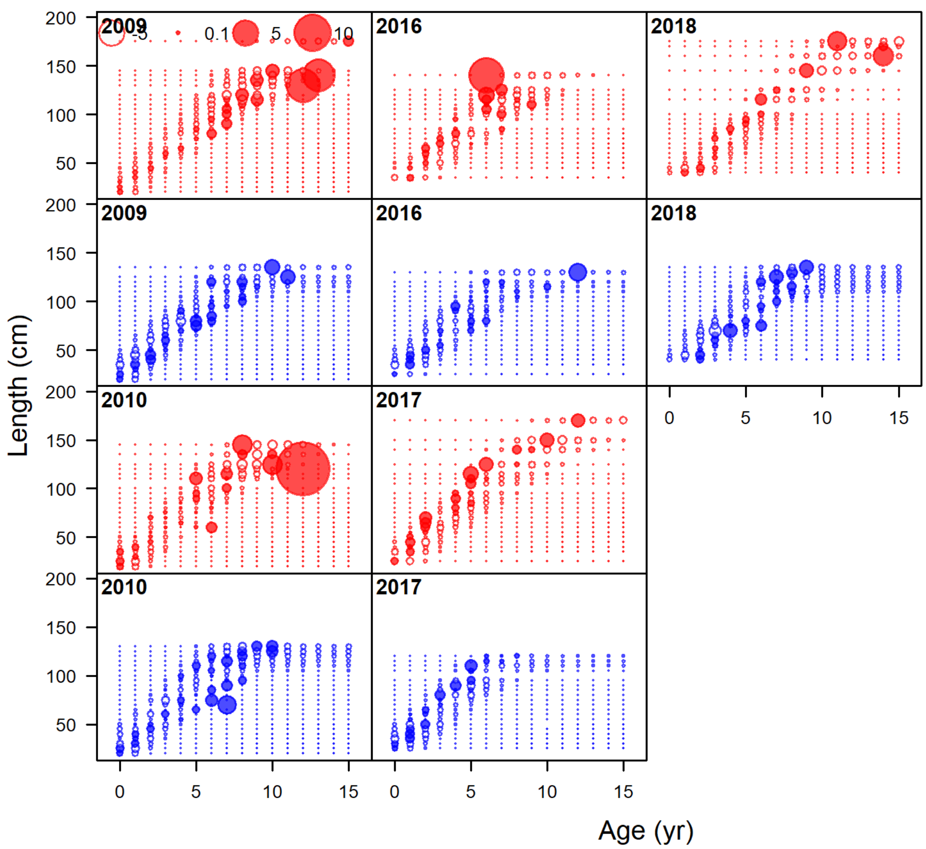

Figure 25: Pearson residuals for the fit to conditional age-at-length data from the WCGBT Survey.

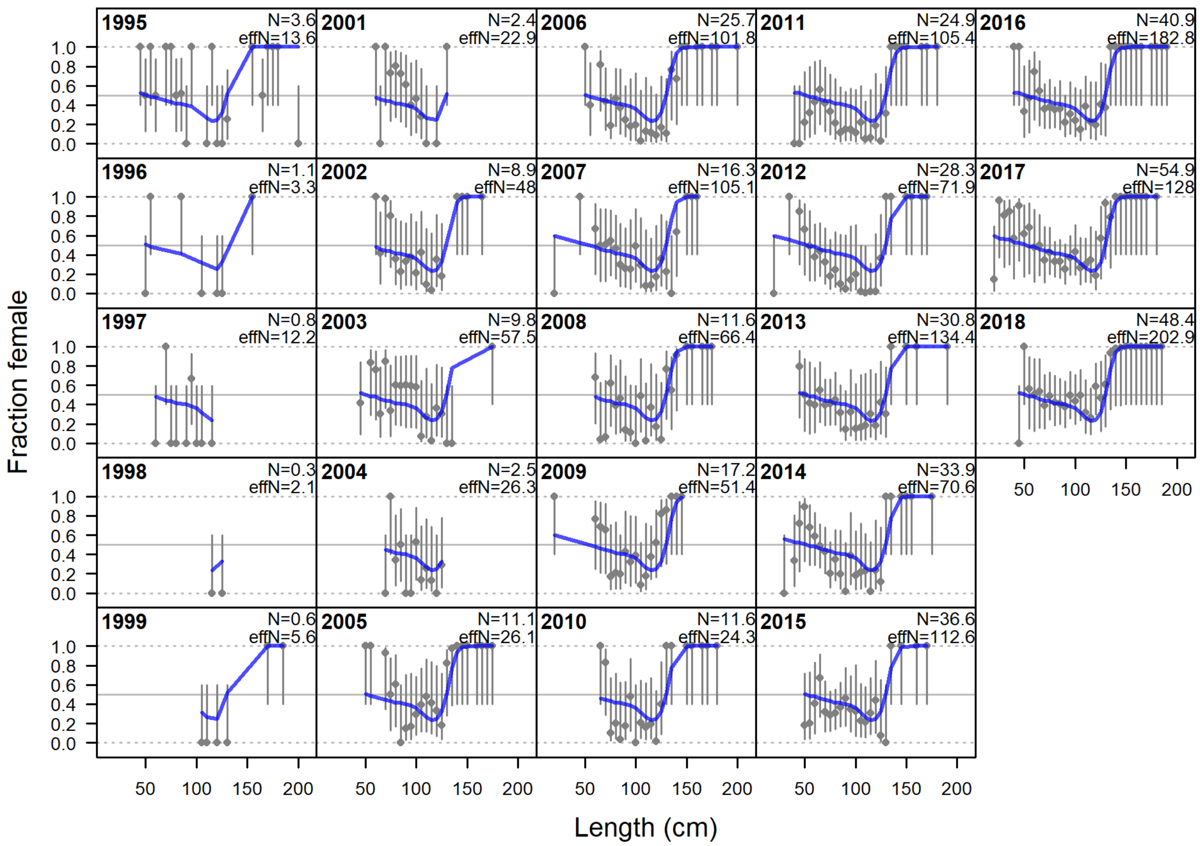

Figure 26: Observed sex ratios (points) from the fishery length comp data with 75% intervals (vertical lines) calculated as a Jeffreys interval based on the adjusted input sample size. The model expectation is shown in the blue line.

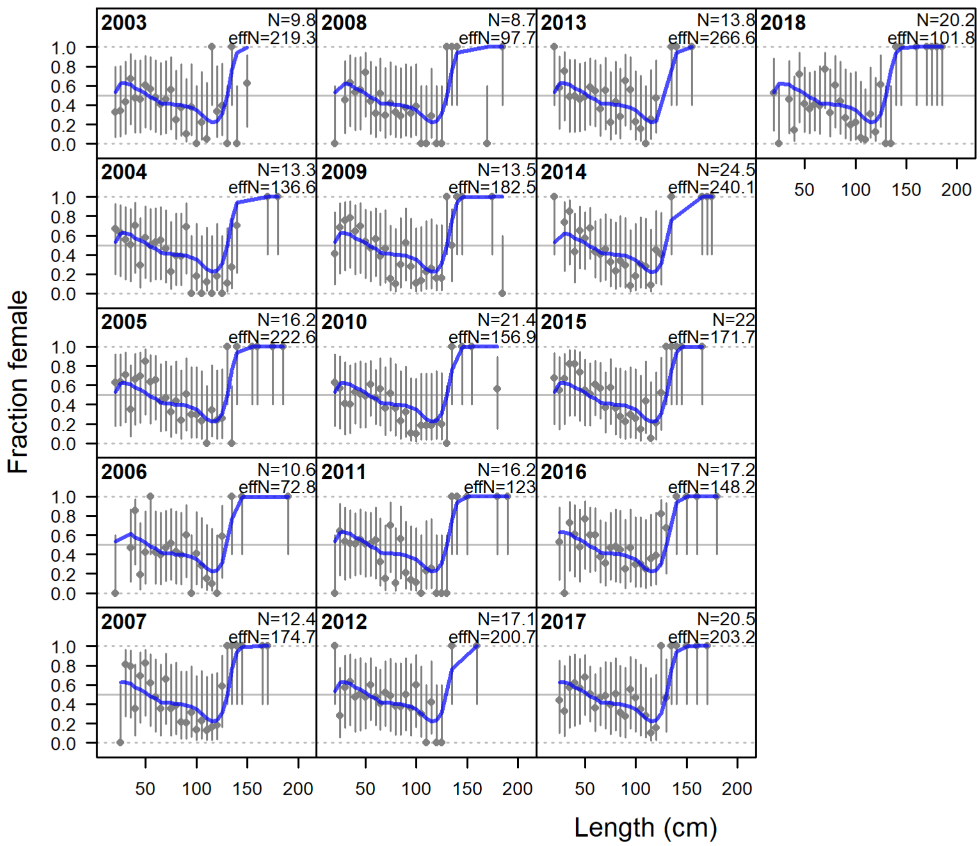

Figure 27: Observed sex ratios (points) from the WCGBT Survey length comp data with 75% intervals (vertical lines) calculated as a Jeffreys interval based on the adjusted input sample size. The model expectation is shown in the blue line.

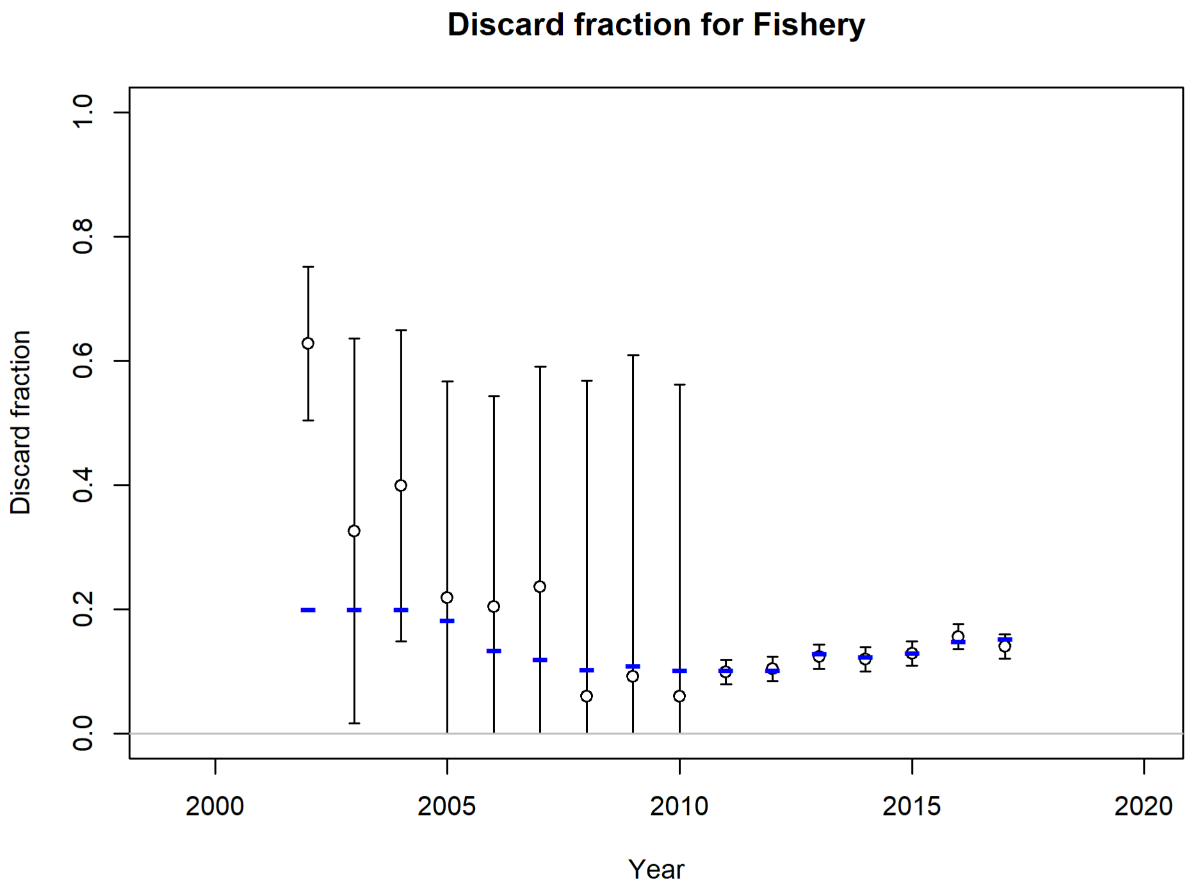

Figure 28: Fit to the discard fraction estimates. Points are model estimates with 95% uncertainty intervals. The model estimate is shown in the blue lines.

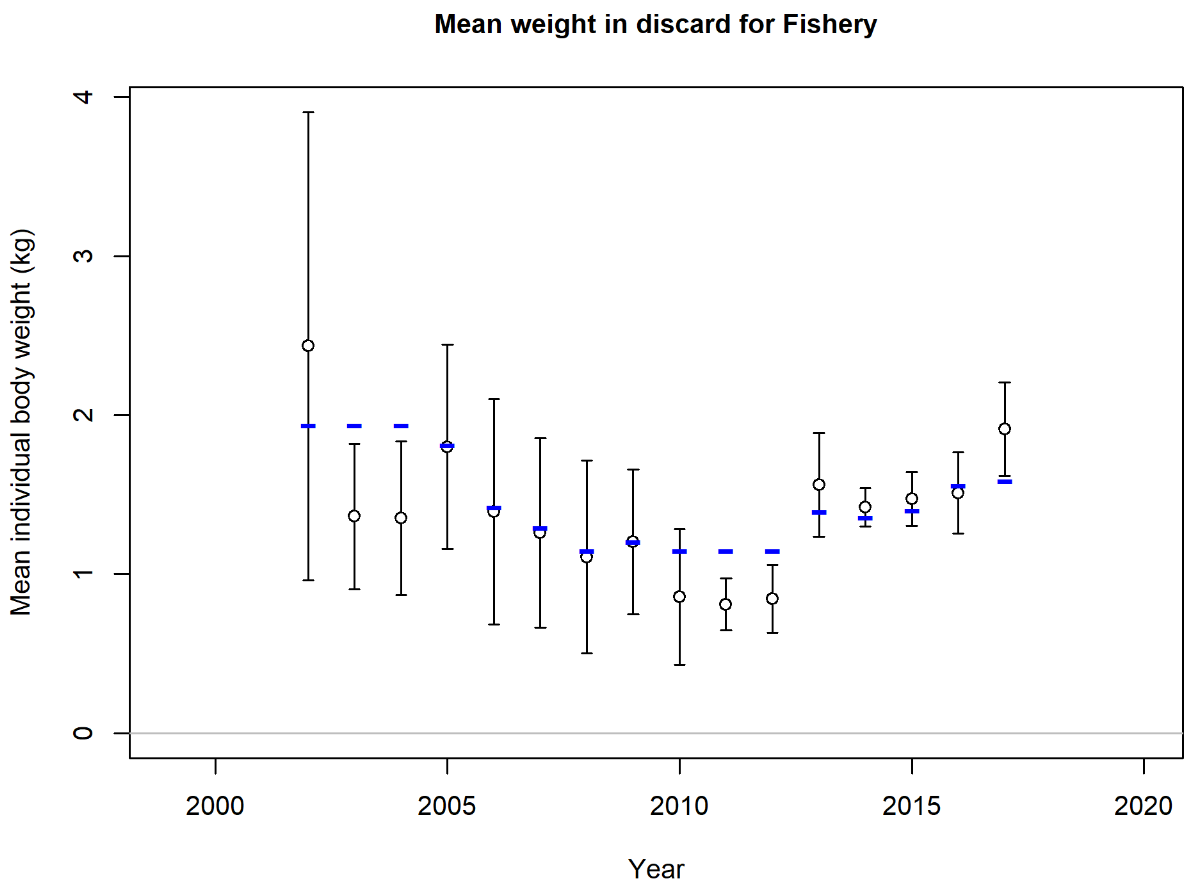

Figure 29: Fit to the mean weight of the discards. Points are model estimates with 95% uncertainty intervals. The model estimate is shown in the blue lines.

10.3.4 Sensitivity Analyses and Retrospectives

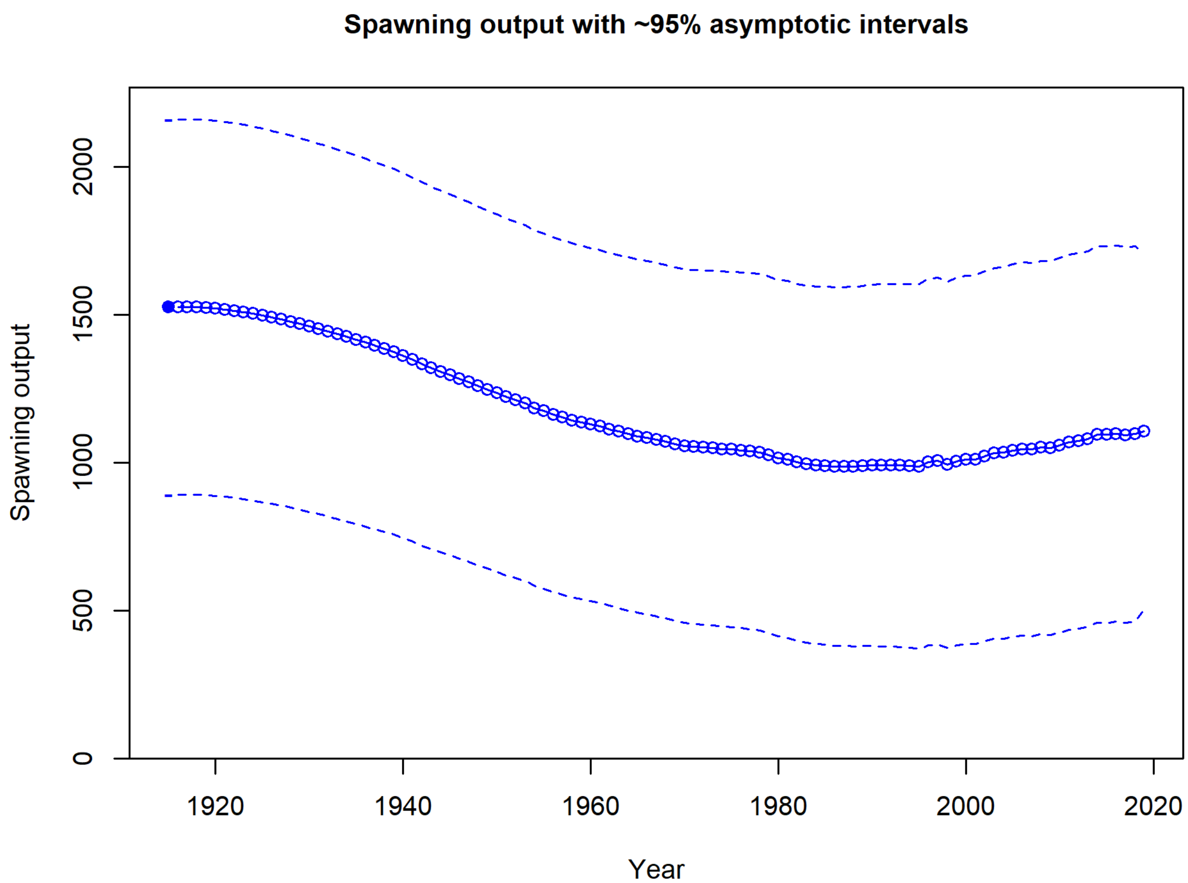

Figure 30: Estimated spawning biomass (mt) with approximate 95% asymptotic intervals.

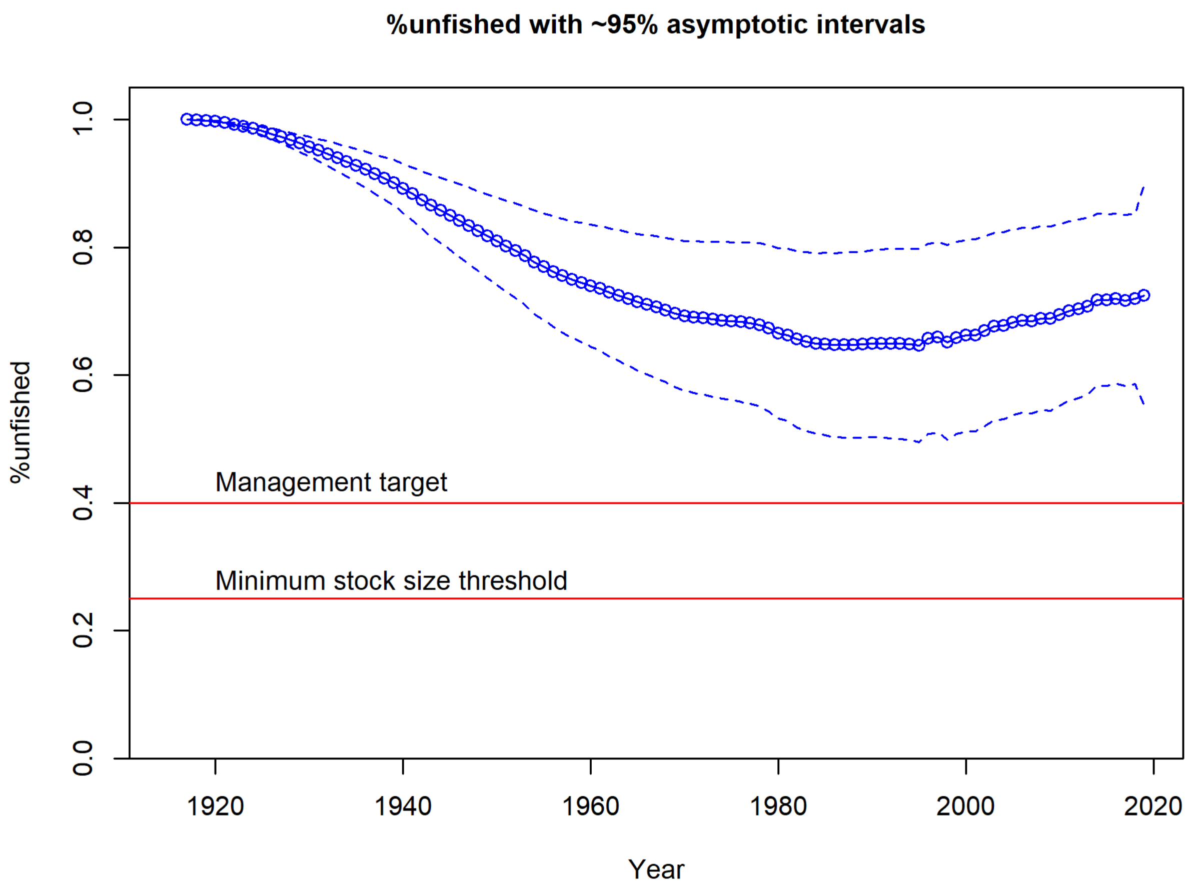

Figure 31: Estimated spawning depletion with approximate 95% asymptotic intervals.

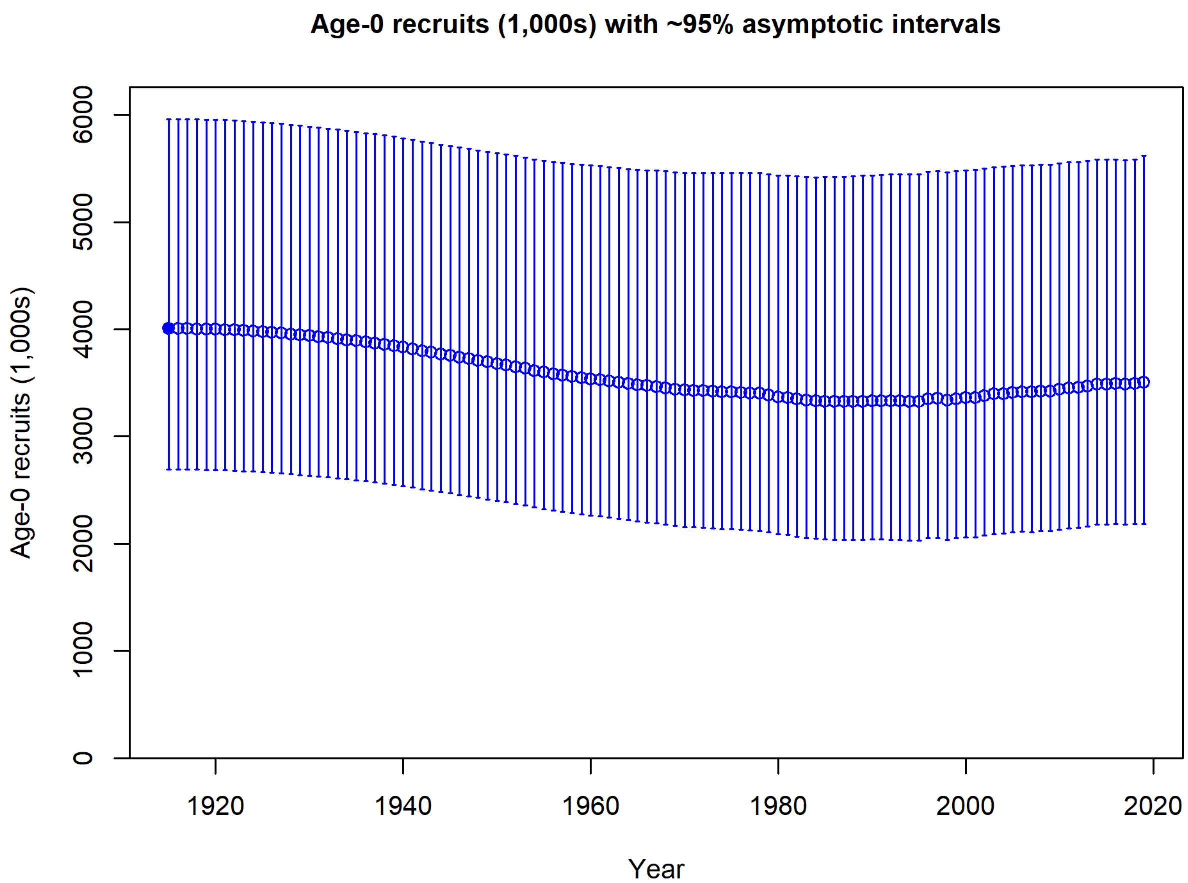

Figure 32: Estimated time-series of recruitment for Big Skate.

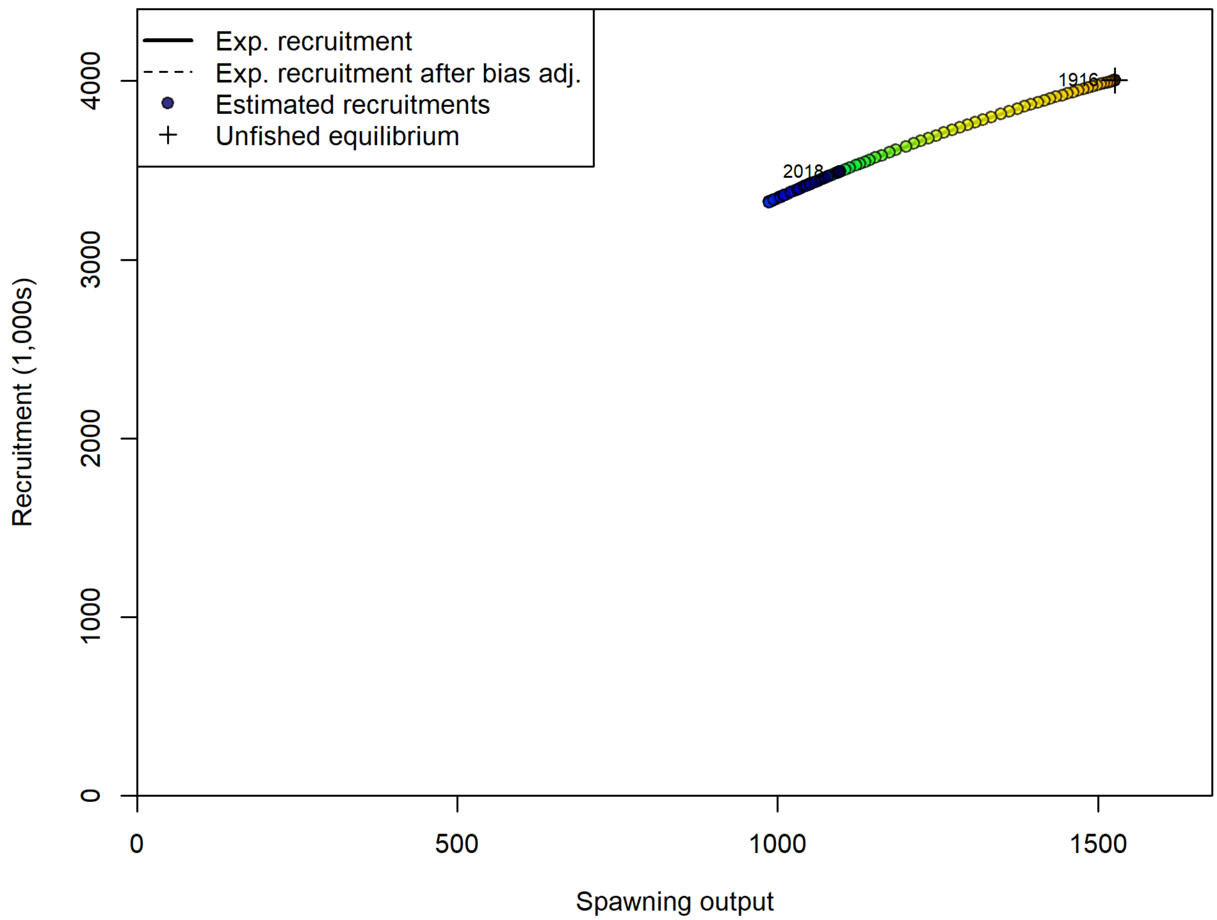

Figure 33: Estimated recruitment and the assumed stock-recruit relationship.

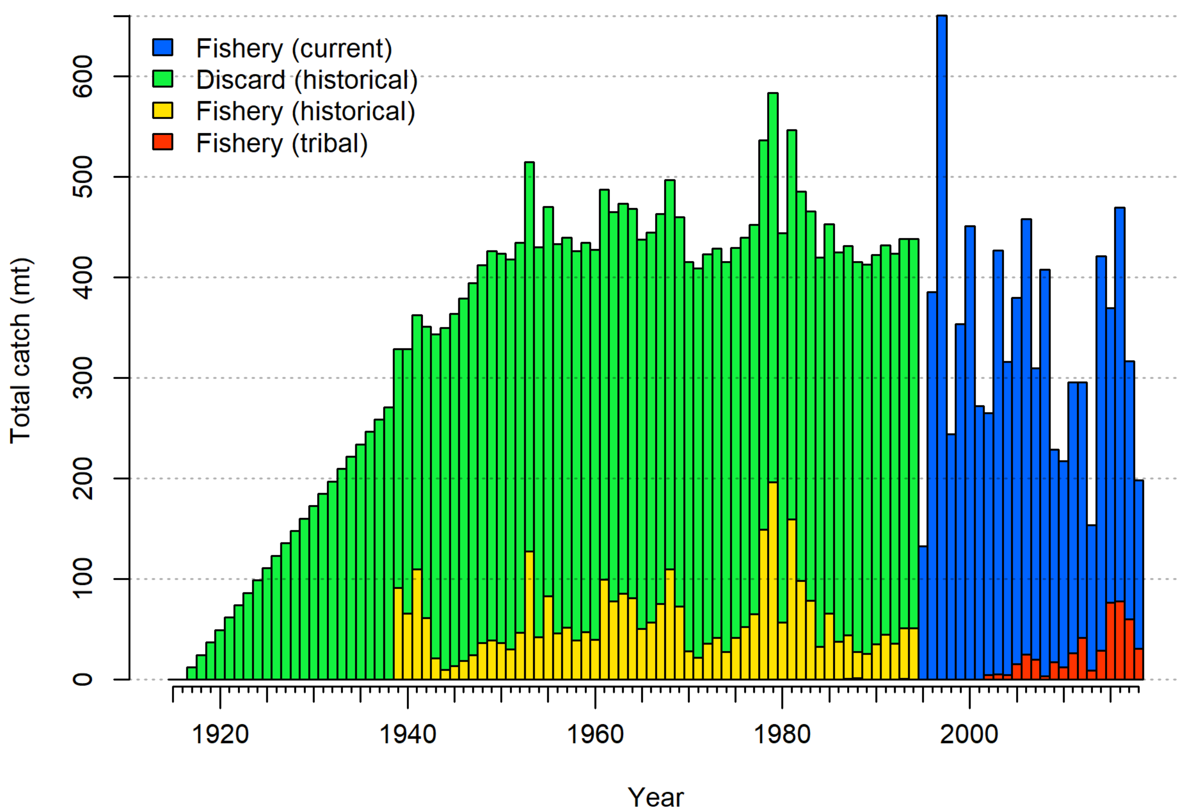

Figure 34: Estimated total catch including discards estimated within the model. The historical discards shown in green have been scaled to account for an assumed 50% discard mortality but the discards in the recent period show both live and dead discards.

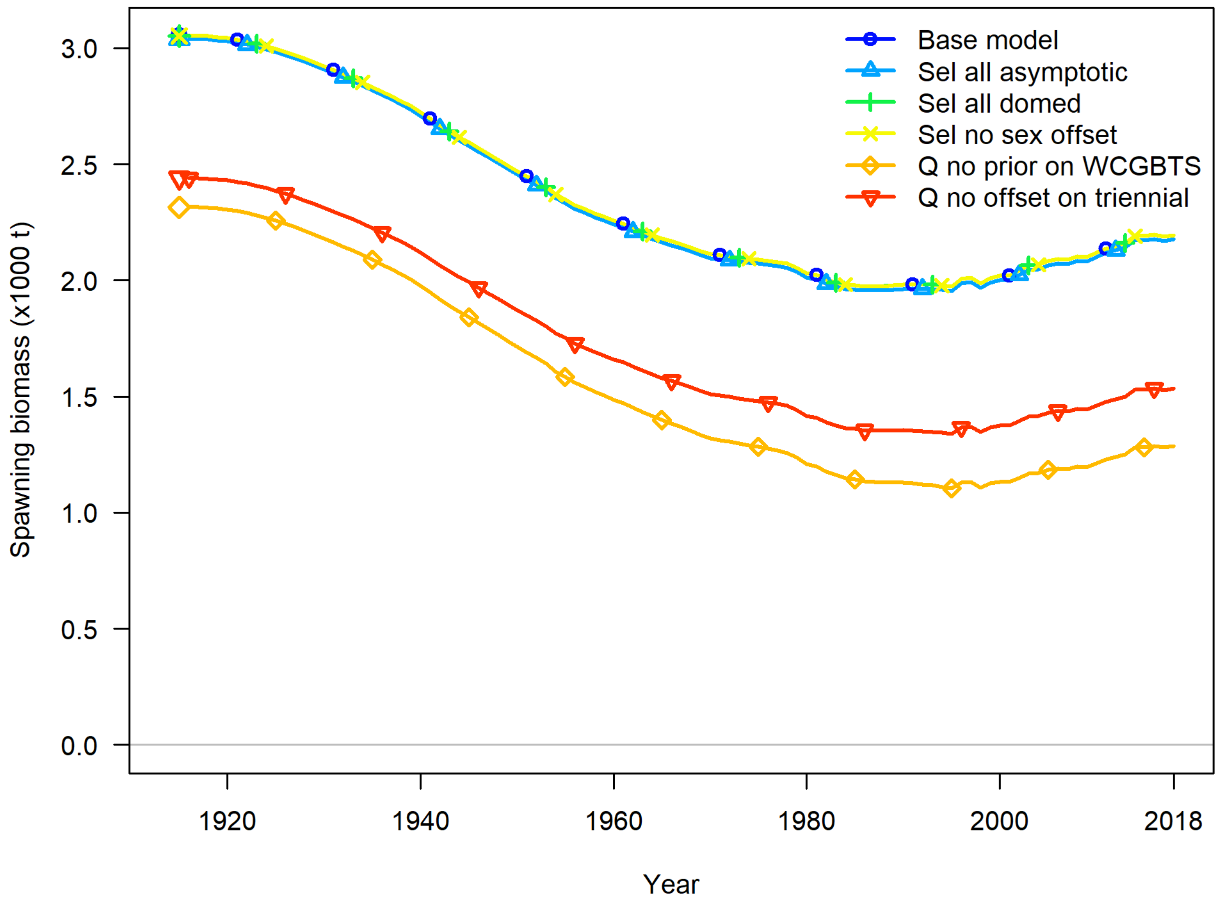

Figure 35: Time series of spawning output estimated in sensitivity analyses related to selectivity and catchability.

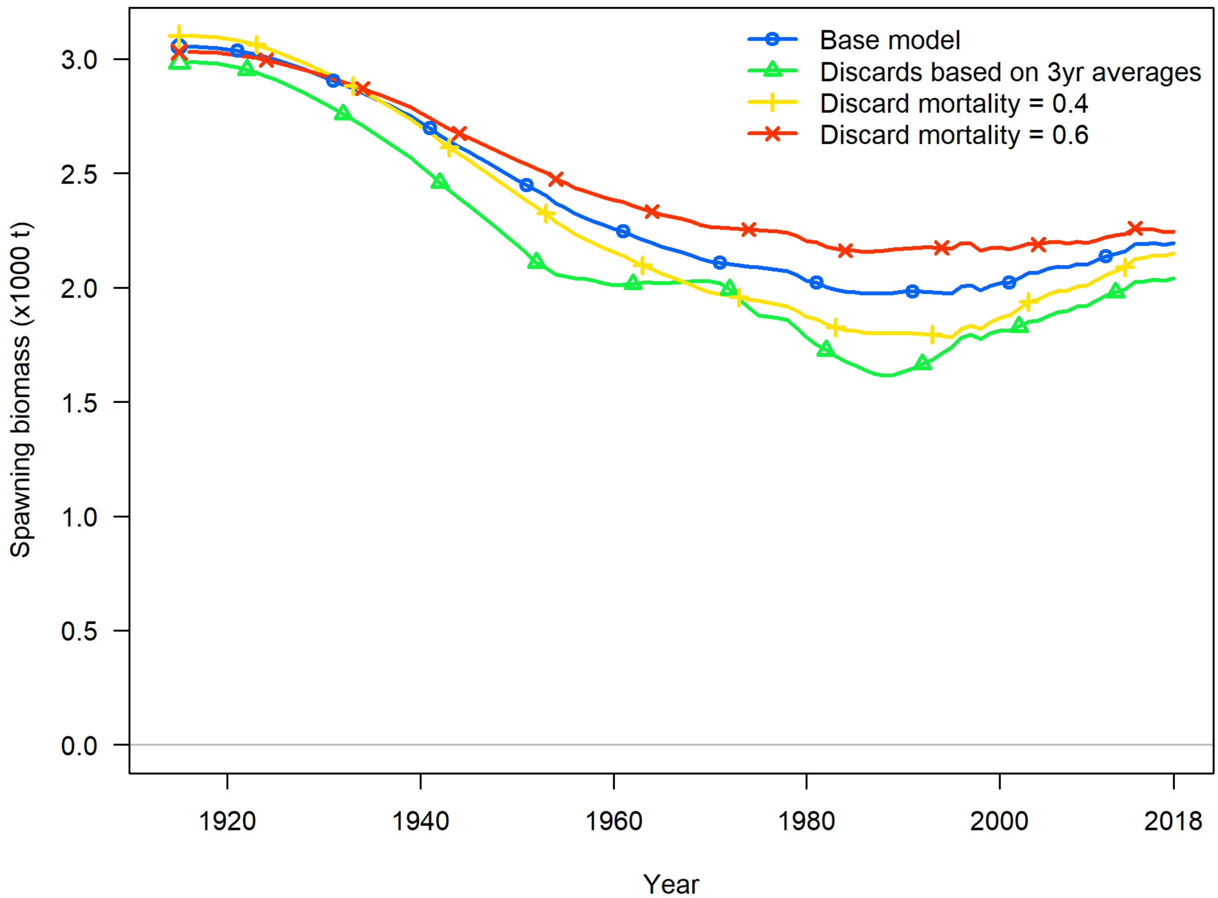

Figure 36: Time series of spawning output estimated in sensitivity analyses related to historic catch and discards.

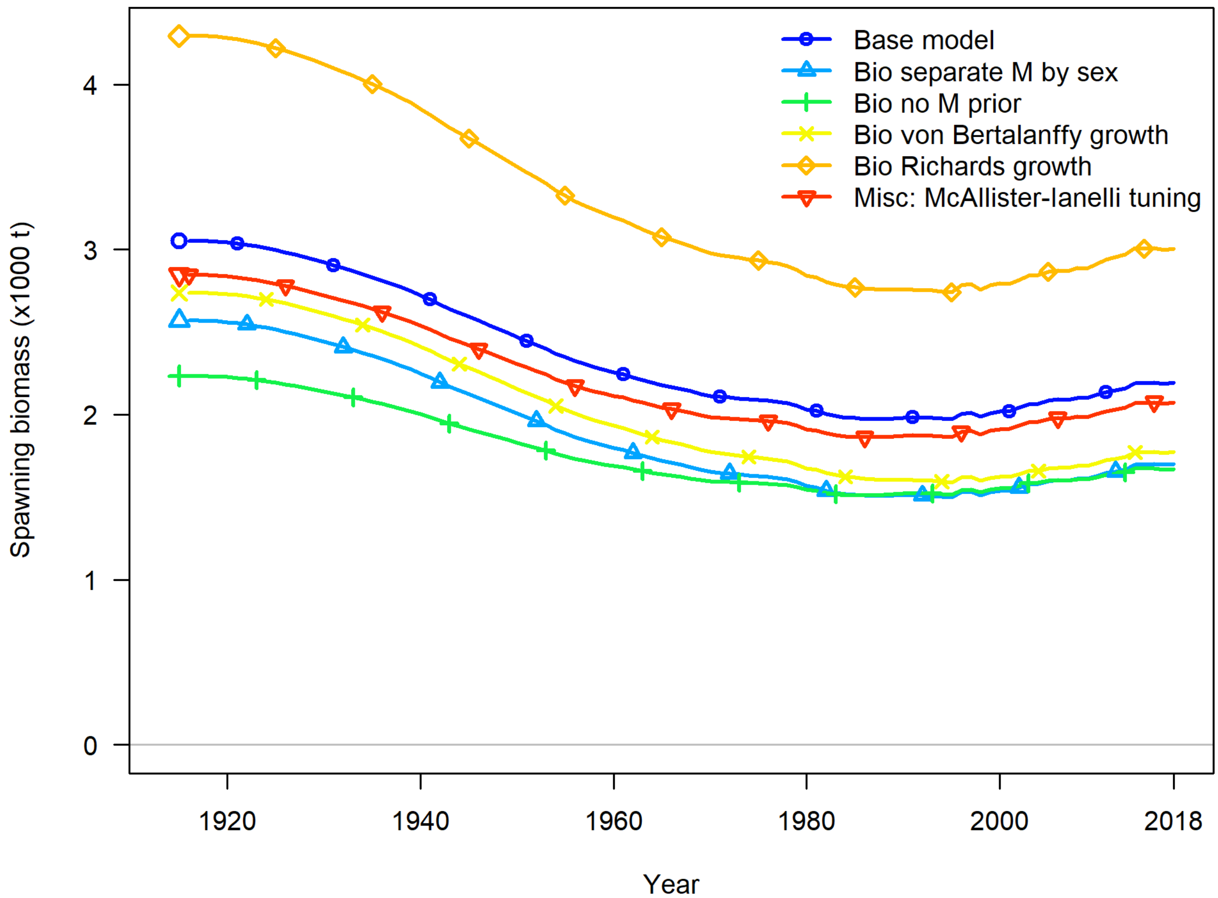

Figure 37: Time series of spawning output estimated in sensitivity analyses related to biology and other assumptions.

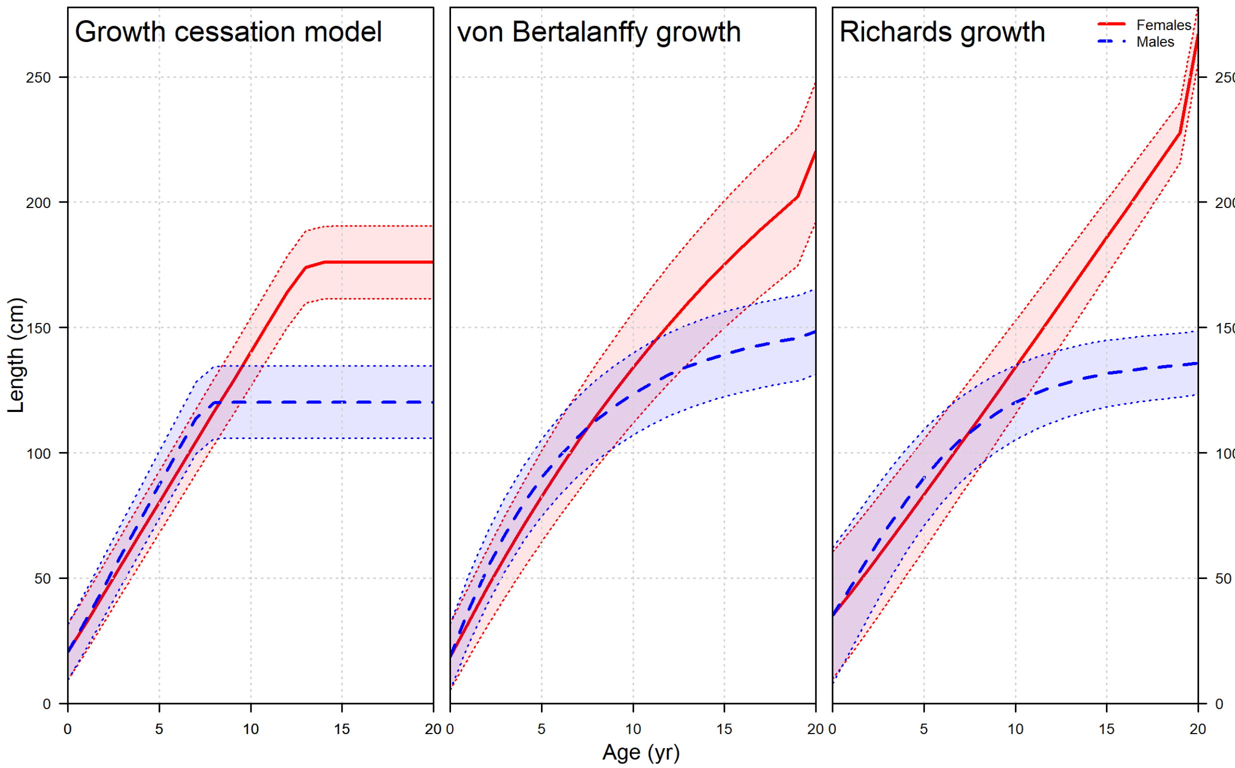

Figure 38: Comparison of the estimated growth curves from the sensitivities analyses.

948 #### 10.3.5 Likelihood Profiles

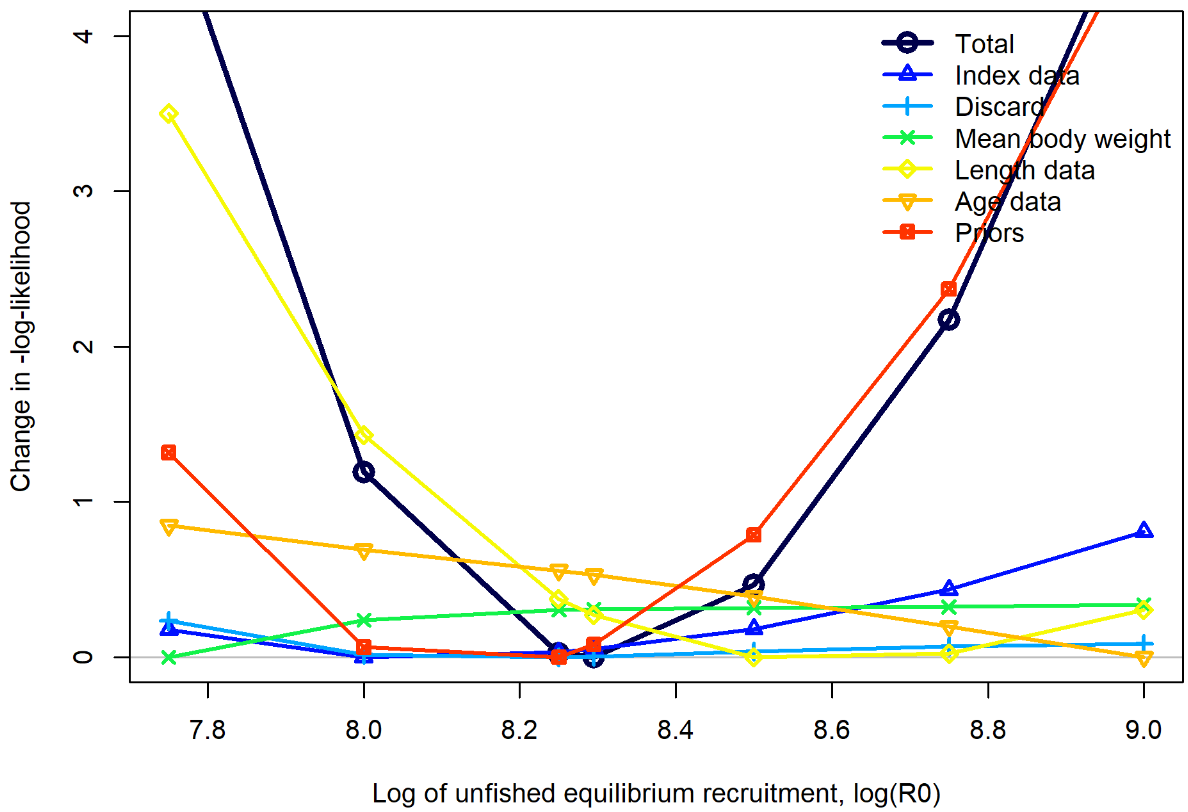

Figure 39: Likelihood profile over the log of equilibrium recruitment (R_0).

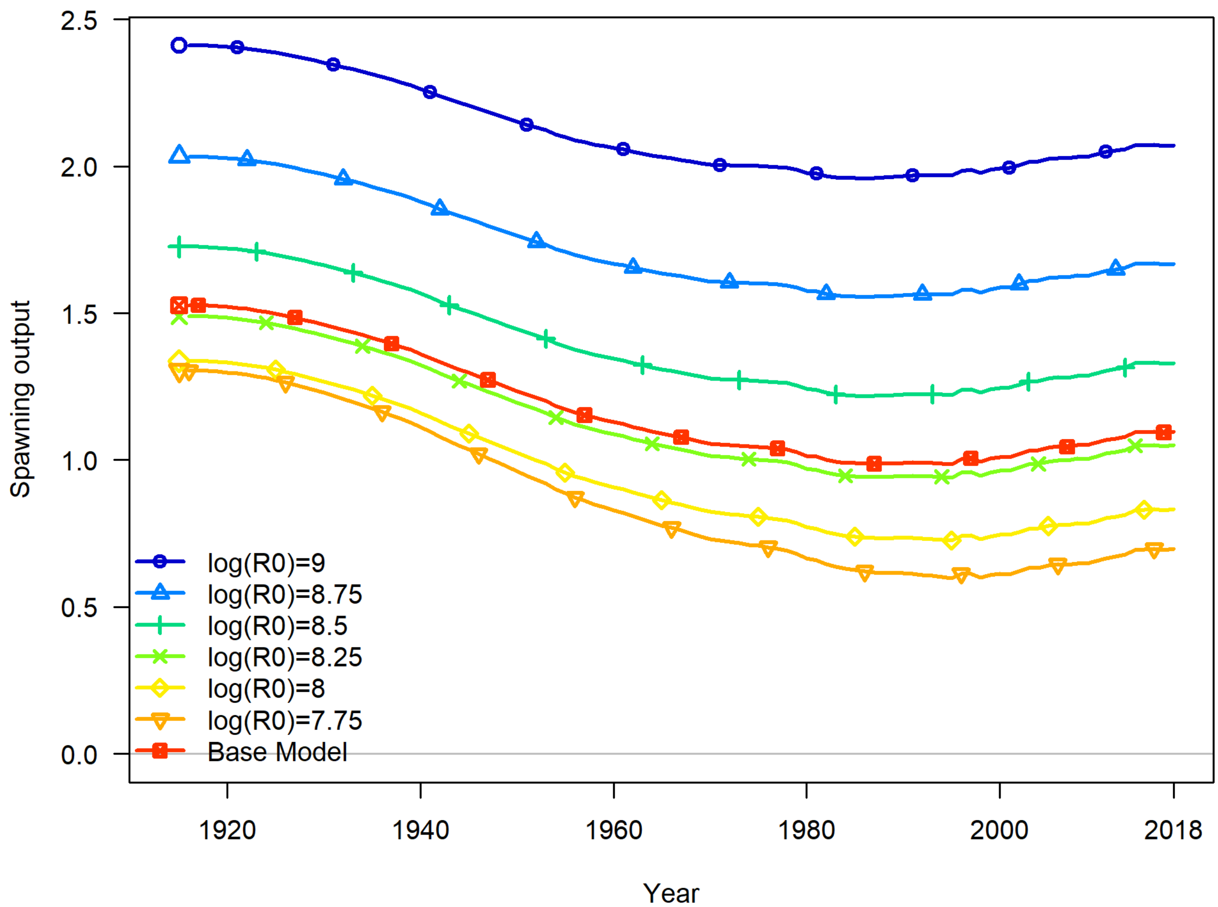

Figure 40: Time series of spawning output estimated for the models included in the profile over the log of equilibrium recruitment (R_0).

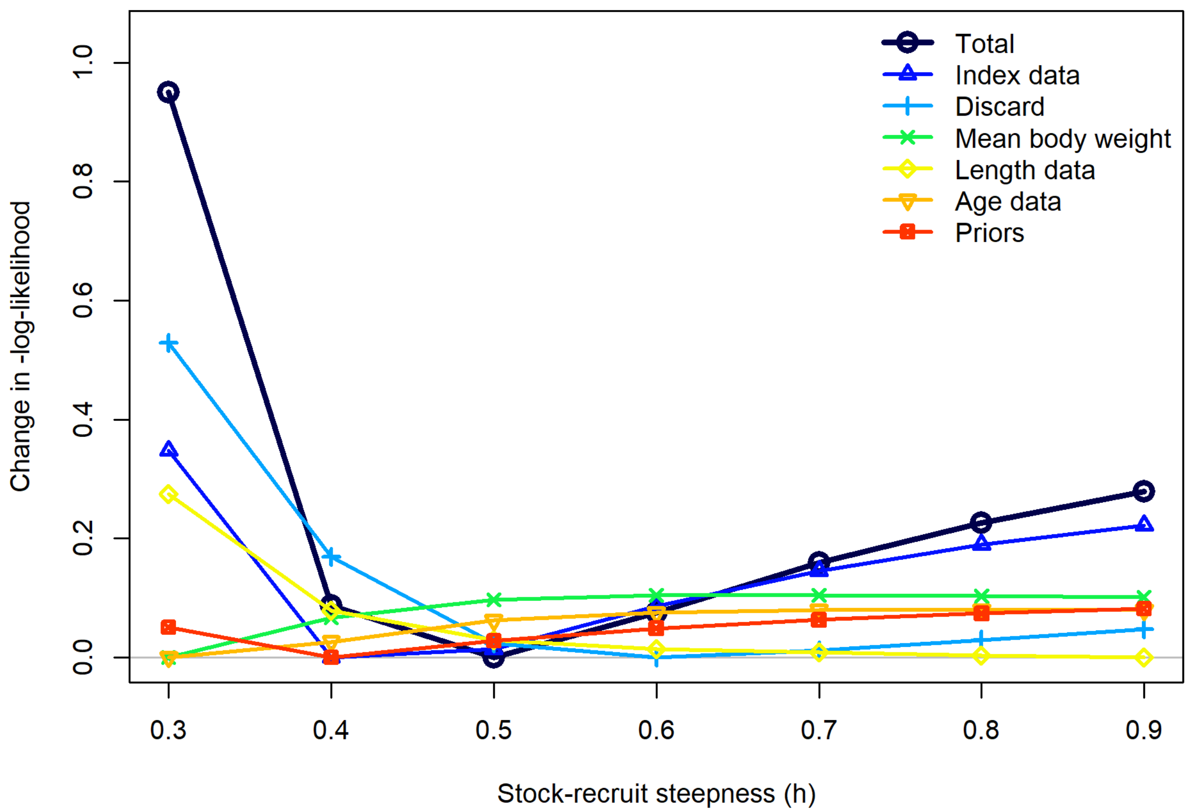

Figure 41: Likelihood profile over stock-recruit steepness (h).

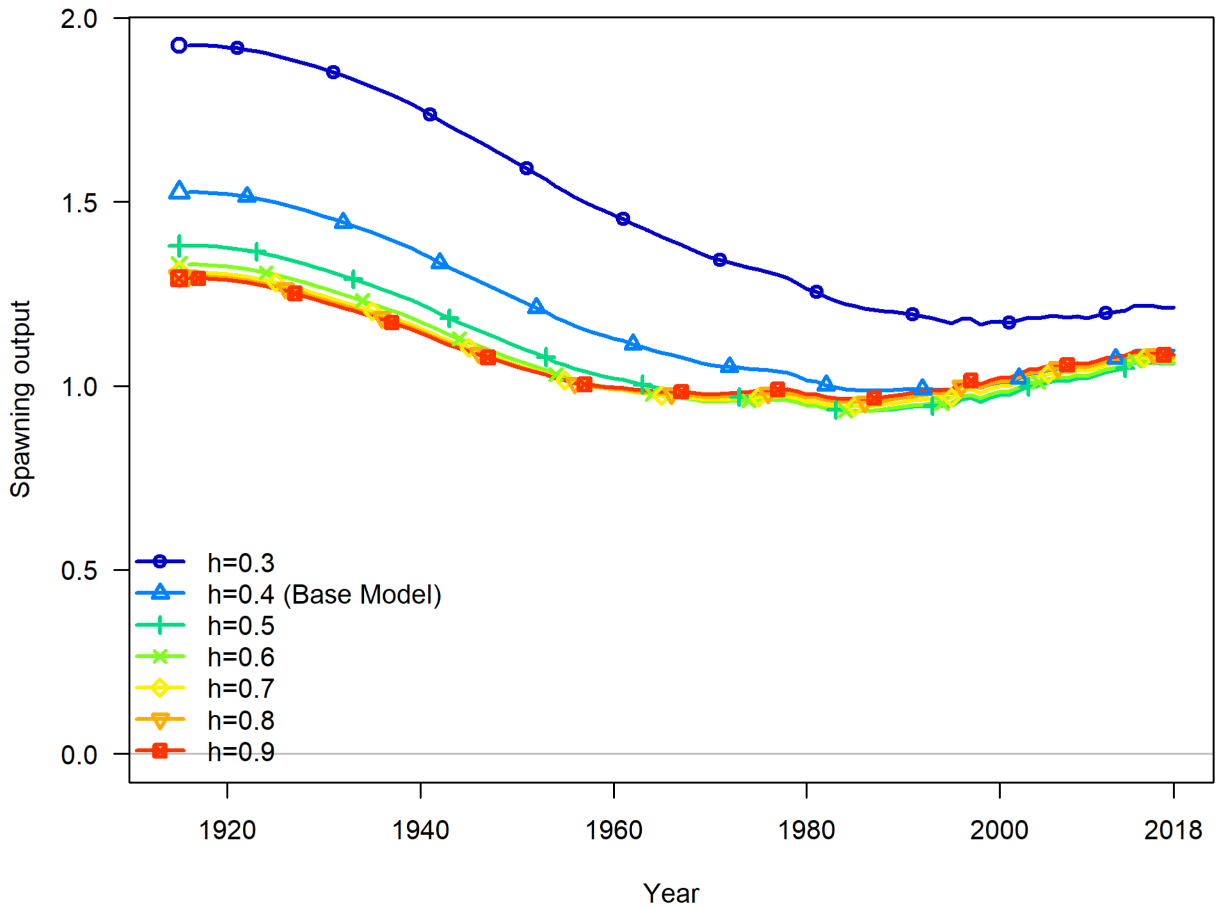

Figure 42: Time series of spawning output estimated for the models included in the profile over stock-recruit steepness (h).

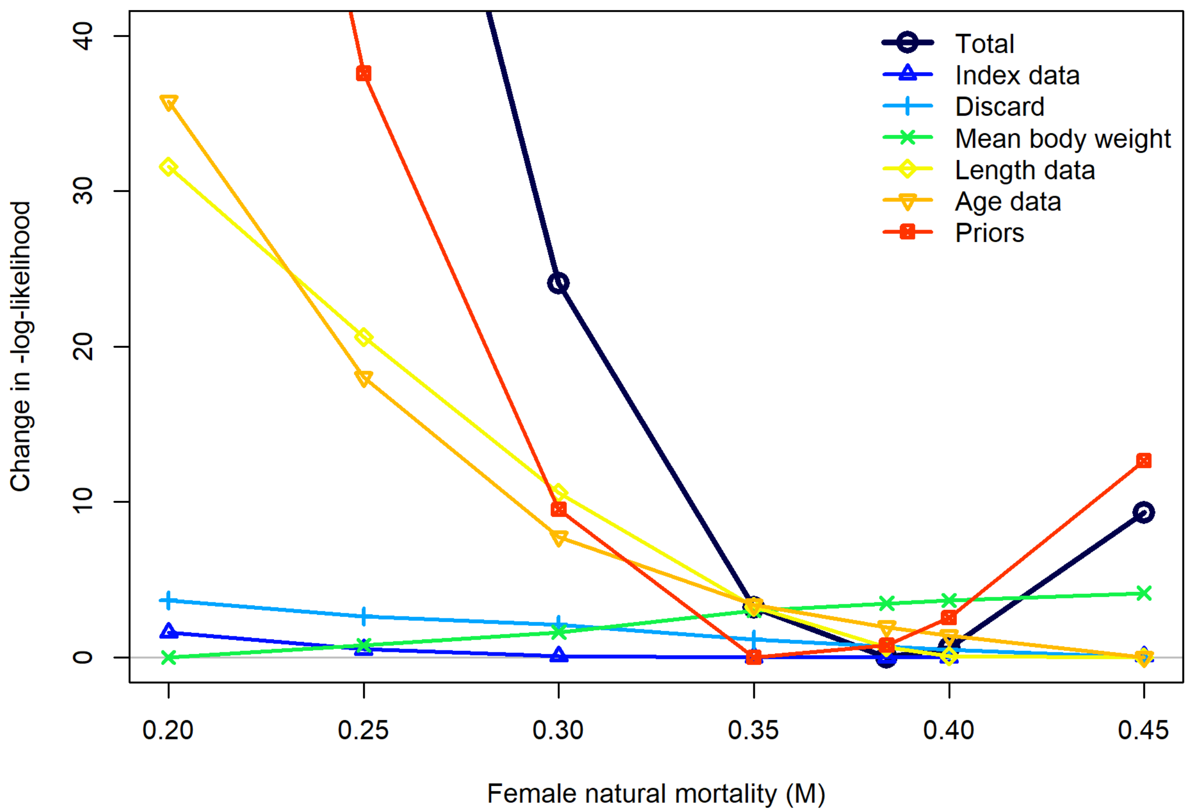

Figure 43: Likelihood profile over natural mortality (M).

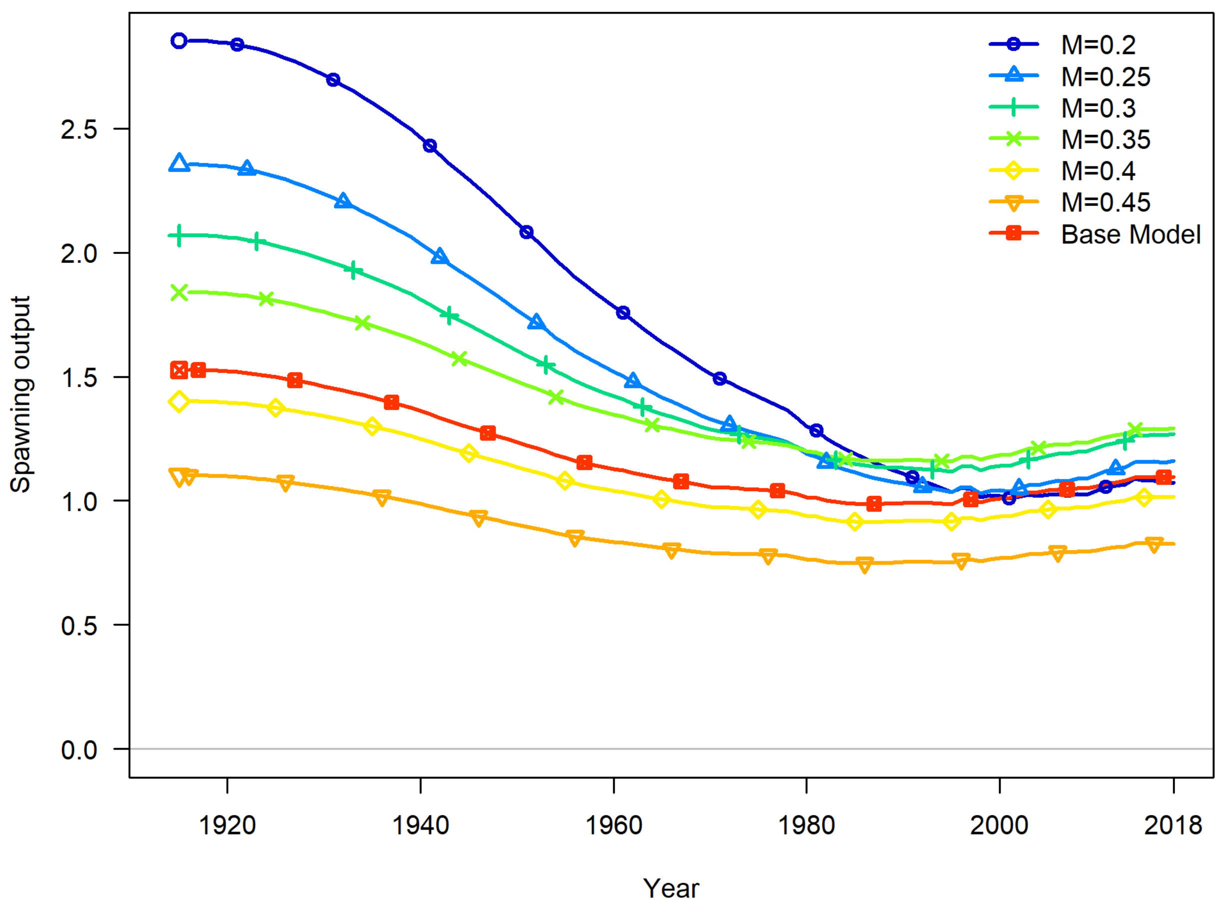

Figure 44: Time series of spawning output estimated for the models included in the profile over natural mortality (M).

10.3.6 Reference Points and Forecasts

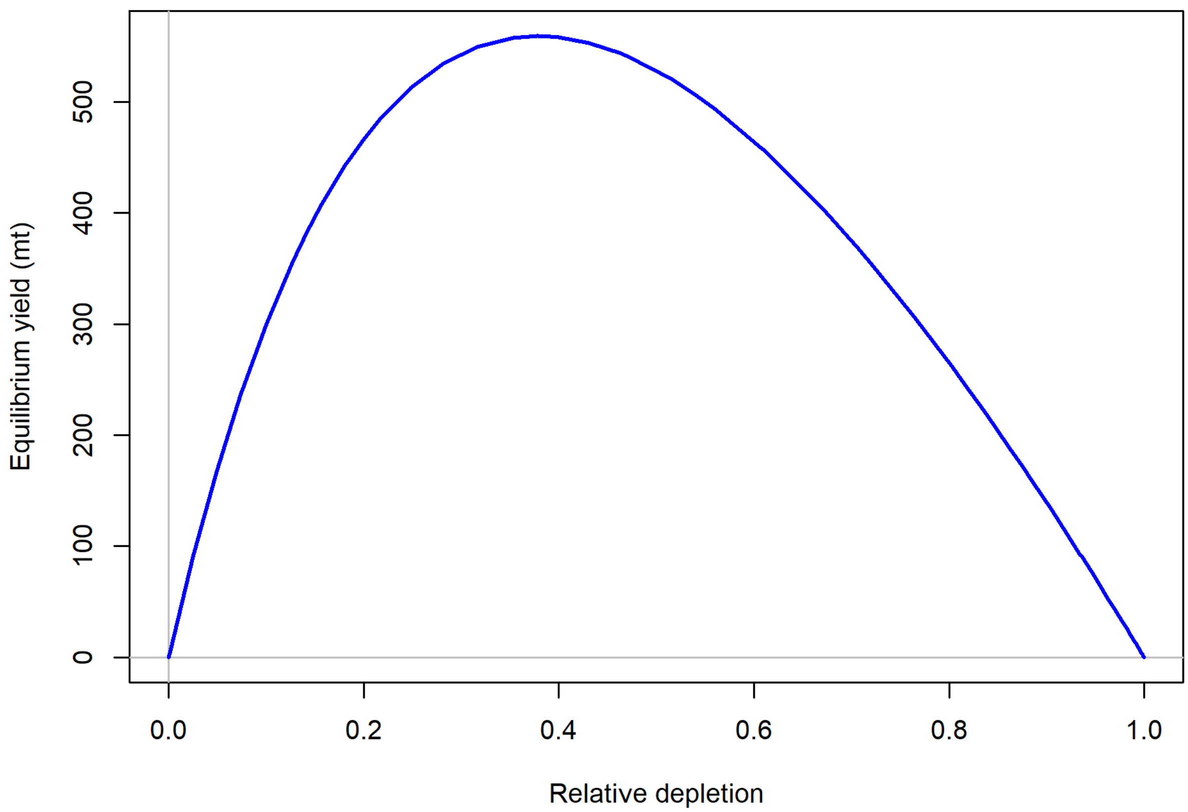

Figure 45: Equilibrium yield curve for the base case model. Values are based on the 2018 fishery selectivity and with steepness fixed at 0.718.

Appendix A. Detailed fits to length composition data

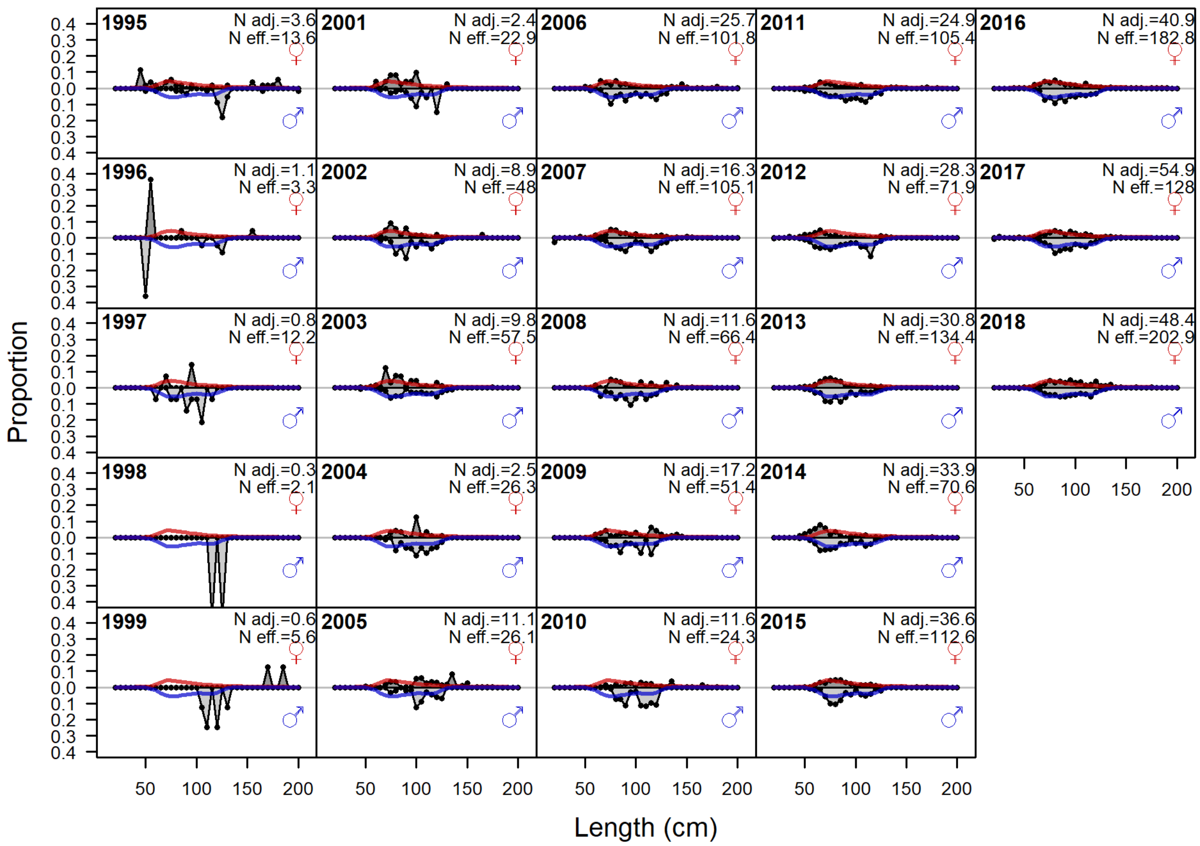

Figure A46: Length comps, retained, Fishery. 'N adj.' is the input sample size after data_weighting adjustment. N eff. is the calculated effective sample size used in the McAllister_Iannelli tuning method.

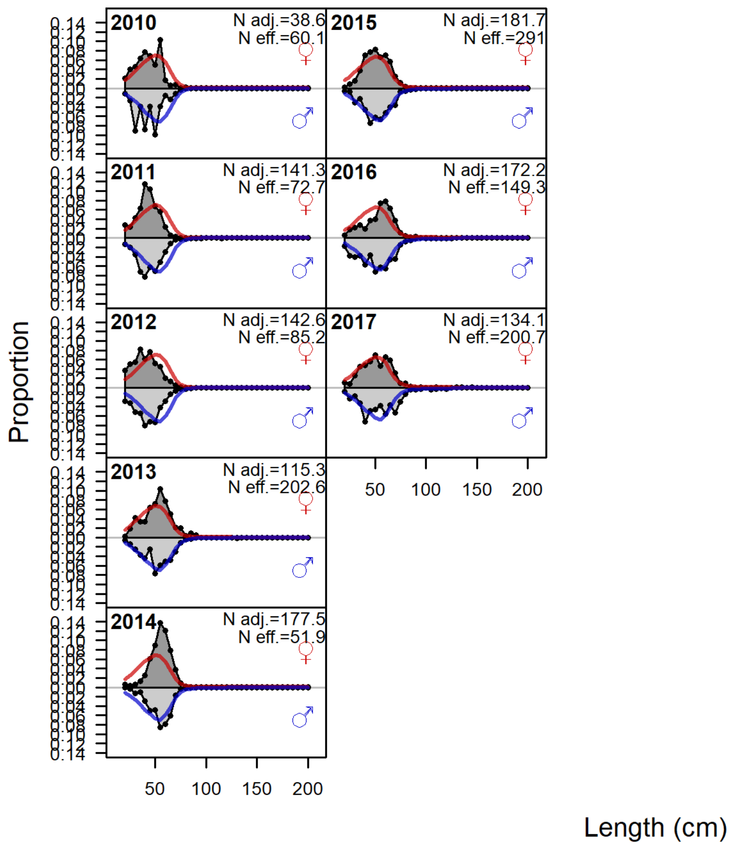

Figure A47: Length comps, discard, Fishery. 'N adj.' is the input sample size after data_weighting adjustment. N eff. is the calculated effective sample size used in the McAllister_Iannelli tuning method.

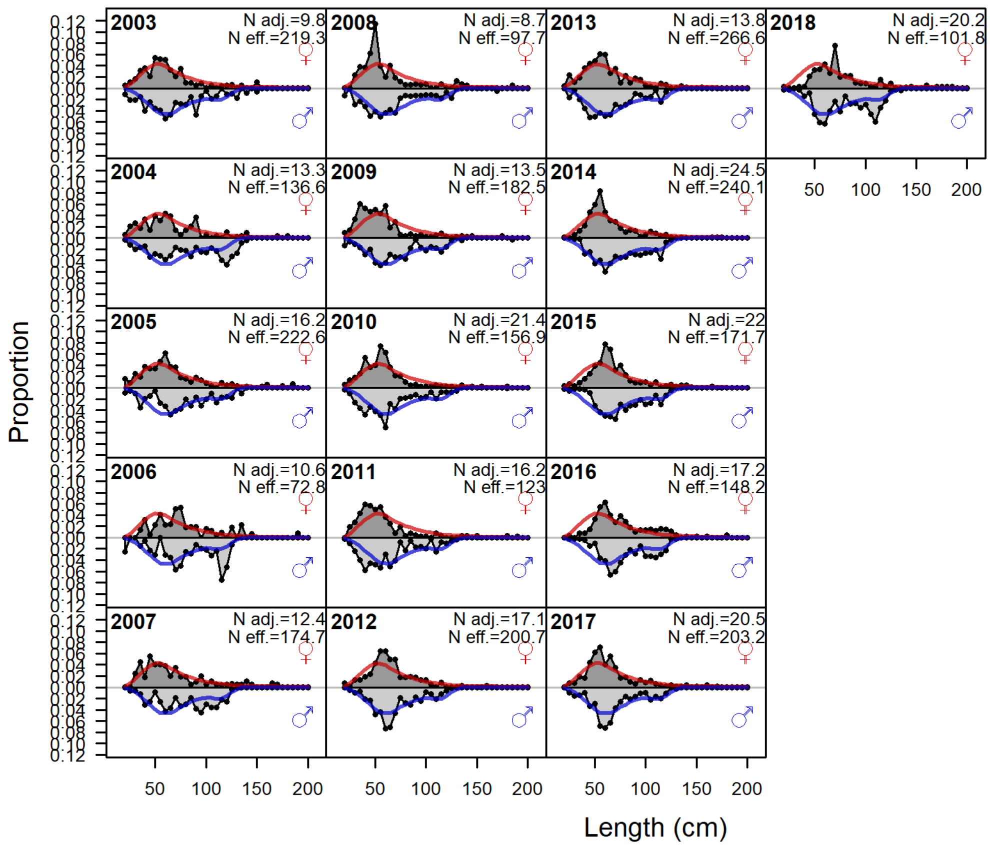

Figure A48: Length comps, whole catch, WCGBT Survey. 'N adj.' is the input sample size after data_weighting adjustment. N eff. is the calculated effective sample size used in the McAllister_Iannelli tuning method.

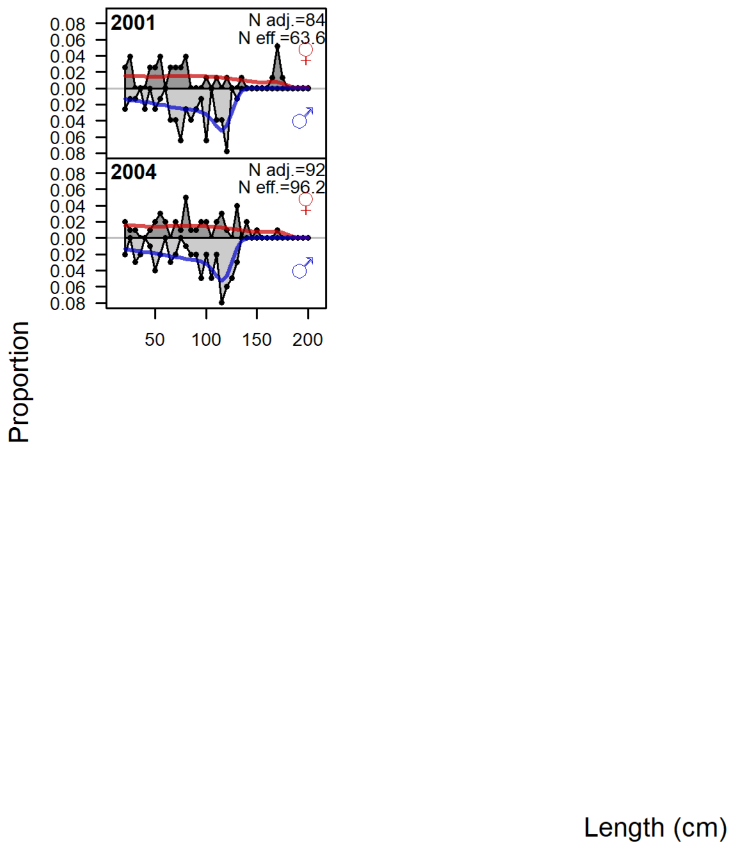

Figure A49: Length comps, whole catch, Triennial Survey. ‘N adj.’ is the input sample size after data_weighting adjustment. N eff. is the calculated effective sample size used in the McAllister_Iannelli tuning method.

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