

Status of Shortspine Thornyhead (*Sebastolobus alascanus*) along the US West coast in 2023

by

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Executive summary

Stock

This assessment applies to shortspine thornyhead (*Sebastolobus alascanus*) off of the west coast of the United States from the U.S.-Canada border to the U.S.-Mexico border using data through 2022. Shortspine thornyhead are modeled in this assessment as a single stock. They have been reported as deep as 1,524 m, and this assessment applies to their full depth range although survey and fishery data are only available down to 1,280 m.

Catches

Historically, landings of shortspine thornyhead remained under 500 metric tons until the late 1960s when landings began to increase steadily, rising to a peak of 4,815 mt in 1989, followed by a sharp decline during a period when trip limits and other management measures were imposed in the 1990s. Since the institution of separate trip limits for shortspine and longspine thornyhead, the fishery has had more moderate removals of between 1,000 and 2,000 mt per year from 1995–1998. Landings fell below 1,000 mt per year from 1999–2006, then rose to 1,531 in 2009 and have declined since that time. Recreational fishery landings of thornyheads were negligible, so only commercial landings were included in the model.

Commercial landings are dominantly bottom trawl caught, and non-trawl landings include all other gear types, the majority of which is longline (Table i; Figure i). For this assessment, trawl landings were divided into northern (the waters off Washington and Oregon) and southern (the waters off California) fleets. Non-trawl landings represent one, coastwide, fleet. Discard rates (landings divided by total catch) for shortspine thornyhead have been estimated as high as 43% per year, but are more frequently below 20%. Discard rates in the trawl fleets, available from the West Coast Groundfish Observer Program (WCGOP), declined from 2003–2011 and have since increased from 2012–present, when the catch shares system began. Catches from the At-Sea Hake fishery were integrated into the North Trawl fleet.

Table i: Recent landings by fleet, total landings summed across fleets, and the total mortality including discards. Total dead fish is the combined landings and model estimated discards.

| Year | North Trawl | South Trawl | Non-Trawl | Total Landings | Total Dead |
|------|----------------|----------------|-----------|-------------------|------------|
| 2013 | 570.11 | 294.83 | 166.40 | 1,031.34 | 1,111.27 |
| 2014 | 456.13 | 254.05 | 147.81 | 858.00 | 928.12 |
| 2015 | 513.66 | 244.29 | 131.30 | 889.26 | 929.06 |
| 2016 | 587.71 | 185.73 | 168.94 | 942.38 | 992.09 |
| 2017 | 634.83 | 158.30 | 223.82 | 1,016.94 | 1,094.53 |
| 2018 | 595.89 | 105.07 | 184.48 | 885.44 | 948.28 |
| 2019 | 460.13 | 127.94 | 143.48 | 731.55 | 785.62 |

Table i: Recent landings by fleet, total landings summed across fleets, and the total mortality including discards. Total dead fish is the combined landings and model estimated discards. (*continued*)

| Year | North Trawl | South Trawl | Non-Trawl | Total Landings | Total Dead |
|------|-------------|-------------|-----------|----------------|------------|
| 2020 | 258.09 | 87.99 | 85.17 | 431.26 | 477.36 |
| 2021 | 302.81 | 73.39 | 78.74 | 454.94 | 499.93 |
| 2022 | 506.30 | 97.61 | 66.22 | 670.12 | 724.14 |

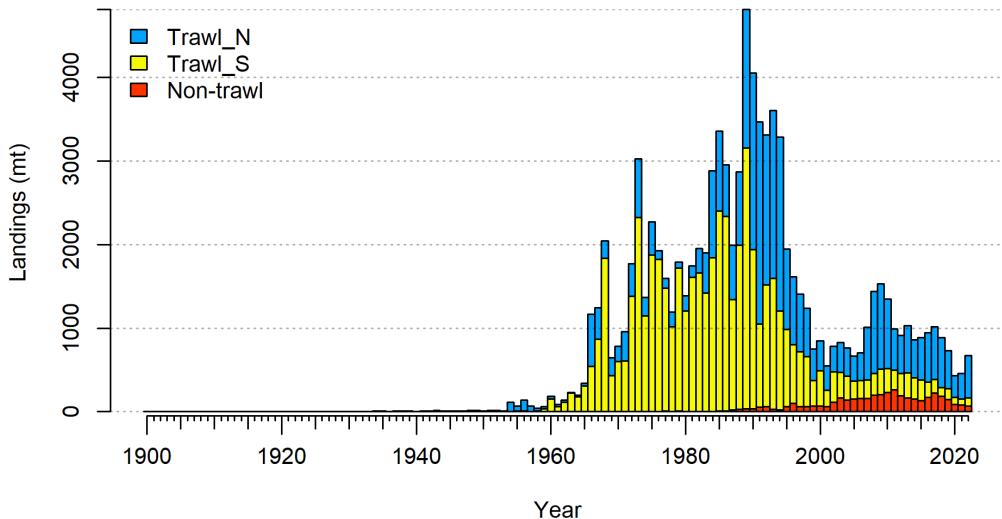


Figure i: Estimated landing history for shortspine thornyhead.

Data and assessment

The most recent assessment for shortspine thornyhead was conducted in 2013 (Taylor and Stephens 2013). Stock status was determined to be above the management target and catches did not attain the full management limits, so reassessment of thornyheads has not been a higher priority. This assessment uses Stock Synthesis (Methot and Wetzel 2013) Version 3.30.21, used in many other recent US West Coast assessments.

Data were divided into three fishery fleets: North trawl (the waters off Washington and Oregon including the At-Sea Hake fishery), South trawl (the waters off California), and coastwide Non-trawl, and three survey fleets: the AFSC/NWFSC West Coast Triennial

Shelf Survey (Triennial Survey) from 1980-2004, which was divided into early (pre-1995) and late period (post-1995) to account for a change in depth-sampling, and the NWFSC West Coast Groundfish Bottom Trawl Survey (WCGBTS), 2003-2022 (Figure ii).

Most data used in the 2013 assessment were newly pulled and processed for this assessment, including length compositions from all fishing and survey fleets, indices of abundance derived from new geostatistical analyses, discard rates from both a 1980s observer study (Pikitch et al. 1988) and the current WCGOP, historical catch data from Washington, Oregon, and California, and all reported catches from 1981-2022. The only data taken from the previous assessment without reanalysis were discard rates from the Enhanced Data Collection Project (EDCP) study in the 1990s.

New maturity analyses of samples collected in the WCGBTS in 2011, 2013, 2014, 2016 and 2018 were available for this assessment (Melissa Head, Northwest Fisheries Science Center (NWFSC), pers. comm.). The larger number and better spatial coverage of these samples allowed the use of statistical modeling to better understand the spatial variation in the proportion of females spawning. This assessment also assumes a new fecundity relationship, in which fecundity is modeled as a power function of length. New growth curves were estimated, using data from Butler (1995), which were similar to the curves assumed in the 2005 and 2013 assessments. In the previous assessment, a Beverton-Holt stock recruitment relationship was assumed and steepness (h) was fixed at 0.60. This assessment fixed steepness at 0.72, as recommended by Thorson et al. (2019). Natural mortality (M) was also slightly updated, from 0.0505 in the 2013 assessment, to be fixed at 0.04.

This assessment estimated 195 parameters. The log of the unfished equilibrium recruitment, $\ln(R_0)$, controls the scale of the population and annual deviations around the stock-recruit curve (135 parameters) allow for more uncertainty in the population trajectory. In addition, 57 selectivity and retention parameters for the three fishery fleets and three surveys allowed for estimation of annual length compositions and discards rates. Two catchability parameters were analytically computed from the data, and one additional parameter, representing additional variability in the early Triennial survey, was directly estimated by the model.

Stock biomass and dynamics

Unfished equilibrium spawning output (B_0) is estimated to be 22.145 trillion eggs, with a 95% confidence interval of 18.166-26.124 trillion eggs. The B_0 estimate here is not comparable to previous assessment as the integration of new fecundity and maturity assumptions have changed the output units from traditional biomass to spawned eggs. Spawning output is estimated to have remained stable until the early-1970s before beginning to decline near linearly through the present day. The estimated spawning output in 2023 is 8.717 trillion eggs (5.545-11.889 trillion eggs), which represents a stock status or “depletion” (B_{2023}/B_0) of 39.4% (31.6%-47.1%; Table ii; Figure iii). The depletion in 2013 was estimated to be 43.5%, a large decrease from what was estimated by the 2013 assessment (~75%). The standard deviation of the log of spawning biomass in 2023 is 0.18, which is less than the 0.36 minimum assumed for use in p^* adjustments to overfishing limit (OFL) values.

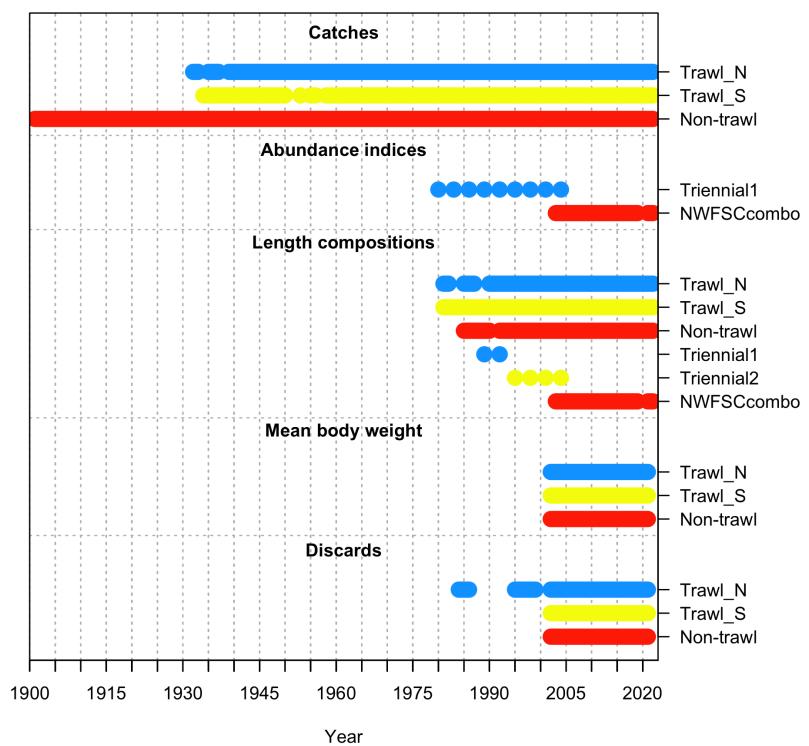


Figure ii: Summary of data sources used in the base model.

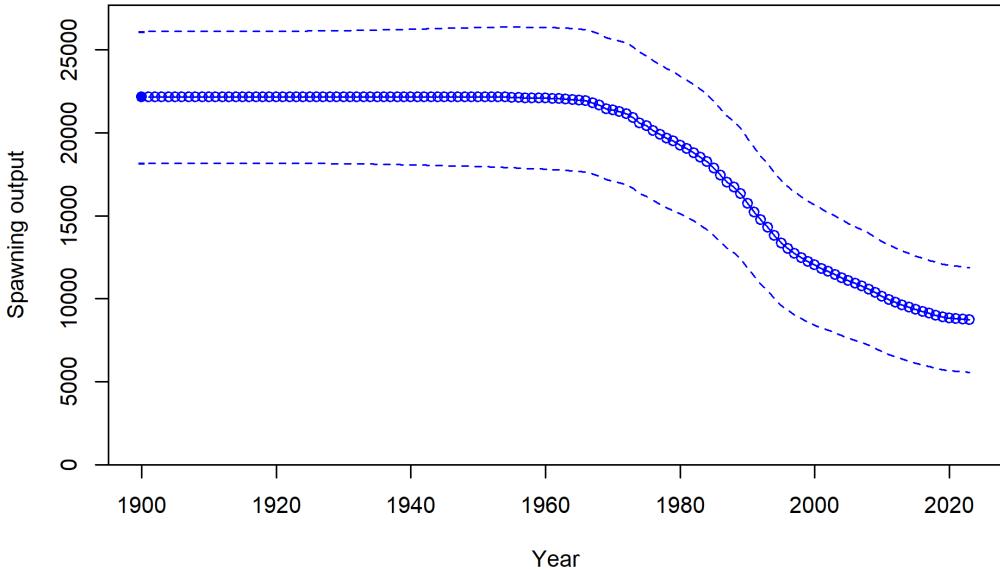


Figure iii: Estimated spawning output trajectory for shortspine thornyhead.

Table ii: Spawning output (millions of eggs) and fraction unfished with associated 95% confidence intervals (CI) from the base model.

| Year | Spawning Output | Spawning Output 95% CI | Fraction Unfished | Fraction Unfished 95% CI |
|------|-----------------|------------------------|-------------------|--------------------------|
| 2013 | 9,626 | 6,360–12,892 | 0.435 | 0.360–0.509 |
| 2014 | 9,476 | 6,228–12,724 | 0.428 | 0.353–0.503 |
| 2015 | 9,348 | 6,116–12,579 | 0.422 | 0.347–0.497 |
| 2016 | 9,228 | 6,011–12,444 | 0.417 | 0.341–0.492 |
| 2017 | 9,112 | 5,908–12,315 | 0.411 | 0.336–0.487 |
| 2018 | 8,997 | 5,804–12,190 | 0.406 | 0.330–0.482 |
| 2019 | 8,902 | 5,718–12,086 | 0.402 | 0.325–0.478 |
| 2020 | 8,829 | 5,651–12,006 | 0.399 | 0.322–0.475 |
| 2021 | 8,787 | 5,614–11,960 | 0.397 | 0.320–0.474 |
| 2022 | 8,754 | 5,583–11,925 | 0.395 | 0.318–0.473 |
| 2023 | 8,717 | 5,545–11,889 | 0.394 | 0.316–0.471 |

Recruitment

This assessment assumed a Beverton-Holt stock recruitment relationship. Steepness (h , the fraction of expected equilibrium recruitment associated with 20% of equilibrium spawning

biomass) was fixed at 0.72, slightly higher than what was assumed in previous assessments ($h = 0.60$). The scale of the population is largely determined by the log of unfished recruitment (R_0), which was estimated to be 9.439. This results in an unfished recruitment of 12,580,000 recruits (10,320,000–14,841,000). Recruitment variation (σ_R) was fixed at 0.50, as was done in the 2013 assessment. Recruitment deviations were estimated for the years 1901 through 2022, and ranged from -0.5 to 1.5 on the log scale. Estimated recruitments do not show high variability, and the uncertainty in each estimate is greater than the variability between estimates (Table iii; Figure iv).

Table iii: Estimated recent trend in recruitment and recruitment deviations and the 95% confidence intervals (CI) from the base model.

| Year | Recruitment | 95% CI | RecDevs | RecDev 95% CI |
|------|-------------|--------------|---------|---------------|
| 2013 | 9,622 | 4,001–23,138 | -0.112 | -1.004–0.781 |
| 2014 | 9,650 | 3,996–23,304 | -0.105 | -1.002–0.791 |
| 2015 | 9,783 | 4,016–23,832 | -0.089 | -0.996–0.818 |
| 2016 | 10,155 | 4,111–25,087 | -0.049 | -0.973–0.875 |
| 2017 | 9,995 | 4,024–24,828 | -0.062 | -0.992–0.868 |
| 2018 | 9,990 | 3,990–25,017 | -0.060 | -1.000–0.879 |
| 2019 | 10,354 | 4,097–26,165 | -0.032 | -0.989–0.926 |
| 2020 | 10,839 | 4,230–27,777 | 0.007 | -0.968–0.981 |
| 2021 | 11,299 | 4,349–29,354 | 0.040 | -0.951–1.031 |
| 2022 | 10,952 | 4,253–28,200 | 0.000 | -0.980–0.980 |
| 2023 | 10,942 | 4,249–28,177 | 0.000 | -0.980–0.980 |

Exploitation status

The summary harvest rate (total catch divided by age-1 and older biomass) closely follows the landings trajectory. The harvest rates are estimated to have never exceeded 5% and have remained below 2% in the past decade. Expressing exploitation rates in terms of spawning potential ratio (SPR) indicates that the exploitation consistently exceeded the $SPR_{50\%}$ reference point from 1980–2018. However, the stock status is estimated to have never fallen below the $B_{40\%}$ management target, though the uncertainty interval around the 2023 estimate does encapsulate the $B_{40\%}$ target (Table iv; Figures v–viii).

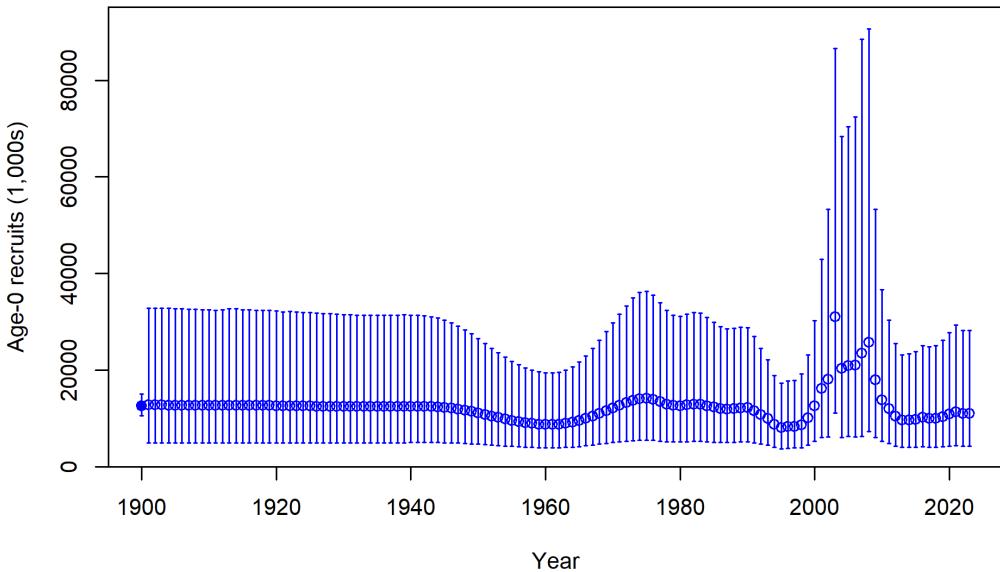
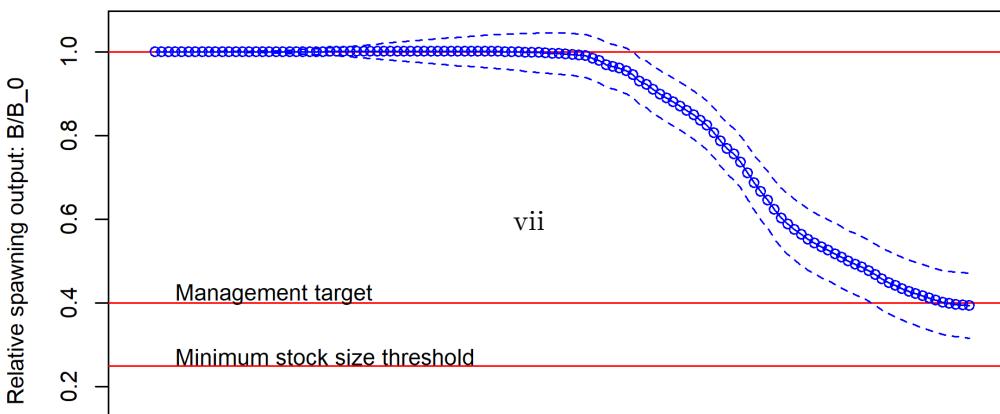


Figure iv: Estimated recruitment timeseries.

Table iv: Estimated recent trend in relative fishing intensity, exploitation rate, and the 95 percent intervals. The spawning potential ratio (SPR) is utilized in the relative fishing intensity calculation as $(1 - SPR)/(1 - SPR_{40\%})$.

| Year | $(1-SPR)/(1-SPR_{50\%})$ | 95% CI | Exploitation Rate | 95% CI |
|------|--------------------------|-----------|-------------------|---------------|
| 2013 | 1.29 | 1.06–1.53 | 0.0120 | 0.0079–0.0160 |
| 2014 | 1.16 | 0.92–1.41 | 0.0100 | 0.0066–0.0134 |
| 2015 | 1.15 | 0.91–1.40 | 0.0100 | 0.0066–0.0135 |
| 2016 | 1.19 | 0.95–1.44 | 0.0107 | 0.0070–0.0144 |
| 2017 | 1.25 | 1.00–1.50 | 0.0118 | 0.0077–0.0159 |
| 2018 | 1.14 | 0.89–1.39 | 0.0103 | 0.0067–0.0138 |
| 2019 | 1.00 | 0.75–1.24 | 0.0085 | 0.0055–0.0114 |
| 2020 | 0.68 | 0.48–0.87 | 0.0051 | 0.0033–0.0069 |
| 2021 | 0.69 | 0.49–0.88 | 0.0053 | 0.0035–0.0072 |
| 2022 | 0.88 | 0.66–1.10 | 0.0076 | 0.0050–0.0103 |



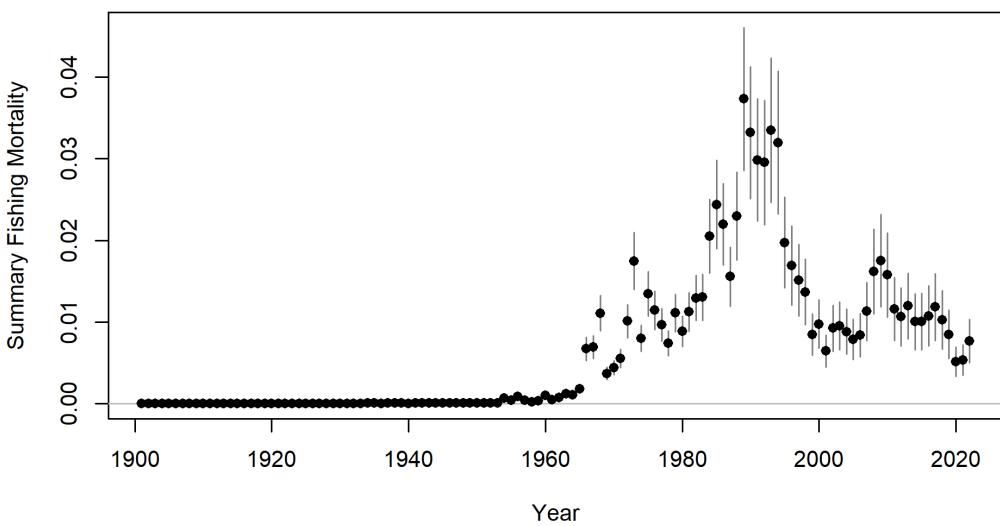


Figure vi: Summary fishing mortality rate (total landings / summary biomass).

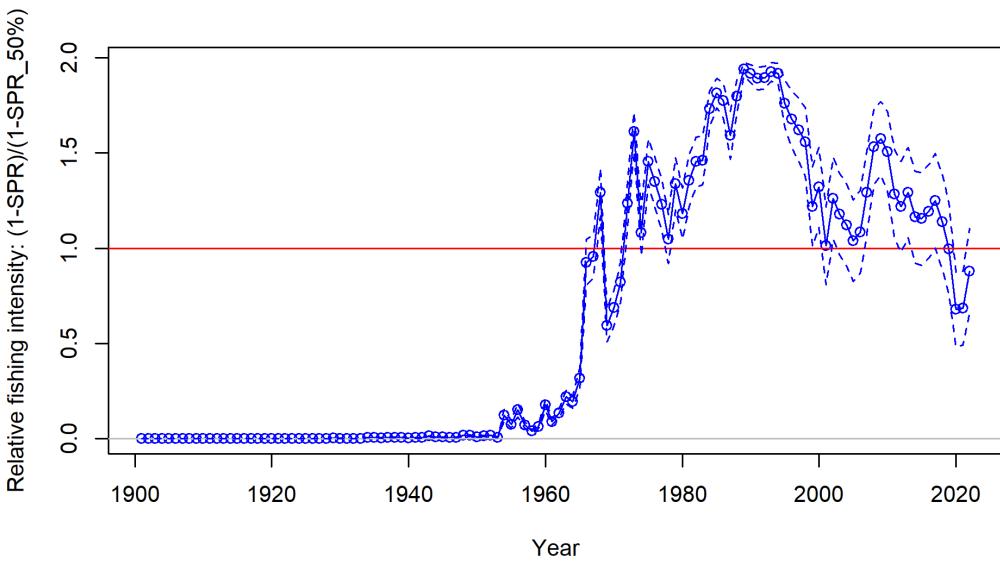


Figure vii: Estimated relative fishing intensity as a function of spawning potential ratio (SPR).

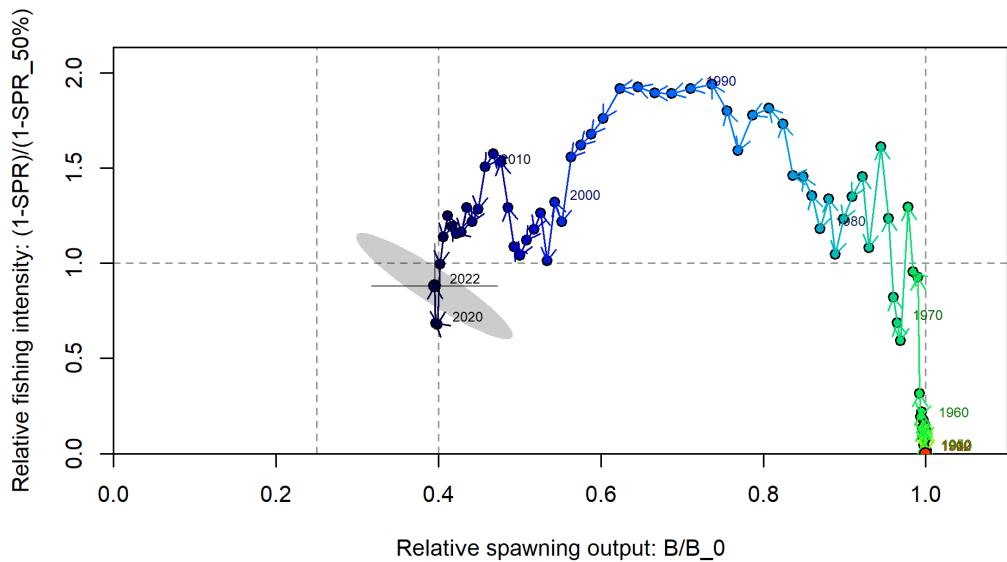


Figure viii: Phase plot of biomass ratio vs. spawning potential ratio (SPR) ratio. Points represent the annual biomass ratio and SPR ratio. Lines through the final point show 95% intervals based on the asymptotic uncertainty for each dimension, while the shaded ellipse is a 95% region accounting for estimated correlation between the two quantities.

Ecosystem considerations

This stock assessment does not explicitly incorporate trophic interactions, habitat factors or environmental factors into the assessment model. More predation, diet, and habitat work, and mechanistic linkages to environmental conditions would be needed to incorporate these elements into the stock assessment.

Reference points

Reference points were calculated using the estimated catch distribution in the final year of the model (2023). In general, the population is on the boundary between “precautionary” ($B/B_0 = 0.40$) and “healthy” ($B/B_0 > 0.40$) status relative to the reference points (Figure ix). Sustainable total yield (landings plus discards) was estimated at 1,108 mt when using an $SPR_{50\%}$ reference harvest rate and ranged from 929–1,288 mt based on estimates of uncertainty (Table v). The spawning output equivalent to 40% of the unfished spawning output ($B_{40\%}$) was 8.858 trillion eggs. The most recent total mortality (landings plus discards) have been lower than the estimated long-term yields calculated using an $SPR_{50\%}$ reference point, but not as low as the lower bound of the 95% uncertainty interval. However, this is due to the fishery not fully attaining the full annual catch limit (ACL). The OFL and Acceptable Biological Catch (ABC) values over the past 6 years have been approximately 3100 mt and 2,500 mt, respectively.

Table v: Summary of reference points and management quantities, including estimates of the 95% intervals.

| Variable of Interest | Estimate | 95% CI |
|--|----------|-----------------|
| Unfished Spawning Output | 22,145 | 18,166–26,124 |
| Unfished Age 1+ Biomass (mt) | 216,864 | 177,897–255,831 |
| Unfished Recruitment (R0) | 12,580 | 10,320–14,841 |
| Spawning Output (2023) | 8,717 | 5,545–11,889 |
| Fraction Unfished (2023) | 0.39 | 0.32–0.47 |
| Reference Points Based SB40% | | |
| Proxy Spawning Output SB40% | 8,858 | 7,266–10,450 |
| SPR Resulting in SB40% | 0.458 | 0.458–0.458 |
| Exploitation Rate Resulting in SB40% | 0.012 | 0.011–0.012 |
| Yield with SPR Based On SB40% (mt) | 1,160 | 971–1,348 |
| Reference Points Based on SPR Proxy for MSY | | |
| Proxy Spawning Output (SPR50) | 9,880 | 8,105–11,656 |
| SPR50 | 0.500 | - |
| Exploitation Rate Corresponding to SPR50 | 0.010 | 0.010–0.011 |
| Yield with SPR50 at SB SPR (mt) | 1,108 | 929–1,288 |
| Reference Points Based on Estimated MSY Values | | |
| Spawning Output at MSY (SB MSY) | 6,155 | 5,057–7,253 |
| SPR MSY | 0.348 | 0.345–0.351 |

Table v: Summary of reference points and management quantities, including estimates of the 95% intervals. (*continued*)

| Variable of Interest | Estimate | 95% CI |
|--|----------------|----------------------------|
| Exploitation Rate Corresponding to SPR MSY MSY (mt) | 0.017 1,227 | 0.016–0.017 1,027–1,426 |

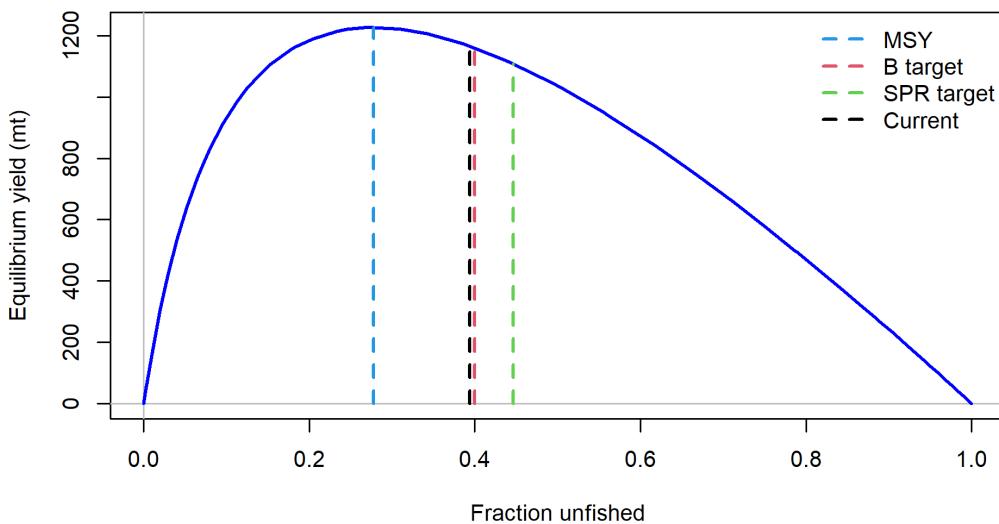


Figure ix: Estimated yield curve with reference points.

Management performance

Catches for shortspine thornyhead have not fully attained the catch limits in recent years. ACLs have hovered around 2500 mt since 2013, while total mortality has never exceeded 1085 mt, and is often smaller than that (Table vi). The fishery for shortspine thornyhead may be limited more by the ACLs on sablefish, with which they co-occur, and by the challenging economics of deep sea fishing, than by the management measures currently in place.

Table vi: Recent trend in the overfishing limits (OFLs), the acceptable biological catches (ABCs), the annual catch limits (ACLs), the total landings, and total mortality (mt). Total mortality is a function of both landings and model estimated discards.

| Year | OFL | ABC | ACL | Landings | Total Mortality |
|------|------|------|------|----------|-----------------|
| 2013 | 2333 | 2230 | 1937 | 1,031.34 | 1,111.27 |
| 2014 | 2310 | 2208 | 1918 | 858.00 | 928.12 |
| 2015 | 3203 | 2668 | 2668 | 889.26 | 929.06 |
| 2016 | 3169 | 2640 | 2639 | 942.38 | 992.09 |
| 2017 | 3144 | 2619 | 2619 | 1,016.94 | 1,094.53 |
| 2018 | 3116 | 2596 | 2596 | 885.44 | 948.28 |
| 2019 | 3089 | 2573 | 2573 | 731.55 | 785.62 |
| 2020 | 3063 | 2551 | 2552 | 431.26 | 477.36 |
| 2021 | 3211 | 2183 | 2184 | 454.94 | 499.93 |
| 2022 | 3194 | 2130 | 2130 | 670.12 | 724.14 |

Unresolved problems and major uncertainties

Major uncertainties in the model are centered around uncertainty in biological processes including growth, maturity, and mortality. The absence of reliable ageing methods for shortspine thornyhead, particularly, makes it difficult to estimate growth and natural mortality.

The assessment does not include age composition data; there is no production ageing of thornyheads for the U.S. West Coast (or Alaska). The assessment model used external estimates of a Von Bertalanffy growth curve based on the Butler research age dataset. The ages in these data were averaged from two age-readers. Nonetheless, there will still be ageing error in the averages. It was also not described how fish were selected for aging or whether they were representative of the overall stock. Age measurement errors and sampling methods are both sources of bias in Von Bertalanffy parameter estimates.

The WCGBTS model-based indices generally followed the design-based trends 9; however, the 2021 and 2022 model-based indices are substantially higher than the design-based indices. Confidence intervals for the model-based indices do not cover the 2021 design-based index, and barely cover the 2022 index. The assessment model could not fit the last two model-based indices which is a potential concern. It is a source of uncertainty why there is such a difference in design- and model-based indices in 2021 and 2022.

Shortspine thornyhead along the Pacific coast could be assessed as a single stock, but recognized that there is a lack of information of recruitment dynamics (e.g., larval transport) that may indicate functional substock structure. These fish do not move much and may be territorial which are attributes that can contribute to substock structure.

There is uncertainty in catch estimates, and more so for historic periods and when interpolations are used to fill in catches for some years. This uncertainty was not quantified and

provided to the Panel. There is an important need for STATs to provide information on the quality of the annual catch estimates, and more specifically to quantify the uncertainty in these estimates. This technical deficiency is common to many assessments.

Decision table and projections

Scientific uncertainty

The model estimated uncertainty around the 2024 spawning biomass was $\sigma = 0.18$ and the uncertainty around the OFL was $\sigma = 0.17$. The category 2 default $\sigma = 1.0$ is used to apply scientific uncertainty in the projections.

Research and data needs

Research and data needs for future assessments include the following:

1. Research into aging methods and availability of reliable age data would be valuable for future stock assessments. Otoliths have been collected in good quantities from the WCGBTS, but there is currently no validated aging method for shortspine thornyhead.
2. Additional investigation into growth patterns would provide valuable information for future population projections. We acknowledge that additional work on aging shortspine thornyhead would be required to make such additional growth research possible. Use of an “Errors-as-Variables” approach (e.g. Dey et al. 2019) could be applied to the Butler growth dataset.
3. More investigation into maturity of shortspine thornyhead is necessary to understand the patterns in maturity observed in WCGBTS samples.
4. Information on possible migration of shortspine thornyhead would be valuable for understanding stock dynamics. Analysis of trace elements and stable isotopes in shortspine thornyhead otoliths may provide valuable information on the extent of potential migrations. Possible connections between migration and maturity could likewise be explored.
5. A greater understanding of the connection between thornyheads and bottom type could be used to refine the indices of abundance. Thornyheads are very well sampled in trawable habitat, but the extrapolation of density to a survey stratum could be improved by accounting for the proportion of different bottom types within a stratum and the relative density of thornyheads within each bottom type.
6. Additional investigation into spatial stock structure could be valuable for determining whether future assessments should develop a spatial assessment model, or if shortspine thornyhead should be assessed at distinct spatial scales in the future.
7. Further research into the Dirichlet-Multinomial (DMN) data-weighting method for length-composition data is needed for integration with length-based data-moderate assessments like shortspine thornyhead. The DMN method has not, to date, been

thoroughly simulation tested with length-composition data, and an attempted sensitivity analysis performed for the 2023 assessment failed to converge entirely. This is a general research need, and is widely applicable to many data-moderate or length-based assessments, not just shortspine thornyhead.

1 Introduction

1.1 Basic Information

This assessment reports the status of shortspine thornyhead (*Sebastolobus alascanus*) off the US West coast using data through 2022.

Shortspine thornyhead are found in the waters off the West Coast of the United States, from northern Baja California to the Bering Sea, at depths of 20 meters to over 1,500 meters. The majority of the spawning biomass occurs in the oxygen minimum zone between 600 and 1,400 meters. The distribution of the smallest shortspine thornyhead suggests that they tend to settle at 100–400 meters and are believed to exhibit ontogenetic migration down the slope, although large individuals are found across the depth range. Higher densities (kg/ha) of shortspine thornyhead occur in shallower areas (under 400 meters) off Oregon and Washington, whereas in California, they occur in deeper areas (above 400 meters; Figure 1).

Despite variation in density across the coast, survey data suggest that shortspine thornyheads are present in almost all trawlable areas below 500 meters, as they are caught in 91% of trawl survey hauls deeper than 500 m. Camera-tows show that thornyheads are spaced randomly across the sea floor, indicating a lack of schooling and territoriality (Wakefield 1990; Du Preez and Tunnicliffe 2011).

1.2 Stock Structure

Genetic studies of stock structure show few genetic differences among shortspine thornyhead along the Pacific coast, and thus do not suggest separate stocks (Siebenaller 1978; Stepien 1995). Stepien (1995) suggested that there may be a separate population of shortspine thornyhead in the isolated area around Cortes Bank off San Diego, California. Stepien (1995) also pointed out that juvenile dispersion might be limited in the area where the Alaska and California currents split, which occurs towards the northern boundary of the assessment area, near 48° N.

Stepien et al. (2000), using a more discerning genetic material (mtDNA), found evidence of a pattern of genetic divergence in shortspine thornyhead corresponding to geographic distance. However, this study, which included samples collected from southern California to Alaska, did not identify a clear difference between stocks even at the extremes of the range. No such pattern was seen in longspine thornyhead, which suggests that the shorter pelagic stage (~1 yr vs. ~2 yrs) of shortspine thornyhead may contribute to an increased genetic separation with distance.

Dorval et al. (2022) applied otolith microchemistry to immature fish to redefine population structure of shortspine thornyhead on the west coast. Their results indicate that the population of immature shortspines belongs to two distinct groups distributed north and south of Cape Mendocino, California.

1.3 Life History

Shortspine thornyheads along the West Coast spawn pelagic, gelatinous floating egg masses between December and May (Wakefield 1990; Erickson and Pikitch 1993; Pearson and Gunderson 2003). Cooper et al. (2005) and Pearson and Gunderson (2003) found no evidence for batch spawning in this species on the West Coast, but more recent histological examination of ovaries suggest that some shortspine thornyhead can be batch spawners with two to three batches developing simultaneously (Melissa Head, NWFSC, pers. comm.). Juveniles settle at around 1 year of age (22- 27 mm in length), likely in the range of 100-200 m (Vetter and Lynn 1997), and migrate down the slope with age and size, although large individuals are found across the depth range.

Shortspine thornyhead are notoriously challenging to age, and a recent age validation study using ^{14}C bomb radiocarbon was inconclusive (Kastelle et al. 2020). However, best available data suggests that the shortspine thornyhead life span may exceed 100 years (Butler 1995; Kline 1996). Estimates of natural mortality for shortspine thornyhead range from 0.013 (Pearson and Gunderson 2003) to 0.07 (Kline 1996). However, the Pearson and Gunderson estimate is based upon a regression model, using the gonadosomatic index as a proxy. Butler (1995) estimated M to be 0.05 based upon a maximum lifespan of 100 years. Butler (1995) also suggested that M may be lower for older, larger shortspine thornyhead residing in the oxygen minimum zone due to lack of predators. All estimates of M for thornyheads are highly uncertain.

Shortspine thornyhead grow very slowly and may continue growing throughout their lives, reaching maximum lengths of over 70 cm. Females grow to larger sizes than males. Maturity in females was previously estimated as occurring near 18 cm, with fish transitioning from immature to mature within a relatively narrow range of sizes between 15 and 20 cm (Pearson and Gunderson 2003). However, more recent histological data of gonads collected in the WGBTS and analyzed using current best practices suggests that functional maturation, which accounts for abortive maturation and skip spawning, occurs over a broader spectrum of sizes between 10 and 55 cm (length-at-50% maturity, $L_{50} = 31.4$; personal communication, Melissa Head, NWFSC, pers. comm.).

1.4 Ecosystem Considerations

Shortspine thornyhead have historically been caught alongside longspine thornyhead in a dover sole, thornyhead, and trawl-caught sablefish complex (DTS). Other groundfishes that

frequently co-occur in deep waters include a complex of slope rockfishes, Rex sole, long-nose skate, roughtail skate, Pacific grenadier, giant grenadier, and Pacific flatnose. Non-groundfish species such as Pacific hagfish and a diverse complex of eelpouts also co-occur with shortspine thornyhead.

Shortspine thornyhead typically occur in shallower water than the shallowest longspine thornyhead, and migrate to deeper water as they age. The majority of spawning shortspine thornyheads occur between 600 and 1,400 meters, where longspine thornyhead are most abundant (Jacobson and Vetter 1996; Bradburn et al. 2011). When shortspine thornyhead have reached a depth where they overlap with longspine thornyheads, they are typically larger than the largest longspine thornyhead.

Species distribution models developed by Liu et al. (in press) suggest that expected environmental changes over the next decades will lead to a decline in shortspine and increase in longspine abundance. Shortspine thornyhead are also projected to shift offshore, into deeper waters, potentially decreasing their availability in fisheries. To date, shortspine thornyhead have been observed by cameras below the 1280 meter limit of the current fishery and survey, but their distribution, abundance, and ecosystem interactions in these deep waters are relatively unknown. Thornyheads spawn gelatinous masses of eggs which float to the surface, which may represent a significant portion of the upward movement of organic carbon from the deep ocean (Wakefield 1990).

Shortspine thornyhead diet composition, as derived from stomach content collection in the 1980s and 1990s, varied by year (Bizzarro et al. 2023). In some years their diet consisted primarily of invertebrate species including pandalid shrimp, pink shrimp, and Tanner crab, while in others their stomach content was dominated by finfish species such as Pacific cod and Pacific Hake. As prey themselves, shortspine thornyheads were only found in the stomachs of other species in two years, 1991 and 1992 as recorded in the CA Current Trophic Database (CCTD), where shortspine thornyhead occurred in sablefish, Pacific hake, and other shortspine thornyhead stomachs (Bizzarro et al. 2023).

1.5 Historical and Current Fishery Information

Harvest of shortspine thornyhead has experienced fluctuations over time due to increased depth range of the fisheries, variable markets, and changes in fisheries management. In the early 1900's, landings were minimal because there were few markets for thornyheads and relatively little trawling at depths where the majority of thornyheads occur. Beginning in the 1930s, thornyhead landings increased as they were landed as incidental catch in the California sablefish fishery. The first significant market for thornyheads began in northern California in the early 1960s, when larger (30-35 cm) thornyhead were sold as "ocean catfish". By the early 1980s, the minimum marketable size decreased to 25 cm, and in the late 1980s a market for small thornyheads (~20 cm) developed due to the depletion of a related species (*Sebastolobus machrochir*) off the coast of Japan. The fishery moved into deeper waters with

the demand for smaller thornyheads and began catching more longspine thornyheads. This is reflected in the changes in proportion of shortspine to total thornyheads through time, which decreased from around 90% in 1981 to 40% in 1994 (Figure 2).

Landings of shortspine thornyheads off the coast of California peaked around 3,500 mt in 1989, and have exceeded those from further north in most years (Figure 3). In the northern area off of Oregon and Washington, the fishery grew in the early 1980s, with landings peaking in 1991 at around 2200 mt.

Non-trawl landings of shortspine thornyhead were relatively low prior to the mid-1990s, at which point non-trawl landings, dominantly longline-caught from California, began to increase steadily from less than 5 mt in 1994 to 237 mt in 2011. The increase in non-trawl landings was driven by the development of live-fish markets for thornyheads and the fact that ex-vessel prices associated with the non-trawl landings are much higher than those for the trawl fishery. Nominal prices for line-caught shortspine thornyhead have increased steadily through time, from \$0.49/lb in 1990 to \$4.71/lb in 2021. This steady increase is also evident when prices are adjusted for inflation, indicating a real price increase in line-caught shortspines that may help to explain the growth, based on landings, in the non-trawl fishery through time. Trawl prices, on the other hand, increased from \$0.32/lb in 1990 to a high of \$0.87/lb in 2002 and have since declined with prices in recent years hovering around \$0.30/lb.

The foreign fishery off of the West Coast is estimated to have caught approximately 7,400 mt of shortspine thornyhead during the 11 year period from 1966-1976 (Rogers 2003), which is similar to the estimated domestic catch (~8,600 mt) during that same period.

Management measures have contributed to a decline in coastwide landings from an estimated peak of 4,815 mt in 1989 to between 1,000 and 2,000 mt per year from 1995 through 1998. Landings fell below 1,000 mt per year from 1999 through 2006, then rose to 1,531 in 2009 and have declined since (Table 9).

In 2011, the west coast trawl fishery was rationalized, with the introduction of the Individual Fishing Quota (IFQ) Program. In order to provide more flexibility for fishers on the west coast, NOAA Fisheries implemented the West Coast Groundfish Trawl Fishery Catch Share Program, which allows for the division of catch allocated to the trawl fishery into shares controlled by individuals or cooperatives (West Coast Regional Office n.d.). All vessels that participate in the IFQ program are required to have 100% observer coverage at all times the vessels are at sea (West Coast Regional Office n.d.).

1.6 Summary of Management History and Performance

Beginning in 1989, both thornyhead species were managed as part of a DTS complex. In 1991, the Pacific Fishery Management Council (PFMC) adopted separate ABC levels for

thornyheads and catch limits were imposed on the thornyhead complex, under the Pacific Coast Groundfish Fishery Management Plan (FMP). Harvest guideline (HG)s were instituted in 1992 along with an increase in the minimum mesh size for bottom trawl fisheries. In 1995 separate landing limits were placed on shortspine and longspine thornyhead and trip limits became more restrictive. Trip limits (predominantly 2-month limits on cumulative vessel landings) have often been adjusted during the year since 1995 in order to not exceed the HG or optimum yield (OY). At first, the HG for shortspine thornyhead was set higher than the ABC (1,500 vs. 1,000 mt in 1995-1997) in order to allow a greater catch of longspine thornyhead, which was considered relatively undepleted. In 1999 the OY was set at less than 1,000 mt and remained close to that level through 2006. As a result of the 2005 shortspine thornyhead assessment, catch limits increased to about 2,000 mt per year and have remained between 2,000 mt and 3,000 mt per year to present.

Since early 2011, trawl harvest of each thornyhead species has been managed under the PFMC's catch share, or individual fishing quota (IFQ), program. Whereas the trip limits previously used to limit harvest restricted only the amount of fish each vessel could land, individual vessels fishing under the catch-share program are now held accountable for all of the quota-share species they catch.

Landings of shortspine thornyhead have been below the catch limits since 1999. The estimated total catch, including discards, has likewise remained below the limit during this period (Table 6).

1.7 Fisheries off Canada, Alaska and/or Mexico

Shortspine thornyhead are also caught, dominantly in mixed species trawl fisheries, in Canada and Alaska. Catches of shortspine thornyhead off the coast of Canada have exhibited a similar pattern to those on the U.S. West Coast, with catches increasing in the late 1990s and then decreasing to present. A stock assessment for the coastwide population of shortspine thornyhead in British Columbia was last conducted in 2015 and indicated that shortspine thornyhead stock status in Canada is well above reference points and not overfished (Starr and Haigh 2017).

In Alaska, total thornyhead (shortspine and longspine) catches averaged 1,090 tons between 1977 and 1983 in the Gulf of Alaska and then declined markedly in 1984 and 1985, primarily due to restrictions on foreign fisheries imposed by U.S. management policies. Starting in 1985, catches of thornyheads increased, reaching a peak in 1989 with a total removal of 2,616 mt. Catches averaged about 980 mt between 2003 and 2018, when annual catch began to decrease (Echave et al. 2022). The Alaska Fisheries Science Center (AFSC) conducts assessments of thornyheads as a mixed stock complex, including shortspine and longspine thornyheads. Similar to the British Columbia assessment, results of the 2022 Alaska Thornyhead complex assessment suggest that Thornyheads are not being subjected to overfishing (Echave et al. 2022).

While the range of shortspine thornyhead extends down into Mexico, there is little information about Mexican catch of shortspine thornyhead and no stock assessment conducted in Mexico.

2 Data

Data comprise the foundational components of stock assessment models. The decision to include or exclude particular data sources in an assessment model depends on many factors. These factors often include, but are not limited to, the way in which data were collected (e.g., measurement method and consistency); the spatial and temporal coverage of the data; the quantity of data available per desired sampling unit; the representativeness of the data to inform the modeled processes of importance; timing of when the data were provided; limitations imposed by the Terms of Reference; and the presence of an avenue for the inclusion of the data in the assessment model. Attributes associated with a data source can change through time, as can the applicability of the data source when different modeling approaches are explored (e.g., stock structure or time-varying processes). Therefore, the specific data sources included or excluded from this assessment should not necessarily constrain the selection of data sources applicable to future stock assessments for shortspine thornyhead. Even if a data source is not directly used in the stock assessment they can provide valuable insights into biology, fishery behavior, or localized dynamics.

Data from a wide range of programs were available for possible inclusion in the current assessment model. Descriptions of each data source included in the model (Figure 4) and sources that were explored but not included in the base model are provided below. Data that were excluded from the base model were explicitly explored during the development of this stock assessment or have not changed since their past exploration in a previous shortspine thornyhead stock assessment. In some cases, the inclusion of excluded data sources were explored through sensitivity analyses.

2.1 Fishery-Dependent Data

2.1.1 Catch History

Data from the Pacific Fisheries Information Network (PacFIN) spanning 1981-present was used to estimate landings in the North (Oregon and Washington) and South (California) by gear type (Trawl and Non-Trawl) (Figure 3). One exception was Oregon data from 2017, which came from ODFW directly due to errors in the PacFIN data. All landings reported for the shortspine thornyhead and nominal shortspine thornyhead categories were considered shortspine thornyhead, whereas landings categorized as unidentified thornyheads were split between longspine thornyhead and shortspine thornyhead by the ratio of identified longspine

and shortspine landings to total thornyhead landings for each year-state-gear combination (Figure 2).

Catches prior to 1981 are based on historical reconstructions provided by the respective states and a reconstruction of foreign fleet catch. Oregon landings for 1892-1986 are provided by Oregon Department of Fish and Wildlife (ODFW) and reconstruction methods are outlined in Karnowski et al. (2014). Shortspine thornyhead landings in Oregon are not available in the PacFIN data for the years 1981-1986, so the state reconstruction is used for this period instead. Washington landings for 1954-1980 are provided by Washington Department of Fish and Wildlife (WDFW). Landings prior to the beginning of this data are assumed to be zero. California landings are provided by California Department of Fish and Wildlife (CDFW) and Southwest Fisheries Science Center (SWFSC), and consist of California commercial data for 1969-1980, and a catch reconstruction documented by Ralston et al. (2010) for 1934-1968. As in the two previous assessments, catch data from Rogers (2003) is used to account for catches by foreign fleets during the years 1966-1976. Foreign catch in the Monterey and Eureka International North Pacific Fishery Commission (INPFC) areas is attributed to the South Trawl fleet, while foreign catch in Columbia and Vancouver areas is attributed to the North Trawl fleet, as was the case in the 2013 assessment.

For historical catches prior to 1981, all shortspine thornyhead, nominal shortspine, and unidentified thornyhead landings in the state catch reconstructions are considered shortspine thornyhead. Neither California reconstructions prior to 1978, nor the Karnowski et al. (2014) reconstruction for Oregon, distinguish between shortspine and longspine thornyhead species. It is likely that assigning all thornyhead landings to shortspine overestimates total shortspine landings, however, the overwhelming majority of thornyhead landings were shortspine until the late 1980s when vessels began to move into deeper waters and a distinct fishery targeting longspine thornyhead developed (Hamel 2005; Karnowski et al. 2014).

This treatment of historical thornyhead landings differs from the 2005 and 2013 assessments. The 2005 assessment did not have access to the historical reconstructions used here, and instead imputed shortspine thornyhead landings as 30% of annual sablefish landings for the years 1901-1961. The 2013 assessment used the same imputed values as the 2005 assessment, but also conducted a sensitivity analysis in which all unassigned thornyheads in historical catch were considered shortspine thornyhead. Stock abundance estimates were found to be largely insensitive to which reconstructions were used (Taylor and Stephens 2013). The imputed historical values used for the 2005 and 2013 assessments will continue to be included as a sensitivity analysis here. Landings after 1961 from the state reconstructions remain very similar to the landings used in the 2013 assessment (Figure 3).

Unlike previous assessments, this assessment includes catches from the at-sea Pacific whiting fishery (data received from V. Tuttle, 5/15/2023). It includes both shortspine thornyhead catches, as well as unidentified thornyhead catches (the latter only available 1990 to present). Unidentified catches are apportioned based on the year-specific ratio of shortspine thornyhead to longspine thornyhead. There are only three years where Shortspine thornyheads represented less than 99% of thornyhead catches. The at-sea hake observer program

does not collect length composition data on thornyheads, so these catches are added to the northern trawl fleet, considered the most similar gear to the midwater trawls used for Pacific whiting.

2.1.2 Discards and retention

Predicted discards were based on estimated retention and selectivity for each fleet (Figure 5). Discards were informed by four data sources covering three different periods. Data sets included, 1) Pikitch et al. (1988) Discard and Mesh Studies, used to estimate both discard rates and length composition of the northern trawl fleet between 1985 and 1987 (John. R. Wallace, NWFSC pers. comm.), 2) the EDCP covering 1995-1999, which only informed discard rates of the northern trawl fleet, 3) the WCGOP, which provided discard rates, length composition, and individual average weight for years between 2002 and 2021 for all fleets, and 4) the Groundfish Expanded Mortality Multi-Year (GEMM) data set, covering the same period as the WCGOP with catch-share participation information and estimates of discard survival rates.

While the estimates from the first two data sets were directly integrated into the model, fleet discard rates after 2011 were available separately for catch-share and non-catch-share programs. Final, fleet-specific, discard rates were thus computed as the average WCGOP discard rate weighted by the relative proportion of total landings belonging to the catch-share and non-catch-share, respectively (Figure 6). Regardless of the type of data, all estimates derived from these data sets had associated uncertainty accounting for the variability observed within the sample of hauls and fishing trips of each fleet. WCGOP-derived discard rates are an exception as, after the catch share program was initiated in 2011, 100% of hauls from catch share fleets were observed, while non-catch share vessels were only partially covered (West Coast Regional Office n.d.).

The discard data sources were the same as those used in the 2013 assessment. The main improvements are the increased representativeness of all 4 fleets (11 more years) and more accurate estimates of discard rates from EDCP that were not ready at the time of the previous assessment. Last, some errors in the previous assessment were corrected regarding the weight units considered for the average individual weight (WCGOP provides weight as pounds and not as kg).

2.1.3 Fishery Length Compositions

Commercial fishery length-composition data were obtained from PacFIN for 1978-2023. Due to variations in sampling effort and because the number of fish sampled by port samplers is not proportional to the amount of landed catch in each trip, the observed length data were expanded using the following algorithm using the **PacFIN.Utilities** package in R (Johnson and Stephens 2023):

1. Length data were acquired at the trip level by sex, year and state.
2. The raw numbers in each trip were scaled by a per-trip expansion factor calculated by dividing the total weight of trip landings by the total weight of the species sampled.
3. A per-year, per-state expansion factor was computed by dividing the total weight of state landings by the total weight of the species sampled for length in the state.
4. The per-trip expanded numbers were multiplied by the per-state expansion factor and summed to provide the coast-wide length-frequency distributions by year.

Only randomly collected samples were used. The sample sizes associated with the length compositions from the fishing fleets are shown in Table 12 (landings) and Table 13 (discards).

Input sample sizes, N_{input} , for fishery length frequency distributions by year were calculated as a function of the number of trips and number of fish via the Stewart Method (Stewart, pers. comm.):

$$N_{input} = N_{trips} + 0.138N_{fish} \quad \text{when } \frac{N_{fish}}{N_{trips}} < 44 \quad (1)$$

$$N_{input} = 7.06N_{trips} \quad \text{when } \frac{N_{fish}}{N_{trips}} \geq 44 \quad (2)$$

The method is based on analysis of the input and model-derived effective sample sizes from west coast groundfish stock assessments. A piece-wise linear regression was used to estimate the increase in effective sample size per sample based on fish-per-sample and the maximum effective sample size for large numbers of individual fish.

All length data from commercial fisheries were included in the model with sexes combined. This avoids the possibility of bias due to difficulty in sex determination of thornyheads.

2.1.4 Age Compositions

No age composition data was used for this assessment because thornyheads are very difficult to age (Patrick MacDonald, NWFSC, pers. comm.). Even in directed studies such as those done by Kline (1996) and Butler (1995), there are large inter-reader differences, and a second reading by the same reader can produce a markedly different result. Kline (1996) reported only about 60% of the multiple reads were within 5 years of each other, and inter-reader differences were as large as 24 years for a sample of 50 otoliths. No production ageing of thornyheads is undertaken at this time for the west coast (or Alaska), although shortspine thornyhead otoliths are routinely collected in the NWFSC trawl survey.

2.2 Fishery-Independent Data

Four trawl surveys have been conducted on the U.S. west coast over the past four decades.

2.2.1 AFSC/NWFSC West Coast Triennial Shelf Survey

The AFSC conducted a triennial groundfish trawl survey (the Triennial Survey) on the continental shelf from 1977 to 2001, although the 1977 survey had incomplete coverage and is not believed to be comparable to the later years. A final survey was conducted in 2004 by the NWFSC using the same survey design. In 1995, the timing of the survey shifted from mid-July and late September to early June through mid-August. In 1980–1992 the survey had a maximum depth of 366 m, while from 1995 onward, the maximum depth was extended to 500 m. The shallow limit of the survey was 55 m in all years, but for purposes of computing indices, only tows deeper than 100 m were used as shortspine thornyhead are rarely seen at shallower depths.

For some species, the shift in timing between the 1992 and 1995 surveys would be expected to influence their catchability, availability, or distribution. However, thornyheads are believed to be sedentary enough that the change in timing would not be as influential. On the other hand, the increase in depth is expected to significantly increase the range of shortspine thornyhead habitat covered by the survey. In the 2013 assessment, the triennial survey was split into two timeseries, separated by the 366 m depth contour, in order to preserve a time series of maximum duration while eliminating the influence of the increased depth range. The first time series, “AFSC Triennial Shelf Survey 1”, consisted of 9 data points spanning the range 1980–2004 and covering the depths 100–366 m. The second, “AFSC Triennial Shelf Survey 2”, consisted of 4 data points spanning 1995–2004 and covering depths 366–500 m. This second time series is recognized as providing little information about stock status due to the limited number of points and depth range, but there was no compelling reason to exclude it from the 2013 assessment. In contrast to the 2013 assessment, this assessment treated the Triennial Survey as a single time series for the geostatistical model-based indices, and used a different set of latitudinal and depth-based strata for survey length compositions (see Section 2.2.7).

2.2.2 AFSC and NWFSC Slope Surveys

Starting in the late 1990s, two slope surveys were conducted on the west coast. The AFSC Slope Survey (AFSC Slope Survey) was conducted during the years 1997 and 1999–2001 using the research vessel Miller Freeman. The NWFSC Slope Survey (NWFSC Slope Survey) was conducted from 1998–2002, and was conducted cooperatively using commercial fishing vessels. The AFSC Slope Survey was a source of valuable information on the depth distribution and overlap of shortspine and longspine thornyheads in the 1980s, but these

early years had a very limited latitudinal range and will not be included. This survey also had a different net and larger roller gear than the NWFSC Slope Survey.

Neither of these surveys were included in the base model, as they represent relatively short temporal scales (4 years for the AFSC Slope Survey, and 5 years for the NWFSC Slope Survey) over a period for which survey data already exists (Triennial Survey covers this period, though at a sparser temporal resolution).

2.2.3 NWFSC West Coast Groundfish Bottom Trawl Survey

In 2003, the design of the NWFSC Slope Survey was modified, and the survey was expanded to cover the shelf and slope between 50 m and 1280 m. This combination shelf-slope survey, “NWFSC Combo Survey”, more recently known as the WCGBTS, has been conducted every year from 2003 to present with consistent design (note that the survey was not conducted in 2020 due to ongoing concerns about COVID-19). Data for the years 2003–2022 were available for this assessment. The WCGBTS represents the largest number of survey observations, the largest depth range, and the most consistent groundfish sampling program in the history of west coast fisheries. Continuing this time series in a consistent manner is vital for improving estimates of current stock status and detecting any future changes in size distribution or abundance of west coast groundfish.

2.2.4 Survey Stratification

Data from these four (nominally five for design-based indices) fishery-independent surveys were considered for use in this assessment (Figure 7) to estimate abundance. Two distinct survey abundance estimation methods were considered: design-based and geostatistical model-based indices. The 2013 assessment utilized delta-GLMMs, following the methods of Thorson and Ward (2013), to compute their indices of abundances, but these methods are no longer considered best practice within the field and were not considered in this assessment.

The five surveys were stratified based on depth and latitude, similar to how they were in 2013 (Table 14). The Triennial Survey was divided into two distinct survey time series, split on the year 1995. The early-Triennial time series (1981-1992) was further stratified into four strata: north and south of 42 ° N, and shallower and deeper than 200m. The late-Triennial time series (1995-2004) was also further stratified into four strata: north and south of 40 ° N, and shallower and deeper than 200m. Note that this stratification scheme, as well as the two timeseries, applied to the Triennial Survey length composition data and design-based indices of abundance only. The geostatistical model-based indices that are used in the base model treat the Triennial Survey as a single timeseries of abundance. The AFSC Slope Survey was split into two coast-wide strata: shallow and deeper than 550m. The NWFSC Slope Survey was divided into 6 strata, with breaks dividing southern, central, and northern strata at

40.5° N and 43° N, each of which was further divided with a break at 550 m. The WCGBTS was divided into 7 strata, with two southern strata below 34.5° N, one covering 183–550 m and the other covering 550–1280 m. Two central strata, between 34.5° N and 40.5° N, had the same depth ranges. The latitudinal divide around 34.5° N is associated with changes in sampling intensity. North of 40.5° N, three strata were used, covering the ranges 100–183 m, 183–550 m, and the other covering 550–1280 m. The depth breaks at 183 m and 550 m are also associated with changes in the sampling intensity of the survey and are recommended to be used. South of 40.5° N, there are very few shortspine thornyhead shallower than 183 m, so no shallow stratum was used in these latitudes. The 2013 stratification was reused for the design-based indices as there was not sufficient evidence to support modifying the existing strata.

2.2.5 Design-based Indices of Abundance

Design-based indices of abundance were derived for all surveys (Figure 8). Note that for these indices of abundance, the Triennial Survey was split into two independent time series, separated by the year 1995. The construction of design-based indices mirrors a weighted average approach. For each survey year, an average CPUE is calculated across all tows within a stratum and expanded by area to determine the total estimated biomass. These values are then summed across all strata within the survey to create a time series of design-based indices of abundance. Design-based indices were computed using the official `nwfscSurvey` R package (Wetzel et al. 2023).

2.2.6 Geostatistical Model-based Indices of Abundance

Model-based indices of abundance (Figure 9) for all surveys were derived using geostatistical models (Thorson et al. 2015) developed using the R package `sdmTMB` (Anderson et al. 2022). This approach utilizes geostatistical GLMMs with spatially and spatiotemporally correlated random effects, which can account for variables that cause correlations in the data across space and time. For this reason, the Triennial Survey can be, and was, treated as a single time series rather than split into two timeseries based on the introduction of additional sampling at greater depths. For the Triennial Survey, the geostatistical model included spatial and spatiotemporal random effects and depth and depth squared as a scaled covariate. Geostatistical models for the NWFSC Slope Survey, AFSC Slope Survey, and WCGBTS surveys were not run with depth as a covariate.

Abundance indices were obtained for models using both gamma and log-normal error structures. There is limited agreement on how best to go about model selection for these types of geostatistical models, and both error structures were tested as sensitivity analyses alongside the simple design-based indices described above. The abundance indices derived from the gamma model were most similar to the design-based indices for the Triennial and WCGBT

surveys and were thus used for the base model (indices derived from the log-normal model displayed a similar trend to the gamma model-based indices, and the design-based indices, but were consistently larger in scale).

2.2.7 Length Composition Data

Length-composition data were available for each year of each survey including the AFSC Slope Survey, the NWFSC Slope Survey, the WCGBTS, and the Triennial Survey. For the Triennial survey, length compositions were divided into an early period (pre-1995), hereafter referred to as the “early-period Triennial” and late period (post-1995), hereafter referred to as the “late-period Triennial” survey, to account for the change in depth-sampling, and resulting selectivity, that occurred during the 1995 season. The early-period Triennial survey only uses data from 1989 and 1992 due to limited spatial coverage and sample sizes in other years. For all surveys, each haul consists of a set number of random samples regardless of the amount of catch, decoupling the sample and catch size. Therefore, the length compositions were calculated using an expansion factor to account for differences in the amount of catch that samples represent. An expansion factor (calculated as weight of caught fish divided by weight of fish sampled) is calculated for each haul, multiplied by the number of fish in each size bin, and then summed across hauls. This algorithm is repeated for each spatial stratum. Length composition data were compiled into 34, 2cm, length bins, ranging from 6 to 72 cm. Year-specific length frequency distributions generated for each survey are shown in Figure 11.

2.2.8 Frequency of Occurrence and Survey Information

The frequency of occurrence of shortspine and longspine thornyhead in trawl surveys remains extremely high. 91% of the tows in the WCGBTS below 500 m have at least one shortspine thornyhead in the catch (and 96% for longspine thornyhead), similar to the 2013 assessment. The number of survey hauls and shortspine thornyhead sampled available for this assessment is described in Table 15.

2.3 Biological Data

2.3.1 Natural Mortality

Butler (1995) estimated the lifespan of shortspine thornyhead to exceed 100 years and suggested that M was likely less than 0.05. M may decrease with age as shortspine migrate ontogenetically down the slope to the oxygen minimum zone, which is largely devoid of

predators for fish of their body size. The 2005 assessment fixed the natural mortality parameter at 0.05, while the 2013 assessment used a prior on natural mortality based on a maximum age of 100 years. The prior had a mean of 0.0505 and a standard deviation on a log scale of 0.5361 (Owen Hamel,NWFSC, pers. comm.). For the base model, natural mortality was fixed at 0.04. This implies an A_{max} of ~135 years following the mortality prior of Hamel and Cope (2022).

2.3.2 Maturation and Fecundity

2.3.2.1 Maturity Pearson and Gunderson (2003) estimated a length at 50% maturity of 18.2 cm on the West Coast, with most females maturing between 17 and 19 cm. This was represented in the 2005 and 2013 assessments by the logistic function,

$$M(L) = (1 + e^{-2.3(L-18.2)}) - 1 \quad (3)$$

where L is the length in cm.

The 2013 assessment considered new (at the time) maturity information from ovaries collected for maturity analysis on the 2011 and 2012 WCGBTS. Histological analysis of those samples (Melissa Head, NWFSC, pers. comm.) indicated puzzling patterns of spawning by female size and by latitude, with a higher fraction of fish spawning in the north than in the south and a higher fraction of spawning fish in the 20-30 cm range than in the 30-40 cm range. However, due to the complexity of these observed patterns and the known ontogenetic migrations of shortspine thornyhead, samples collected in 2011 and 2013 were not considered adequate for estimation of a new representative maturity curve for the entire shortspine thornyhead population in 2013. Nonetheless, such a maturity curve was considered in a sensitivity analysis. On the basis of the sensitivity analysis, the 2013 assessment suggested that the slow but steady rate of growth for shortspine thornyhead, with growth still occurring at age 100, reduces the importance of assumptions about maturity because older individuals have significantly higher spawning output due to their much larger size, regardless of the fraction spawning.

New maturity analyses of samples collected on the WCGBTS in 2011, 2013, 2014, 2016 and 2018 were available for the 2023 assessment (Melissa Head, NWFSC, pers. comm.). The larger number ($N=397$) and better spatial coverage of these samples allowed the use of statistical modeling to better understand the spatial variation in the proportion of female spawning.

In the 2013 assessment, the exploration of maturity analyses from the WCGBTS samples highlighted maturity gradients along latitude and depth. To assess a potential relationship between fish location and the shape of the maturity curve, a Generalized Linear Model (GLM) was designed for estimating maturity curve parameters while integrating latitude

and depth as covariates. This GLM consists of a logistic regression in which the functional maturity of samples, modeled with a Bernoulli distribution, is expressed as a linear combination of fish length, latitude, latitude squared, depth and depth squared. Once fitted, the GLM was used to predict the response of the probability of being mature along the range of individual shortspine thornyhead length considered in the model. For the 2023 assessment, this model prediction was made while setting the latitude and depth at the values of the center of gravity (using number of fish as a weighing factor) of the population of shortspine thornyhead sampled by the WCGBTS to develop a single curve for the coastwide population assessment. Thus, this response of functional maturity to length was considered the mean maturity curve of the west coast shortspine thornyhead population. The parameters of the maturity curve L_{50} and k were arithmetically derived from this response to fish length. The new maturity curve is expressed as follows:

$$M(L) = (1 + e^{-2.3(L-31.42)})^{-1} \quad (4)$$

Figure 15 shows the fit of the maturity curve of the model per class of depth and latitude.

A sensitivity analysis assessed the impact of this change in the maturity curve on the model estimates by considering the newly estimated parameters, the Pearson and Gunderson relationship from 2013, and an intermediate option (Figure 14).

2.3.2.2 Fecundity The previous assessments assumed spawning biomass was equivalent to spawning output. The current assessment uses fecundity-at-length parameters reported in Cooper et al. (2005). Fecundity is modeled as a power function of length:

$$F = 0.0544L^{3.978} \quad (5)$$

where F is fecundity in the number of eggs per female and L is length in cm. Cooper et al. (2005) estimated the fecundity of 54 females collected from the West Coast and Alaska. They found no difference in the length-fecundity relationship by region and pooled the samples. That study suggested that fecundity increases at a faster rate with length than body weight with length for shortspine thornyhead, meaning that larger females have greater relative fecundity compared to small females. This assessment models a fecundity-at-length relationship using the fecundity parameters from Cooper et al. (2005) (Figure 16) and scaling the fecundity intercept by one million to report fecundity in billions of eggs.

Uncertainty remains in the spawning strategy of shortspine thornyhead. Cooper et al. (2005) and Pearson and Gunderson (2003) found no evidence of batch spawning in this species (i.e., a determinate, total spawning strategy). However, updated histological information suggests a possibility of batch spawning (Melissa Head, NWFSC, pers. comm.). Batch spawning could influence the fecundity-at-length relationship if not properly accounted for and should be a focus of future research.

2.3.3 Length-Weight Relationship

Fisheries-independent length and weight specimen data were available from the AFSC Slope Survey (1997, 1999-2001; $N=7,623$) and the WGBTS (2003-2021, excluding 2020; $N=20,142$). The WGBTS data were used to estimate the length-weight relationship because it had the largest sample size and covered the greatest spatio-temporal resolution. Unsexed fish <16 cm in length, and obvious outliers were removed from the dataset prior to fitting the relationship. The allometric function models weight (W) as a power function of length (L), where:

$$W = \alpha L^\beta \quad (6)$$

This function can be linearized by taking the natural logarithm of both sides. The predicted weight-at-length values were bias-corrected using a multiplier of $\sigma^2/2$. The length-weight parameters were estimated for both sexes in R using the `lm()` function (R Core Team 2021).

The resulting parameters for 2023 (females: $\alpha = 4.86 \times 10^{-6}$, $\beta = 3.26$; males: $\alpha = 4.69 \times 10^{-6}$, $\beta = 3.25$; Figure 13) were very similar to the 2013 assessment values, which estimated a single length-weight relationship for males and females combined using WGBTS data through 2012 (sexes combined: $\alpha = 4.77 \times 10^{-6}$, $\beta = 3.26$). The available data suggested that length-weight is highly conserved in shortspine thornyhead; therefore, no sensitivity analysis was conducted for this set of parameters in the 2023 assessment.

2.3.4 Growth (Length-at-Age)

No validated ageing methods currently exist for shortspine thornyhead; therefore, this species is not aged by the NWFSC or SWFSC and length-at-age data were limited for this stock assessment. Two research age datasets exist for shortspine thornyhead in the West Coast region: (1) Kline (1996) includes 319 unsexed fish collected from Monterey Bay in central California in 1991, and (2) Butler (1995) includes 1,023 sexed fish collected in the waters off northern California and Oregon in 1978-1988 and 1990. The Kline specimens were aged by one age reader, and lengths were reported as total lengths, whereas the Butler specimens were aged independently by two separate age readers, and lengths were reported in fork length. The Butler data age data used in this assessment are the mean ages between the two age readers.

The length-at-age curve developed in the 2005 stock assessment and used again in 2013 was based on a Schnute parameterization of the Von-Bertalanffy growth function fit to the Kline data. The resulting parameter estimates for this growth function were as follows: growth rate k was 0.018 for both males and females, length at age-2 was 7 cm for both males and females, and length at age-100 was 67.5 cm for males and 75 cm for females based on the

assumption that the asymptotic length for males should be 90% of the asymptotic length for females (Hamel 2005). The data and associated analysis from 2005 were lost; however, the original Kline and Butler datasets were obtained for use in this assessment (Donna Kline, pers. comm., March 2023). Using these newly obtained data, we could not reproduce the parameters used in the 2005 assessment.

Because the Butler data were sex-specific, had a higher sample size, were aged by two readers instead of one, and were collected from a larger geographic area and over more years compared to the Kline data, we determined that Butler was the preferred dataset to estimate the length-at-age relationship for the 2023 stock assessment. We fit sex-specific Schnute growth functions to the Butler data:

$$\hat{L}_a = L_{a_1} + \frac{(L_{a_2} - L_{a_1})(1 - \exp(-k(a_2 - a_1)))}{(1 - \exp(-k(a_2 - a_1)))} \quad (7)$$

where: L_{a_1} and L_{a_2} are the lengths at reference ages a_1 and a_2 where $a_1 = 1$; $a_2 = 100$ and k is the growth rate. Growth curve estimation was conducted in R using the optim() function (R Core Team 2021). Errors were assumed to be lognormally distributed and predicted length-at-age was bias-corrected using a multiplier of $\sigma^2/2$. Updated growth parameters were fixed in the assessment at the following values using the reference ages and equation described above:

Females: $La_1 = 11.4$ cm; $La_2 = 73.6$ cm; $k = 0.0099$ per year

Males: $La_1 = 9.2$ cm; $La_2 = 66.1$ cm; $k = 0.0168$ per year

For reference, the equivalent von-Bertalanffy growth parameters are:

Females: $t_0 = -8.931$; $L_{inf} = 111.0$ cm; $k = 0.0099$ per year

Males: $t_0 = -5.314$; $L_{inf} = 79.4$ cm; $k = 0.0168$ per year

Shortspine thornyhead are slow-growing fish that appear to continue to grow throughout their lifespan (i.e., the growth curve does not asymptote). The new growth curves estimated using the Butler dataset exhibited similar trends to those assumed in the 2005 and 2013 assessments (Figure 12). The male curves were almost identical, with the 2005/2013 curve exhibiting slightly lower length-at-age at young ages and slightly higher length-at-age at older ages. The 2005/2013 female curve was defined by a higher growth rate, leading to the higher length-at-age in the intermediate age range.

Two alternative sensitivity analyses were developed for the 2023 assessment. During the exploratory data analysis phase, we found that specimens collected in the Kline study exhibited higher size-at-age when compared to the Butler specimens (Figure 12). It is unknown if these differences should be attributed to spatial differences in growth between central California and northern California/Oregon, bias among age readers, or discrepancies between

the total and fork length measurements (Donna Kline, pers. comm., March 2023). In order to account for this alternative growth pattern, we increased the lengths at ages 2 and 100 by 25% in the upper sensitivity analysis (Figure 12). The lower sensitivity analysis was defined by decreasing the lengths at ages 2 and 100 by 10% from the base model.

2.4 Environmental and Ecosystem Data

No ecological or environmental information was used in this assessment.

2.5 Changes in data from the 2013 assessment

Most of the data used in the previous assessment has been newly extracted and processed, including length compositions from each fishing fleet and survey, indices of abundance derived from new geostatistical models of survey data, discard rates from both the 1980s Pikitch study and the current WCGOP, and the time series of catch from 1900-2023.

New data or uses of data for this assessment include the geostatistical model-based indices of abundance for the four fisheries independent surveys, the histological maturity samples from the WCCBTS survey, and the historical state catch reconstructions. Previous assessments have treated the AFSC Triennial Shelf Survey as two separate indices of abundance separated by the 366m depth contour, but the transition to using geostatistical model-based indices have rendered this separation unnecessary by implicitly accounting for changes in depth sampling within the model. State-level historical reconstructions also replace previous analyses that imputed historical shortspine thornyhead catch as a fixed proportion of sablefish catch.

3 Assessment Model

3.1 Summary of Previous Assessments and Reviews

3.1.1 History of Modeling Approaches

Shortspine thornyhead was first assessed in 1990 by Jacobson (1990) and Jacobson (1991), and subsequently by Ianelli et al. (1994), Rogers et al. (1998), and Piner and Methot (2001). What would now be called a data-moderate assessment was conducted in 2005 (Hamel 2005) using Stock Synthesis (SS2). More recently, shortspine thornyhead were assessed by Taylor and Stephens (2013) using SS3. The 2013 model retained many of the assumptions made by Hamel (2005) including a four fisheries fleet structure, sex-specific growth, and no fecundity relationship. A catch-only projection was conducted in 2019 (Taylor 2019).

3.1.2 Most Recent STAR Panel Recommendations

The most recent assessment made a number of recommendations for data availability and modeling. Major recommendations included:

1. More investigation into maturity of shortspine thornyhead.

Progress: A new maturity curve was derived from new histological samples taken during the WCGBTS and processed by Melissa Head. The new maturity curve implies that maturation occurs at much larger lengths, and much more slowly, than what was assumed in 2013.

2. Information on possible migration of shortspine thornyhead would be valuable for understanding stock dynamics.
3. A greater understanding of catchability of shortspine thornyhead would help define the scale of the populations.

Progress: The degree of uncertainty in the scale of the population has substantially decreased since 2012, and the catchability coefficients in the current model are computed analytically by Stock Synthesis. Likelihood profiles over R_0 and M imply they have a much stronger relationship with overall population scale the analytically derived catchability values.

4. Age data and additional research on ageing methods for thornyheads would be valuable.

Progress: Age data and aging methods remain limited for shortspine thornyhead.

5. A greater understanding of the connection between shortspine thornyhead and bottom type could be used to refine the indices of abundance.
6. A comprehensive catch reconstruction for shortspine and longspine thornyheads should be completed to estimate landings for each species prior to 1981 in each of the three states.

Progress: State-level catch reconstructions were integrated into the base model for 2023. They represented a minimal change in the catch timeseries as compared to the 2013 assessment.

7. Exploration of simpler assessment methods for shortspine thornyhead and evaluation of whether such methods would provide a more robust management strategy than the current approach.

Progress: While simpler methods were not tested for this assessment, the model structure was significantly reduced from four fleets and five surveys, to three fleets and two surveys. This significantly reduced the total number of parameters that needed to be estimated by the model.

8. More tows or visual surveys south of 34.5 deg. N. lat. including the large Cowcod Conservation Area (CCA). Because the southern Conception Area is a large potential habitat for shortspine thornyhead, more sampling effort would help refine the estimations of their abundance in this area.

3.1.3 Response to STAR Panel and SSC Requests

TBD

3.2 Model Structure and Assumptions

3.2.1 Model Changes from the Last Assessment

The most notable changes from the previous assessment, conducted in 2013, include significant modifications to the fleet and survey structure, and major changes to the maturity and fecundity relationships that underlie the model’s biological assumptions.

The 2013 assessment consisted of four fisheries fleets, and used information from four (nominally five) scientific surveys, while the new assessment uses a condensed structure consisting of just three fisheries fleets and only two (nominally three) surveys (see Section 3.2.3 for more details).

This assessment assumes a new fecundity relationship, in which fecundity increases with body size, as well as a new maturity relationship, in which fish mature at much larger sizes and thus older ages, than were assumed in the 2013 assessment. Further details on the fecundity and maturity relationships can be found in Section 2.3.2. A sensitivity analysis was performed to determine the effect of different maturity assumptions on the final model output.

3.2.2 Modeling Platform and Bridging Analysis

This new assessment, including all exploratory models, profiles, and related analyses, was performed using Stock Synthesis Version 3.30.21 [Methot and Wetzel (2013); Methot et al.

(2020)). The majority of analyses were performed using multiple recent versions of R (R Core Team 2021), and relied heavily on the `r4ss` R package (Taylor et al. 2021) among others. The assessment model was developed and tested across multiple operating systems, including recent versions of Windows and macOS.

The process of bridging to a new model occurred in two steps. The initial bridging phase focused on the conversion from version SS-V3.24o to version SS-V3.30.21 using the same data and model assumptions used in the 2013 assessment. Two models were built during this first step: an initial model which fixed parameter values at the values estimated in the 2013 assessment (“2013 Model SS V3.30.21 Fixed Params”) and a second model which estimated all parameters as assumed in the 2013 assessment (“2013 Model SS V3.30.21”).

The subsequent bridging exercise involved updating the model (“2013 Model SS V3.30.21”) with the addition of new and reprocessed data through 2023 as well as updating biological parameters (growth, maturity, fecundity, and mortality parameters - see Section 2.3 for more details). Additional data include new catch, discard, survey indices, length-composition, and mean body weight (for discards only) data. The contribution of each data component and parameter update to the changes in the model outcome were analyzed by adding data and updating parameters in a linear piecewise fashion.

While there were no discernible changes between the 2013 assessment and the “2013 Model SS V3.30.21 Fixed Params” model, differences were observed in the estimated spawning biomass, recruitment (age-0 fish), and fraction of unfished time series between these two models and the “2013 Model SS V3.30.21” model (marginally smaller spawning biomass and recruitment along with a smaller depletion level from the end 1970s onward; Figure 17). The source of these changes can be attributed to differences in the way of analytically computing survey catchability (“floatQ” approach, see Section 3.2.4.3) between the two versions of Stock Synthesis.

Inclusion of new data and updated parameters resulted in a series of changes to model outcomes (Figure 18, Figure 19). While the update of both growth and maturity parameters led to variation of spawning biomass in the range of the uncertainty previously observed (models “Updated Growth” and “Updated Maturity”, respectively), the one notable change in the estimates of spawning biomass occurs with the update of fecundity parameters (model “Updated Fecundity”) which resulted in a strong downward revision of the spawning biomass time series. This major change can be explained by the use of a new length-based fecundity relationship which was not considered in the previous assessment (see Section 1.1.1 for more information).

3.2.3 Model Structure

Similar to the 2013 assessment, the 2023 assessment model is a two-sex, length-based age-structured model that estimates population dynamics from 1901 onwards. The model as-

sumes a steady equilibrium state with no fishing prior to the start year of the model (1901) and considers a spatially homogeneous unit stock in the waters off the U.S. West Coast.

Commercial fisheries landings were divided into three distinct fisheries fleets: a northern trawl fleet (hereinafter referred to as North Trawl) operating off the coasts of Oregon and Washington, a southern trawl fleet (hereinafter referred to as South Trawl) operating off the coast of California, and a coastwide non-trawl fleet (hereinafter referred to as Non-trawl).

Data from two fisheries-independent scientific surveys were used in this model: the Triennial Survey from 1980-2004, and the more recent WCGBTS from 2003-2022. The Triennial Survey length compositions were further divided into an early (pre-1995) and late period (post-1995) survey to account for changes in selectivity due to the change in depth-sampling that occurred during the 1995 season. These two periods for the Triennial Survey were treated as separate surveys in the model. The Triennial Survey abundance index timeseries is treated as a single timeseries spanning 1980-2004. The contribution of each new data component to the changes in the assessment outcome was analyzed by adding data in a linear piecewise way in order to understand how each change contributed to the model outcome.

3.2.4 Model Parameters

There are 195 estimated parameters in this assessment. The log of unfished recruitment, $\ln(R_0)$, controls the overall scale of the population, while annual deviations in recruitment about the assumed stock-recruit relationship (135 parameters) allow for additional uncertainty in the population trajectory and tracking of recent recruitment events. Selectivity and retention parameters (57 parameters) for three fisheries fleets and three scientific surveys allow for estimation of annual length compositions and discards rates. Two catchability parameters are analytically computed from the data, and one additional parameter, representing additional variability in the early Triennial Survey, is directly estimated by the model. A variety of selectivity and retention blocks are utilized to improve fits to the length composition and discard rate information (Figure 69)

3.2.4.1 Growth, Maturity, Fecundity, Mortality, and Recruitment

Growth, maturity, and fecundity parameters were fixed at values determined by external analyses (see **Section 2.3** for more information). Due to a lack of aging data, growth could not be modeled internally by the assessment, though, like in the 2005 and 2013 models, there is no systematic misfit to the data suggesting that the externally derived growth curves were misspecified. Sensitivity analyses were performed to determine the overall effect of different assumptions regarding growth and maturity.

For this assessment, natural mortality (M) was fixed at a value of 0.04, as such a value provided better fits to the data and literature information implies that the maximum age of

shortspine thornyhead could be well over 100 years. A likelihood profile exploring alternative natural mortality values was also conducted (Figure 53). In the 2013 assessment, M was fixed at 0.0505 Taylor and Stephens (2013), however, because shortspine thornyhead are difficult to age, aging error may bias age to be lower and they may live longer than those caught in surveys or fishing fleets, likely at deeper depths. Recent shortspine thornyhead assessments in Alaska and British Columbia used much lower M, as low as 0.03, in their models (Starr and Haigh 2017; Echave et al. 2022).

As in the previous shortspine thornyhead assessment, a Beverton-Holt stock recruitment relationship was assumed. Unlike the 2013 assessment, where steepness was fixed at a value of 0.60, this assessment fixed steepness at 0.72, as recommended by Thorson et al. (2019). A likelihood profile exploring alternative steepness parameters was conducted and the model results were found to be largely insensitive to the assumed value (Figure 52).

The overall scale of the population is estimated through the log of the initial recruitment parameter (R_0). Recruitment deviations were additionally estimated for the years 1901-2022. Recruitment bias adjustments were phased in beginning in 1950, and were adjusted by a factor of 0.75 in the years 1982-2022 (Taylor and Methot 2013). The σ_R parameter which controls the variability in recruitment deviations was fixed at 0.5 as in the previous assessment. Past assessments performed likelihood profiles over σ_R , finding the model results to be relatively insensitive to its value, and thus further profiles over the parameter were not conducted here.

3.2.4.2 Selectivity and Retention Gear selectivity parameters used in this assessment were specified as a function of size with the additional assumption that age 0 fish were not selected, regardless of their size. Separate size-based selectivity curves were fit to each fishery fleet and survey.

The selectivity curves for all fisheries and surveys were allowed to be dome-shaped and modeled with double-normal selectivity. The double-normal selectivity curve parameterization has six parameters, including: (1) peak, the length at which individuals are first fully selected, (2) width of the selectivity plateau, (3) width of the ascending part of the curve, (4) width of the descending part of the curve, (5) starting selectivity, and (6) final selectivity. Parameters 5 and 6 were not estimated and fixed at 0.0. The 2013 model allowed for all selectivity parameters to be estimated, regardless of whether one or more were estimated to be on the parameter bound. This model fixed parameter 2 (the plateau width) to the value of -15 for the North Trawl and Non-trawl fleets to alleviate them hitting the lower parameter bound. Though exploratory models run with the plateau width on its lower bound still converged, fixing the parameter had negligible impact on the fits to the length composition data for those fleets. Sex-specific selectivity curves were fit to the WCGBTS and Triennial Survey length composition data.

As a new exploration in this assessment, a sensitivity analysis was conducted to assess the response of the model to time-varying selectivity peak for trawl fleets. Different combinations

of time blocks were considered, all designed to account for potential structural changes in these fisheries: 2003, for the implementation of rockfish conservation areas, 2011 for the start of the IFQ program and 2020 for potential COVID-induced changes in fisheries dynamics.

Retention curves are defined as a logistic function of size. These are controlled by four parameters: (1) inflection, (2) slope, (3) asymptotic retention, and (4) male offset to inflection. Male offset to retention was fixed at 0 (i.e. no male offset was applied). The parameters for inflection and asymptotic retention (asymptotic retention was estimated for North Trawl and Non-Trawl, and fixed for South Trawl as estimate was hitting the upper parameter bound) were modeled as time-varying quantities via use of time blocks, as was done in the 2013 assessment. Both North Trawl and South Trawl fleets were broken into the same three periods as in the 2013 assessment: (1) 1901–2006, (2) 2007–2010, (3) 2011–2022. The first break was based on observation of a strong reduction in discard rates for both North and South Trawl in this year, while the later break was associated with the beginning of the IFQ program. After merging the two Non-Trawl fleets previously considered in the 2013, the reasons that justified the time blocks used in the 2013 assessment were not pertinent anymore and we decided not to represent time-varying retention for this fleet.

Alternative retention blocking schemes were investigated as part of a sensitivity analysis. Notably, a sequence of shorter time blocks starting after 2007 was investigated in order to better fit noticeably lower discards rates in the mid 2010s. Additionally, a short, 3-year, timeblock for the years 2020 and 2022 was also attempted, as discard rates were noticeably higher in those years than in previous.

3.2.4.3 Catchability Catchability coefficients (q) were calculated for each of the two survey abundance time series. Like the 2013 model, catchability was analytically for each survey using the Stock Synthesis “floatQ” option, though the exact analytical computation has changed from what was used in 2013 (Methot et al. 2020).

This model depends on the assumptions that thornyheads are long-lived, slow-growing, and relatively sedentary groundfish. They are assumed to represent a single stock within the area considered for this assessment. If the assumptions about growth, natural mortality, or stock structure turn out to be far from the true life history and ecology of shortspine thornyheads, this assessment will be highly inaccurate.

3.3 Base Model Results

3.3.1 Parameter Estimates

A complete set of parameter estimates are available in Table 18.

3.3.1.1 Recruitment The model estimated 135 annual recruitment deviations (1901-2034) as well as the log of unfished recruitment $\ln(R_0)$. Unfished recruitment was estimated to be ~12,580,000 annual age-0 recruits ($\ln(R_0) = 9.44$) while annual log deviations were generally estimated between -0.5 and 0.5 (Figure 20 ; Table 3). Recruitment in 2003 was estimated to be substantially larger than other years. As in the 2013 assessment, uncertainty in the scale of annual deviations was substantially larger than the variation between the deviations. Recruitment bias adjustments were performed following the advice of Methot et al. (2011).

3.3.1.2 Selectivity and Retention Selectivity curves for all three fisheries fleets and the three scientific surveys were estimated as dome-shaped (Figure 22).

The early- and late-period Triennial Surveys had narrow dome-shapes, with peak selectivity occurring at relatively small length (~26 cm, and ~22 cm respectively). This shape is consistent with the design of the survey which focused its sampling on the relatively shallow shelf, where younger, smaller, shortspine thornyhead live before migrating to deeper waters as they age and mature . There was little difference in the estimated selectivity curves between male and female fish. Meanwhile, the WCGBTS was estimated to have a wide plateau (beginning at ~30cm) over which the species is fully selected for, including the lengths over which the species spends the bulk of its lifespan. This indicates that the WCGBTS is sampling a large proportion of the stock, and that annual length composition data from the survey is likely a good representation of the true distribution of lengths in the population.

The North Trawl fleet was estimated to have a dome-shaped curve with a small plateau around 28 cm in length, and a long tail that spanned nearly the entire range of observed lengths. The South trawl fleet was estimated to have a very large selectivity plateau, (beginning at ~30cm and ranging from 30-55cm), with very steep ascending and descending limbs. Finally the Non-Trawl fleet was estimated to have a relatively small plateau beginning at a much higher length than any other fleet or survey (~45 cm). This can be explained by the fact that hook and line gear, the dominant gear type in the Non-Trawl fleet, selectively catches larger shortspine thornyhead.

Retention curves for all three fisheries were asymptotic in shape, with the two trawl fisheries asymptoting at a retention value of 1.0 and the non-trawl fishery asymptoting a value just below 1.0 (Figure 48), indicating that the Non-Trawl fishery still discards large fish in limited cases. Retention was modeled in distinct time blocks to allow for better fits to the discard rate data. The time-blocked fits to the North Trawl fleet show the fishery to have begin retaining smaller fish in more recent years than they have historically. A similar pattern is observed for the South Trawl fleet, but to a much smaller extent (Figure 48).

3.3.2 Fits to the Data

3.3.2.1 Abundance Indices The base model reasonably fit the available index data with the exception of the most recent two years of the WCGBTS. The fit to the Triennial Survey was relatively flat across the entire timeseries (1980-2004; Figure 23). An extra parameter was used to estimate additional variance beyond that estimated by the geostatistical model for this survey. The model fit to the WCGBTS indices appropriately captured the lack of trend in the early and middle portions of the timeseries, but struggled to fully capture the recent increase in abundance displayed by the indices (Figure 24). The model fit for this survey only just falls within the estimated confidence interval for the 2021 and 2022 indices. This could be, in part, due to the lack of index data from 2020 (surveys were not conducted due to the ongoing COVID-19 pandemic), which may have helped the model more accurately capture the increase.

3.3.2.2 Fishery Discard Rates The model fit the discard rates for all three fisheries fleets quite well (Figure 25; Figure 26; Figure 27). The timeblocking scheme for retention that was inherited from the 2013 model was expanded to encompass a variety of additional changes in fishing behavior and observed patterns in the data. The final set of timeblocks are provided in Figure 69, and justification for their use is presented in Section 3.2.4.2.

3.3.2.3 Fishery Length Compositions The base model fit the fishery and discard length compositions reasonably well in aggregate (Figure 28), though there was significant annual variability in the quality of fit, often due to differences in effective sample sizes. The South trawl and Non-trawl fleets were exceptionally well fit by the model, while the model fit to the length compositions from the North trawl fleet underestimated the scale of the peak of the distribution. This type of misfit was similarly observed in the model fits on an annual basis, with all years 2018-2022 displaying a similar underestimation of either the location or scale of the peak of the distribution (Figures 29 - 30). The exact causes of this underestimation remain unknown at this time, but could be due to subtle changes in selectivity or availability. Time-varying selectivity in the form selectivity time-blocks slightly improved overall fit to the length composition data. The final set of timeblocks are provided in Figure 69, and justification for their use is presented in Section 3.2.4.2.

Trawl discards length compositions were well fit by the model in both the north and south regions, while the model struggled to adequately fit discard compositions from the Non-Trawl fleet (Figure 28). The Non-Trawl discards were of a larger size and were generally more dispersed than the discard compositions in the two trawl fleets, a feature the model did pick up on, but the model fit a wide plateau rather than narrow peak to these composition data. This is likely due to the wide variability in annual length compositions seen in this fleet, as well as the wide spatial coverage.

3.3.2.4 Survey Length Compositions Like the fishery derived length compositions, survey-derived length compositions were reasonably well fit in aggregate by the base model (Figure 28), though there was considerable annual variability in the quality of the model fit (Figure 37). The early-period Triennial Survey length composition data for both sexes were exceptionally well fit by the model. Length compositions from the late-period Triennial survey were slightly less well fit, with the model under-estimating the location of the peak for both sexes. For the WCGBTS length compositions, the male, female, and unsexed location of the compositional peaks were well estimated, though the overall scales were slightly underestimated. Pearson residuals did not demonstrate any obvious trends that would indicate systematic misfits to the data (Figure 39).

3.3.2.5 Mean Body Weight Mean body weight of discarded fish was well fit in the two trawl fleets, and no major trends were observed in either the data or the model estimates (Figure 40; Figure 41; Figure 42). Mean discard weight in the Non-Trawl fleet was observed to have increased in the last ten years, but this trend was not captured by the model. The model, instead, fit a declining trend in discard weight to the Non-Trawl fleet data (Figure 42). The reason for this disparity between the observed data and the model fit is unclear.

3.3.3 Population Trajectory

Unfished equilibrium spawning output (B_0) is estimated to be 22,145 trillion eggs (18,166-26,124 trillion eggs). The B_0 estimate is not directly comparable to estimates made in previous assessments, which assumed no fecundity relationship, and thus calculated B_0 in terms of biomass rather than egg production. Spawning output is estimated to have remained stable until the mid-1960s and then declined in the 1970s to about 80% in the mid-1980s, followed by a slower decline under the lower catch levels in the 2000s (Table 10; Figure 43). While the spawning output of the stock has declined near linearly since 1975, total biomass has stabilized in recent decades around ~85,000 mt. The estimated spawning output in 2023 is 8.717 trillion eggs (5.545-11.889 trillion eggs), which represents a stock status (depletion level) of 39% (32%-47%; Table 7, Figure 44). The new depletion estimated for 2013 is 43.5%, which is significantly lower than the 74.2% estimated for 2013 in the previous assessment.

Twelve-year projections predict that the population is unlikely to experience a large increase in spawning output or spawning biomass in the near future, if the full ACL is taken each year.

3.4 Model Diagnostics

3.4.1 Convergence

The maximum likelihood parameter estimates found by AD Model Builder (ADMB) indicated a well-converged model. The base model had a small maximum gradient component (0.00002317) and a positive definite Hessian matrix, both of which are associated with converged models.

Runs with 100 alternative sets of starting parameter values found no models with a better likelihood (Table 16). Of the 100 jittered model runs, 74 re-converged to the best estimates associated with the base model, while 76 re-converged to within 2% of the best estimate. No jittered model runs achieved a better likelihood than the base model. This indicates that the data is relatively informative about the population dynamics of the stock, as the model fits to the data were virtually identical.

3.4.2 Sensitivity Analyses

3.4.2.1 Sensitivity to growth parameters Growth parameters are uncertain for shortspine thornyhead due to difficulties in determining age from otoliths and subsequent lack of length-at-age information for this species, thus, sensitivities of length-at-age 25% higher and 10% lower was conducted to encompass the uncertainty in growth within and between data sets. Different assumptions about growth did not have much influence on relative spawning depletion. Depletion levels in the final year were slightly greater in a higher growth scenario and slightly lower in a lower growth scenario (Figure 63). Spawning output was more sensitive to assumptions about growth, with much higher spawning output when assuming a higher growth scenario (Figure 62). The high growth sensitivity had a slightly better overall fit to the data, including to the survey indices and length compositions (Table 17). Different assumptions about growth influence recruitment patterns and the timing of strong year classes. However, the influence of different growth assumptions is also sensitive to changes in other parameters, such as natural mortality.

3.4.2.2 Sensitivity to maturity The 2023 assessment used updated maturity-at-length information from the WCGBTS and port-sampling (Melissa Head,NWFSC, pers. comms.), which showed a larger length at 50% maturity ($L_{50\%} = 31.4\text{cm}$) and slower rate of maturation (slope = -0.177) in the logistic curve compared to the smaller $L_{50\%}$ (18.1 cm) and faster rate of maturation (slope = -2.304) assumed in the 2013 assessment based on Pearson and Gunderson (2003). A sensitivity was conducted to maturity information from the two datasets and to an intermediate maturity-at-length logistic curve (mix_curve, $L_{50\%} = 24.8\text{cm}$ and slope = -0.350). As in the 2013 assessment, estimates of population scale and status in the base model were not sensitive to different maturity assumptions (Figure 65);

Figure 66). Differences in fits to the data were negligible. The slightly higher stock status in the final year with the Pearson and Gunderson (2003) maturity assumptions is likely due to females from strong cohorts in the 2000s assumed to mature at younger ages compared to the base model. As stated in the 2013 assessment, the slow growth rate of shortspine thornyhead, with growth still occurring at age 100, reduces the importance of assumptions about maturity because older individuals will have significantly higher spawning output due to their much larger size, regardless of the fraction spawning.

3.4.2.3 Sensitivity to Landings Two sensitivities were conducted to explore how changes in the historical landings timeseries effect modern-day estimates of stock status. One sensitivity replaces the historical landings reconstructions prior to 1962 with the imputed landings that were used in the 2005 and 2013 assessments. A second sensitivity replaces all landings information prior to 2013 with the values that were used in the 2013 assessment. There was little appreciable difference to base model fits across the two sensitivities (Figure 67; Figure 68). This is likely due to the fact that historical catches (pre-1962), and changes in catches due to state-level catch reconstruction updates, were relatively small and thus would have had minimal impact of the biomass timeseries.

3.4.2.4 Sensitivity to retention and selectivity The 2023 assessment substantially extends the period over both length data of retained and discarded catch, mean individual weight in discards and discard rates estimates are available. This data may reflect the dynamics of the thornyhead of the population but also structural, technical or behavioral changes in the fishing fleets. Due to the uncertainty around the impact of such changes on the retention and selectivity of the fleets, we assessed the sensitivity of the model to alternative combinations of time blocks for these parameters. The sensitivity to time blocks in retention (inflection, asymptotic retention) was first performed and the most pertinent model (good fit to the data and parsimony) and the base model were then used to conduct the sensitivity to time blocks in selectivity (peak). Time blocks explored were based on a combination of breaks related to relevant changes to management or fleet behavior. A summary of blocking for selectivity and retention in the REVIEW 69.

Setting up additional time blocks for the retention parameters improved the fit of the model to the length distributions and the discard rates, hence reducing the corresponding likelihood of the model. However, the impact on the other components of the model likelihood were very limited. None of the time blocks tested substantially reduced other components of the model likelihood. Except a slight offset for the estimated trends in spawning output between the models with selectivity change considered in 2011 only (Figure 70), all model estimates produced similar diagnostic of the population status. In particular, with no regard to the number or the location of time blocks used for retention or selectivity, the fraction of unfished biomass overlay (Figure 71).

3.4.2.5 Sensitivity to Abundance Index Methods The 2023 assessment uses model-based indices (MBIs) of abundance derived from geostatistical models, which differs from previously used design-based approaches (DBIs). There remains limited agreement on how best to approach model selection for such models. Therefore, two sensitivity analyses were conducted on the methods used to estimate indices of abundance: 1) using MBIs derived from a geostatistical model that assumed a lognormal error structure (compared to a gamma error structure in the base model); and 2) using newly calculated DBIs.

Estimates of population scale and status were not sensitive to changes in error structure used in the MBIs or changes in estimation methods (i.e. use of design-based indices). Small reductions in estimated spawning output were observed when lognormal error structures were used in MBIs as well as when design-based indices were used. No appreciable improvements to model fit were observed between model-based indices that used gamma or lognormal error structures. The use of DBIs reduced model fit compared to the base model (Figure ??-??).

3.4.3 Retrospective Analysis

Retrospective analysis indicates that removing the most recent years of data has minimal impact on the estimates of spawning output (Figure 59) and stock status (Figure 60). This is consistent with the results of the likelihood profile over R_0 (Figure 49) which showed that the data are moderately informative about stock scale. While the analysis does display some very minimal evidence of a retrospective pattern, all estimates of spawning output in the retrospective analysis fell within the 95% uncertainty interval around the base model spawning output time series (Figure 60).

As in the previous assessment, there is little evidence that such retrospective patterns are the result of additional years of survey abundance data (Figure 61), and thus, it is most likely that removal of informative length composition data is the source of such pattern.

3.4.4 Likelihood Profiles

Likelihood profiles were conducted over the log of unfished recruitment (R_0), the steepness of the stock recruit relationship (h), the value of natural mortality (M), and the growth curve.

A likelihood profile over $\ln(R_0)$ was performed to assess the influence of the various data sources on the unfished scale of the population. The profile shows most of the data sources to be in agreement regarding the best estimate of R_0 , with the exception of the indices of abundance, which are best fit by larger values of R_0 (Figure 49). Similarly, there is little inconsistency in likelihood contribution by fleet across the range of plausible R_0 values (Figure 49). This indicates that the data, together, are relatively informative about the

overall scale of the population. The highest spawning output and lowest depletion levels were associated with higher R_0 values (Figure 50).

Likelihood values and model results were largely insensitive to changes in steepness (Figure 51). The change in negative log likelihood over the range of $h = 0.5\text{--}1.0$ was less than 10 units with the largest contribution coming from recruitment and abundance indices. No other likelihood component had a change of greater than 1 unit. The lowest B_0 and depletion values were associated with the most productive population, with $h = 1.0$, but there was no qualitative difference between any of these cases (total change in depletion values across the range of h tested was 0.02 units; Figure 52). The apparent lack of influence of h on population dynamics for shortspine thornyhead is likely the result of the relatively high estimated stock status across the entire time series, which makes estimation of h difficult.

A likelihood profile over natural mortality (M) found the model results to be quite sensitive to the assumed value of M : with all values of M 0.025–0.055 resulting in likelihoods within 5 units of the base model (Figure 53). Meanwhile there was no support in the data for values of M above 0.06 or below 0.02. Length composition data, particularly from the two trawl fleets, was the major contributor to the changes in likelihood observed over the range of tested values for M (Figure 53). All plausible values of M resulted in similar levels of depletion (Figure 55), but a wide range of levels for unfished spawning output (Figure 58)

Because reliable age data are sparse for shortspine thornyhead, making growth a major uncertainty in this assessment, a likelihood profile over growth coefficients, length at minimum age (a_{min}) and length at maximum age (a_{max}), for each sex, was conducted. For the profile, length at a_{min} for females ranged from 10 cm to 15 cm and length at a_{max} ranged from 60 cm to 150 cm. For males, length at a_{min} ranged from 8cm to 12 cm and length at a_{max} ranged from 55 cm to 140 cm. As with the growth sensitivity analysis described above, likelihood was minimized for higher growth scenarios (Figure 56). Spawning biomass trajectories showed similar patterns to the growth sensitivity, with higher growth scenarios producing substantially higher spawning output (Figure 57). Based on both the fishery and survey length compositions, the largest fish, under a high growth model, are not necessarily being observed in the data. This, in combination with a low natural mortality, may be driving the higher spawning output patterns under high growth scenarios.

3.4.5 Unresolved Problems and Major Uncertainties

Few problems remain totally unresolved, though improvements to the model fit to the WCG-BTS abundance indices and to the North Trawl fleet length compositions would be desirable. In addition, being able to freely estimate the width of the selectivity plateaus for many of the fleets and surveys would also improve the model.

The model fails, at this time, to fully capture the observed increase in abundance seen in the WCGBTS index time series, significantly underestimating the abundance in 2021

and 2022 (Figure 24). Better fits to WCGBTS length compositions in those years could possibly improve fits to the indices, but improvements to the length composition fits proved difficult without introducing time-blocked selectivity. As the WCGBTS is supposed to follow highly standardized survey methodologies, there seems to be minimal justification for introducing time-varying selectivity in the model at this time. The model also fails to fully capture the peak of the length compositions for the Northern Trawl fleet, underestimating the number of mid-sized fish that the fleet takes (Figure 28). This underestimation appears to be consistent, particularly in the last 10 years (Figure 30), implying a possible recent change in selectivity. While time-varying selectivity was not investigated here, if this trend persists, future assessments may wish to apply a selectivity time block to this fleet in order to better capture the peaks of the length compositions.

Major uncertainties in the model are centered around uncertainty in the biological parameters that govern growth, maturity, and natural mortality. Due to a lack of reliable aging methods, growth was estimated externally to data collected in the 1990s (see Section 2.3.4 for more information). Sensitivities conducted on length-at-age demonstrated that changes to the assumed growth function could have large effects on the estimated stock status (Figure 63). Due to inconsistent histological data, which suggest spatial variation in maturity-at-length for shortspine thornyhead, there remains some uncertainty about the shape of the species' maturity curve, though the model appears to be largely insensitive to variation in maturity (Figure 66). Finally, likelihood profiles over natural mortality demonstrate the model to be quite sensitive to its assumed value. There is insufficient information in the data to estimate natural mortality directly, constraining us to using meta-analyses or other natural mortality estimators, which frequently make use of aging information that is largely unavailable and highly uncertain for shortspine thornyhead.

4 Management

4.1 Reference Points

Reference points were calculated using the estimated catch distribution in the final year of the model (2023). In general, the population is on the boundary between “precautionary” ($B/B_0 = 0.40$) and “healthy” status relative to the reference points (Figure 44). Sustainable total yield (landings plus discards) was estimated at 1,160 mt when using an $SPR_{50\%}$ reference harvest rate and ranged from 971-1,348 mt based on estimates of uncertainty (Table 5). The spawning output equivalent to 40% of the unfished spawning output ($B_{40\%}$) was 8.858 trillion eggs. The most recent catches (landings plus discards) have been lower than the estimated long-term yields calculated using an $SPR_{50\%}$ reference point, but not as low as the lower bound of the 95% uncertainty interval. However, this is due to the fishery not fully attaining the full ACL. The OFL and ABC values over the past 6 years have been approximately 3100 mt and 2,500 mt, respectively. Both of those values are higher than the OFL and ACL values predicted in short-term forecasts, which are around 900 mt

and 700 mt respectively for 2025–2026 (Table 7). This is reflected in the timeseries of low harvest rates (Figure 45), high 1-SPR values (Figure 46), and the phase plot showing the history of being above the target biomass but also above the target fishing intensity reference points (Figure 47). The sharp decline in the OFL and ACL in coming years is the result of continued decline in the relative spawning output of the stock, which has placed it very near the “precautionary” zone for management.

4.2 Harvest Projections and Decision Tables

4.3 Evaluation of Scientific Uncertainty

Scientific uncertainty was evaluated via several likelihood profiles and a wide range of sensitivity analyses, not all of which are reported on here. Likelihood profiles were performed over unfished recruitment (R_0), recruitment steepness (h), and natural mortality (M), as required by the Groundfish Terms of Reference. The profiles found the model results, particularly estimates of stock scale, to be relatively sensitive to changes to R_0 and M , as would be expected, but largely insensitive to changes in steepness. An additional likelihood profile was also run over growth, and found the model results to be quite sensitive to the assumed values of the growth curve. Sensitivities were performed using alternative growth and maturity curves, alternative time blocks for selectivity and retention, and alternative historical landings timeseries. Model results (particularly estimates of stock status) were largely insensitive to all changes except for growth.

The model estimated uncertainty around the 2023 spawning biomass was $\sigma = 0.18$ and the uncertainty around the OFL was $\sigma = 0.16$.

4.4 Research and Data Needs

Research and data needs for future assessments include the following:

1. Research into aging methods and availability of reliable age data would be valuable for future stock assessments. Otoliths have been collected in good quantities from the NWFSC survey, but there is currently no validated aging method for shortspine thornyhead.
2. Additional investigation into growth patterns would provide valuable information for future population projections. We acknowledge that additional work on aging short-spine thornyhead would be required to make such additional growth research possible.
3. More investigation into maturity of shortspine thornyhead is necessary to understand the patterns in maturity observed in WCGBTS samples.

4. Information on possible migration of shortspine thornyheads would be valuable for understanding stock dynamics. Analysis of trace elements and stable isotopes in shortspine otoliths may provide valuable information on the extent of potential migrations. Possible connections between migration and maturity could likewise be explored.
5. A greater understanding of the connection between thornyheads and bottom type could be used to refine the indices of abundance. Thornyheads are very well sampled in trawlable habitat, but the extrapolation of density to a survey stratum could be improved by accounting for the proportion of different bottom types within a stratum and the relative density of thornyheads within each bottom type.
6. Additional investigation into spatial stock structure could be valuable for determining whether future assessments should develop a spatial assessment model, or if shortspine thornyhead should be assessed at distinct spatial scales in the future.
7. Further research into the Dirichlet-Multinomial (DMN) data-weighting method for length-composition data is needed for integration with length-based data-moderate assessments like shortspine thornyhead. The DMN method has not, to date, been thoroughly simulation tested with length-composition data, and an attempted sensitivity analysis performed for the 2023 assessment failed to converge entirely. This is a general research need, and is widely applicable to many data-moderate or length-based assessments, not just shortspine thornyhead.

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7 Tables

Table 1: Recent landings by fleet, total landings summed across fleets, and the total mortality including discards.

| Year | North Trawl | South Trawl | Non-Trawl | Total Landings | Total Dead |
|------|-------------|-------------|-----------|----------------|------------|
| 2013 | 570.11 | 294.83 | 166.40 | 1,031.34 | 1,111.27 |
| 2014 | 456.13 | 254.05 | 147.81 | 858.00 | 928.12 |
| 2015 | 513.66 | 244.29 | 131.30 | 889.26 | 929.06 |
| 2016 | 587.71 | 185.73 | 168.94 | 942.38 | 992.09 |
| 2017 | 634.83 | 158.30 | 223.82 | 1,016.94 | 1,094.53 |
| 2018 | 595.89 | 105.07 | 184.48 | 885.44 | 948.28 |
| 2019 | 460.13 | 127.94 | 143.48 | 731.55 | 785.62 |
| 2020 | 258.09 | 87.99 | 85.17 | 431.26 | 477.36 |
| 2021 | 302.81 | 73.39 | 78.74 | 454.94 | 499.93 |
| 2022 | 506.30 | 97.61 | 66.22 | 670.12 | 724.14 |

Table 2: Spawning output (millions of eggs) and fraction unfished with associated 95% confidence intervals (CI) from the base model.

| Year | Spawning Output | Spawning Output 95% CI | Fraction Unfished | Fraction Unfished 95% CI |
|------|-----------------|------------------------|-------------------|--------------------------|
| 2013 | 9,626 | 6,360–12,892 | 0.435 | 0.360–0.509 |
| 2014 | 9,476 | 6,228–12,724 | 0.428 | 0.353–0.503 |
| 2015 | 9,348 | 6,116–12,579 | 0.422 | 0.347–0.497 |
| 2016 | 9,228 | 6,011–12,444 | 0.417 | 0.341–0.492 |
| 2017 | 9,112 | 5,908–12,315 | 0.411 | 0.336–0.487 |
| 2018 | 8,997 | 5,804–12,190 | 0.406 | 0.330–0.482 |
| 2019 | 8,902 | 5,718–12,086 | 0.402 | 0.325–0.478 |
| 2020 | 8,829 | 5,651–12,006 | 0.399 | 0.322–0.475 |
| 2021 | 8,787 | 5,614–11,960 | 0.397 | 0.320–0.474 |
| 2022 | 8,754 | 5,583–11,925 | 0.395 | 0.318–0.473 |
| 2023 | 8,717 | 5,545–11,889 | 0.394 | 0.316–0.471 |

Table 3: Estimated recent trend in recruitment and recruitment deviations (RecDevs) and the 95% confidence intervals (CI) from the base model.

| Year | Recruitment | 95% CI | RecDevs | RecDev 95% CI |
|------|-------------|--------------|---------|---------------|
| 2013 | 9,622 | 4,001–23,138 | -0.112 | -1.004–0.781 |
| 2014 | 9,650 | 3,996–23,304 | -0.105 | -1.002–0.791 |
| 2015 | 9,783 | 4,016–23,832 | -0.089 | -0.996–0.818 |
| 2016 | 10,155 | 4,111–25,087 | -0.049 | -0.973–0.875 |
| 2017 | 9,995 | 4,024–24,828 | -0.062 | -0.992–0.868 |
| 2018 | 9,990 | 3,990–25,017 | -0.060 | -1.000–0.879 |
| 2019 | 10,354 | 4,097–26,165 | -0.032 | -0.989–0.926 |
| 2020 | 10,839 | 4,230–27,777 | 0.007 | -0.968–0.981 |
| 2021 | 11,299 | 4,349–29,354 | 0.040 | -0.951–1.031 |
| 2022 | 10,952 | 4,253–28,200 | 0.000 | -0.980–0.980 |
| 2023 | 10,942 | 4,249–28,177 | 0.000 | -0.980–0.980 |

Table 4: Estimated recent trend in relative fishing intensity, exploitation rate, and the 95% intervals. The spawning potential ratio (SPR) is utilized in the relative fishing intensity calculation as $(1 - SPR)/(1 - SPR_{30\%})$

| Year | $(1-SPR)/(1-SPR\ 50\%)$ | 95% CI | Exploitation Rate | 95% CI |
|------|-------------------------|-----------|-------------------|---------------|
| 2013 | 1.29 | 1.06–1.53 | 0.0120 | 0.0079–0.0160 |
| 2014 | 1.16 | 0.92–1.41 | 0.0100 | 0.0066–0.0134 |
| 2015 | 1.15 | 0.91–1.40 | 0.0100 | 0.0066–0.0135 |
| 2016 | 1.19 | 0.95–1.44 | 0.0107 | 0.0070–0.0144 |
| 2017 | 1.25 | 1.00–1.50 | 0.0118 | 0.0077–0.0159 |
| 2018 | 1.14 | 0.89–1.39 | 0.0103 | 0.0067–0.0138 |
| 2019 | 1.00 | 0.75–1.24 | 0.0085 | 0.0055–0.0114 |
| 2020 | 0.68 | 0.48–0.87 | 0.0051 | 0.0033–0.0069 |
| 2021 | 0.69 | 0.49–0.88 | 0.0053 | 0.0035–0.0072 |
| 2022 | 0.88 | 0.66–1.10 | 0.0076 | 0.0050–0.0103 |

Table 5: Summary of reference points and management quantities, including estimates of the 95% intervals.

| Variable of Interest | Estimate | 95% CI |
|--|----------|-----------------|
| Unfished Spawning Output | 22,145 | 18,166–26,124 |
| Unfished Age 1+ Biomass (mt) | 216,864 | 177,897–255,831 |
| Unfished Recruitment (R0) | 12,580 | 10,320–14,841 |
| Spawning Output (2023) | 8,717 | 5,545–11,889 |
| Fraction Unfished (2023) | 0.39 | 0.32–0.47 |
| Reference Points Based SB40% | | |
| Proxy Spawning Output SB40% | 8,858 | 7,266–10,450 |
| SPR Resulting in SB40% | 0.458 | 0.458–0.458 |
| Exploitation Rate Resulting in SB40% | 0.012 | 0.011–0.012 |
| Yield with SPR Based On SB40% (mt) | 1,160 | 971–1,348 |
| Reference Points Based on SPR Proxy for MSY | | |
| Proxy Spawning Output (SPR50) | 9,880 | 8,105–11,656 |
| SPR50 | 0.500 | - |
| Exploitation Rate Corresponding to SPR50 | 0.010 | 0.010–0.011 |
| Yield with SPR50 at SB SPR (mt) | 1,108 | 929–1,288 |
| Reference Points Based on Estimated MSY Values | | |
| Spawning Output at MSY (SB MSY) | 6,155 | 5,057–7,253 |
| SPR MSY | 0.348 | 0.345–0.351 |
| Exploitation Rate Corresponding to SPR MSY | 0.017 | 0.016–0.017 |
| MSY (mt) | 1,227 | 1,027–1,426 |

Table 6: Recent trend in the overfishing limits (OFLs), the acceptable biological catches (ABCs), the annual catch limits (ACLs), the total landings, and total mortality (mt). Total mortality includes fishery catch and model estimated discards.

| Year | OFL | ABC | ACL | Landings | Total Mortality |
|------|------|------|------|----------|-----------------|
| 2013 | 2333 | 2230 | 1937 | 1,031.34 | 1,111.27 |
| 2014 | 2310 | 2208 | 1918 | 858.00 | 928.12 |
| 2015 | 3203 | 2668 | 2668 | 889.26 | 929.06 |
| 2016 | 3169 | 2640 | 2639 | 942.38 | 992.09 |
| 2017 | 3144 | 2619 | 2619 | 1,016.94 | 1,094.53 |
| 2018 | 3116 | 2596 | 2596 | 885.44 | 948.28 |
| 2019 | 3089 | 2573 | 2573 | 731.55 | 785.62 |
| 2020 | 3063 | 2551 | 2552 | 431.26 | 477.36 |
| 2021 | 3211 | 2183 | 2184 | 454.94 | 499.93 |
| 2022 | 3194 | 2130 | 2130 | 670.12 | 724.14 |

Table 7: Projections of potential OFLs (mt), ABCs (mt), estimated spawning output, and fraction unfished. The OFL and ABC for years 2023 and 2024 are fixed, while the OFL and ABC for years 2025 and on are estimated by the model.

| Year | Predicted OFL (mt) | ABC (mt) | Age 1 Biomass (mt) | Spawning Output | Fraction Unfished |
|------|--------------------|----------|--------------------------|-----------------|-------------------|
| 2023 | 894.13 | 756.11 | 95,317.90 | 8,716.84 | 0.394 |
| 2024 | 917.11 | 756.11 | 95,942.30 | 8,686.69 | 0.392 |
| 2025 | 939.75 | 710.84 | 96,595.20 | 8,666.24 | 0.391 |
| 2026 | 962.46 | 713.47 | 97,317.90 | 8,658.74 | 0.391 |
| 2027 | 984.52 | 716.19 | 98,058.60 | 8,660.12 | 0.391 |
| 2028 | 1,005.90 | 718.04 | 98,813.40 | 8,669.87 | 0.391 |
| 2029 | 1,026.58 | 720.05 | 99,580.20 | 8,687.53 | 0.392 |
| 2030 | 1,046.56 | 721.25 | 100,356.00 | 8,712.50 | 0.393 |
| 2031 | 1,065.88 | 721.67 | 101,138.00 | 8,744.22 | 0.395 |
| 2032 | 1,084.54 | 721.32 | 101,927.00 | 8,782.10 | 0.397 |
| 2033 | 1,102.57 | 720.20 | 102,719.00 | 8,825.59 | 0.399 |
| 2034 | 1,119.95 | 719.01 | 103,514.00 | 8,874.11 | 0.401 |

Table 8: Summary of recent estimates and management quantities.

Table 9: Landings (mt) by fleet for all years, total landings (mt), and total mortality (mt) summed by year. Total dead includes fishery catch and model estimated discards.

| Year | North Trawl | South Trawl | Non-Trawl | Total Landings | Total Dead |
|------|----------------|----------------|-----------|-------------------|------------|
| 1901 | 0.00 | 0.00 | 0.09 | 0.09 | 0.11 |
| 1902 | 0.00 | 0.00 | 0.11 | 0.11 | 0.14 |
| 1903 | 0.00 | 0.00 | 0.13 | 0.13 | 0.16 |
| 1904 | 0.00 | 0.00 | 0.15 | 0.15 | 0.19 |
| 1905 | 0.00 | 0.00 | 0.17 | 0.17 | 0.21 |
| 1906 | 0.00 | 0.00 | 0.19 | 0.19 | 0.24 |
| 1907 | 0.00 | 0.00 | 0.21 | 0.21 | 0.27 |
| 1908 | 0.00 | 0.00 | 0.23 | 0.23 | 0.29 |
| 1909 | 0.00 | 0.00 | 0.26 | 0.26 | 0.32 |
| 1910 | 0.00 | 0.00 | 0.28 | 0.28 | 0.34 |
| 1911 | 0.00 | 0.00 | 0.30 | 0.30 | 0.37 |
| 1912 | 0.00 | 0.00 | 0.32 | 0.32 | 0.39 |
| 1913 | 0.00 | 0.00 | 0.34 | 0.34 | 0.42 |
| 1914 | 0.00 | 0.00 | 0.36 | 0.36 | 0.44 |
| 1915 | 0.00 | 0.00 | 0.38 | 0.38 | 0.47 |
| 1916 | 0.00 | 0.00 | 0.40 | 0.40 | 0.49 |
| 1917 | 0.00 | 0.00 | 0.42 | 0.42 | 0.52 |
| 1918 | 0.00 | 0.00 | 0.44 | 0.44 | 0.54 |
| 1919 | 0.00 | 0.00 | 0.46 | 0.46 | 0.57 |
| 1920 | 0.00 | 0.00 | 0.48 | 0.48 | 0.59 |
| 1921 | 0.00 | 0.00 | 0.50 | 0.50 | 0.62 |
| 1922 | 0.00 | 0.00 | 0.52 | 0.52 | 0.65 |
| 1923 | 0.00 | 0.00 | 0.54 | 0.54 | 0.67 |
| 1924 | 0.00 | 0.00 | 0.56 | 0.56 | 0.70 |
| 1925 | 0.00 | 0.00 | 0.58 | 0.58 | 0.72 |
| 1926 | 0.00 | 0.00 | 0.60 | 0.60 | 0.75 |
| 1927 | 0.00 | 0.00 | 0.63 | 0.63 | 0.77 |
| 1928 | 0.00 | 0.00 | 1.05 | 1.05 | 1.29 |
| 1929 | 0.00 | 0.00 | 1.66 | 1.66 | 2.05 |
| 1930 | 0.00 | 0.00 | 1.39 | 1.39 | 1.71 |
| 1931 | 0.00 | 0.00 | 1.13 | 1.13 | 1.40 |
| 1932 | 0.00 | 0.00 | 0.42 | 0.42 | 0.52 |
| 1933 | 0.00 | 0.00 | 0.62 | 0.62 | 0.77 |
| 1934 | 0.00 | 4.57 | 0.71 | 5.28 | 6.04 |
| 1935 | 0.00 | 6.33 | 0.67 | 6.99 | 7.98 |
| 1936 | 0.00 | 2.70 | 1.45 | 4.15 | 4.85 |
| 1937 | 0.01 | 5.42 | 1.44 | 6.87 | 7.92 |
| 1938 | 0.00 | 5.62 | 1.34 | 6.96 | 8.00 |
| 1939 | 0.01 | 5.81 | 0.42 | 6.24 | 7.09 |

Table 9: Landings (mt) by fleet for all years, total landings (mt), and total mortality (mt) summed by year. Total dead includes fishery catch and model estimated discards.
(continued)

| Year | North | South | Non-Trawl | Total | Total Dead |
|------|--------|----------|-----------|----------|------------|
| | Trawl | Trawl | | Landings | |
| 1940 | 0.19 | 0.95 | 1.60 | 2.74 | 3.30 |
| 1941 | 0.29 | 1.96 | 2.65 | 4.90 | 5.87 |
| 1942 | 0.69 | 1.03 | 3.77 | 5.49 | 6.74 |
| 1943 | 3.06 | 1.43 | 10.17 | 14.66 | 18.24 |
| 1944 | 5.34 | 0.21 | 1.82 | 7.38 | 9.59 |
| 1945 | 5.34 | 0.99 | 0.68 | 7.01 | 9.05 |
| 1946 | 4.07 | 0.61 | 0.99 | 5.68 | 7.32 |
| 1947 | 4.75 | 0.04 | 0.72 | 5.51 | 7.24 |
| 1948 | 13.38 | 0.02 | 1.02 | 14.42 | 19.03 |
| 1949 | 13.52 | 0.02 | 0.34 | 13.88 | 18.37 |
| 1950 | 6.93 | 0.01 | 0.82 | 7.75 | 10.20 |
| 1951 | 11.16 | 0.00 | 0.59 | 11.76 | 15.54 |
| 1952 | 13.85 | 0.00 | 0.28 | 14.13 | 18.70 |
| 1953 | 2.63 | 2.96 | 0.24 | 5.83 | 7.12 |
| 1954 | 112.45 | 0.00 | 0.38 | 112.83 | 149.50 |
| 1955 | 62.93 | 4.99 | 0.28 | 68.20 | 89.35 |
| 1956 | 133.04 | 6.82 | 0.48 | 140.34 | 184.48 |
| 1957 | 63.88 | 0.00 | 0.49 | 64.37 | 85.17 |
| 1958 | 27.80 | 9.51 | 0.14 | 37.45 | 47.67 |
| 1959 | 28.81 | 32.26 | 0.24 | 61.31 | 74.69 |
| 1960 | 31.09 | 149.61 | 0.10 | 180.80 | 209.37 |
| 1961 | 28.55 | 56.76 | 0.38 | 85.68 | 101.87 |
| 1962 | 22.47 | 113.69 | 0.45 | 136.60 | 157.67 |
| 1963 | 7.77 | 223.17 | 0.27 | 231.21 | 260.51 |
| 1964 | 25.19 | 173.49 | 0.78 | 199.45 | 228.07 |
| 1965 | 31.75 | 307.58 | 0.13 | 339.46 | 385.26 |
| 1966 | 623.08 | 542.10 | 0.13 | 1,165.31 | 1,419.32 |
| 1967 | 375.82 | 867.40 | 0.34 | 1,243.57 | 1,455.70 |
| 1968 | 207.45 | 1,834.26 | 0.26 | 2,041.97 | 2,307.78 |
| 1969 | 215.73 | 430.43 | 0.95 | 647.10 | 758.09 |
| 1970 | 179.79 | 599.25 | 0.26 | 779.30 | 896.52 |
| 1971 | 347.53 | 607.82 | 0.08 | 955.43 | 1,120.43 |
| 1972 | 390.43 | 1,380.65 | 0.11 | 1,771.19 | 2,028.48 |
| 1973 | 704.17 | 2,321.09 | 0.44 | 3,025.70 | 3,467.33 |
| 1974 | 219.17 | 1,146.08 | 1.32 | 1,366.58 | 1,548.21 |
| 1975 | 401.92 | 1,872.54 | 0.53 | 2,274.99 | 2,583.44 |
| 1976 | 105.65 | 1,824.32 | 0.51 | 1,930.48 | 2,155.09 |
| 1977 | 114.67 | 1,472.13 | 9.21 | 1,596.01 | 1,789.93 |
| 1978 | 176.78 | 1,013.53 | 2.96 | 1,193.27 | 1,354.92 |

Table 9: Landings (mt) by fleet for all years, total landings (mt), and total mortality (mt) summed by year. Total dead includes fishery catch and model estimated discards.
(continued)

| Year | North | South | Non-Trawl | Total | Total Dead |
|------|----------|----------|-----------|----------|------------|
| | Trawl | Trawl | | Landings | |
| 1979 | 69.69 | 1,715.69 | 6.56 | 1,791.94 | 2,009.80 |
| 1980 | 180.55 | 1,204.88 | 2.25 | 1,387.68 | 1,580.54 |
| 1981 | 133.01 | 1,608.49 | 2.74 | 1,744.24 | 1,979.58 |
| 1982 | 293.69 | 1,654.79 | 2.71 | 1,951.19 | 2,245.38 |
| 1983 | 480.91 | 1,416.64 | 2.76 | 1,900.31 | 2,225.99 |
| 1984 | 1,039.34 | 1,841.97 | 1.18 | 2,882.49 | 3,438.62 |
| 1985 | 957.63 | 2,397.97 | 6.00 | 3,361.60 | 3,989.88 |
| 1986 | 613.68 | 2,331.52 | 7.98 | 2,953.18 | 3,487.19 |
| 1987 | 646.13 | 1,322.44 | 22.19 | 1,990.76 | 2,401.12 |
| 1988 | 882.88 | 1,965.85 | 24.92 | 2,873.65 | 3,476.63 |
| 1989 | 1,655.68 | 3,123.78 | 35.74 | 4,815.20 | 5,491.29 |
| 1990 | 2,111.95 | 1,911.73 | 31.36 | 4,055.04 | 4,667.22 |
| 1991 | 2,417.55 | 995.94 | 53.54 | 3,467.03 | 4,030.93 |
| 1992 | 1,794.46 | 1,455.11 | 61.25 | 3,310.82 | 3,842.94 |
| 1993 | 2,010.72 | 1,571.84 | 26.59 | 3,609.15 | 4,201.69 |
| 1994 | 2,083.41 | 1,182.92 | 21.00 | 3,287.33 | 3,849.80 |
| 1995 | 960.14 | 929.27 | 57.01 | 1,946.42 | 2,281.71 |
| 1996 | 812.28 | 699.59 | 100.09 | 1,611.95 | 1,903.53 |
| 1997 | 690.20 | 654.17 | 62.74 | 1,407.11 | 1,666.52 |
| 1998 | 585.18 | 593.35 | 62.18 | 1,240.72 | 1,475.58 |
| 1999 | 373.93 | 309.07 | 64.39 | 747.39 | 895.69 |
| 2000 | 361.30 | 421.91 | 66.59 | 849.80 | 1,018.95 |
| 2001 | 292.26 | 197.49 | 57.98 | 547.73 | 663.05 |
| 2002 | 300.48 | 364.76 | 114.25 | 779.50 | 942.43 |
| 2003 | 361.85 | 302.40 | 166.56 | 830.80 | 960.59 |
| 2004 | 334.19 | 286.59 | 139.49 | 760.27 | 879.28 |
| 2005 | 299.68 | 214.11 | 149.69 | 663.48 | 775.07 |
| 2006 | 334.59 | 210.53 | 159.17 | 704.30 | 826.54 |
| 2007 | 628.77 | 222.56 | 158.80 | 1,010.12 | 1,103.22 |
| 2008 | 979.54 | 259.94 | 196.97 | 1,436.45 | 1,569.39 |
| 2009 | 1,023.19 | 308.38 | 200.62 | 1,532.20 | 1,673.89 |
| 2010 | 838.83 | 284.22 | 228.36 | 1,351.41 | 1,488.11 |
| 2011 | 496.88 | 232.99 | 260.52 | 990.39 | 1,083.82 |
| 2012 | 457.67 | 263.59 | 192.07 | 913.33 | 989.98 |
| 2013 | 570.11 | 294.83 | 166.40 | 1,031.34 | 1,111.27 |
| 2014 | 456.13 | 254.05 | 147.81 | 858.00 | 928.12 |
| 2015 | 513.66 | 244.29 | 131.30 | 889.26 | 929.06 |
| 2016 | 587.71 | 185.73 | 168.94 | 942.38 | 992.09 |
| 2017 | 634.83 | 158.30 | 223.82 | 1,016.94 | 1,094.53 |

Table 9: Landings (mt) by fleet for all years, total landings (mt), and total mortality (mt) summed by year. Total dead includes fishery catch and model estimated discards.
(continued)

| Year | North | South | Non-Trawl | Total | Total Dead |
|------|--------|--------|-----------|----------|------------|
| | Trawl | Trawl | | Landings | |
| 2018 | 595.89 | 105.07 | 184.48 | 885.44 | 948.28 |
| 2019 | 460.13 | 127.94 | 143.48 | 731.55 | 785.62 |
| 2020 | 258.09 | 87.99 | 85.17 | 431.26 | 477.36 |
| 2021 | 302.81 | 73.39 | 78.74 | 454.94 | 499.93 |
| 2022 | 506.30 | 97.61 | 66.22 | 670.12 | 724.14 |

Table 10: Time series of population estimates from the base model.

| Year | Total Biomass (mt) | Spawning Output | Total Biomass (mt) | % Un-fished | Age 0 Recruits | Total Mortality | SPR Ratio | Expl Rate |
|------|--------------------|-----------------|--------------------|-------------|----------------|-----------------|-----------|-----------|
| 1901 | 216,876 | 22,145 | 216,864 | 100.0 | 12,739 | 0.11 | 0.00 | 0.00 |
| 1902 | 216,877 | 22,145 | 216,866 | 100.0 | 12,742 | 0.14 | 0.00 | 0.00 |
| 1903 | 216,879 | 22,145 | 216,867 | 100.0 | 12,741 | 0.16 | 0.00 | 0.00 |
| 1904 | 216,882 | 22,145 | 216,870 | 100.0 | 12,724 | 0.19 | 0.00 | 0.00 |
| 1905 | 216,885 | 22,145 | 216,873 | 100.0 | 12,705 | 0.21 | 0.00 | 0.00 |
| 1906 | 216,888 | 22,145 | 216,876 | 100.0 | 12,698 | 0.24 | 0.00 | 0.00 |
| 1907 | 216,892 | 22,145 | 216,880 | 100.0 | 12,690 | 0.27 | 0.00 | 0.00 |
| 1908 | 216,897 | 22,145 | 216,885 | 100.0 | 12,673 | 0.29 | 0.00 | 0.00 |
| 1909 | 216,902 | 22,145 | 216,890 | 100.0 | 12,661 | 0.32 | 0.00 | 0.00 |
| 1910 | 216,908 | 22,145 | 216,896 | 100.0 | 12,636 | 0.34 | 0.00 | 0.00 |
| 1911 | 216,914 | 22,145 | 216,902 | 100.0 | 12,628 | 0.37 | 0.00 | 0.00 |
| 1912 | 216,921 | 22,145 | 216,909 | 100.0 | 12,660 | 0.39 | 0.00 | 0.00 |
| 1913 | 216,928 | 22,145 | 216,917 | 100.0 | 12,703 | 0.42 | 0.00 | 0.00 |
| 1914 | 216,937 | 22,146 | 216,925 | 100.0 | 12,714 | 0.44 | 0.00 | 0.00 |
| 1915 | 216,946 | 22,146 | 216,934 | 100.0 | 12,655 | 0.47 | 0.00 | 0.00 |
| 1916 | 216,956 | 22,146 | 216,944 | 100.0 | 12,640 | 0.49 | 0.00 | 0.00 |
| 1917 | 216,966 | 22,146 | 216,954 | 100.0 | 12,632 | 0.52 | 0.00 | 0.00 |
| 1918 | 216,977 | 22,146 | 216,965 | 100.0 | 12,617 | 0.54 | 0.00 | 0.00 |
| 1919 | 216,988 | 22,146 | 216,976 | 100.0 | 12,638 | 0.57 | 0.00 | 0.00 |
| 1920 | 216,999 | 22,147 | 216,988 | 100.0 | 12,599 | 0.59 | 0.00 | 0.00 |
| 1921 | 217,011 | 22,147 | 217,000 | 100.0 | 12,522 | 0.62 | 0.00 | 0.00 |
| 1922 | 217,023 | 22,148 | 217,012 | 100.0 | 12,551 | 0.65 | 0.00 | 0.00 |
| 1923 | 217,035 | 22,148 | 217,024 | 100.0 | 12,541 | 0.67 | 0.00 | 0.00 |
| 1924 | 217,047 | 22,149 | 217,035 | 100.0 | 12,522 | 0.70 | 0.00 | 0.00 |
| 1925 | 217,059 | 22,149 | 217,047 | 100.0 | 12,502 | 0.72 | 0.00 | 0.00 |
| 1926 | 217,070 | 22,150 | 217,059 | 100.0 | 12,482 | 0.75 | 0.00 | 0.00 |
| 1927 | 217,081 | 22,151 | 217,070 | 100.0 | 12,463 | 0.77 | 0.00 | 0.00 |
| 1928 | 217,092 | 22,152 | 217,080 | 100.0 | 12,444 | 1.29 | 0.00 | 0.00 |
| 1929 | 217,101 | 22,153 | 217,089 | 100.0 | 12,428 | 2.05 | 0.00 | 0.00 |

Table 10: Time series of population estimates from the base model. (*continued*)

| Year | Total Biomass (mt) | Spawning Output | Total Biomass (mt) | % Un-fished | Age 0 Recruits | Total Mortality | SPR Ratio | Expl Rate |
|------|--------------------|-----------------|--------------------|-------------|----------------|-----------------|-----------|-----------|
| 1930 | 217,108 | 22,154 | 217,097 | 100.0 | 12,414 | 1.71 | 0.00 | 0.00 |
| 1931 | 217,115 | 22,154 | 217,104 | 100.0 | 12,404 | 1.40 | 0.00 | 0.00 |
| 1932 | 217,121 | 22,156 | 217,110 | 100.0 | 12,399 | 0.52 | 0.00 | 0.00 |
| 1933 | 217,127 | 22,157 | 217,116 | 100.1 | 12,398 | 0.77 | 0.00 | 0.00 |
| 1934 | 217,131 | 22,158 | 217,120 | 100.1 | 12,402 | 6.04 | 0.00 | 0.00 |
| 1935 | 217,129 | 22,158 | 217,117 | 100.1 | 12,412 | 7.98 | 0.01 | 0.00 |
| 1936 | 217,122 | 22,159 | 217,111 | 100.1 | 12,426 | 4.85 | 0.00 | 0.00 |
| 1937 | 217,118 | 22,160 | 217,106 | 100.1 | 12,444 | 7.92 | 0.01 | 0.00 |
| 1938 | 217,108 | 22,160 | 217,097 | 100.1 | 12,462 | 8.00 | 0.01 | 0.00 |
| 1939 | 217,098 | 22,161 | 217,086 | 100.1 | 12,479 | 7.09 | 0.01 | 0.00 |
| 1940 | 217,086 | 22,162 | 217,075 | 100.1 | 12,490 | 3.30 | 0.00 | 0.00 |
| 1941 | 217,078 | 22,162 | 217,066 | 100.1 | 12,489 | 5.87 | 0.00 | 0.00 |
| 1942 | 217,065 | 22,163 | 217,054 | 100.1 | 12,470 | 6.74 | 0.00 | 0.00 |
| 1943 | 217,050 | 22,163 | 217,039 | 100.1 | 12,427 | 18.24 | 0.01 | 0.00 |
| 1944 | 217,021 | 22,162 | 217,010 | 100.1 | 12,352 | 9.59 | 0.01 | 0.00 |
| 1945 | 217,000 | 22,162 | 216,988 | 100.1 | 12,241 | 9.05 | 0.01 | 0.00 |
| 1946 | 216,976 | 22,162 | 216,965 | 100.1 | 12,089 | 7.32 | 0.01 | 0.00 |
| 1947 | 216,952 | 22,162 | 216,941 | 100.1 | 11,896 | 7.24 | 0.01 | 0.00 |
| 1948 | 216,924 | 22,161 | 216,913 | 100.1 | 11,663 | 19.03 | 0.02 | 0.00 |
| 1949 | 216,879 | 22,160 | 216,868 | 100.1 | 11,397 | 18.37 | 0.01 | 0.00 |
| 1950 | 216,829 | 22,158 | 216,819 | 100.1 | 11,104 | 10.20 | 0.01 | 0.00 |
| 1951 | 216,781 | 22,157 | 216,771 | 100.1 | 10,784 | 15.54 | 0.01 | 0.00 |
| 1952 | 216,719 | 22,155 | 216,710 | 100.0 | 10,459 | 18.70 | 0.02 | 0.00 |
| 1953 | 216,645 | 22,153 | 216,635 | 100.0 | 10,138 | 7.12 | 0.01 | 0.00 |
| 1954 | 216,571 | 22,151 | 216,562 | 100.0 | 9,832 | 149.50 | 0.12 | 0.00 |
| 1955 | 216,331 | 22,138 | 216,322 | 100.0 | 9,548 | 89.35 | 0.07 | 0.00 |
| 1956 | 216,140 | 22,129 | 216,132 | 99.9 | 9,294 | 184.48 | 0.15 | 0.00 |
| 1957 | 215,830 | 22,111 | 215,821 | 99.8 | 9,077 | 85.17 | 0.07 | 0.00 |
| 1958 | 215,608 | 22,101 | 215,599 | 99.8 | 8,903 | 47.67 | 0.04 | 0.00 |
| 1959 | 215,407 | 22,094 | 215,399 | 99.8 | 8,778 | 74.69 | 0.06 | 0.00 |
| 1960 | 215,157 | 22,084 | 215,149 | 99.7 | 8,708 | 209.37 | 0.18 | 0.00 |
| 1961 | 214,739 | 22,063 | 214,731 | 99.6 | 8,701 | 101.87 | 0.09 | 0.00 |
| 1962 | 214,414 | 22,049 | 214,406 | 99.6 | 8,767 | 157.67 | 0.13 | 0.00 |
| 1963 | 214,006 | 22,030 | 213,998 | 99.5 | 8,915 | 260.51 | 0.22 | 0.00 |
| 1964 | 213,462 | 22,002 | 213,454 | 99.4 | 9,156 | 228.07 | 0.19 | 0.00 |
| 1965 | 212,930 | 21,975 | 212,921 | 99.2 | 9,495 | 385.26 | 0.32 | 0.00 |
| 1966 | 212,202 | 21,933 | 212,193 | 99.0 | 9,931 | 1419.32 | 0.93 | 0.01 |
| 1967 | 210,327 | 21,803 | 210,318 | 98.5 | 10,445 | 1455.70 | 0.96 | 0.01 |
| 1968 | 208,376 | 21,666 | 208,366 | 97.8 | 11,011 | 2307.78 | 1.29 | 0.01 |
| 1969 | 205,459 | 21,453 | 205,448 | 96.9 | 11,587 | 758.09 | 0.59 | 0.00 |
| 1970 | 204,203 | 21,364 | 204,192 | 96.5 | 12,153 | 896.52 | 0.69 | 0.00 |
| 1971 | 202,782 | 21,261 | 202,770 | 96.0 | 12,698 | 1120.43 | 0.82 | 0.01 |
| 1972 | 201,106 | 21,136 | 201,093 | 95.4 | 13,226 | 2028.48 | 1.24 | 0.01 |
| 1973 | 198,423 | 20,929 | 198,410 | 94.5 | 13,702 | 3467.33 | 1.61 | 0.02 |

Table 10: Time series of population estimates from the base model. (*continued*)

| Year | Total Biomass (mt) | Spawning Output | Total Biomass (mt) | % Un-fished | Age 0 Recruits | Total Mortality | SPR Ratio | Expl Rate |
|------|--------------------|-----------------|--------------------|-------------|----------------|-----------------|-----------|-----------|
| 1974 | 194,148 | 20,594 | 194,134 | 93.0 | 14,028 | 1548.21 | 1.08 | 0.01 |
| 1975 | 191,947 | 20,414 | 191,934 | 92.2 | 14,103 | 2583.44 | 1.46 | 0.01 |
| 1976 | 188,609 | 20,141 | 188,596 | 91.0 | 13,860 | 2155.09 | 1.35 | 0.01 |
| 1977 | 185,727 | 19,899 | 185,714 | 89.9 | 13,406 | 1789.93 | 1.23 | 0.01 |
| 1978 | 183,244 | 19,683 | 183,232 | 88.9 | 12,934 | 1354.92 | 1.05 | 0.01 |
| 1979 | 181,244 | 19,500 | 181,232 | 88.1 | 12,626 | 2009.80 | 1.34 | 0.01 |
| 1980 | 178,530 | 19,257 | 178,518 | 87.0 | 12,572 | 1580.54 | 1.18 | 0.01 |
| 1981 | 176,296 | 19,047 | 176,284 | 86.0 | 12,729 | 1979.58 | 1.35 | 0.01 |
| 1982 | 173,634 | 18,800 | 173,622 | 84.9 | 12,882 | 2245.38 | 1.45 | 0.01 |
| 1983 | 170,693 | 18,526 | 170,681 | 83.7 | 12,838 | 2225.99 | 1.46 | 0.01 |
| 1984 | 167,788 | 18,250 | 167,776 | 82.4 | 12,602 | 3438.62 | 1.73 | 0.02 |
| 1985 | 163,566 | 17,865 | 163,554 | 80.7 | 12,301 | 3989.88 | 1.81 | 0.02 |
| 1986 | 158,728 | 17,429 | 158,717 | 78.7 | 12,030 | 3487.19 | 1.78 | 0.02 |
| 1987 | 154,430 | 17,031 | 154,419 | 76.9 | 11,888 | 2401.12 | 1.59 | 0.02 |
| 1988 | 151,336 | 16,722 | 151,325 | 75.5 | 11,967 | 3476.63 | 1.80 | 0.02 |
| 1989 | 147,071 | 16,320 | 147,059 | 73.7 | 12,126 | 5491.29 | 1.94 | 0.04 |
| 1990 | 140,583 | 15,741 | 140,572 | 71.1 | 12,179 | 4667.22 | 1.92 | 0.03 |
| 1991 | 134,998 | 15,223 | 134,987 | 68.7 | 11,560 | 4030.93 | 1.89 | 0.03 |
| 1992 | 130,121 | 14,754 | 130,111 | 66.6 | 10,746 | 3842.94 | 1.90 | 0.03 |
| 1993 | 125,437 | 14,300 | 125,428 | 64.6 | 9,979 | 4201.69 | 1.93 | 0.03 |
| 1994 | 120,357 | 13,814 | 120,349 | 62.4 | 8,733 | 3849.80 | 1.92 | 0.03 |
| 1995 | 115,663 | 13,355 | 115,656 | 60.3 | 8,004 | 2281.71 | 1.76 | 0.02 |
| 1996 | 112,686 | 13,030 | 112,678 | 58.8 | 8,224 | 1903.53 | 1.68 | 0.02 |
| 1997 | 110,145 | 12,739 | 110,137 | 57.5 | 8,321 | 1666.52 | 1.62 | 0.02 |
| 1998 | 107,895 | 12,471 | 107,886 | 56.3 | 8,645 | 1475.58 | 1.56 | 0.01 |
| 1999 | 105,886 | 12,223 | 105,877 | 55.2 | 10,113 | 895.69 | 1.22 | 0.01 |
| 2000 | 104,557 | 12,025 | 104,545 | 54.3 | 12,605 | 1018.95 | 1.32 | 0.01 |
| 2001 | 103,147 | 11,822 | 103,132 | 53.4 | 16,120 | 663.05 | 1.01 | 0.01 |
| 2002 | 102,195 | 11,651 | 102,178 | 52.6 | 18,032 | 942.43 | 1.26 | 0.01 |
| 2003 | 101,026 | 11,462 | 100,997 | 51.8 | 31,062 | 960.59 | 1.18 | 0.01 |
| 2004 | 99,935 | 11,267 | 99,916 | 50.9 | 20,287 | 879.28 | 1.12 | 0.01 |
| 2005 | 99,074 | 11,085 | 99,055 | 50.1 | 20,927 | 775.07 | 1.04 | 0.01 |
| 2006 | 98,399 | 10,918 | 98,380 | 49.3 | 21,018 | 826.54 | 1.09 | 0.01 |
| 2007 | 97,763 | 10,752 | 97,741 | 48.6 | 23,488 | 1103.22 | 1.29 | 0.01 |
| 2008 | 96,940 | 10,569 | 96,916 | 47.7 | 25,728 | 1569.39 | 1.53 | 0.02 |
| 2009 | 95,731 | 10,354 | 95,714 | 46.8 | 17,944 | 1673.89 | 1.58 | 0.02 |
| 2010 | 94,518 | 10,135 | 94,505 | 45.8 | 13,805 | 1488.11 | 1.51 | 0.02 |
| 2011 | 93,568 | 9,937 | 93,557 | 44.9 | 12,001 | 1083.82 | 1.28 | 0.01 |
| 2012 | 93,118 | 9,774 | 93,108 | 44.1 | 10,431 | 989.98 | 1.22 | 0.01 |
| 2013 | 92,847 | 9,626 | 92,838 | 43.5 | 9,622 | 1111.27 | 1.29 | 0.01 |
| 2014 | 92,527 | 9,476 | 92,518 | 42.8 | 9,650 | 928.12 | 1.16 | 0.01 |
| 2015 | 92,475 | 9,348 | 92,466 | 42.2 | 9,783 | 929.06 | 1.16 | 0.01 |
| 2016 | 92,496 | 9,228 | 92,487 | 41.7 | 10,155 | 992.09 | 1.19 | 0.01 |
| 2017 | 92,522 | 9,112 | 92,513 | 41.1 | 9,995 | 1094.53 | 1.25 | 0.01 |

Table 10: Time series of population estimates from the base model. (*continued*)

| Year | Total Biomass (mt) | Spawning Output | Total Biomass (mt) | % Un-fished | Age 0 Recruits | Total Mortality | SPR Ratio | Expl Rate |
|------|--------------------|-----------------|--------------------|-------------|----------------|-----------------|-----------|-----------|
| 2018 | 92,505 | 8,997 | 92,496 | 40.6 | 9,990 | 948.28 | 1.14 | 0.01 |
| 2019 | 92,697 | 8,902 | 92,687 | 40.2 | 10,354 | 785.62 | 1.00 | 0.01 |
| 2020 | 93,109 | 8,829 | 93,099 | 39.9 | 10,839 | 477.36 | 0.68 | 0.01 |
| 2021 | 93,892 | 8,787 | 93,882 | 39.7 | 11,299 | 499.93 | 0.69 | 0.01 |
| 2022 | 94,704 | 8,754 | 94,694 | 39.5 | 10,952 | 724.14 | 0.88 | 0.01 |
| 2023 | 95,328 | 8,717 | 95,318 | 39.4 | 10,942 | 756.11 | 0.90 | 0.01 |
| 2024 | 95,952 | 8,687 | 95,942 | 39.2 | 10,933 | 756.11 | 0.88 | 0.01 |
| 2025 | 96,605 | 8,666 | 96,595 | 39.1 | 10,928 | 710.84 | 0.82 | 0.01 |
| 2026 | 97,328 | 8,659 | 97,318 | 39.1 | 10,926 | 713.47 | 0.81 | 0.01 |
| 2027 | 98,069 | 8,660 | 98,059 | 39.1 | 10,926 | 716.19 | 0.80 | 0.01 |
| 2028 | 98,824 | 8,670 | 98,813 | 39.1 | 10,929 | 718.04 | 0.79 | 0.01 |
| 2029 | 99,590 | 8,688 | 99,580 | 39.2 | 10,934 | 720.05 | 0.78 | 0.01 |
| 2030 | 100,366 | 8,712 | 100,356 | 39.3 | 10,940 | 721.25 | 0.76 | 0.01 |
| 2031 | 101,149 | 8,744 | 101,138 | 39.5 | 10,949 | 721.67 | 0.76 | 0.01 |
| 2032 | 101,937 | 8,782 | 101,927 | 39.7 | 10,959 | 721.32 | 0.74 | 0.01 |
| 2033 | 102,729 | 8,826 | 102,719 | 39.9 | 10,970 | 720.20 | 0.74 | 0.01 |
| 2034 | 103,525 | 8,874 | 103,514 | 40.1 | 10,983 | 719.01 | 0.72 | 0.01 |

Table 11: Likelihood components by source.

| Source | Likelihood Component |
|--------------------------------------|----------------------|
| TOTAL | 242.840 |
| Catch | 0.000 |
| Equil catch | 0.000 |
| Survey | -53.277 |
| Discard | 100.666 |
| Mean body wt | -78.582 |
| Length comp | 265.307 |
| Recruitment | 1.480 |
| InitEQ Regime | 0.000 |
| Forecast Recruitment | 0.005 |
| Parm priors | 7.241 |
| Parm devs | 0.000 |
| F Ballpark | 0.000 |
| F Ballpark(info only) 1999 estF tgtF | 0.016 |
| Crash Pen | 0.000 |

Table 12: Sample sizes of length composition samples for shortspine thornyhead landings.

| Year | Samples North Trawl | Tows North Trawl | Samples South Trawl | Tows South Trawl | Samples Non-trawl | Tows Non-trawl |
|------|---------------------------|------------------------|---------------------------|------------------------|----------------------|-------------------|
| 1981 | 30 | 1 | 737 | 42 | NA | NA |
| 1982 | 150 | 5 | 723 | 57 | NA | NA |
| 1983 | NA | NA | 1230 | 91 | NA | NA |
| 1984 | NA | NA | 2755 | 118 | NA | NA |
| 1985 | NA | NA | 3176 | 136 | 3 | 3 |
| 1986 | NA | NA | 978 | 42 | 9 | 9 |
| 1987 | NA | NA | 343 | 26 | 54 | 15 |
| 1988 | NA | NA | 140 | 15 | 8 | 7 |
| 1989 | NA | NA | 741 | 38 | 18 | 12 |
| 1990 | 390 | 33 | 517 | 32 | 24 | 14 |
| 1991 | 1059 | 47 | 532 | 41 | NA | NA |
| 1992 | 1227 | 52 | 448 | 36 | 75 | 4 |
| 1993 | 281 | 12 | 993 | 56 | 3 | 3 |
| 1994 | 40 | 1 | 1367 | 65 | 46 | 12 |
| 1995 | 24 | 2 | 2248 | 103 | 36 | 6 |
| 1996 | 497 | 15 | 2078 | 94 | 26 | 1 |
| 1997 | 2322 | 49 | 1720 | 92 | 36 | 2 |
| 1998 | 757 | 28 | 1130 | 57 | 130 | 7 |
| 1999 | 819 | 27 | 821 | 48 | 1852 | 73 |
| 2000 | 660 | 23 | 1027 | 63 | 447 | 20 |
| 2001 | 1632 | 45 | 1413 | 73 | 132 | 8 |
| 2002 | 2183 | 50 | 2320 | 108 | 1036 | 42 |
| 2003 | 2431 | 67 | 1909 | 80 | 834 | 29 |
| 2004 | 1509 | 53 | 1073 | 61 | 133 | 10 |
| 2005 | 1649 | 50 | 1393 | 75 | 620 | 34 |
| 2006 | 1573 | 53 | 3109 | 156 | 596 | 32 |
| 2007 | 2452 | 76 | 1893 | 98 | 393 | 17 |
| 2008 | 2660 | 90 | 2212 | 106 | 2037 | 80 |
| 2009 | 2854 | 85 | 2137 | 87 | 1298 | 60 |
| 2010 | 3130 | 91 | 1720 | 88 | 1346 | 75 |
| 2011 | 2381 | 67 | 2950 | 106 | 3276 | 163 |
| 2012 | 2262 | 67 | 2423 | 102 | 2419 | 137 |
| 2013 | 2519 | 84 | 2505 | 102 | 2010 | 115 |
| 2014 | 2036 | 73 | 1490 | 77 | 3283 | 149 |
| 2015 | 1915 | 65 | 1615 | 69 | 2971 | 152 |
| 2016 | 1495 | 59 | 2362 | 82 | 3087 | 147 |
| 2017 | 2158 | 75 | 1571 | 48 | 2504 | 139 |
| 2018 | 1828 | 78 | 1222 | 29 | 1333 | 91 |
| 2019 | 1539 | 68 | 740 | 29 | 1702 | 134 |

Table 12: Sample sizes of length composition samples for shortspine thornyhead landings.
(continued)

| Year | Samples North Trawl | Tows North Trawl | Samples South Trawl | Tows South Trawl | Samples Non-trawl | Tows Non-trawl |
|------|---------------------------|------------------------|---------------------------|------------------------|----------------------|-------------------|
| 2020 | 951 | 47 | 897 | 26 | 696 | 64 |
| 2021 | 1505 | 80 | 294 | 15 | 1067 | 108 |
| 2022 | 1103 | 57 | 273 | 13 | 863 | 75 |

Table 13: Sample sizes of length composition samples for discards.

| Year | North Trawl | South Trawl | Non-trawl |
|------|-------------|-------------|-----------|
| 2005 | NA | NA | 4 |
| 2006 | 148 | 56 | 102 |
| 2007 | 249 | 64 | 145 |
| 2008 | 354 | 79 | 102 |
| 2009 | 485 | 102 | 71 |
| 2010 | 271 | 43 | 98 |
| 2011 | 282 | 74 | 168 |
| 2012 | 378 | 126 | 224 |
| 2013 | 366 | 155 | 55 |
| 2014 | 311 | 126 | 120 |
| 2015 | 204 | 154 | 148 |
| 2016 | 216 | 108 | 189 |
| 2017 | 182 | 39 | 153 |
| 2018 | 211 | 47 | 148 |
| 2019 | 175 | 79 | 77 |
| 2020 | 163 | 99 | 43 |
| 2021 | 210 | 97 | 104 |

Table 14: Survey stratification information for each of the fishery independent surveys

| Survey | Strata Definitions |
|--|---|
| Survey | Strata Definitions |
| AFSC Slope | 2 strata: 32.0-49.0 degrees N: 150-500 m, 500-1280 m |
| NWFSC Combo (West Coast Groundfish Bottom Trawl Survey) | 7 strata 32.0-34.5 degrees N: 183-550 m, 550-1280 m 34.5-40.5 degrees N: 183-550 m, 550-1280 m 40.5-49.0 degrees N: 100-183 m, 183-550 m, 550-1280 m The depth breaks at 183 m and 550 m are associated with changes in sampling intensity of the survey and are recommended to be used. |
| NWFSC Slope | 6 strata 32.0-40.5 degrees N: 55-500m, 550-1280m 40.5-43.0 degrees N: 55-550m, 550-1280m 43.0-49.0 degrees N: 55-550m, 550-1280m |
| AFSC Triennial 1 | 1 stratum: <=366 m |
| AFSC Triennial 2 | 1 stratum: 366-500 m |

Table 15: Survey samples and hauls for each of the fishery independent surveys for available years spanning from 1989 to 2022.

| Year | Survey | Fish | Hauls |
|------|-----------------|-------|-------|
| 1989 | Early Triennial | 1770 | 51 |
| 1992 | Early Triennial | 1143 | 23 |
| 1995 | Late Triennial | 9984 | 128 |
| 1997 | AFSC Slope | 7454 | 171 |
| 1998 | NWFSC Slope | 8946 | 270 |
| 1998 | Late Triennial | 9871 | 147 |
| 1999 | AFSC Slope | 6752 | 188 |
| 1999 | NWFSC Slope | 10061 | 302 |
| 2000 | AFSC Slope | 7017 | 196 |
| 2000 | NWFSC Slope | 8057 | 295 |
| 2001 | AFSC Slope | 6072 | 196 |
| 2001 | NWFSC Slope | 8091 | 297 |
| 2001 | Late Triennial | 10147 | 190 |
| 2002 | NWFSC Slope | 11835 | 374 |
| 2003 | WCGBTS | 7693 | 293 |
| 2004 | WCGBTS | 6694 | 214 |
| 2004 | Late Triennial | 8508 | 137 |
| 2005 | WCGBTS | 8047 | 315 |
| 2006 | WCGBTS | 6198 | 332 |
| 2007 | WCGBTS | 5499 | 367 |
| 2008 | WCGBTS | 4697 | 362 |
| 2009 | WCGBTS | 4195 | 340 |
| 2010 | WCGBTS | 3859 | 360 |
| 2011 | WCGBTS | 4697 | 347 |
| 2012 | WCGBTS | 4678 | 349 |
| 2013 | WCGBTS | 3119 | 247 |
| 2014 | WCGBTS | 4617 | 346 |
| 2015 | WCGBTS | 4511 | 332 |
| 2016 | WCGBTS | 4604 | 355 |
| 2017 | WCGBTS | 4730 | 363 |
| 2018 | WCGBTS | 4996 | 368 |
| 2019 | WCGBTS | 2401 | 175 |
| 2021 | WCGBTS | 4690 | 345 |
| 2022 | WCGBTS | 4202 | 312 |

Table 16: Jitter results.

| Total Likelihood | Change from Base | % Change | Frequency |
|------------------|------------------|----------|-----------|
| 536.263 | 0.000 | 0.00% | 74 |
| 545.676 | 9.413 | 1.73% | 1 |
| 546.320 | 10.057 | 1.84% | 1 |
| 572.534 | 36.271 | 6.34% | 1 |
| 622.788 | 86.525 | 13.89% | 1 |
| 638.932 | 102.669 | 16.07% | 1 |
| 654.891 | 118.628 | 18.11% | 5 |
| 654.998 | 118.735 | 18.13% | 6 |
| 655.191 | 118.928 | 18.15% | 7 |
| 655.997 | 119.734 | 18.25% | 1 |
| 664.680 | 128.417 | 19.32% | 1 |
| 698.582 | 162.319 | 23.24% | 0 |

Table 17: Comparison of likelihoods for all sensitivity analyses

| Source | Base Model | Low Growth | High Growth | 2013 Maturity | Inde-term. Maturity | Imputed Landings | 2013 Landings |
|----------------|------------|------------|-------------|---------------|---------------------|------------------|---------------|
| Total L | 242.84 | 269.27 | 234.08 | 242.85 | 242.87 | 252.21 | 242.94 |
| Survey L | -53.28 | -50.23 | -54.68 | -53.28 | -53.27 | -50.93 | -53.26 |
| Length Comp L | 265.31 | 257.70 | 275.24 | 265.33 | 265.32 | 272.18 | 265.52 |
| Discards L | 100.67 | 131.48 | 86.44 | 100.66 | 100.66 | 100.83 | 100.87 |
| Mean Body Wt L | -78.58 | -78.91 | -78.82 | -78.58 | -78.58 | -78.60 | -78.59 |
| Recruitment L | 1.48 | 2.45 | -1.08 | 1.49 | 1.50 | 1.53 | 1.11 |
| Prior L | 7.24 | 6.78 | 6.90 | 7.23 | 7.24 | 7.20 | 7.28 |
| R0 | 12580.20 | 17129.40 | 8184.94 | 12580.20 | 12582.00 | 12593.10 | 13164.10 |
| B0 | 8716.84 | 8183.13 | 13376.00 | 10015.90 | 9506.39 | 8275.08 | 8839.78 |
| Depletion | 0.39 | 0.43 | 0.40 | 0.42 | 0.41 | 0.37 | 0.38 |
| Relative SPR | 0.89 | 0.75 | 1.04 | 0.86 | 0.87 | 0.92 | 0.88 |

Table 18: All parameter estimates for the proposed base model

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|-----------------------|------------|-------|-----------|-----------------|-----------------|
| NatM_break_1_Fem_GP_1 | 0.0400000 | -3 | NA | 0.040000 | 0.040000 |
| NatM_break_2_Fem_GP_1 | 0.0400000 | -3 | NA | NA | NA |
| L_at_Amin_Fem_GP_1 | 11.3832000 | -2 | NA | NA | NA |
| L_at_Amax_Fem_GP_1 | 73.6079000 | -2 | NA | NA | NA |
| VonBert_K_Fem_GP_1 | 0.0098986 | -3 | NA | NA | NA |
| CV_young_Fem_GP_1 | 0.1090340 | -3 | NA | NA | NA |
| CV_old_Fem_GP_1 | 0.1090340 | -3 | NA | NA | NA |
| Wtlen_1_Fem_GP_1 | 0.0000065 | -3 | NA | NA | NA |
| Wtlen_2_Fem_GP_1 | 3.1797500 | -3 | NA | NA | NA |
| Mat50%_Fem_GP_1 | 31.4247000 | -3 | NA | NA | NA |
| Mat_slope_Fem_GP_1 | -0.1772910 | -3 | NA | NA | NA |
| Eggs_scalar_Fem_GP_1 | 0.0000001 | -3 | NA | NA | NA |
| Eggs_exp_len_Fem_GP_1 | 3.9780000 | -3 | NA | NA | NA |
| NatM_break_1_Mal_GP_1 | 0.0400000 | -3 | NA | NA | NA |
| NatM_break_2_Mal_GP_1 | 0.0400000 | -3 | NA | NA | NA |
| L_at_Amin_Mal_GP_1 | 9.1733000 | -3 | NA | NA | NA |
| L_at_Amax_Mal_GP_1 | 66.0728000 | -2 | NA | NA | NA |
| VonBert_K_Mal_GP_1 | 0.0167854 | -3 | NA | NA | NA |
| CV_young_Mal_GP_1 | 0.1090340 | -3 | NA | NA | NA |
| CV_old_Mal_GP_1 | 0.1090340 | -3 | NA | NA | NA |
| Wtlen_1_Mal_GP_1 | 0.0000067 | -3 | NA | NA | NA |
| Wtlen_2_Mal_GP_1 | 3.1732500 | -3 | NA | NA | NA |
| CohortGrowDev | 1.0000000 | -1 | NA | NA | NA |
| FracFemale_GP_1 | 0.5000000 | -99 | NA | NA | NA |
| SR_LN(R0) | 9.3544800 | 4 | 0.0001044 | NA | NA |
| SR_BH_stEEP | 0.7200000 | -2 | NA | NA | NA |
| SR_sigmaR | 0.5000000 | -4 | NA | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|--------------------|------------|-------|------------|-----------------|-----------------|
| SR_regime | 0.0000000 | -4 | NA | NA | NA |
| SR_autocorr | 0.0000000 | -1 | NA | NA | NA |
| Early_InitAge_1 | -0.0212086 | 6 | -0.0000012 | NA | NA |
| Early_RecrDev_1901 | -0.0231360 | 6 | 0.0000000 | NA | NA |
| Early_RecrDev_1902 | -0.0254220 | 6 | 0.0000011 | NA | NA |
| Early_RecrDev_1903 | -0.0283702 | 6 | -0.0000005 | NA | NA |
| Early_RecrDev_1904 | -0.0319698 | 6 | 0.0000020 | NA | NA |
| Early_RecrDev_1905 | -0.0355489 | 6 | 0.0000036 | NA | NA |
| Early_RecrDev_1906 | -0.0385733 | 6 | -0.0000019 | NA | NA |
| Early_RecrDev_1907 | -0.0414951 | 6 | 0.0000025 | NA | NA |
| Early_RecrDev_1908 | -0.0451950 | 6 | -0.0000019 | NA | NA |
| Early_RecrDev_1909 | -0.0487619 | 6 | 0.0000017 | NA | NA |
| Early_RecrDev_1910 | -0.0529210 | 6 | -0.0000073 | NA | NA |
| Early_RecrDev_1911 | -0.0562301 | 6 | 0.0000016 | NA | NA |
| Early_RecrDev_1912 | -0.0571398 | 6 | 0.0000020 | NA | NA |
| Early_RecrDev_1913 | -0.0571633 | 6 | 0.0000058 | NA | NA |
| Early_RecrDev_1914 | -0.0614764 | 6 | 0.0000008 | NA | NA |
| Early_RecrDev_1915 | -0.0662355 | 6 | -0.0000012 | NA | NA |
| Early_RecrDev_1916 | -0.0686894 | 6 | -0.0000014 | NA | NA |
| Early_RecrDev_1917 | -0.0705061 | 6 | 0.0000064 | NA | NA |
| Early_RecrDev_1918 | -0.0722232 | 6 | 0.0000061 | NA | NA |
| Early_RecrDev_1919 | -0.0747498 | 6 | -0.0000012 | NA | NA |
| Early_RecrDev_1920 | -0.0764656 | 6 | -0.0000017 | NA | NA |
| Early_RecrDev_1921 | -0.0784239 | 6 | 0.0000041 | NA | NA |
| Early_RecrDev_1922 | -0.0795038 | 6 | 0.0000050 | NA | NA |
| Early_RecrDev_1923 | -0.0797302 | 6 | 0.0000051 | NA | NA |
| Early_RecrDev_1924 | -0.0801474 | 6 | 0.0000042 | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|--------------------|------------|-------|------------|-----------------|-----------------|
| Early_RecrDev_1925 | -0.0800694 | 6 | 0.0000076 | NA | NA |
| Early_RecrDev_1926 | -0.0794285 | 6 | 0.0000037 | NA | NA |
| Early_RecrDev_1927 | -0.0781531 | 6 | 0.0000000 | NA | NA |
| Early_RecrDev_1928 | -0.0761695 | 6 | -0.0000007 | NA | NA |
| Early_RecrDev_1929 | -0.0734039 | 6 | 0.0000010 | NA | NA |
| Early_RecrDev_1930 | -0.0697849 | 6 | 0.0000091 | NA | NA |
| Early_RecrDev_1931 | -0.0652490 | 6 | -0.0000003 | NA | NA |
| Early_RecrDev_1932 | -0.0597442 | 6 | 0.0000033 | NA | NA |
| Early_RecrDev_1933 | -0.0532400 | 6 | 0.0000054 | NA | NA |
| Early_RecrDev_1934 | -0.0457363 | 6 | 0.0000005 | NA | NA |
| Early_RecrDev_1935 | -0.0372755 | 6 | 0.0000061 | NA | NA |
| Early_RecrDev_1936 | -0.0279592 | 6 | 0.0000062 | NA | NA |
| Early_RecrDev_1937 | -0.0179638 | 6 | 0.0000021 | NA | NA |
| Early_RecrDev_1938 | -0.0075590 | 6 | 0.0000060 | NA | NA |
| Early_RecrDev_1939 | 0.0028729 | 6 | 0.0000057 | NA | NA |
| Early_RecrDev_1940 | 0.0128254 | 6 | 0.0000044 | NA | NA |
| Early_RecrDev_1941 | 0.0216624 | 6 | 0.0000029 | NA | NA |
| Early_RecrDev_1942 | 0.0286306 | 6 | 0.0000073 | NA | NA |
| Early_RecrDev_1943 | 0.0328934 | 6 | 0.0000042 | NA | NA |
| Early_RecrDev_1944 | 0.0335935 | 6 | 0.0000061 | NA | NA |
| Early_RecrDev_1945 | 0.0299395 | 6 | 0.0000045 | NA | NA |
| Early_RecrDev_1946 | 0.0213064 | 6 | 0.0000046 | NA | NA |
| Early_RecrDev_1947 | 0.0073268 | 6 | 0.0000034 | NA | NA |
| Early_RecrDev_1948 | -0.0120490 | 6 | 0.0000022 | NA | NA |
| Early_RecrDev_1949 | -0.0365423 | 6 | 0.0000079 | NA | NA |
| Early_RecrDev_1950 | -0.0655857 | 6 | 0.0000017 | NA | NA |
| Early_RecrDev_1951 | -0.0981321 | 6 | 0.0000054 | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|--------------------|------------|-------|------------|-----------------|-----------------|
| Early_RecrDev_1952 | -0.1333580 | 6 | 0.0000045 | NA | NA |
| Early_RecrDev_1953 | -0.1702910 | 6 | 0.0000035 | NA | NA |
| Early_RecrDev_1954 | -0.2079570 | 6 | 0.0000025 | NA | NA |
| Early_RecrDev_1955 | -0.2453950 | 6 | 0.0000053 | NA | NA |
| Early_RecrDev_1956 | -0.2817010 | 6 | 0.0000040 | NA | NA |
| Early_RecrDev_1957 | -0.3159610 | 6 | 0.0000021 | NA | NA |
| Early_RecrDev_1958 | -0.3472870 | 6 | 0.0000048 | NA | NA |
| Early_RecrDev_1959 | -0.3747180 | 6 | 0.0000048 | NA | NA |
| Early_RecrDev_1960 | -0.3971880 | 6 | 0.0000033 | NA | NA |
| Early_RecrDev_1961 | -0.4134930 | 6 | 0.0000026 | NA | NA |
| Early_RecrDev_1962 | -0.4223490 | 6 | 0.0000025 | NA | NA |
| Early_RecrDev_1963 | -0.4223980 | 6 | 0.0000027 | NA | NA |
| Early_RecrDev_1964 | -0.4124790 | 6 | 0.0000030 | NA | NA |
| Early_RecrDev_1965 | -0.3919790 | 6 | 0.0000025 | NA | NA |
| Early_RecrDev_1966 | -0.3610010 | 6 | 0.0000057 | NA | NA |
| Early_RecrDev_1967 | -0.3206150 | 6 | 0.0000034 | NA | NA |
| Early_RecrDev_1968 | -0.2730580 | 6 | 0.0000047 | NA | NA |
| Early_RecrDev_1969 | -0.2207630 | 6 | 0.0000034 | NA | NA |
| Early_RecrDev_1970 | -0.1660450 | 6 | 0.0000042 | NA | NA |
| Early_RecrDev_1971 | -0.1102690 | 6 | 0.0000048 | NA | NA |
| Early_RecrDev_1972 | -0.0555105 | 6 | -0.0000016 | NA | NA |
| Early_RecrDev_1973 | -0.0064973 | 6 | 0.0000078 | NA | NA |
| Early_RecrDev_1974 | 0.0285943 | 6 | 0.0000078 | NA | NA |
| Early_RecrDev_1975 | 0.0417962 | 6 | 0.0000059 | NA | NA |
| Early_RecrDev_1976 | 0.0316066 | 6 | 0.0000050 | NA | NA |
| Early_RecrDev_1977 | 0.0060750 | 6 | 0.0000071 | NA | NA |
| Early_RecrDev_1978 | -0.0207783 | 6 | -0.0000014 | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|--------------------|------------|-------|------------|-----------------|-----------------|
| Early_RecrDev_1979 | -0.0349278 | 6 | 0.0000093 | NA | NA |
| Early_RecrDev_1980 | -0.0286589 | 6 | 0.0000057 | NA | NA |
| Early_RecrDev_1981 | -0.0059002 | 6 | 0.0000048 | NA | NA |
| Early_RecrDev_1982 | 0.0173986 | 6 | 0.0000057 | NA | NA |
| Early_RecrDev_1983 | 0.0267644 | 6 | 0.0000044 | NA | NA |
| Early_RecrDev_1984 | 0.0234703 | 6 | 0.0000057 | NA | NA |
| Early_RecrDev_1985 | 0.0169923 | 6 | 0.0000046 | NA | NA |
| Early_RecrDev_1986 | 0.0125559 | 6 | 0.0000031 | NA | NA |
| Early_RecrDev_1987 | 0.0167085 | 6 | 0.0000042 | NA | NA |
| Early_RecrDev_1988 | 0.0381407 | 6 | 0.0000038 | NA | NA |
| Early_RecrDev_1989 | 0.0642914 | 6 | 0.0000015 | NA | NA |
| Early_RecrDev_1990 | 0.0829343 | 6 | 0.0000003 | NA | NA |
| Early_RecrDev_1991 | 0.0490698 | 6 | 0.0000016 | NA | NA |
| Early_RecrDev_1992 | 0.0039841 | 6 | 0.0000012 | NA | NA |
| Early_RecrDev_1993 | -0.0254987 | 6 | -0.0000009 | NA | NA |
| Early_RecrDev_1994 | -0.1043340 | 6 | -0.0000016 | NA | NA |
| Early_RecrDev_1995 | -0.1125850 | 6 | -0.0000029 | NA | NA |
| Main_RecrDev_1996 | -0.3889790 | 6 | 0.0000025 | NA | NA |
| Main_RecrDev_1997 | -0.2999770 | 6 | -0.0000012 | NA | NA |
| Main_RecrDev_1998 | -0.2388930 | 6 | -0.0000013 | NA | NA |
| Main_RecrDev_1999 | -0.0452484 | 6 | -0.0000046 | NA | NA |
| Main_RecrDev_2000 | 0.1842930 | 6 | -0.0000038 | NA | NA |
| Main_RecrDev_2001 | 0.3730210 | 6 | -0.0000105 | NA | NA |
| Main_RecrDev_2002 | 0.1797160 | 6 | -0.0000084 | NA | NA |
| Main_RecrDev_2003 | 1.2078500 | 6 | -0.0000102 | NA | NA |
| Main_RecrDev_2004 | 0.1423860 | 6 | -0.0000039 | NA | NA |
| Main_RecrDev_2005 | 0.2522910 | 6 | -0.0000020 | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|-------------------|------------|-------|------------|-----------------|-----------------|
| Main_RecrDev_2006 | 0.2805240 | 6 | -0.0000005 | NA | NA |
| Main_RecrDev_2007 | 0.2594420 | 6 | 0.0000046 | NA | NA |
| Main_RecrDev_2008 | 1.2964800 | 6 | -0.0000063 | NA | NA |
| Main_RecrDev_2009 | 0.0628162 | 6 | 0.0000040 | NA | NA |
| Main_RecrDev_2010 | -0.0717626 | 6 | 0.0000043 | NA | NA |
| Main_RecrDev_2011 | -0.1599470 | 6 | 0.0000048 | NA | NA |
| Main_RecrDev_2012 | -0.3369110 | 6 | 0.0000075 | NA | NA |
| Main_RecrDev_2013 | -0.4389960 | 6 | 0.0000070 | NA | NA |
| Main_RecrDev_2014 | -0.4468810 | 6 | 0.0000072 | NA | NA |
| Main_RecrDev_2015 | -0.4461790 | 6 | 0.0000113 | NA | NA |
| Main_RecrDev_2016 | -0.4270100 | 6 | 0.0000011 | NA | NA |
| Main_RecrDev_2017 | -0.4622620 | 6 | 0.0000074 | NA | NA |
| Main_RecrDev_2018 | -0.4757690 | 6 | 0.0000082 | NA | NA |
| Late_RecrDev_2019 | -0.0641552 | 5 | 0.0000019 | NA | NA |
| Late_RecrDev_2020 | -0.0132446 | 5 | -0.0000027 | NA | NA |
| Late_RecrDev_2021 | 0.0443739 | 5 | -0.0000015 | NA | NA |
| Late_RecrDev_2022 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2023 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2024 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2025 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2026 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2027 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2028 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2029 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2030 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2031 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2032 | 0.0000000 | 5 | 0.0000000 | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|-------------------------------------|-------------|-------|------------|-----------------|-----------------|
| ForeRecr_2033 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| ForeRecr_2034 | 0.0000000 | 5 | 0.0000000 | NA | NA |
| LnQ_base_Triennial1(4) | -0.4725640 | -1 | NA | NA | NA |
| Q_extraSD_Triennial1(4) | 0.0387429 | 4 | 0.0000001 | NA | NA |
| LnQ_base_NWFSCcombo(6) | 0.1823020 | -1 | NA | NA | NA |
| Size_DblN_peak_Trawl_N(1) | 27.8920000 | 1 | 0.0001238 | NA | NA |
| Size_DblN_top_logit_Trawl_N(1) | -15.0000000 | -3 | NA | NA | NA |
| Size_DblN_ascend_se_Trawl_N(1) | 4.6011700 | 3 | -0.0001243 | NA | NA |
| Size_DblN_descend_se_Trawl_N(1) | 6.9088400 | 4 | 0.0001059 | NA | NA |
| Size_DblN_start_logit_Trawl_N(1) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Size_DblN_end_logit_Trawl_N(1) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Retain_L_infl_Trawl_N(1) | 29.0502000 | 3 | -0.0002307 | NA | NA |
| Retain_L_width_Trawl_N(1) | 2.7569300 | 3 | -0.0000938 | NA | NA |
| Retain_L_asymptote_logit_Trawl_N(1) | 9.9999800 | 3 | 0.0000000 | NA | NA |
| Retain_L_maleoffset_Trawl_N(1) | 0.0000000 | -4 | NA | NA | NA |
| Size_DblN_peak_Trawl_S(2) | 29.4637000 | 1 | 0.0000586 | NA | NA |
| Size_DblN_top_logit_Trawl_S(2) | -0.4208990 | 3 | 0.0000671 | NA | NA |
| Size_DblN_ascend_se_Trawl_S(2) | 3.9103400 | 3 | -0.0000537 | NA | NA |
| Size_DblN_descend_se_Trawl_S(2) | 4.7143800 | 4 | 0.0000235 | NA | NA |
| Size_DblN_start_logit_Trawl_S(2) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Size_DblN_end_logit_Trawl_S(2) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Retain_L_infl_Trawl_S(2) | 25.9045000 | 3 | -0.0000512 | NA | NA |
| Retain_L_width_Trawl_S(2) | 2.7373100 | 3 | -0.0000433 | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|---------------------------------------|-------------|-------|------------|-----------------|-----------------|
| Retain_L_asymptote_logit_Trawl_S(2) | 10.0000000 | -3 | NA | NA | NA |
| Retain_L_maleoffset_Trawl_S(2) | 0.0000000 | -4 | NA | NA | NA |
| Size_DblN_peak_Non-trawl(3) | 45.3712000 | 2 | -0.0000012 | NA | NA |
| Size_DblN_top_logit_Non-trawl(3) | -3.3853700 | 3 | -0.0000026 | NA | NA |
| Size_DblN_ascend_se_Non-trawl(3) | 5.1284900 | 3 | -0.0000006 | NA | NA |
| Size_DblN_descend_se_Non-trawl(3) | 4.7080400 | 4 | -0.0000042 | NA | NA |
| Size_DblN_start_logit_Non-trawl(3) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Size_DblN_end_logit_Non-trawl(3) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Retain_L_infl_Non-trawl(3) | 25.2560000 | 3 | 0.0000003 | NA | NA |
| Retain_L_width_Non-trawl(3) | 2.7244000 | 3 | -0.0000002 | NA | NA |
| Retain_L_asymptote_logit_Non-trawl(3) | 1.4966000 | 3 | 0.0000018 | NA | NA |
| Retain_L_maleoffset_Non-trawl(3) | 0.0000000 | -4 | NA | NA | NA |
| Size_DblN_peak_Triennial1(4) | 26.7034000 | 2 | 0.0000003 | NA | NA |
| Size_DblN_top_logit_Triennial1(4) | -7.0000000 | -3 | NA | NA | NA |
| Size_DblN_ascend_se_Triennial1(4) | 4.1400700 | 3 | 0.0000018 | NA | NA |
| Size_DblN_descend_se_Triennial1(4) | 3.1583700 | 4 | -0.0000002 | NA | NA |
| Size_DblN_start_logit_Triennial1(4) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Size_DblN_end_logit_Triennial1(4) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| SzSel_Male_Peak_Triennial1(4) | -1.9920600 | 3 | -0.0000010 | NA | NA |
| SzSel_Male_Ascend_Triennial1(4) | -0.0989113 | 3 | 0.0000043 | NA | NA |
| SzSel_Male_Descend_Triennial1(4) | 0.0000000 | -3 | NA | NA | NA |
| SzSel_Male_Final_Triennial1(4) | 0.0000000 | -3 | NA | NA | NA |
| SzSel_Male_Scale_Triennial1(4) | 1.0000000 | -4 | NA | NA | NA |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|---|-------------|-------|------------|-----------------|-----------------|
| Size_DblN_peak_Triennial2(5) | 23.1266000 | 2 | 0.0000001 | NA | NA |
| Size_DblN_top_logit_Triennial2(5) | -7.0000000 | -3 | NA | NA | NA |
| Size_DblN_ascend_se_Triennial2(5) | 4.3565000 | 3 | 0.0000018 | NA | NA |
| Size_DblN_descend_se_Triennial2(5) | 4.1375700 | 4 | 0.0000007 | NA | NA |
| Size_DblN_start_logit_Triennial2(5) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Size_DblN_end_logit_Triennial2(5) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| SzSel_Male_Peak_Triennial2(5) | -1.7395500 | 3 | -0.0000005 | NA | NA |
| SzSel_Male_Ascend_Triennial2(5) | -0.2840780 | 3 | 0.0000007 | NA | NA |
| SzSel_Male_Descend_Triennial2(5) | 0.0000000 | -3 | NA | NA | NA |
| SzSel_Male_Final_Triennial2(5) | 0.0000000 | -3 | NA | NA | NA |
| SzSel_Male_Scale_Triennial2(5) | 1.0000000 | -4 | NA | NA | NA |
| Size_DblN_peak_NWFSCcombo(6) | 29.9823000 | 2 | 0.0000138 | NA | NA |
| Size_DblN_top_logit_NWFSCcombo(6) | -0.8537680 | 3 | 0.0000046 | NA | NA |
| Size_DblN_ascend_se_NWFSCcombo(6) | 4.9374300 | 3 | -0.0000211 | NA | NA |
| Size_DblN_descend_se_NWFSCcombo(6) | 4.5447800 | 4 | 0.0000023 | NA | NA |
| Size_DblN_start_logit_NWFSCcombo(6) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| Size_DblN_end_logit_NWFSCcombo(6) | - | -99 | NA | NA | NA |
| | 999.0000000 | | | | |
| SzSel_Male_Peak_NWFSCcombo(6) | -4.1440800 | 3 | 0.0000040 | NA | NA |
| SzSel_Male_Ascend_NWFSCcombo(6) | -0.5434570 | 3 | -0.0000282 | NA | NA |
| SzSel_Male_Descend_NWFSCcombo(6) | 0.0000000 | -3 | NA | NA | NA |
| SzSel_Male_Final_NWFSCcombo(6) | 0.0000000 | -3 | NA | NA | NA |
| SzSel_Male_Scale_NWFSCcombo(6) | 1.0000000 | -4 | NA | NA | NA |
| Retain_L_infl_Trawl_N(1)_BLK1delta_2007 | -5.7314400 | 4 | -0.0000607 | -7.379180 | -4.083690 |

Table 18: All parameter estimates for the proposed base model (*continued*)

| Source | Value | Phase | Gradient | Lower 95% CI | Upper 95% CI |
|--|------------|-------|------------|-----------------|-----------------|
| Retain_L_infl_Trawl_N(1)_BLK1delta_2011 | -2.4994900 | 4 | -0.0000675 | -3.712360 | -1.286620 |
| Retain_L_asymptote_logit_Trawl_N(1)_BLK1delta_2007 | 0.0002155 | 4 | 0.0000000 | -0.391742 | 0.392173 |
| Retain_L_asymptote_logit_Trawl_N(1)_BLK1delta_2011 | 0.0001030 | 4 | -0.0000002 | -0.391877 | 0.392083 |
| Retain_L_infl_Trawl_S(2)_BLK2delta_2007 | -5.2047800 | 4 | -0.0000120 | -7.293730 | -3.115830 |
| Retain_L_infl_Trawl_S(2)_BLK2delta_2011 | -3.4190500 | 4 | -0.0000137 | -4.345530 | -2.492580 |
| Retain_L_asymptote_logit_Trawl_S(2)_BLK2delta_2007 | 0.0017796 | 4 | 0.0000004 | -0.389867 | 0.393426 |
| Retain_L_asymptote_logit_Trawl_S(2)_BLK2delta_2011 | 0.0015285 | 4 | 0.0000000 | -0.390168 | 0.393225 |

8 Figures

8.1 Introduction and Data

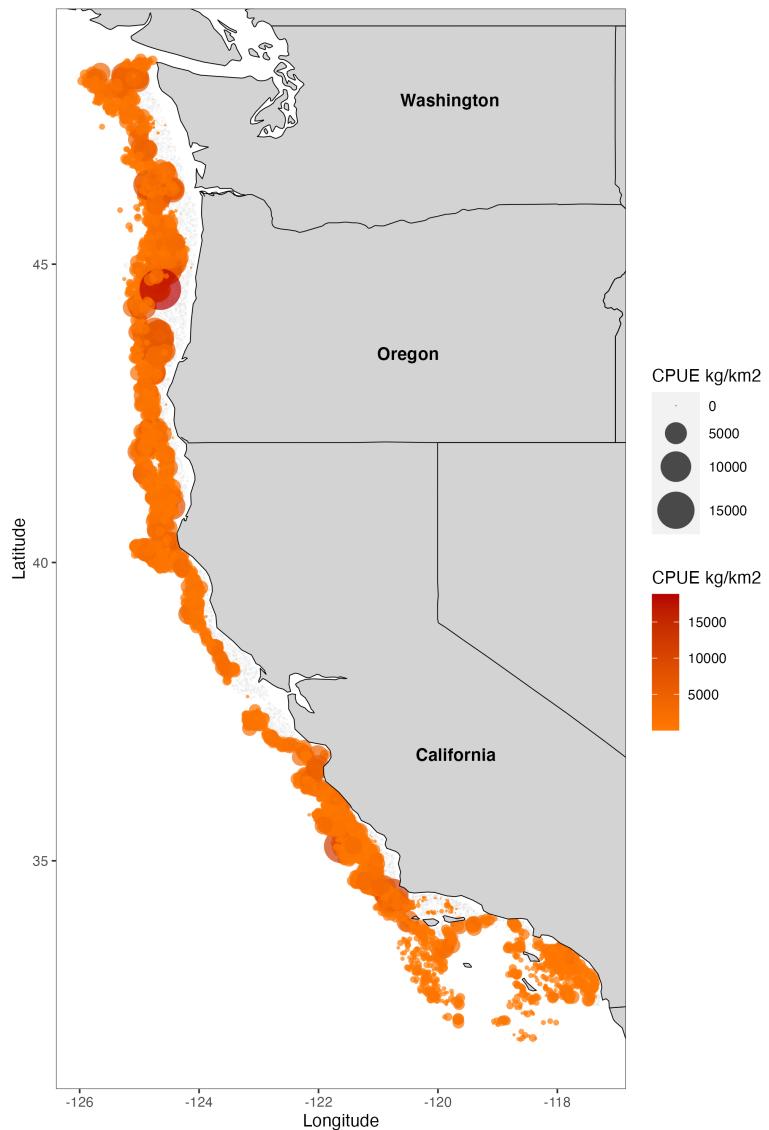


Figure 1: Biomass of shortspine thornyhead found in the NWFSC West Coast Groundfish Bottom Trawl Survey annual survey (2003-2022) coastwide.

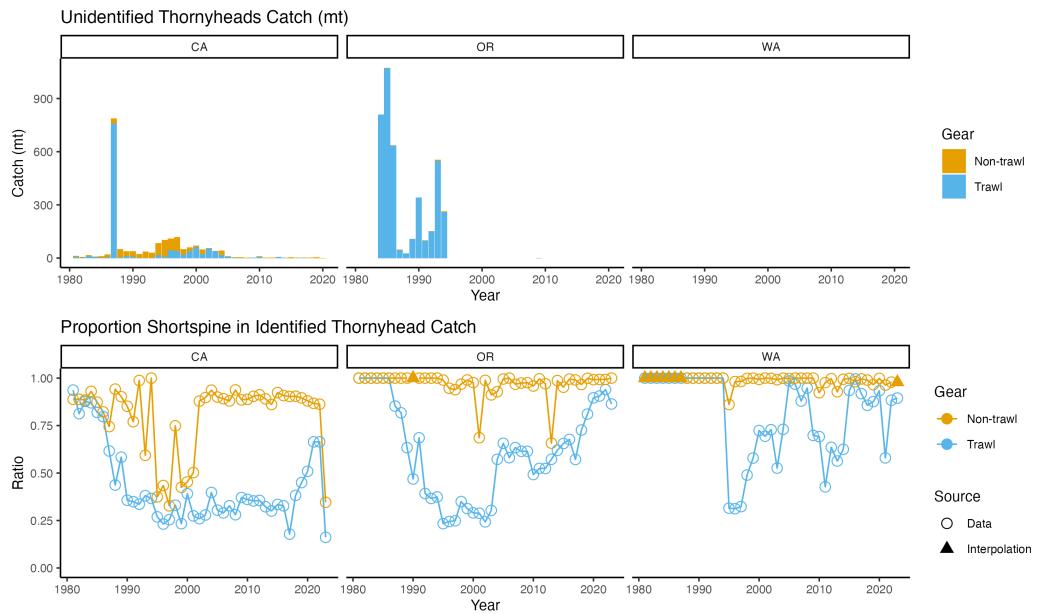


Figure 2: Unidentified thornyhead catches (mt) and the proportion identified as short-spines, calculated as the ratio of shortspine thornyhead catches to combined longspine and shortspine catches.

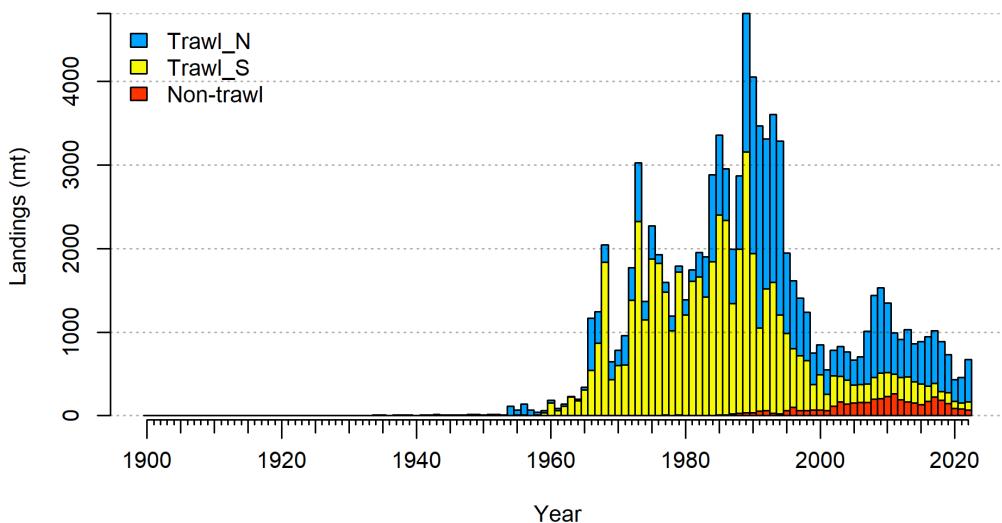


Figure 3: Landing history for shortspine thornyhead.

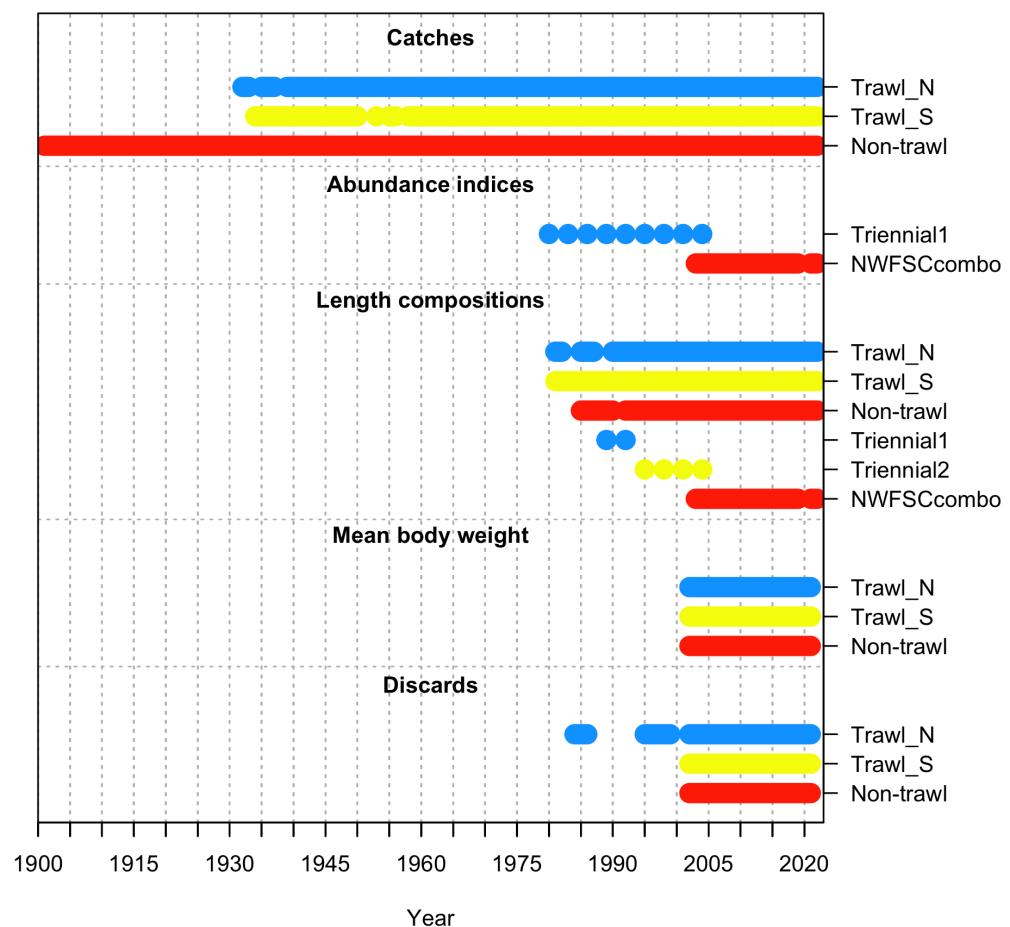


Figure 4: Summary of data sources used in the base model.

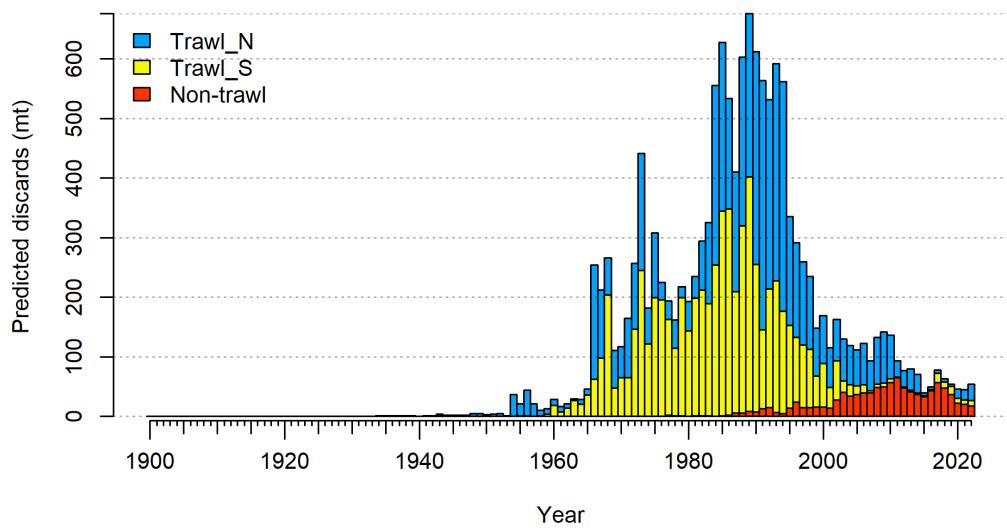


Figure 5: Predicted discards based estimated retention and selectivity for each fleet.

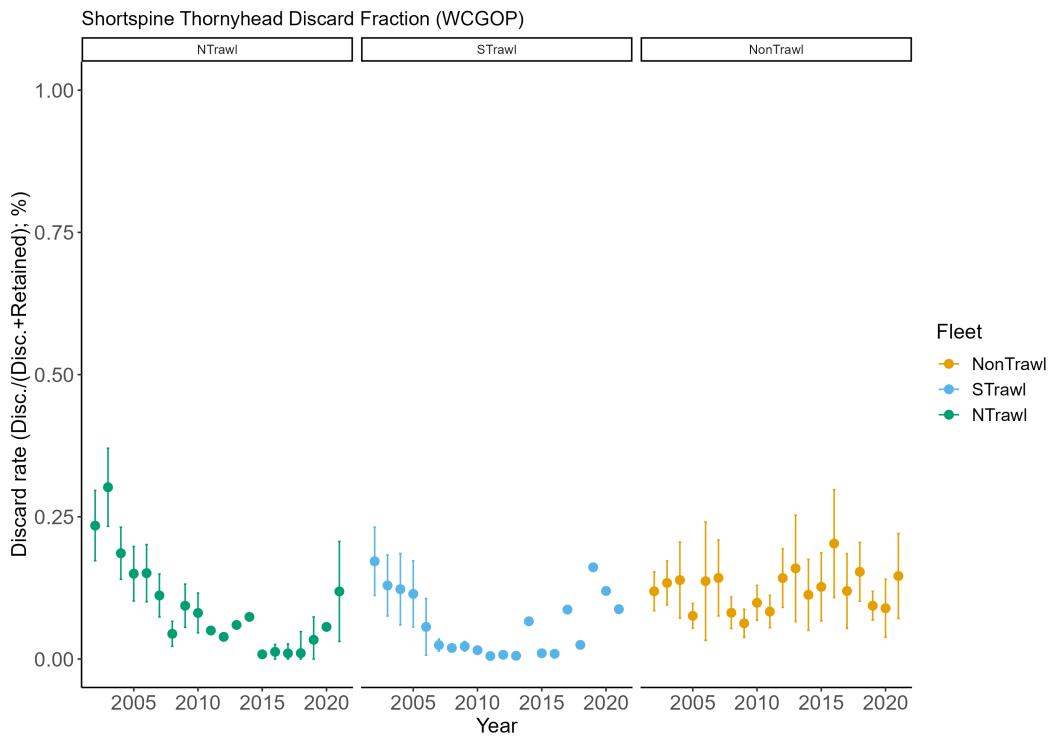


Figure 6: Discard rates from the WCGOP data set with catch share and non-catch share considerations from the GEMM dataset.

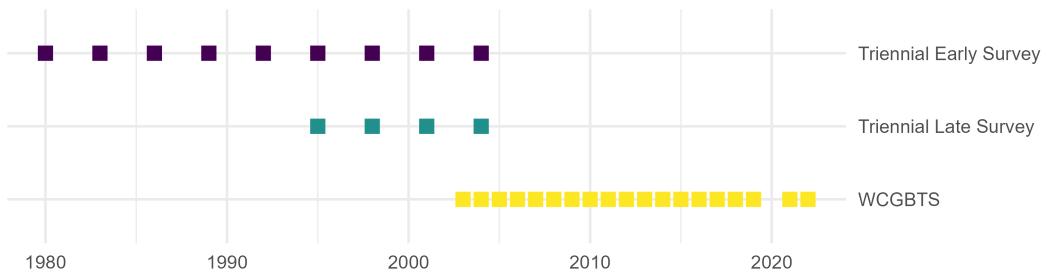


Figure 7: Summary of survey data sources used in the base model.

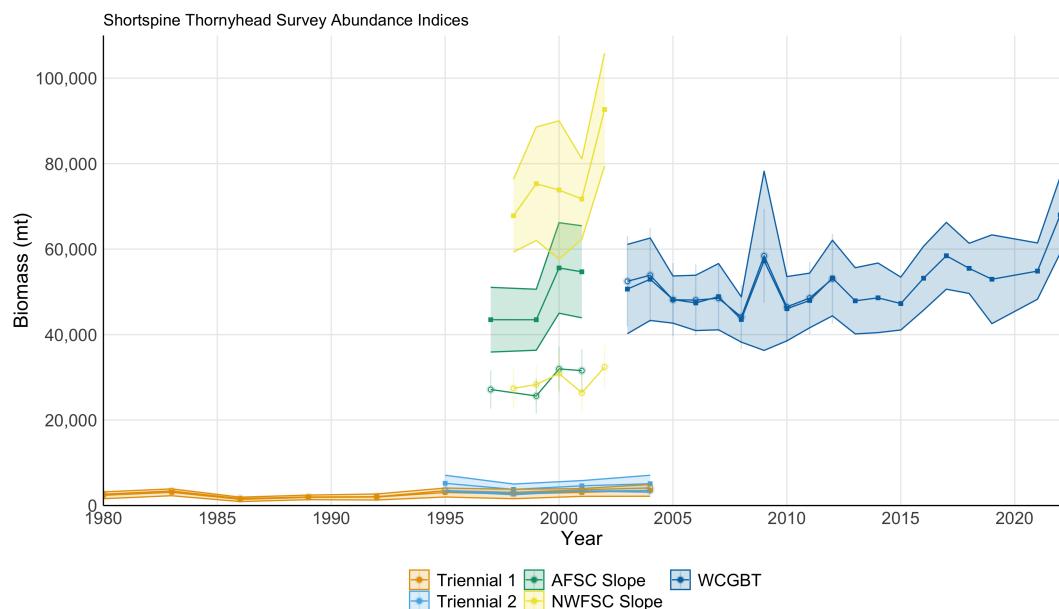


Figure 8: Abundance index timeseries. Points with shaded regions were calculated with survey data through 2023 using the `nwfscSurvey` R package, while points with errorbars are taken directly from the 2013 assessment which used GLMs.

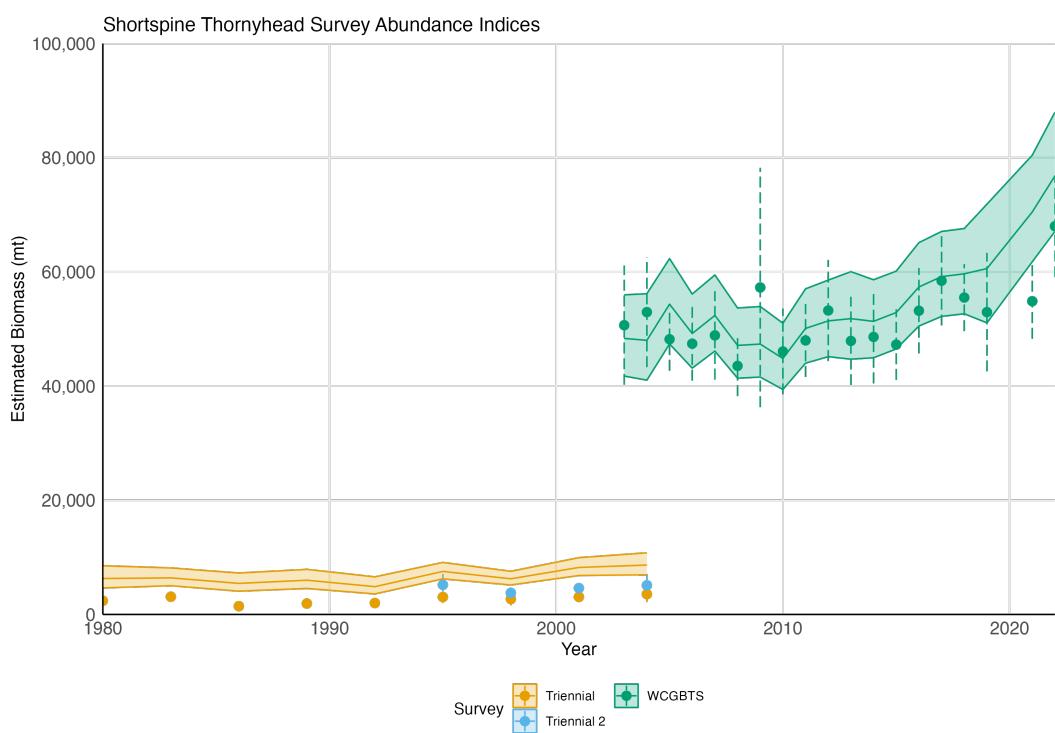


Figure 9: Abundance index timeseries. Points with shaded regions are the derived from geostatistical models, while points with errorbars are derived from design-based calculations.

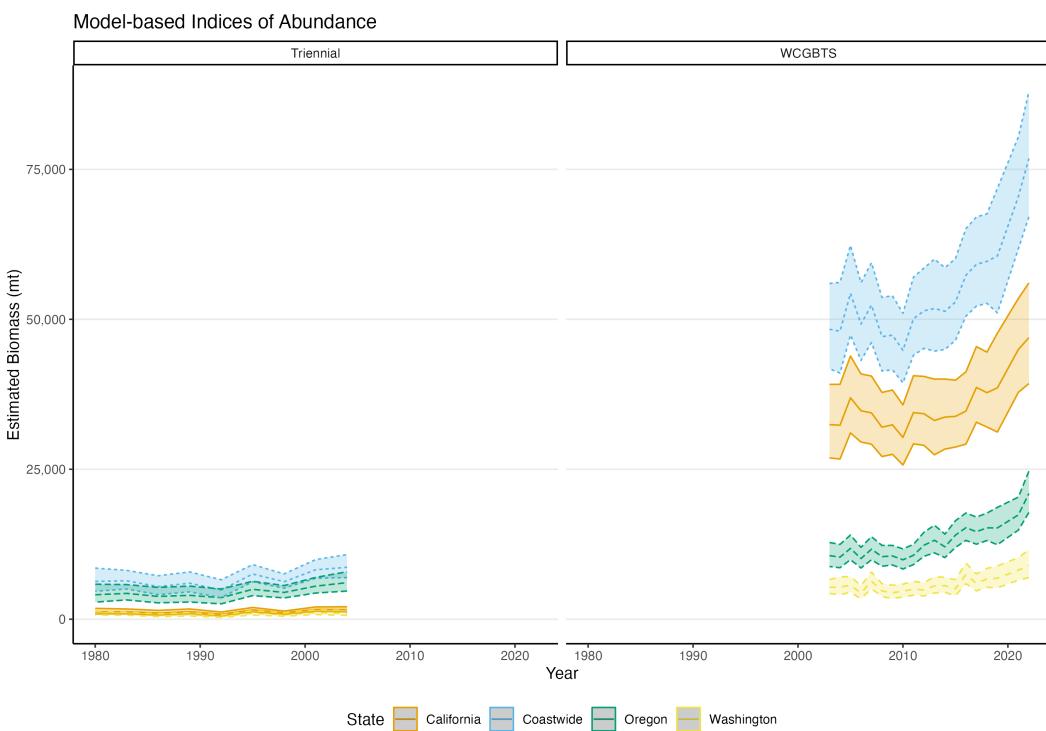


Figure 10: State level trends in abundance indices for the Triennial Surveys and WCGBTS. Coastwide indices were computed separately and should not be interpreted as the sum of the state-level indexes.

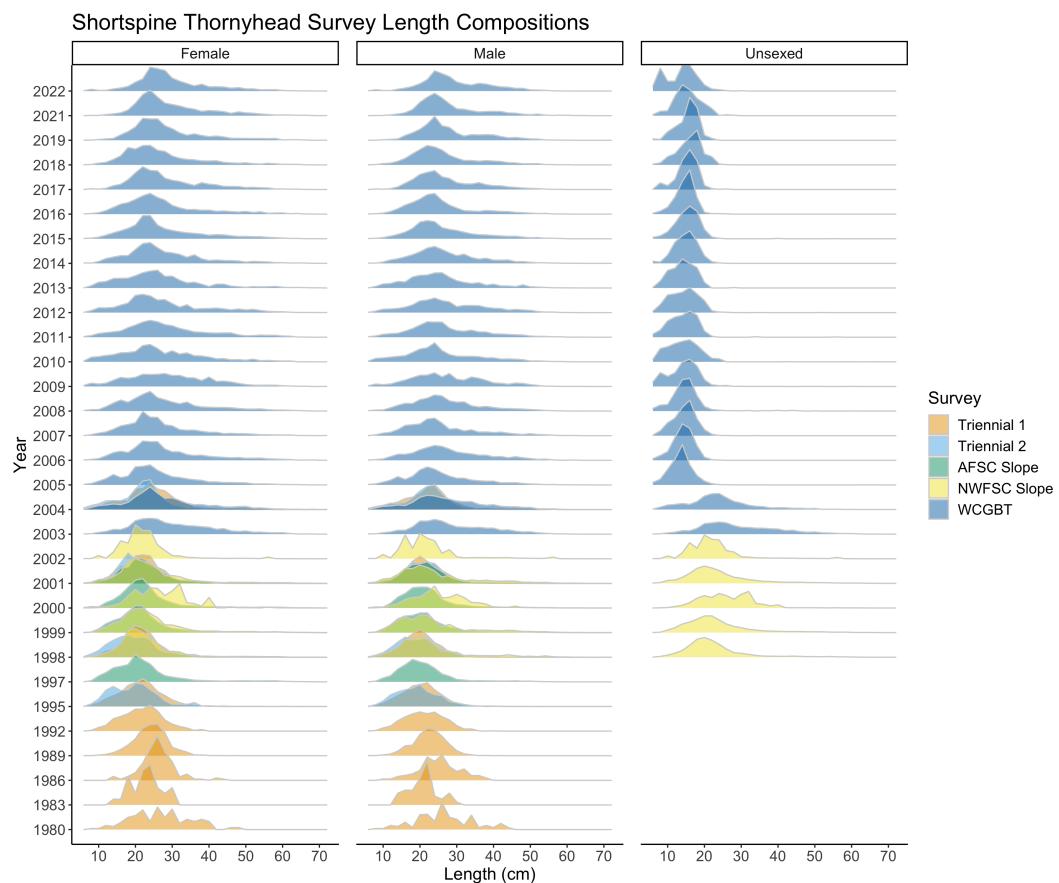


Figure 11: Summary of annual length composition data from available scientific surveys.

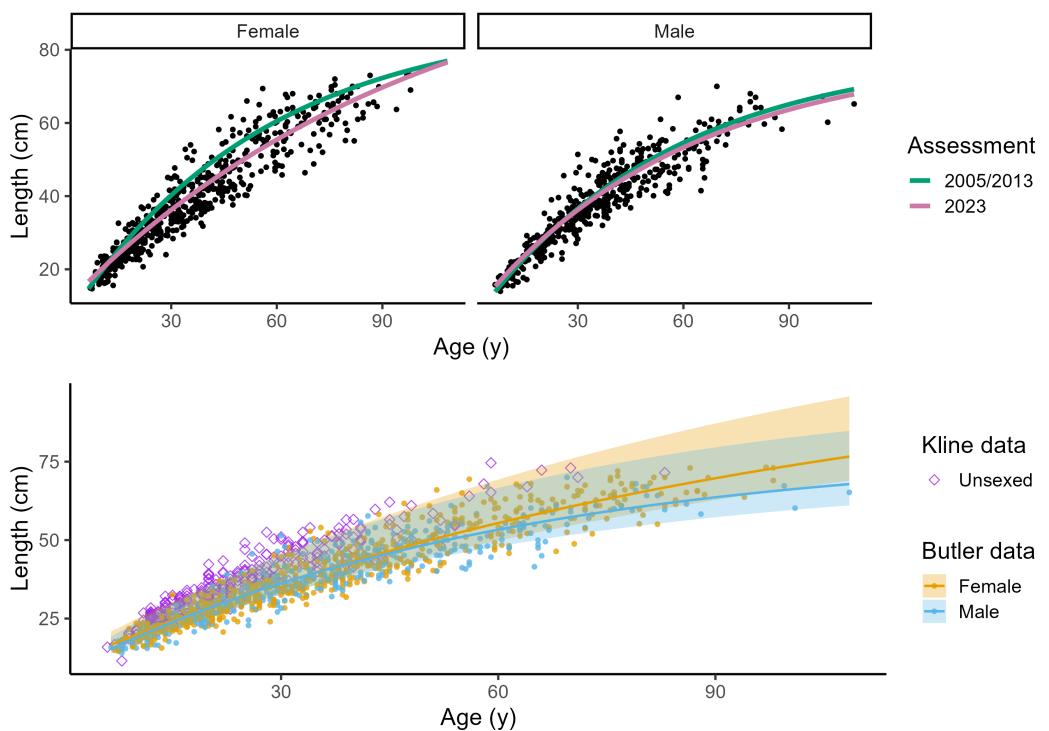


Figure 12: Comparison of growth curves used in the 2005/2013 assessment and the 2023 assessment, as well as high and low growth sensitivities.

Shortspine thornyhead length-weight relationship
NWFSC shelf/slope survey data, 2003-2021

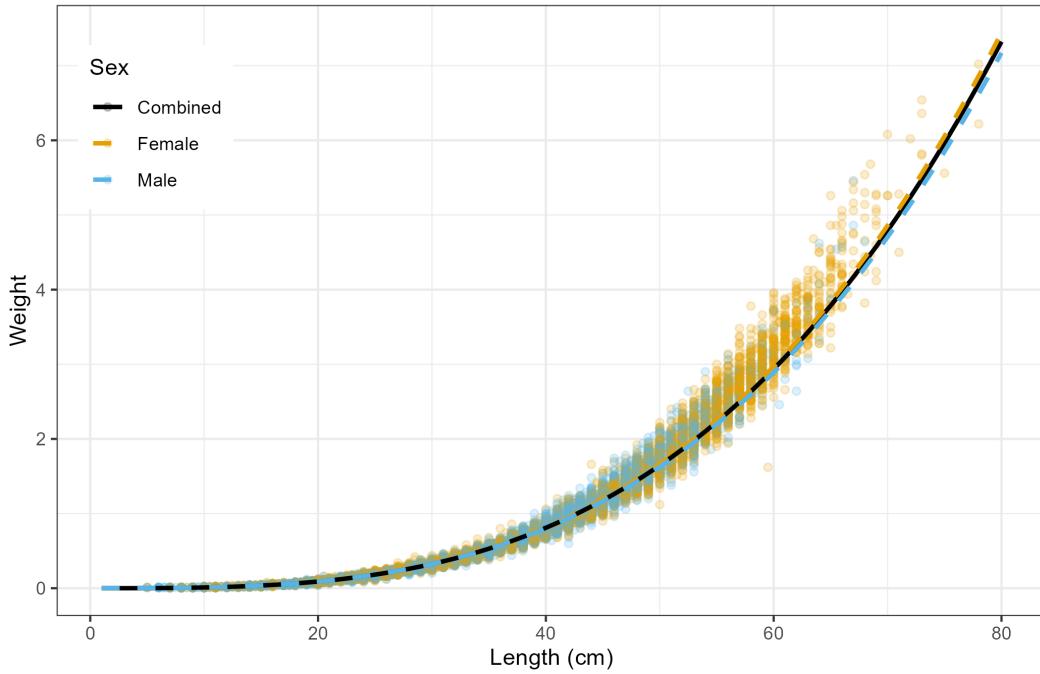


Figure 13: 2023 length-weight relationship and fits to WCGBTS weight-length data.

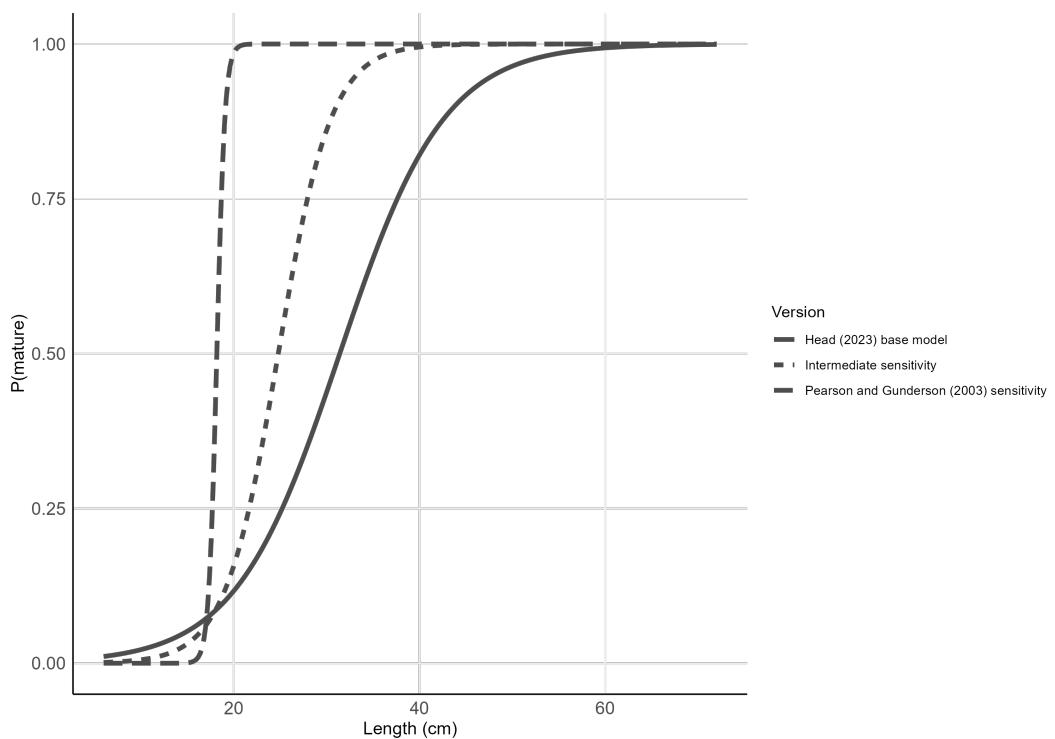


Figure 14: Maturity curves considered in the present assessment (Head (2023)) and alternative versions considered in the sensitivity analysis.

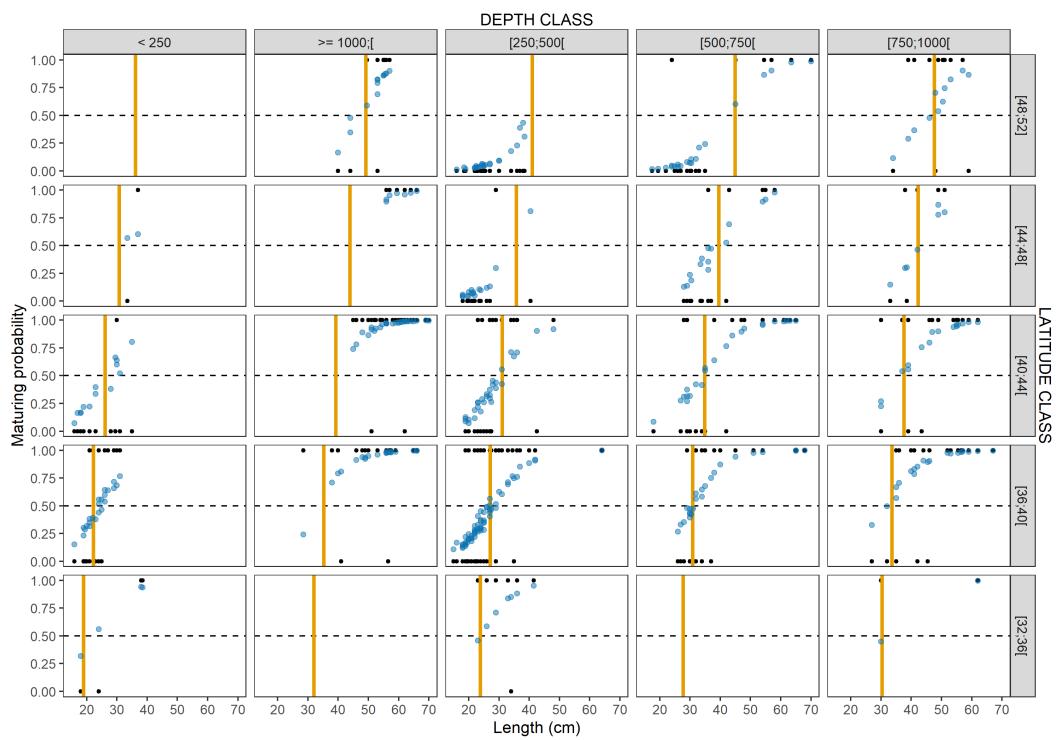


Figure 15: Fit of the maturity curves per size and depth classes. Classes are designed for visual check of the model predictions only since the model assumes continuous and not categorical response to these variables.

Shortspine thornyhead fecundity-at-length

Source: Cooper et al. 2005

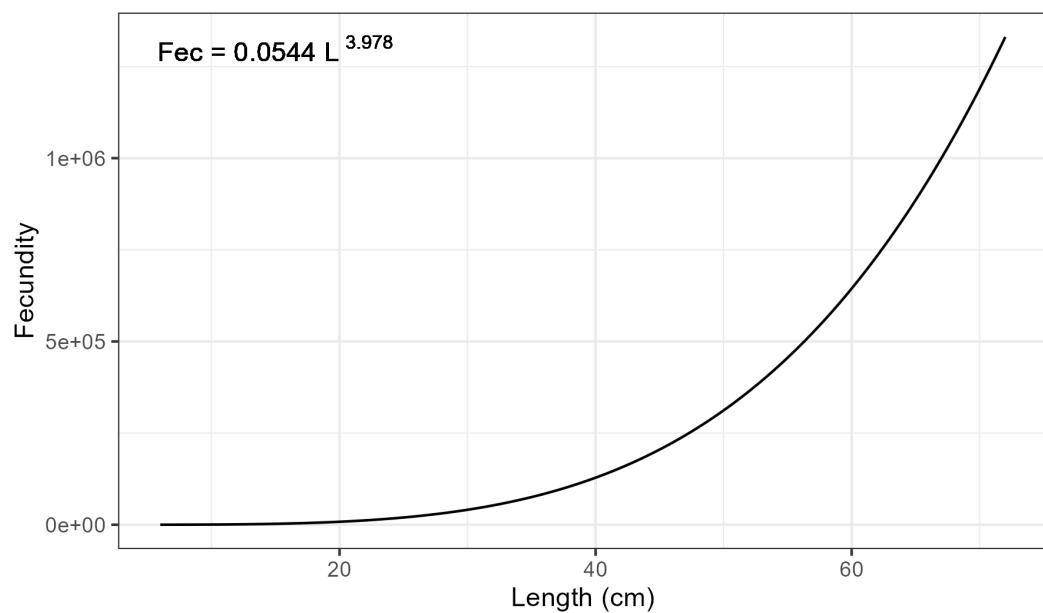


Figure 16: Fecundity-at-length relationship.

8.2 Bridging Analyses

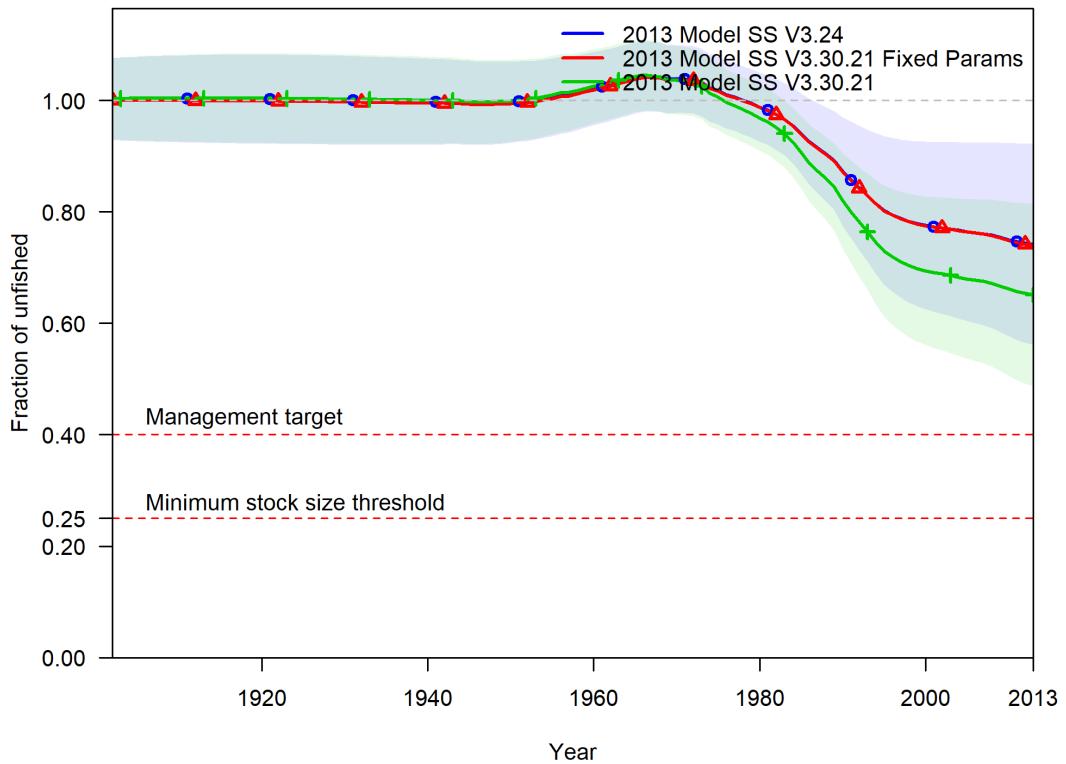


Figure 17: Relative spawning biomass timeseries for models run on updated Stock Synthesis versions.

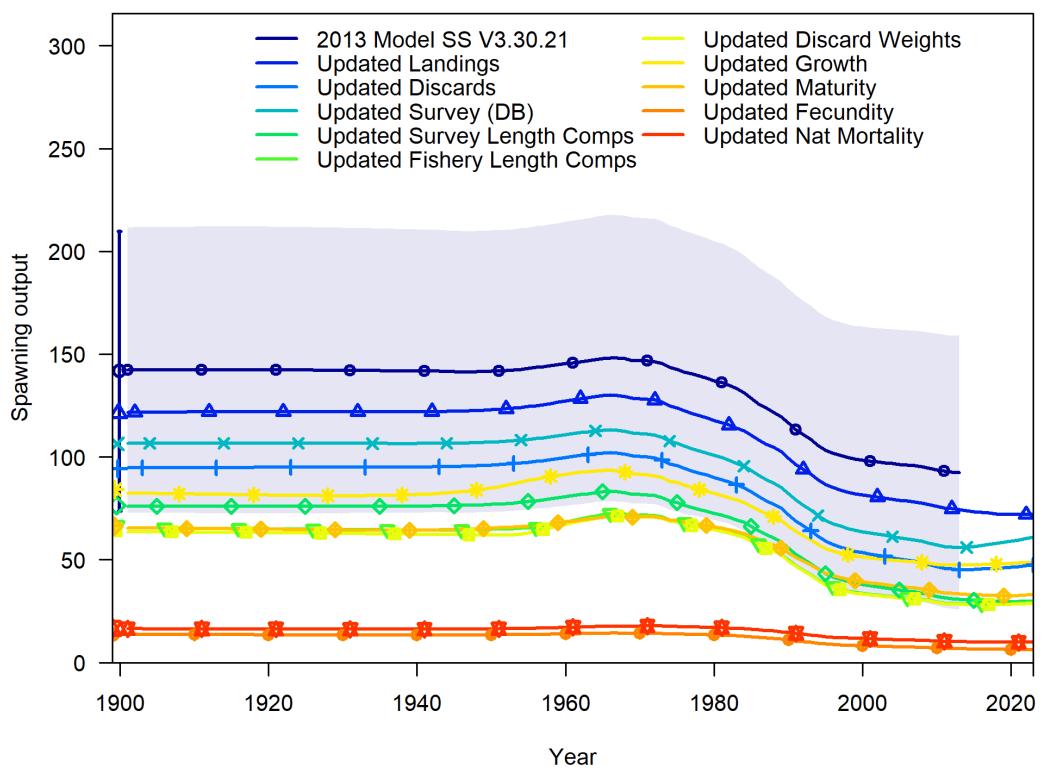


Figure 18: Spawning output timeseries for piecewise data updates.

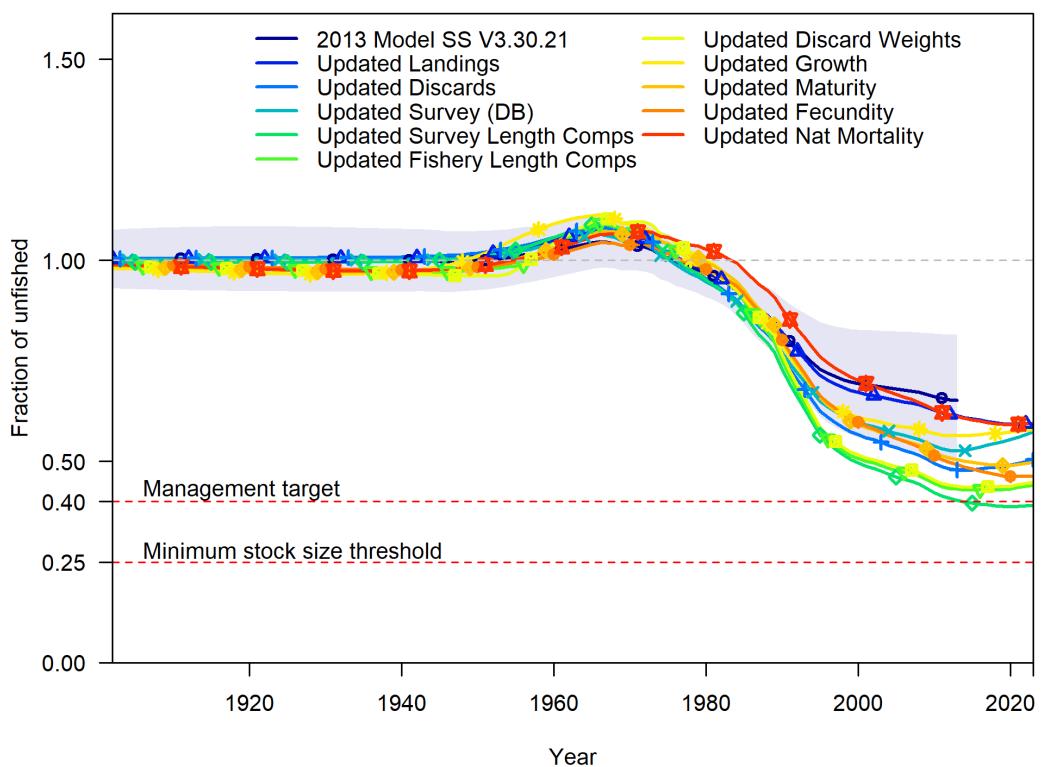


Figure 19: Relative spawning biomass timeseries for piecewise data updates.

8.3 Base Model Results and Fits

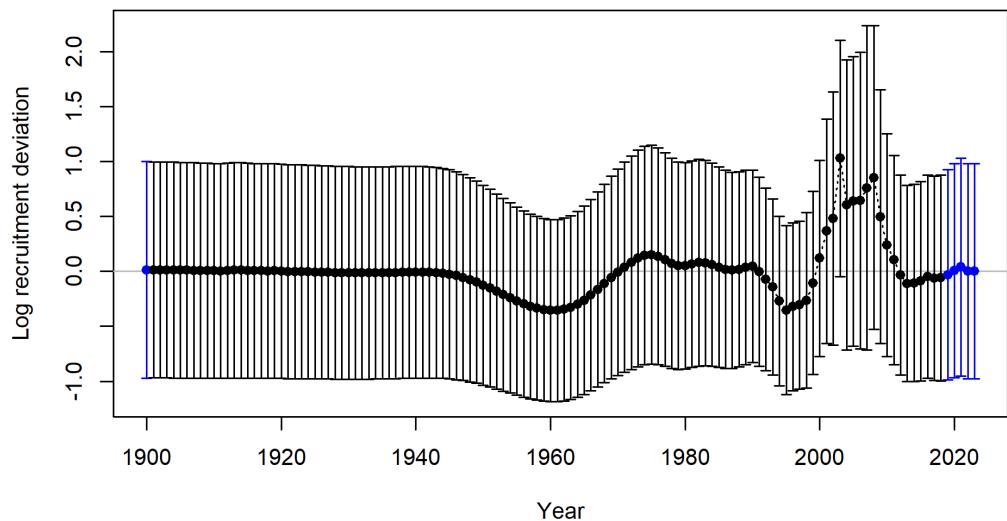


Figure 20: Annual recruitment deviations with 95% intervals.

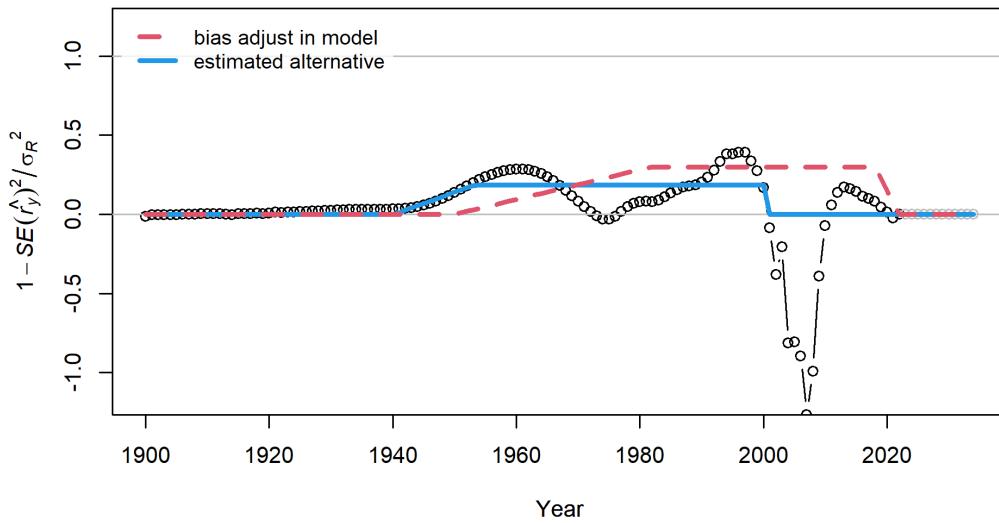


Figure 21: Recommended bias adjustment for recruitment deviations, from Hamel and Cope (2022).

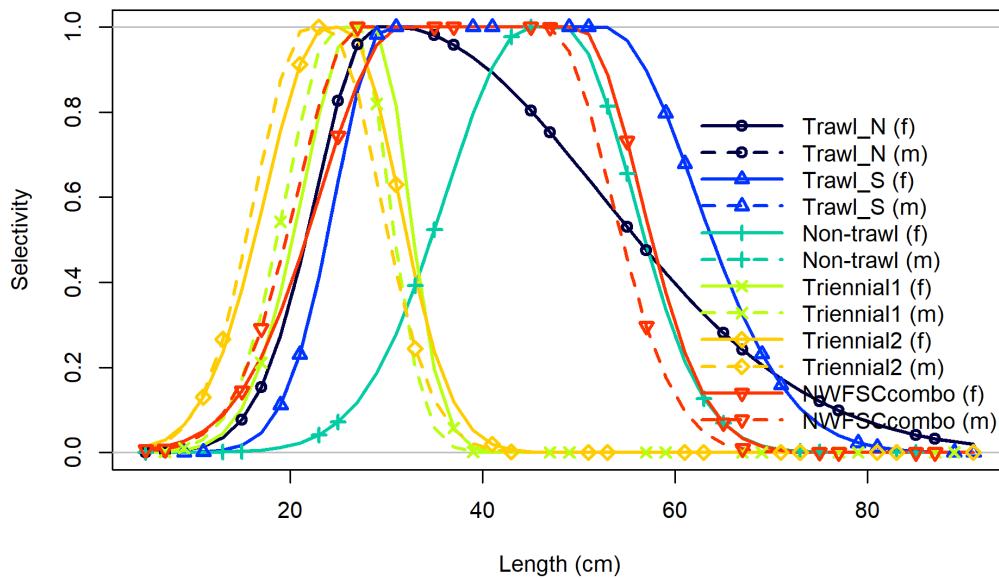


Figure 22: Selectivity at length for each combination of sex and fleet. Note that the three commercial fishery fleets were not modeled as having sex-specific selectivity.

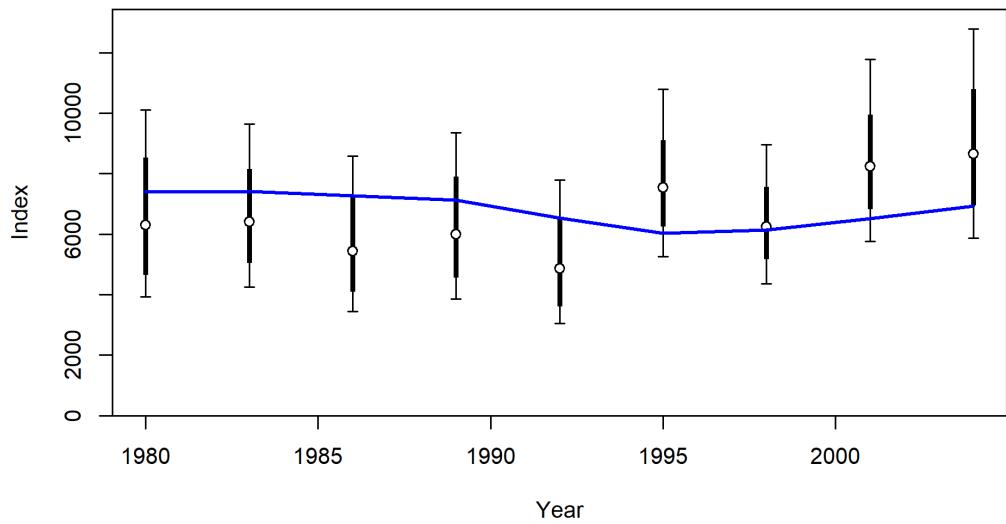


Figure 23: Fit to index of abundance data for the Triennial Survey. Lines indicate 95% uncertainty interval around index values based on the model assumption of lognormal error. Thicker lines indicate input uncertainty before addition of estimated additional uncertainty parameter.

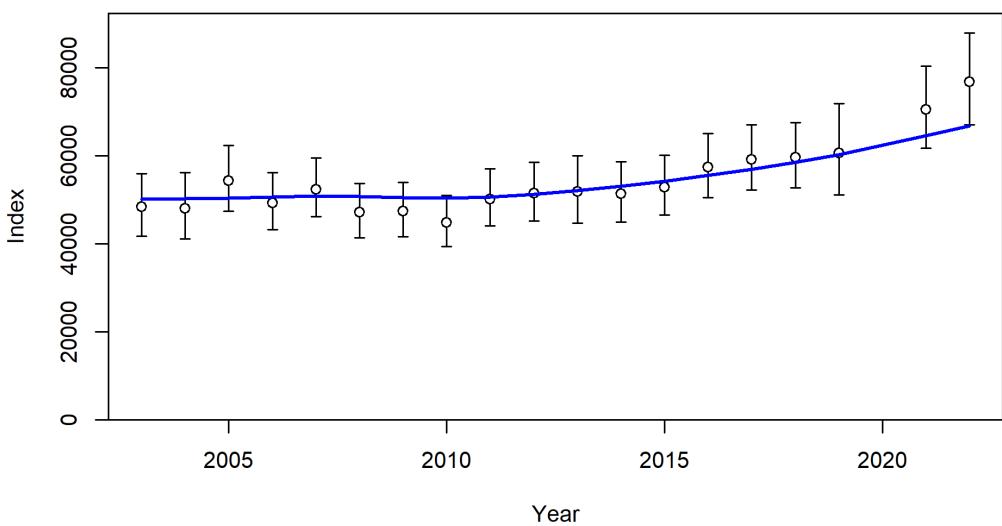


Figure 24: Fit to index of abundance data for the WCGBTS. Lines indicate 95% uncertainty interval around index values based on the model assumption of lognormal error. Thicker lines indicate input uncertainty before addition of estimated additional uncertainty parameter.

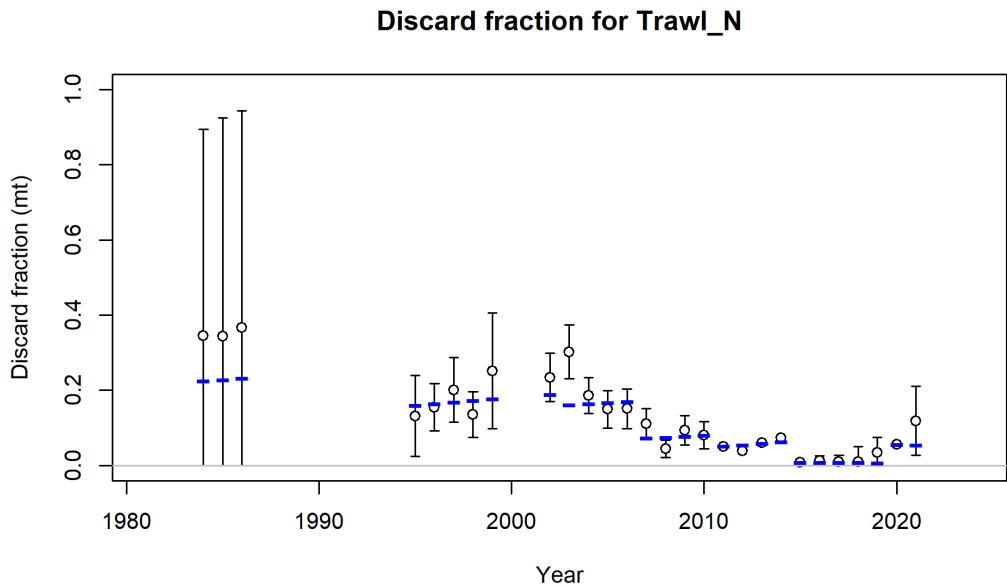


Figure 25: Discard fraction (percent of total catch that is not landed) for the North trawl fleet.

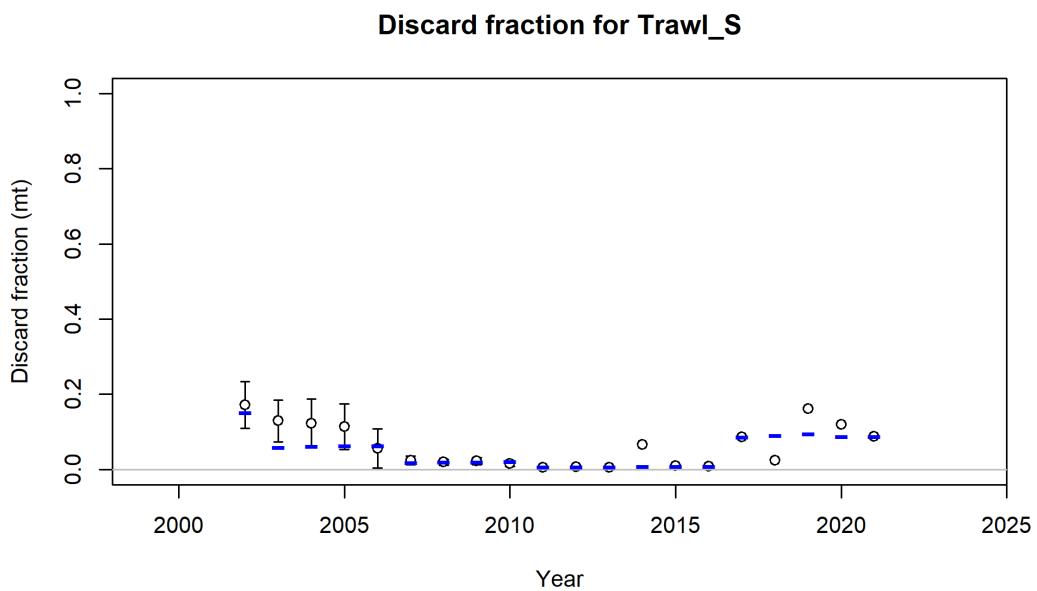


Figure 26: Discard fraction (percent of total catch that is not landed) for the South trawl fleet.

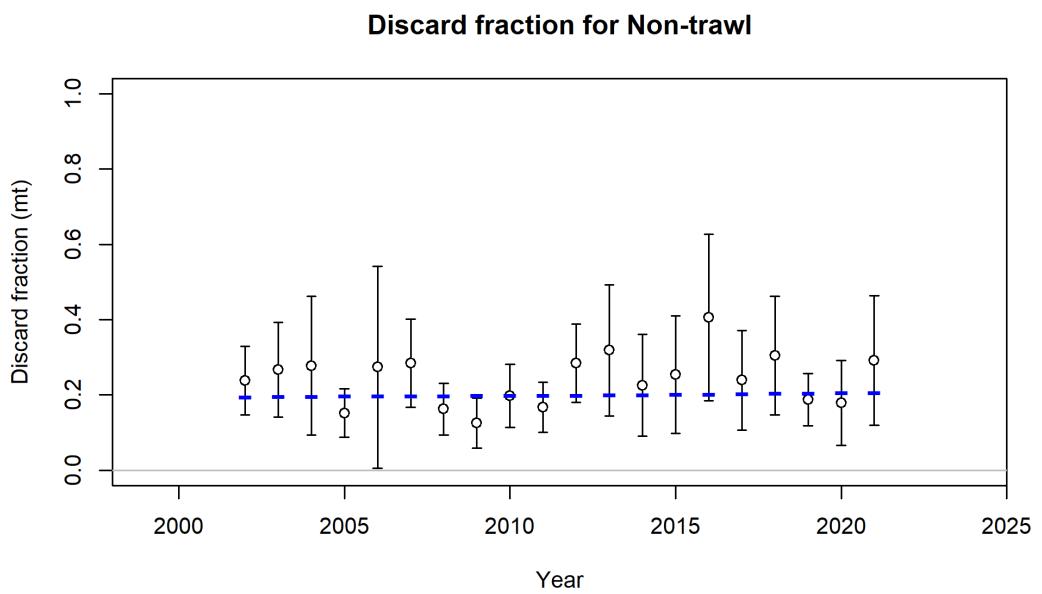


Figure 27: Discard fraction (percent of total catch that is not landed) for the Non-trawl fleet.

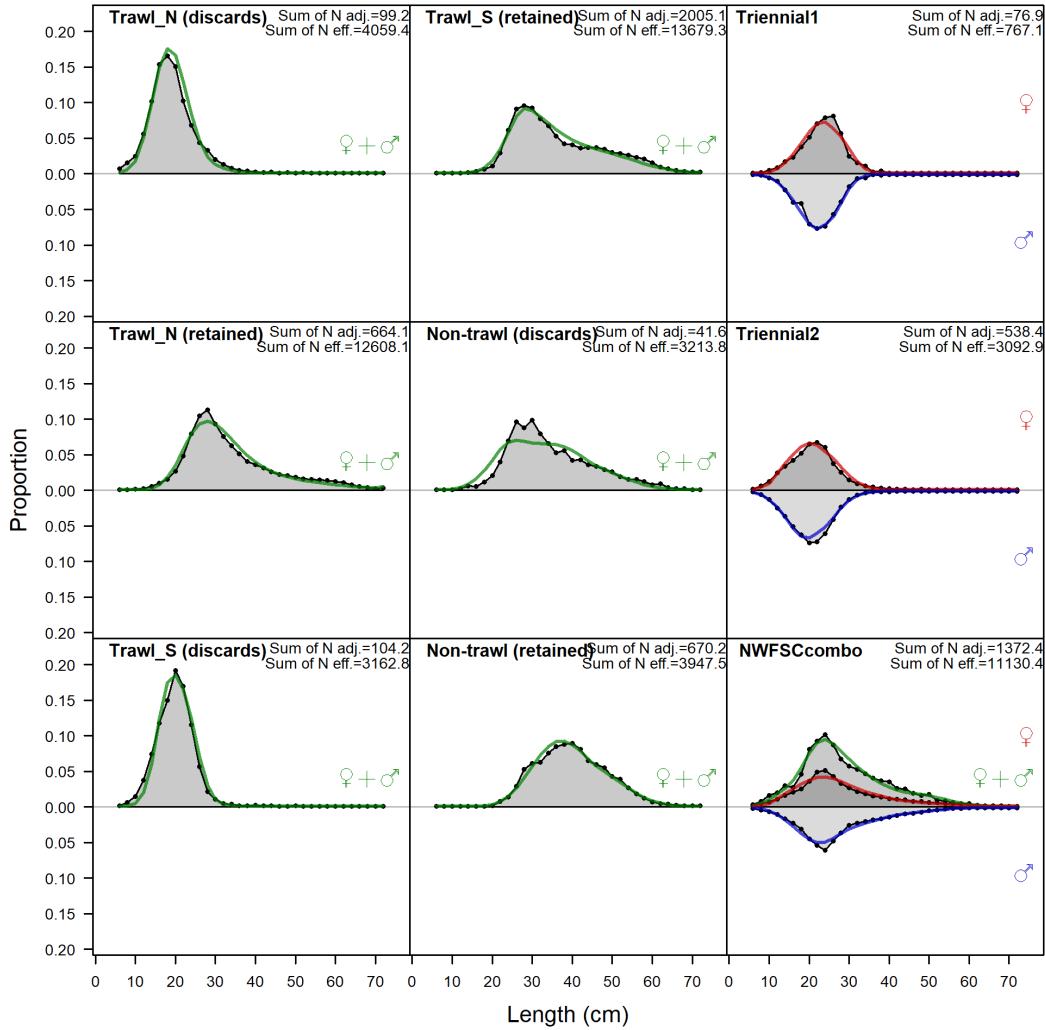


Figure 28: Length comps, aggregated across time by fleet. Labels ‘retained’ and ‘discard’ indicate discarded or retained samples for each fleet. Panels without this designation represent the whole catch.

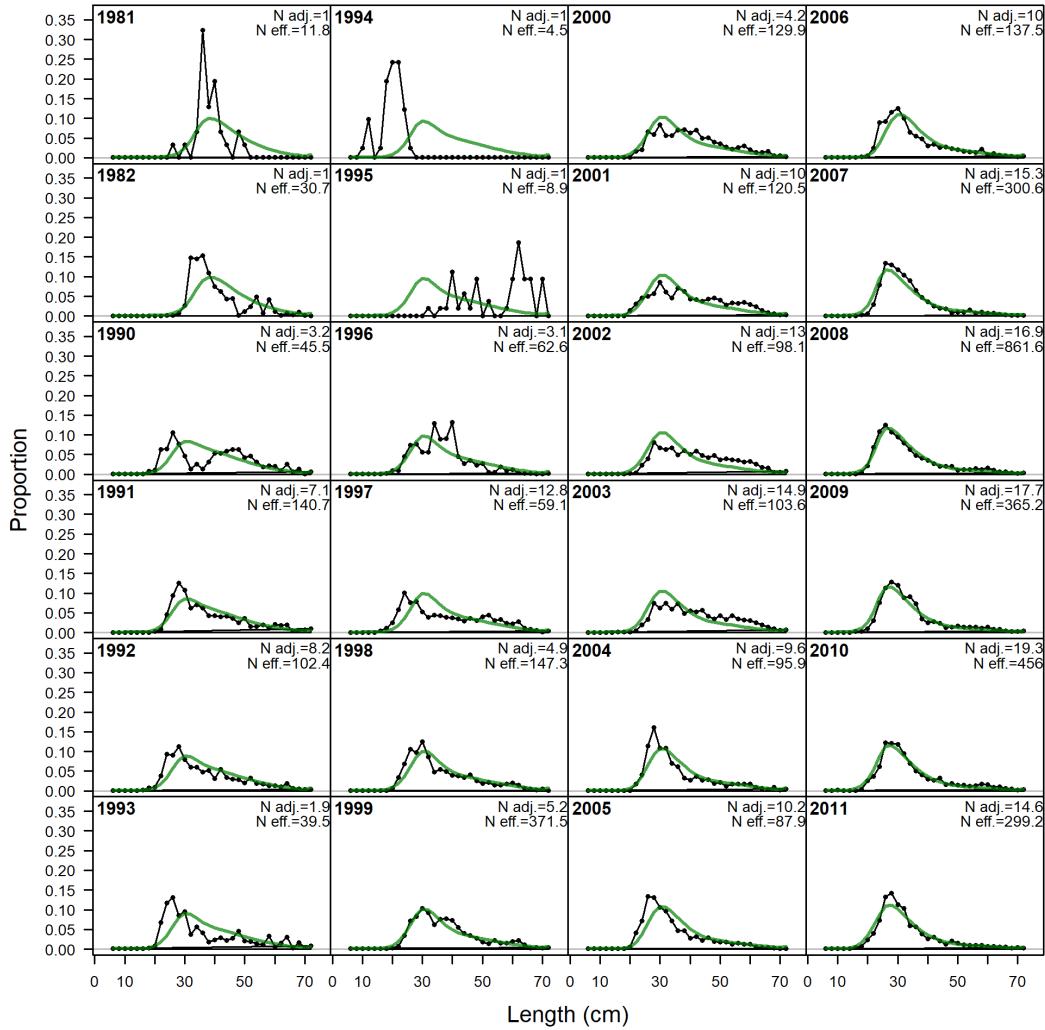


Figure 29: Annual length comps and model fit for North trawl retained catch. 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

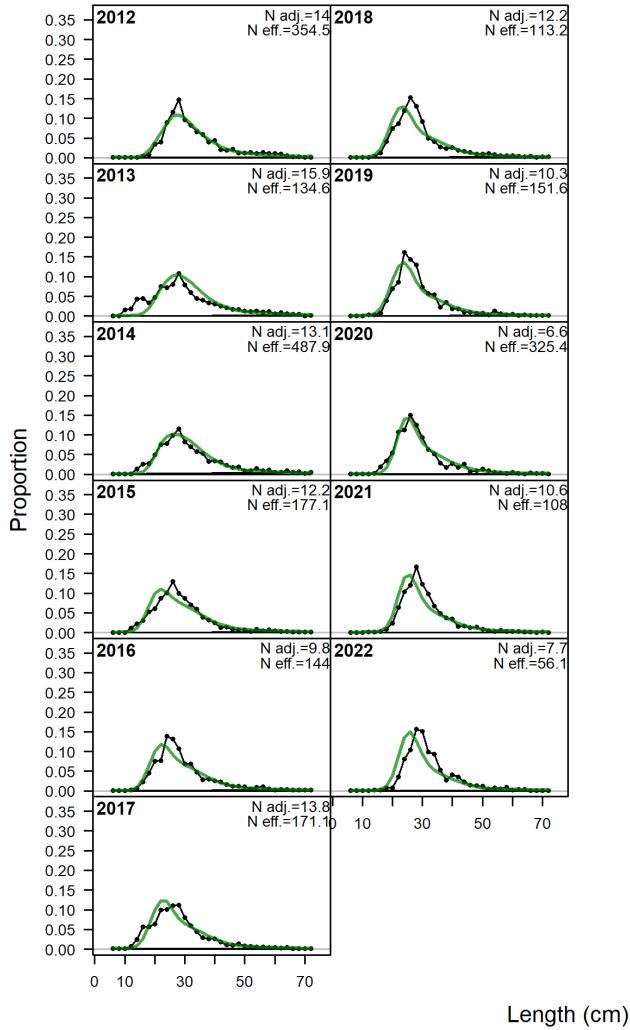


Figure 30: Annual length comps and model fit for North trawl retained catch. ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

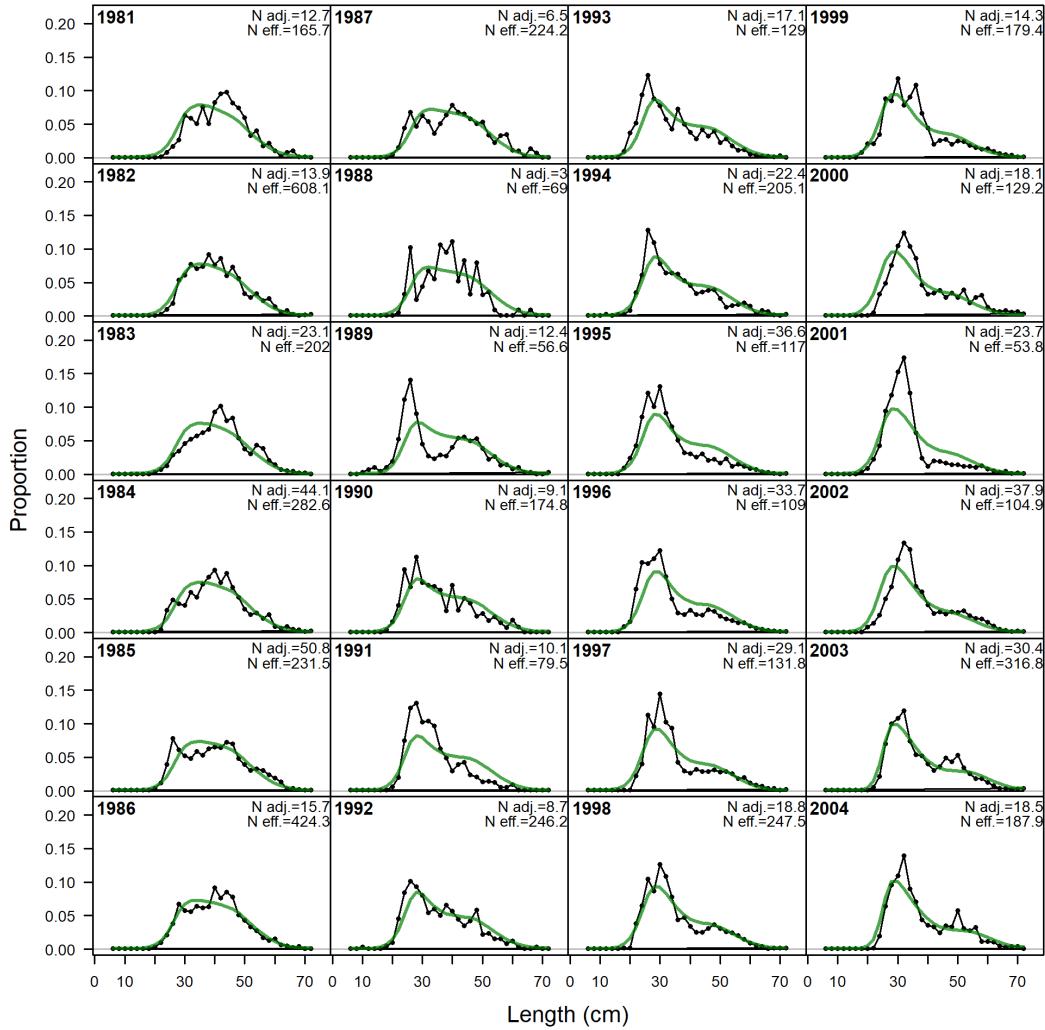


Figure 31: Annual length comps and model fit for South trawl retained catch. ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

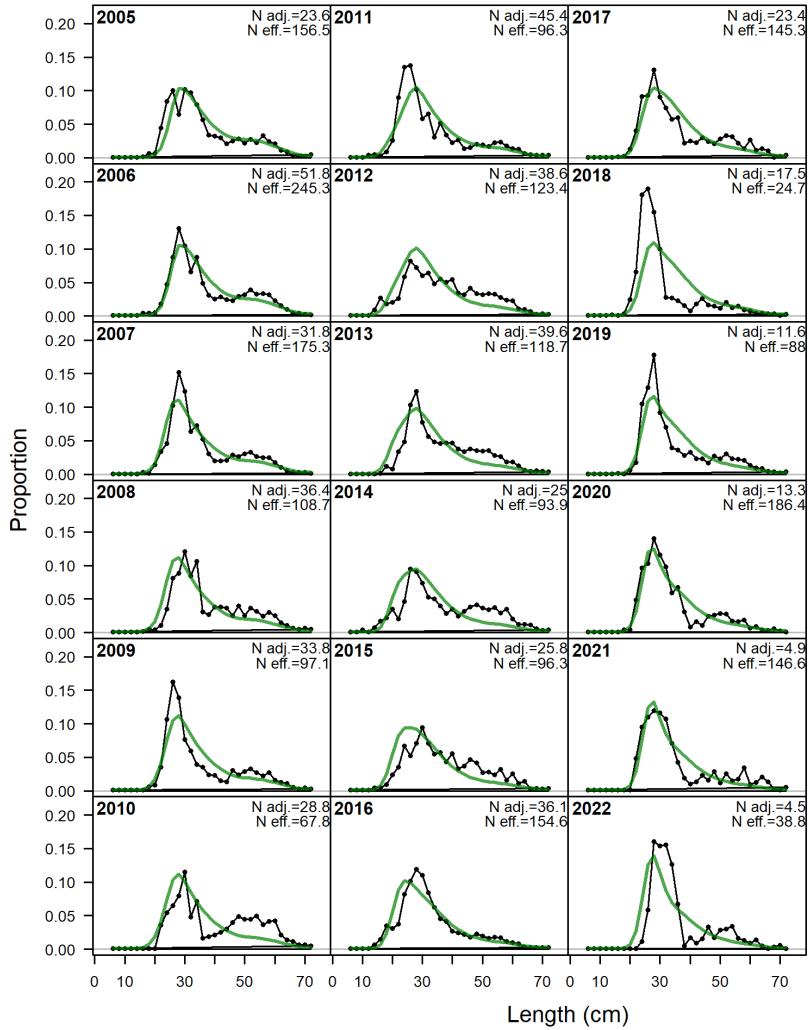


Figure 32: Annual length comps and model fit for South trawl retained catch. ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

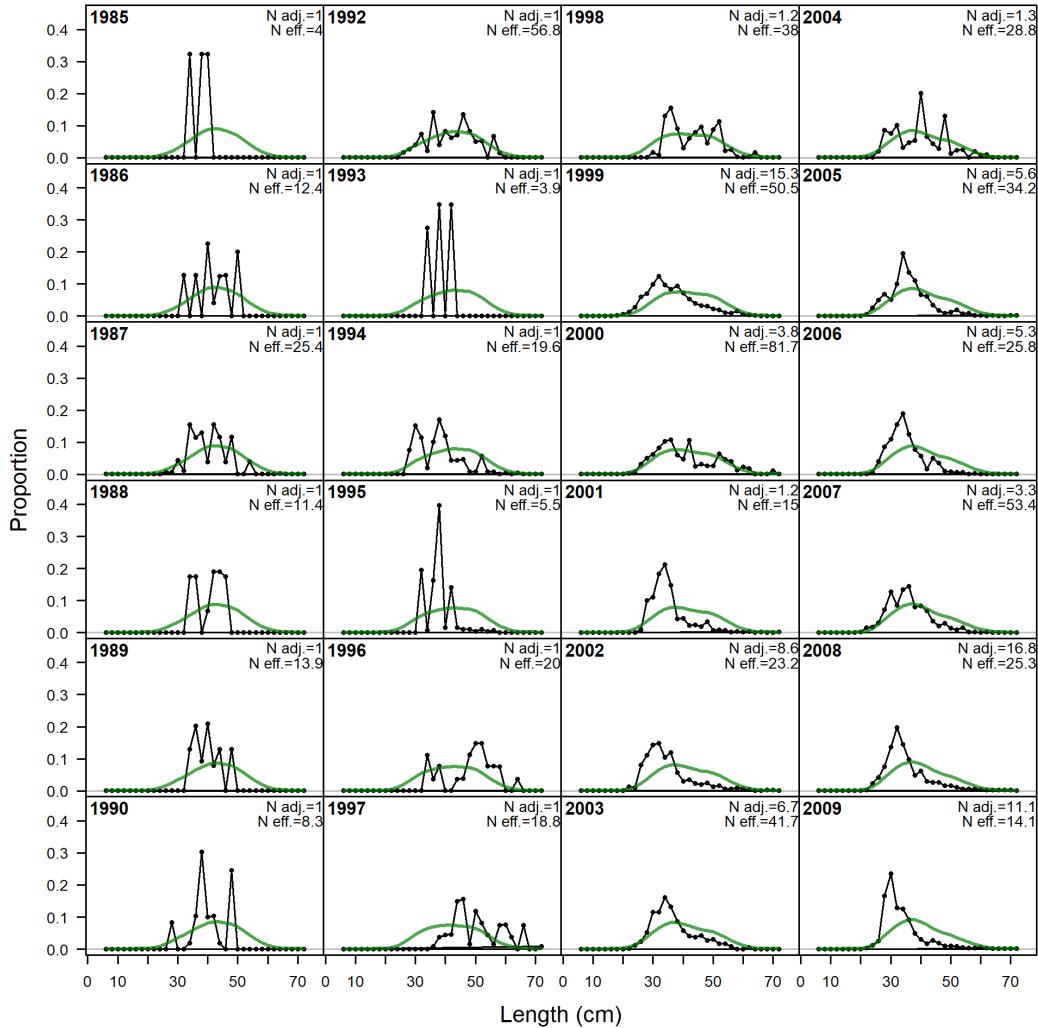


Figure 33: Annual length comps and model fit for Non-trawl retained catch. ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

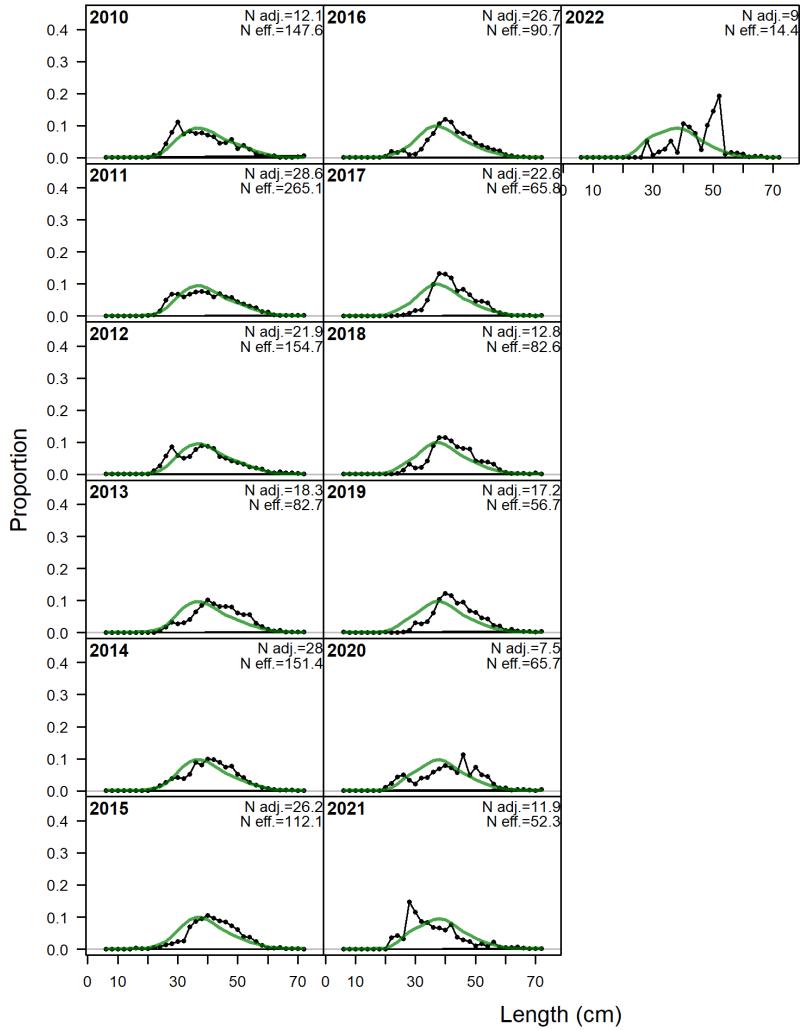


Figure 34: Annual length comps and model fit for Non-trawl retained catch. ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

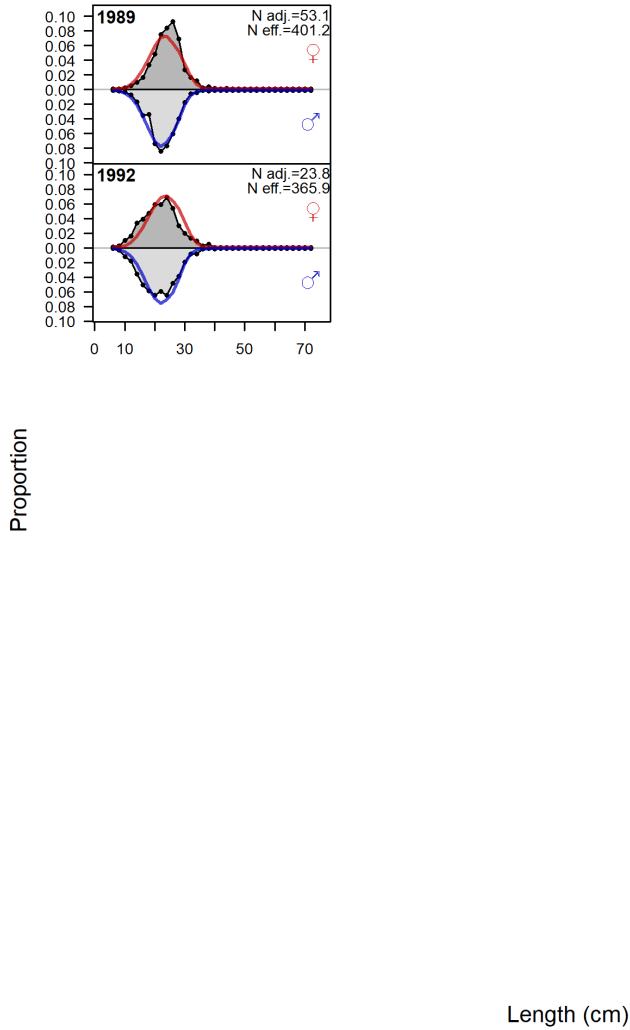


Figure 35: Length combs, whole catch, for the early-Triennial Survey (1980-1992). ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

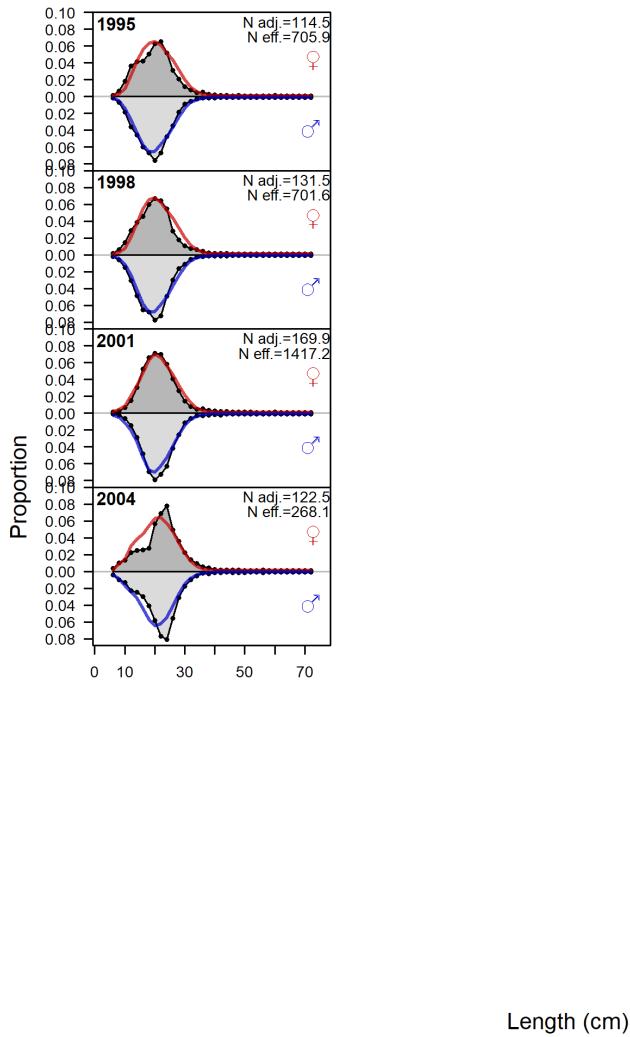


Figure 36: Length comps, whole catch, for the late-Triennial Survey (1995-2004). ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

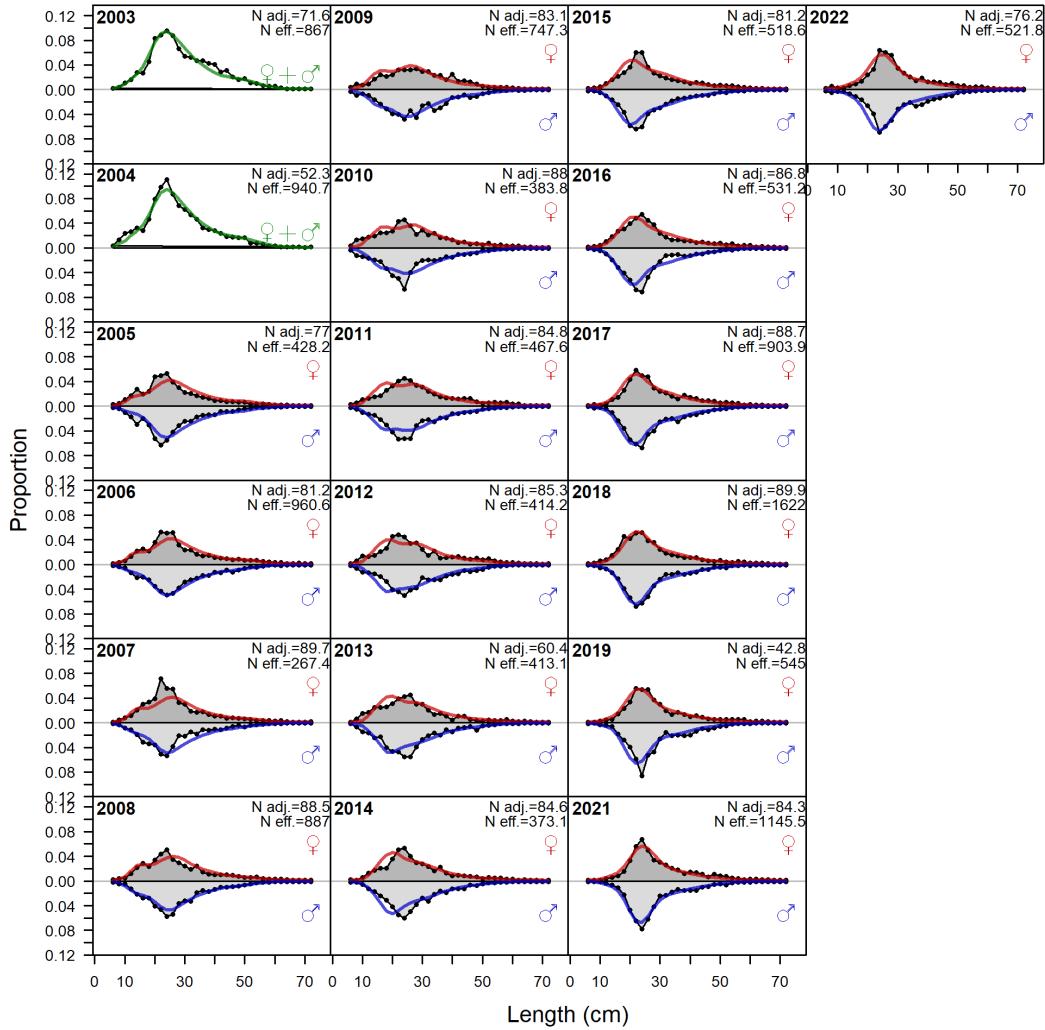


Figure 37: Length comps, whole catch, for the WCGBTS. ‘N adj.’ is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

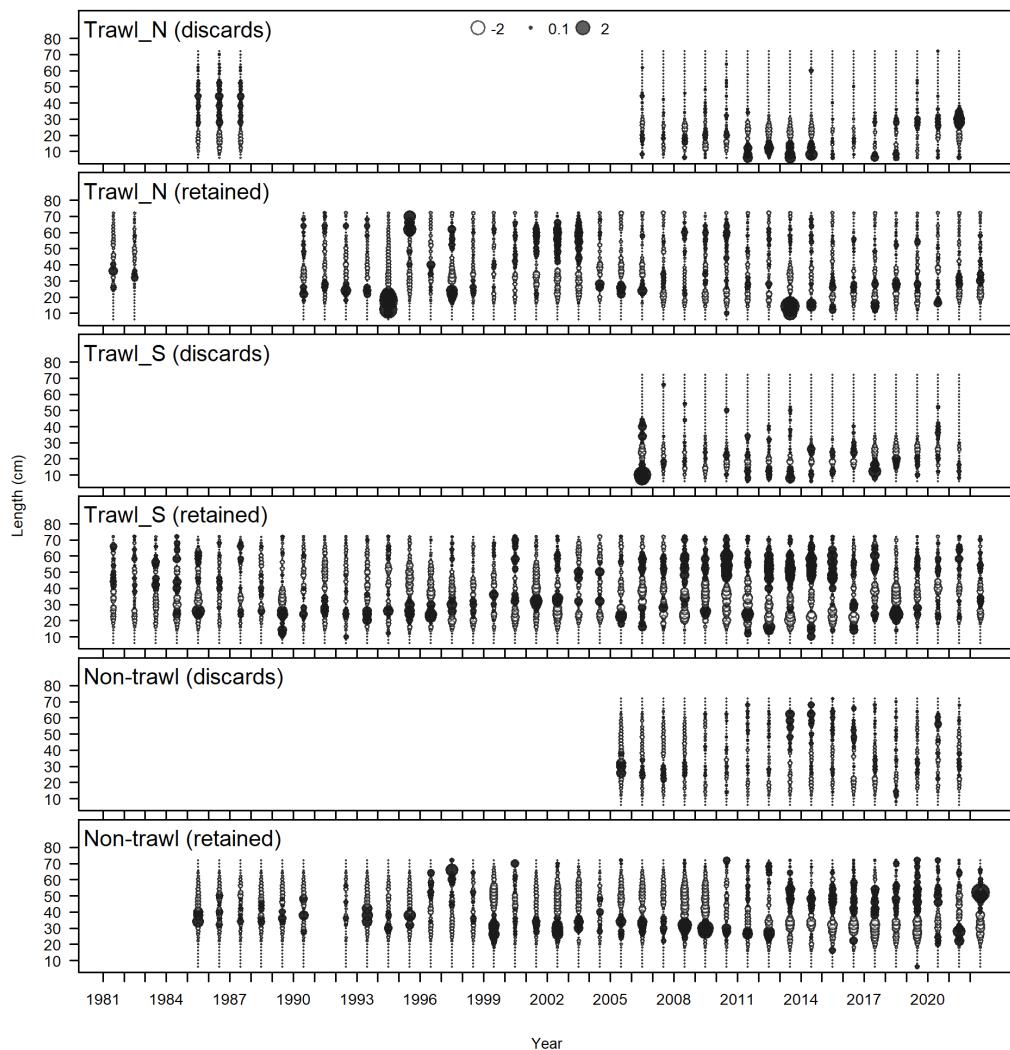


Figure 38: Pearson residuals, whole catch, for the three fisheries fleets. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

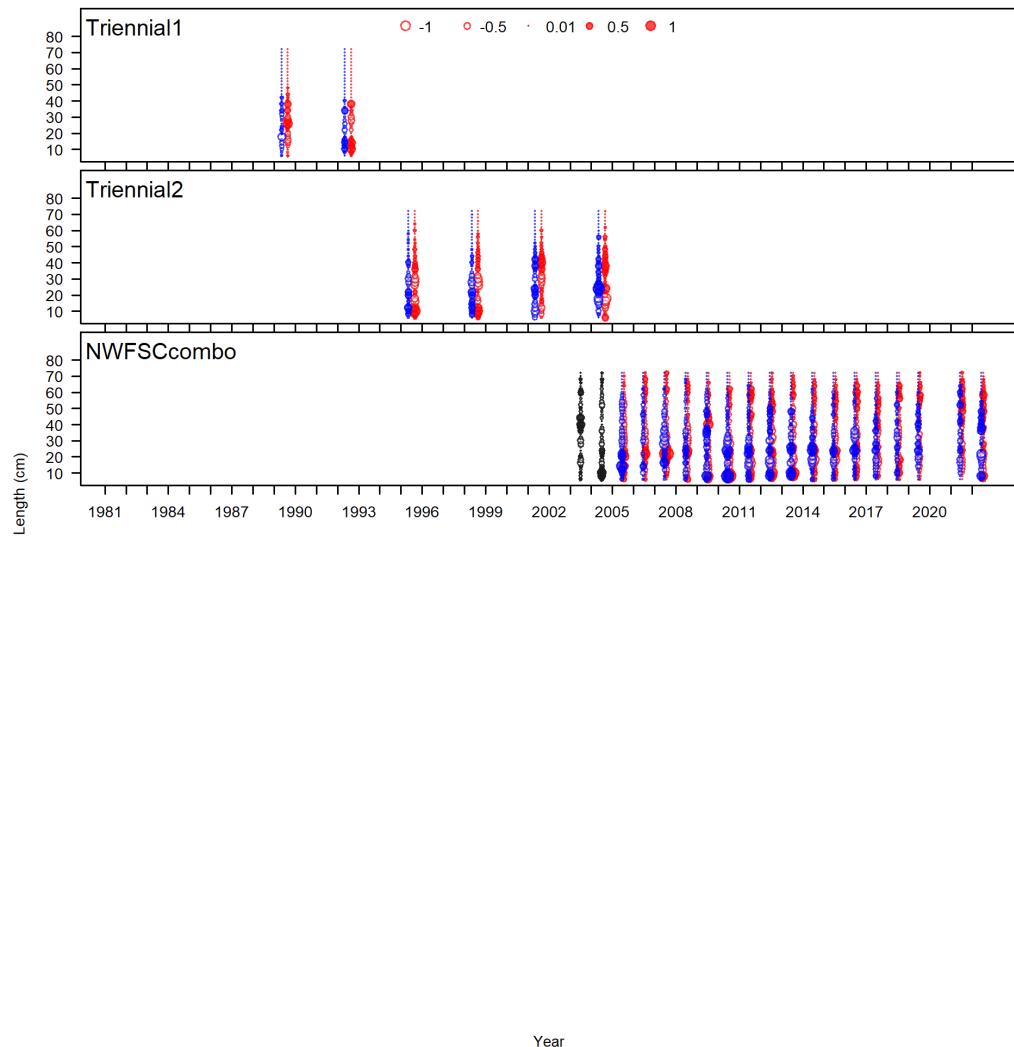


Figure 39: Pearson residuals, whole catch, for the three scientific surveys. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected). Red bubbles are female, blue bubbles are male, and grey bubble are unsexed.

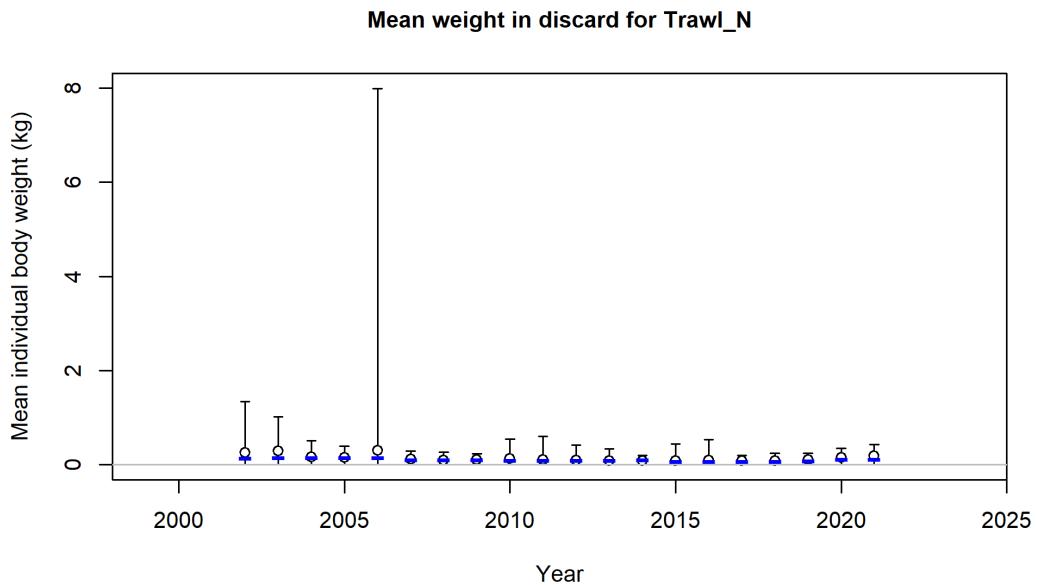


Figure 40: Mean individual body weight (kg) in discard for the North trawl fleet.

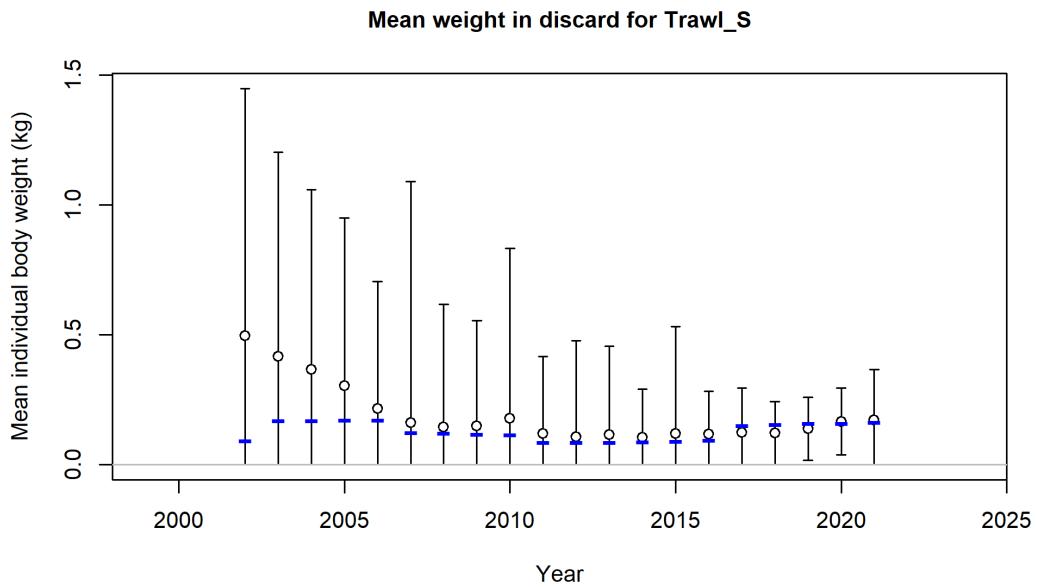


Figure 41: Mean individual body weight (kg) in discard for the South trawl fleet.

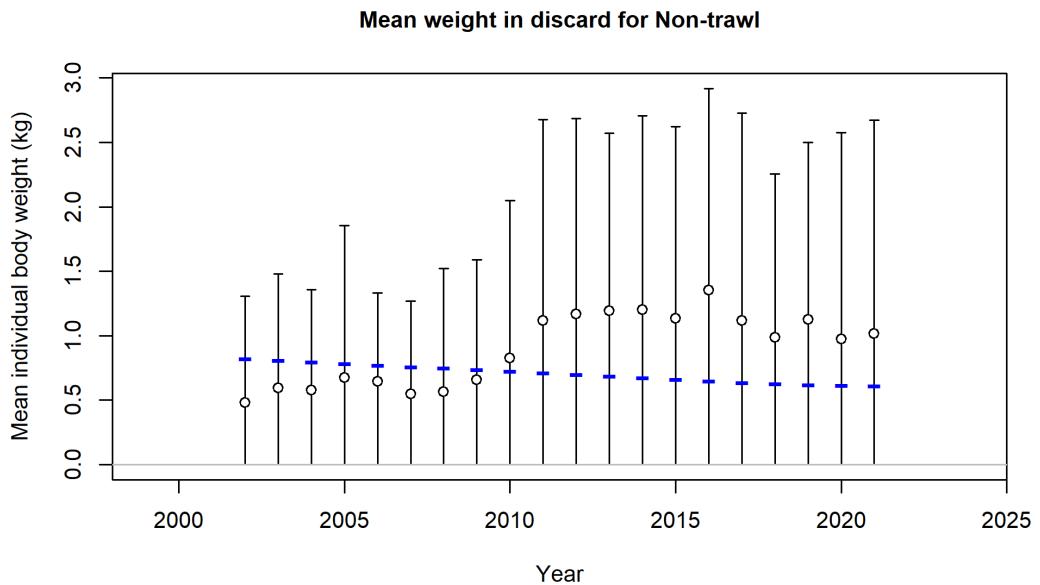


Figure 42: Mean individual body weight (kg) in discard for the Non-trawl fleet.

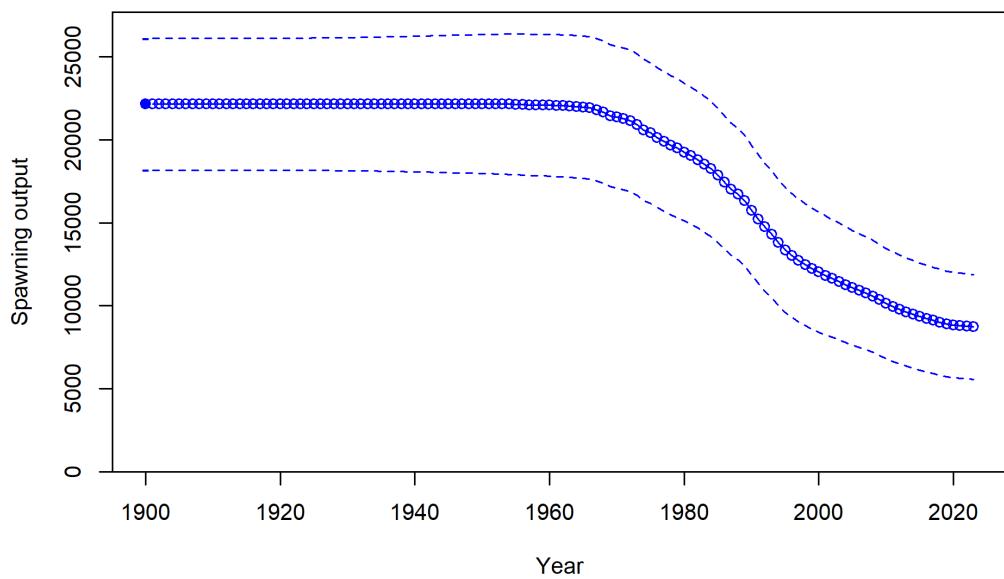


Figure 43: Spawning output (eggs) with ~95% asymptotic intervals.

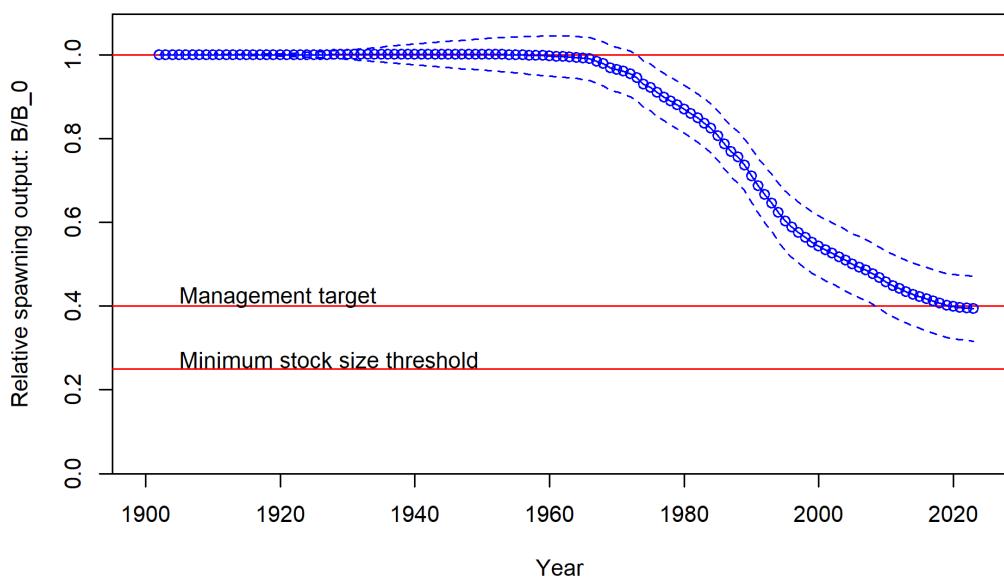


Figure 44: Relative spawning output: B/B_0 with $\sim 95\%$ asymptotic intervals.

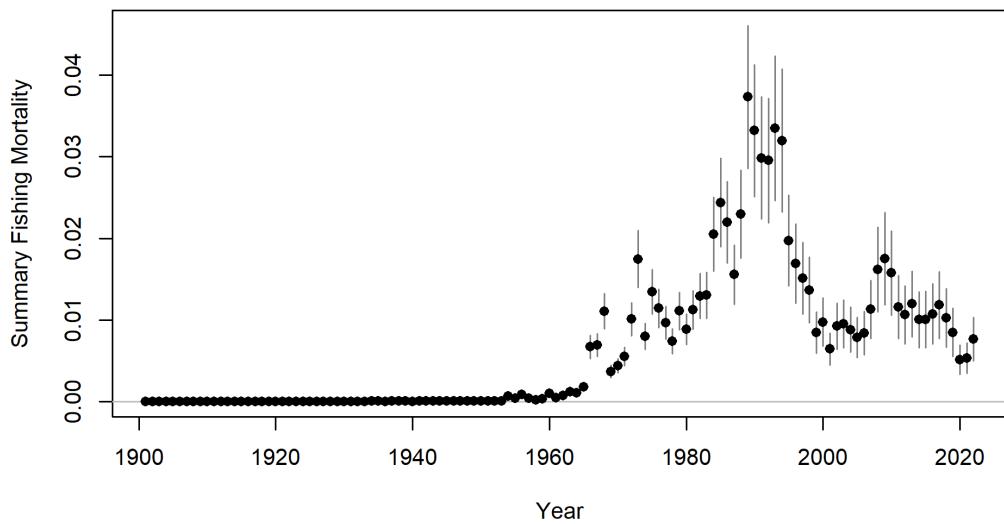


Figure 45: Summary fishing mortality rate (total landings / summary biomass).

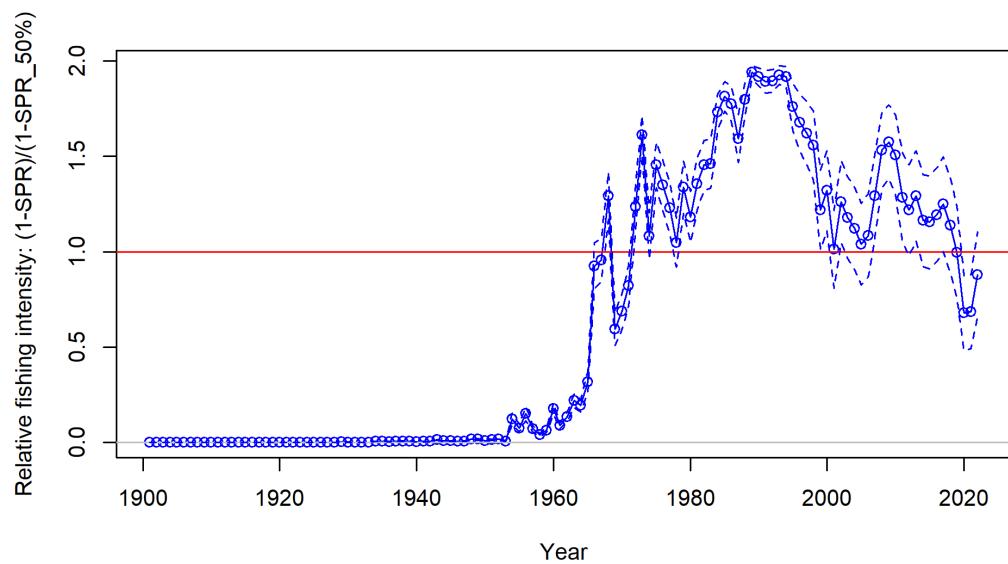


Figure 46: Estimated relative fishing intensity as a function of spawning potential ratio (SPR).

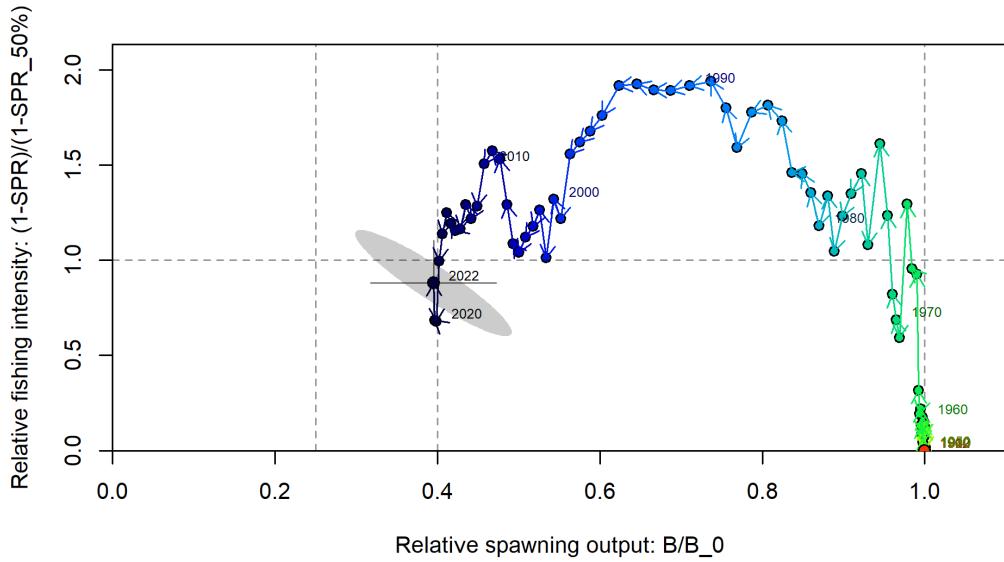


Figure 47: Phase plot of biomass ratio vs. spawning potential ratio (SPR) ratio. Points represent the annual biomass ratio and SPR ratio. Lines through the final point show 95% intervals based on the asymptotic uncertainty for each dimension, while the shaded ellipse is a 95% region accounting for estimated correlation between the two quantities.

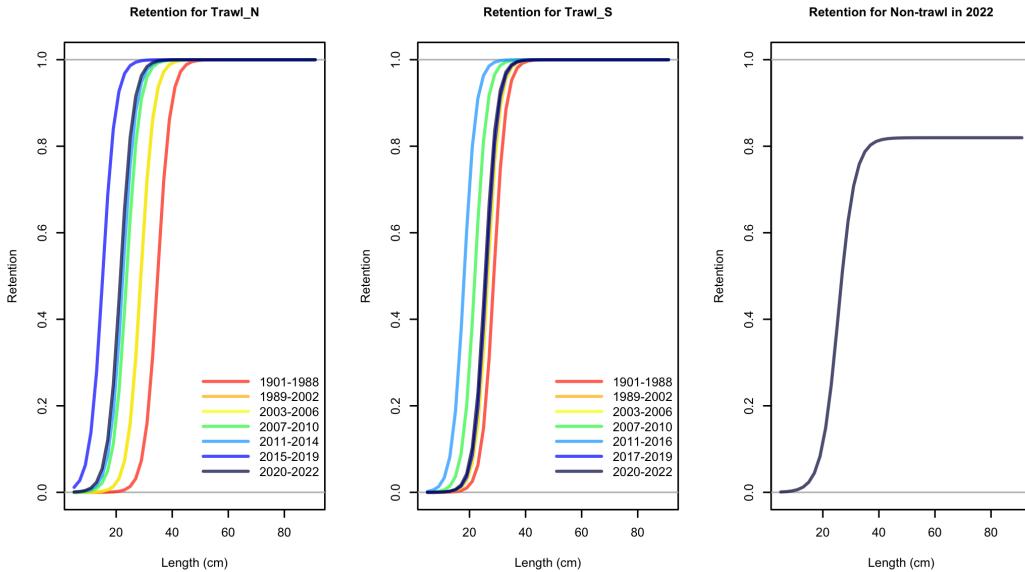


Figure 48: Retention curves for all fleets.

8.4 Likelihood Profiles, Retrospectives, and Sensitivity Analyses

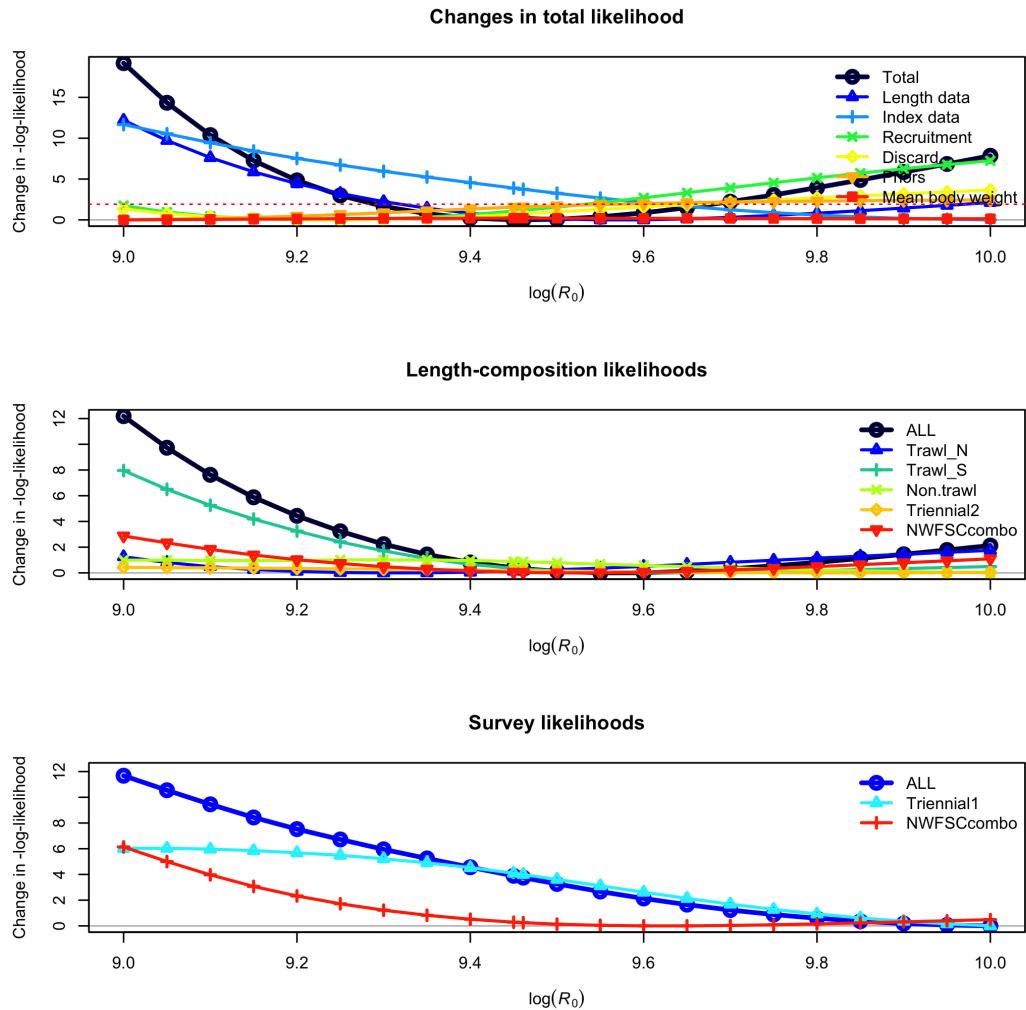


Figure 49: Piner panel plot showing the impact of changing R_0 on the overall (top), length composition (middle), and survey (bottom) likelihoods.

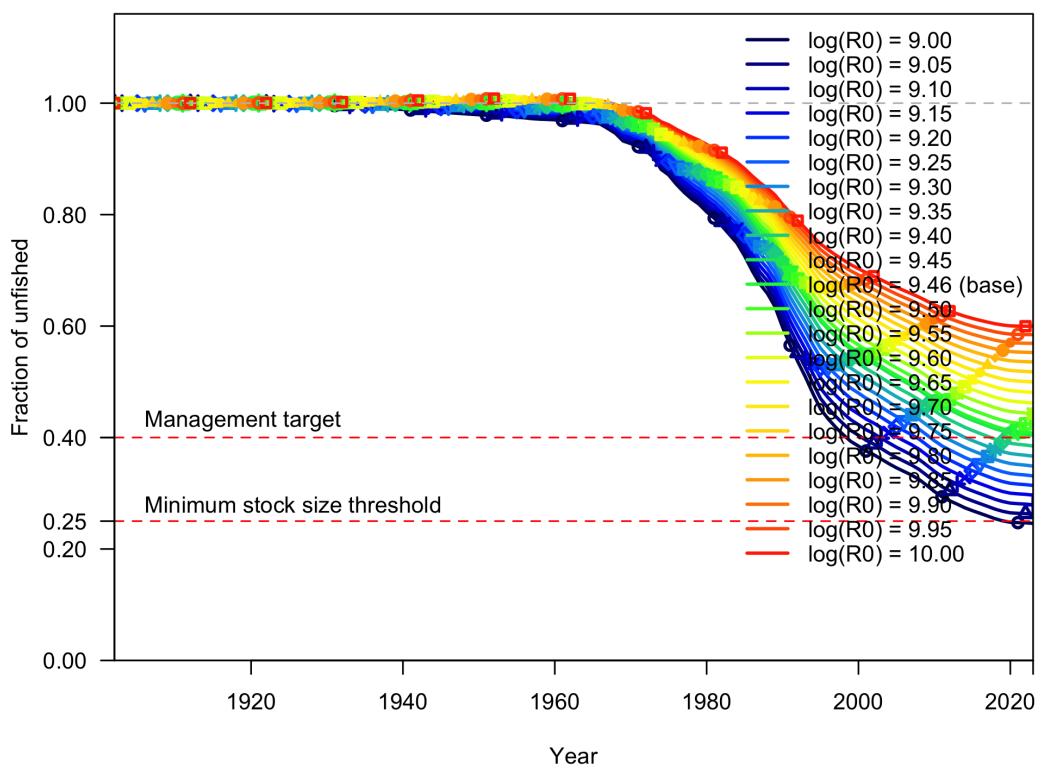


Figure 50: High to low values of R_0 and impact on spawning output.

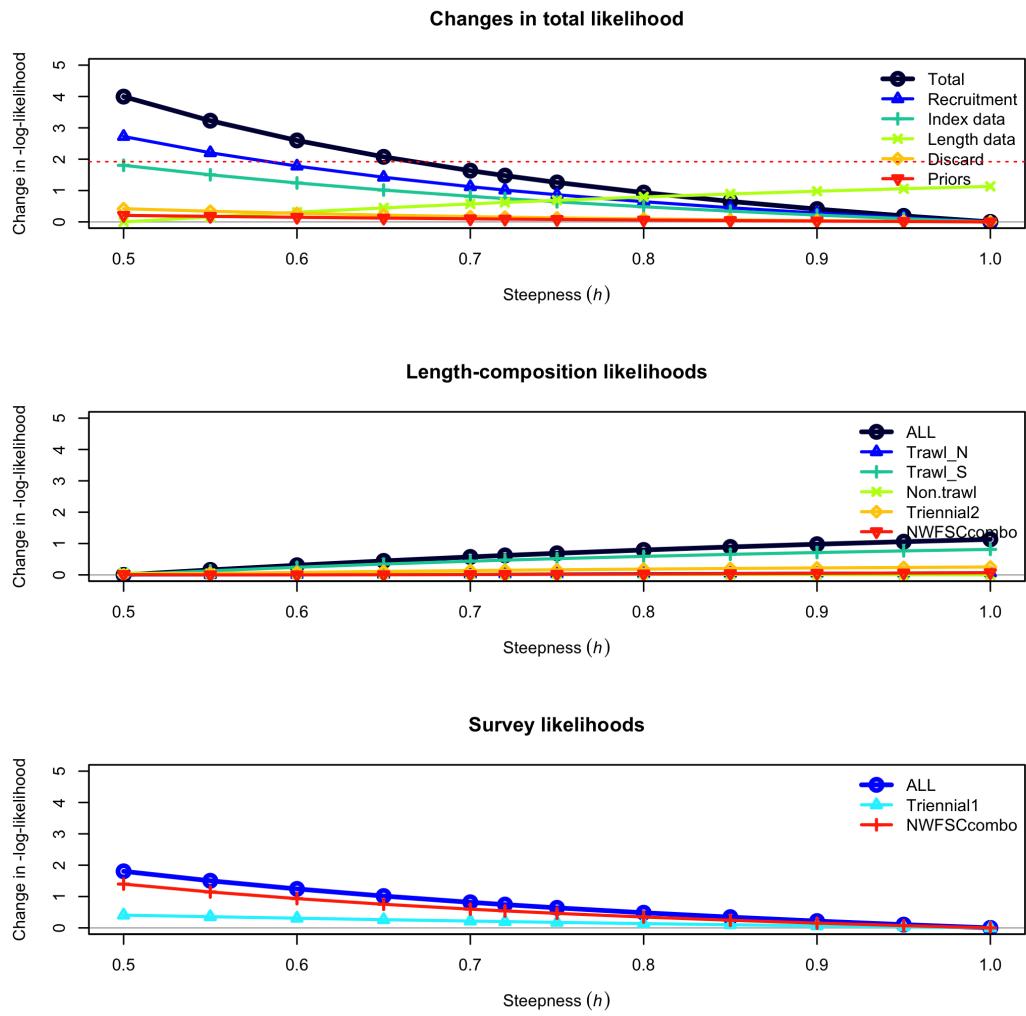


Figure 51: Piner panel plot showing the impact of changing h on the overall (top), length composition (middle), and survy (bottom) likeihoods.

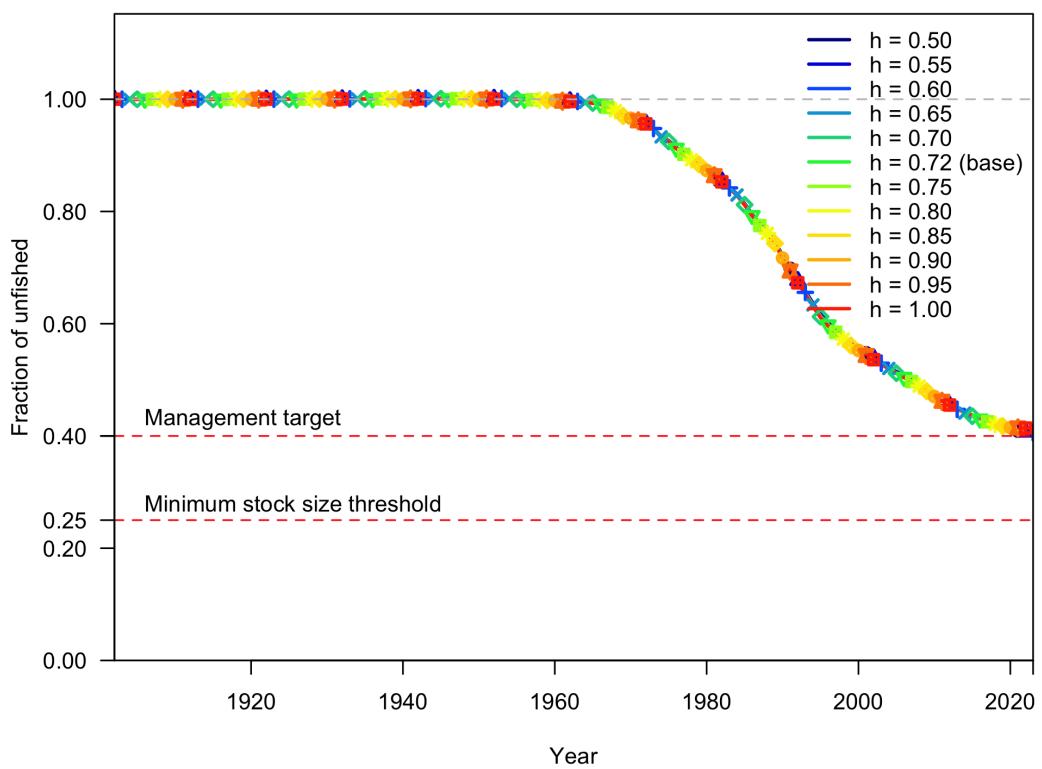


Figure 52: High to low values of h and impact on relative spawning output.

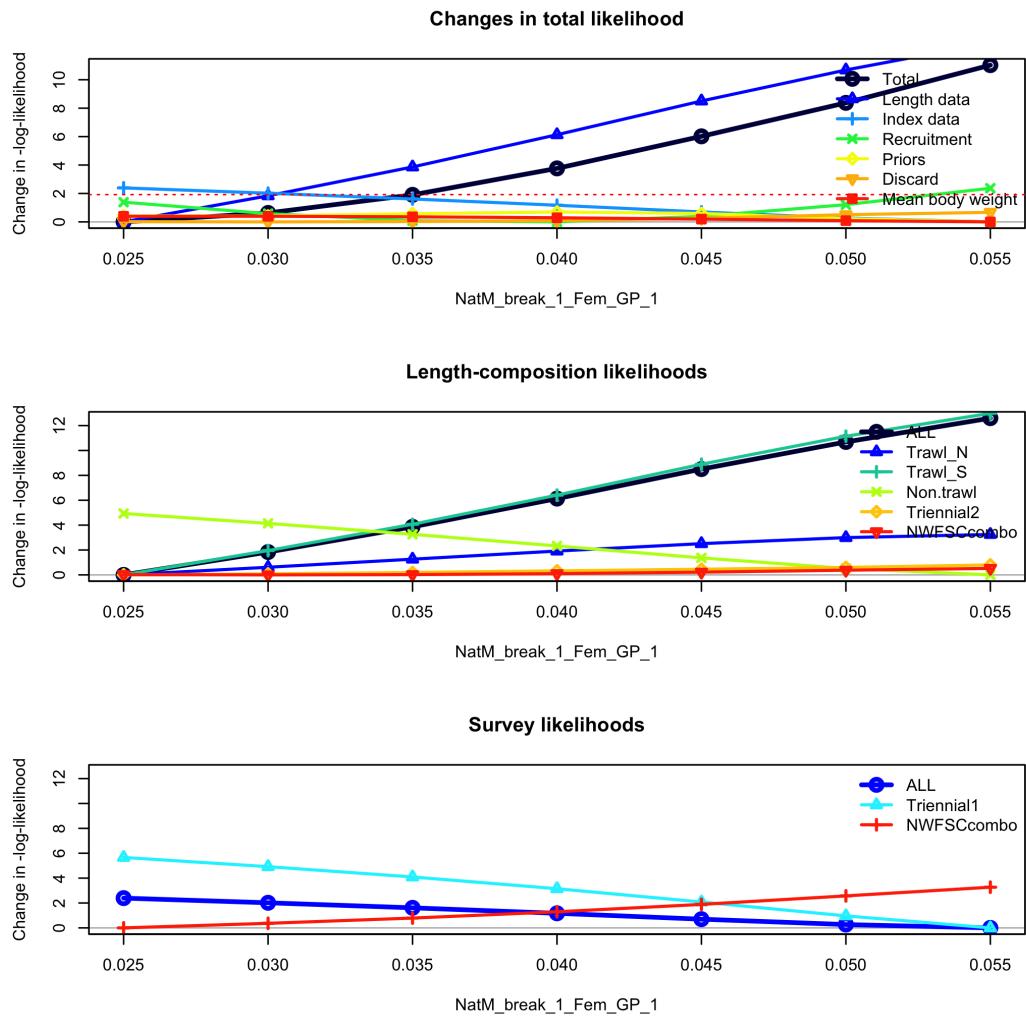


Figure 53: Piner panel plot showing the impact of changing natural mortality (M) on the overall (top), length composition (middle), and survey (bottom) likelihoods.

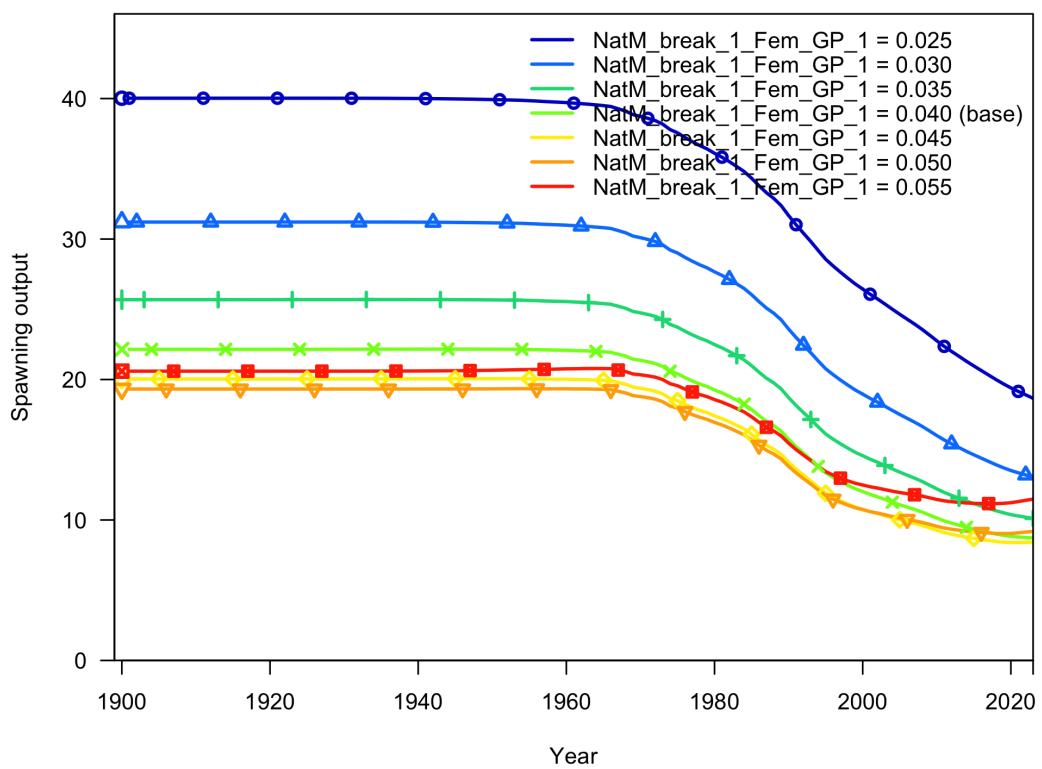


Figure 54: High to low values of M and impact on spawning output.

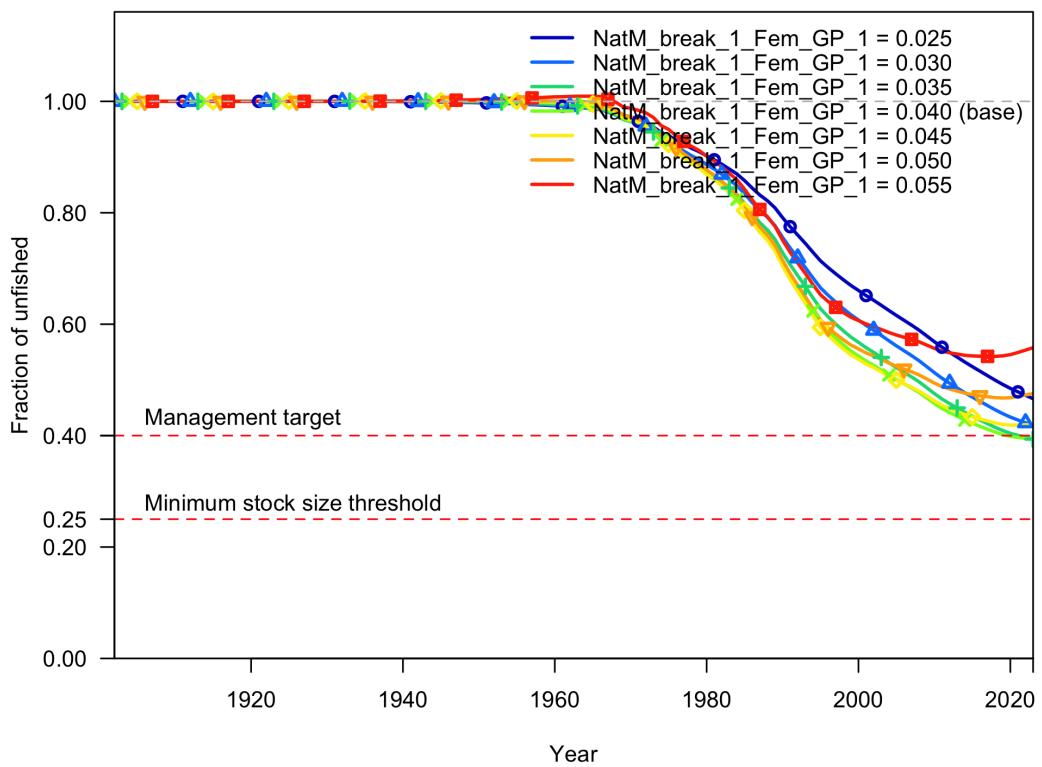


Figure 55: High to low values of M and impact on relative spawning output.

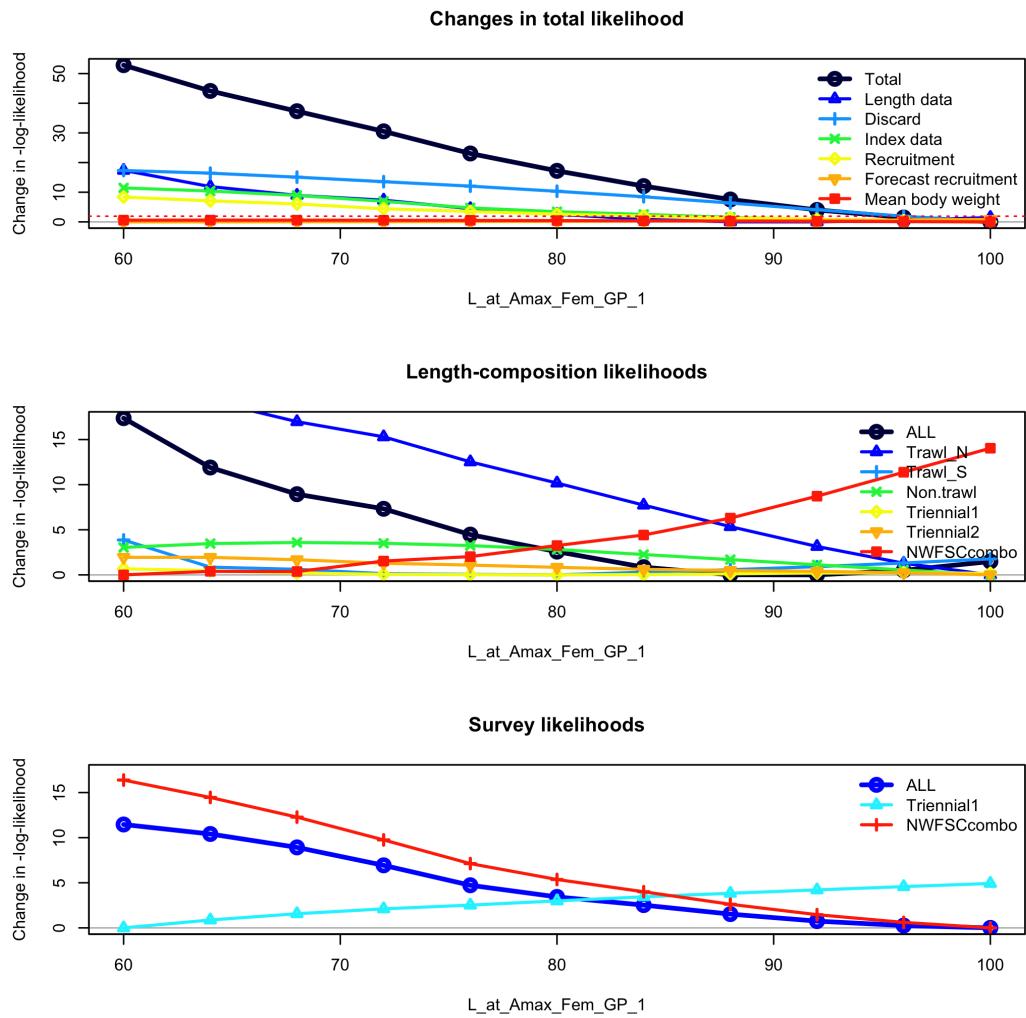


Figure 56: Piner panel plot showing the impact of low to high a_{max} assumptions on the overall (top), length composition (middle), and survy (bottom) likeihoods.

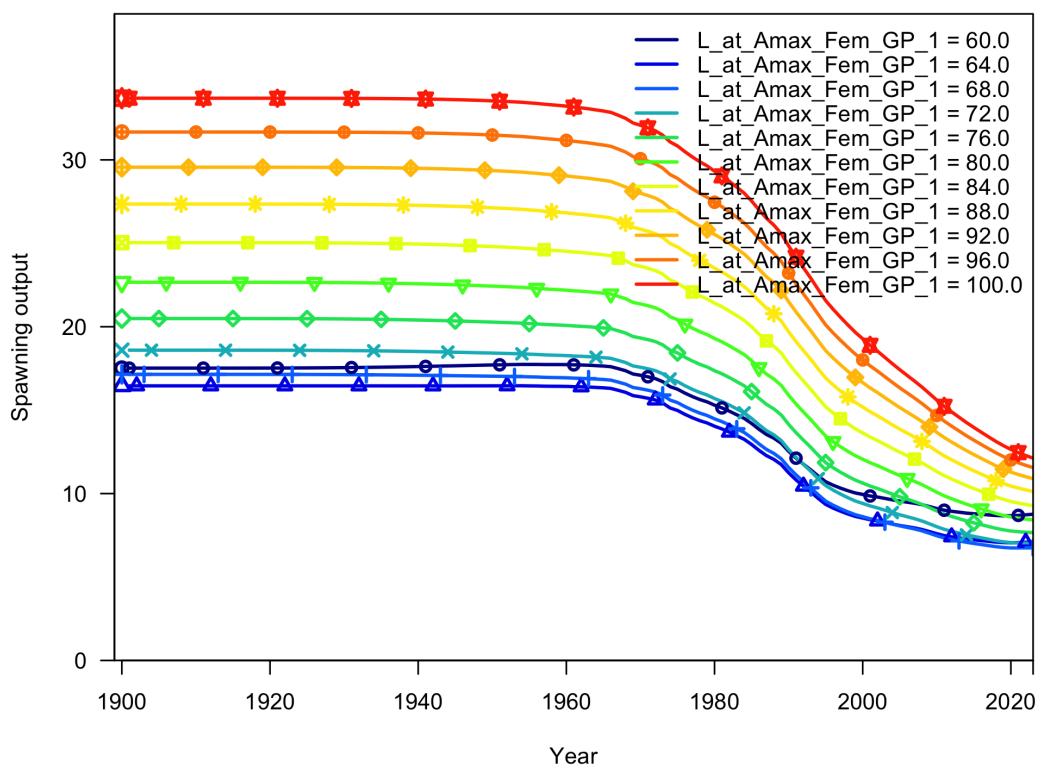


Figure 57: Low to high values of a_{max} and impact on spawning output.

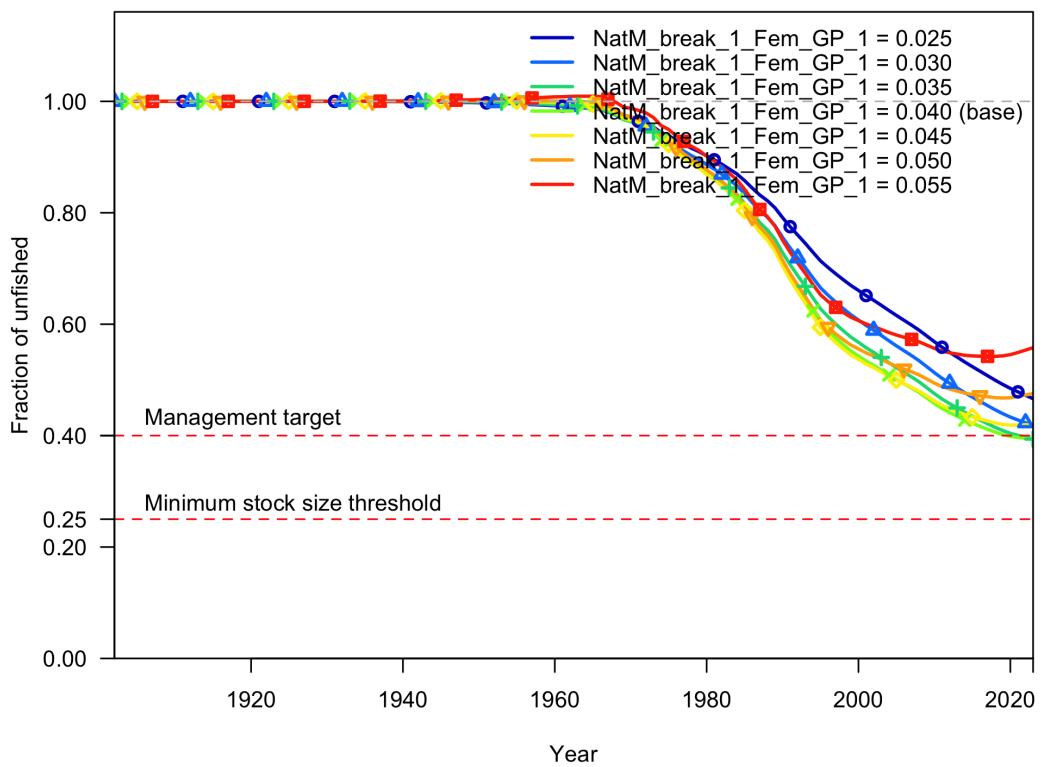


Figure 58: High to low values of M and impact on spawning output.

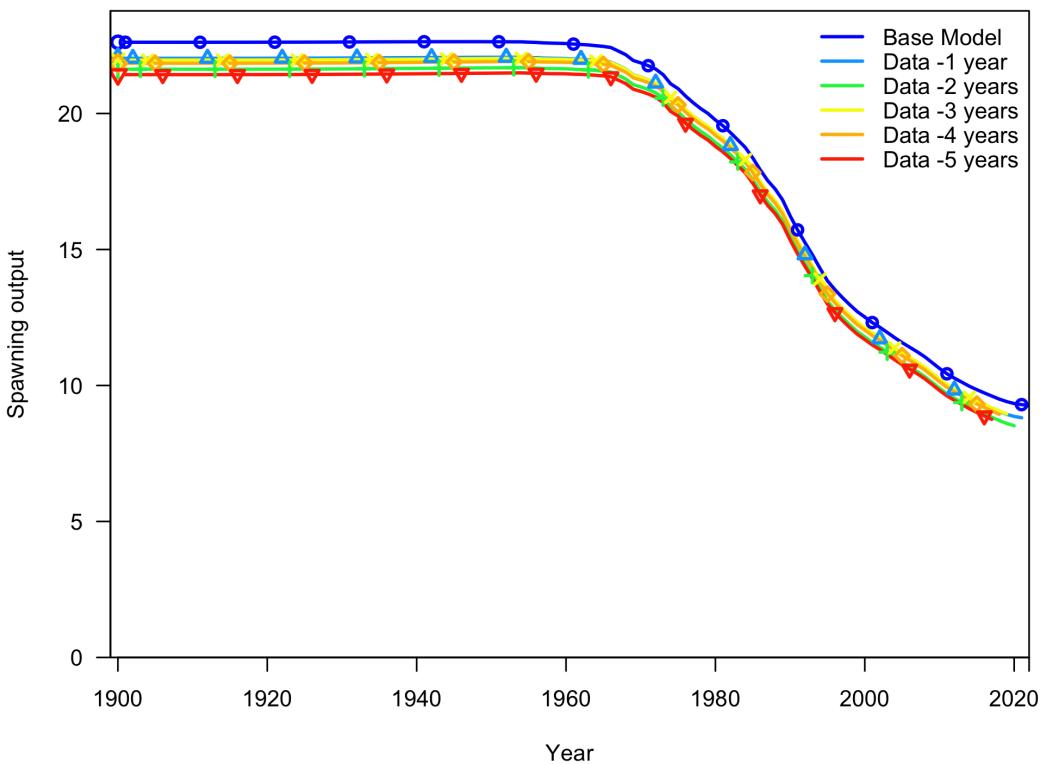


Figure 59: Impact of removing 1-5 years of data on estimated spawning output from retrospective analysis.

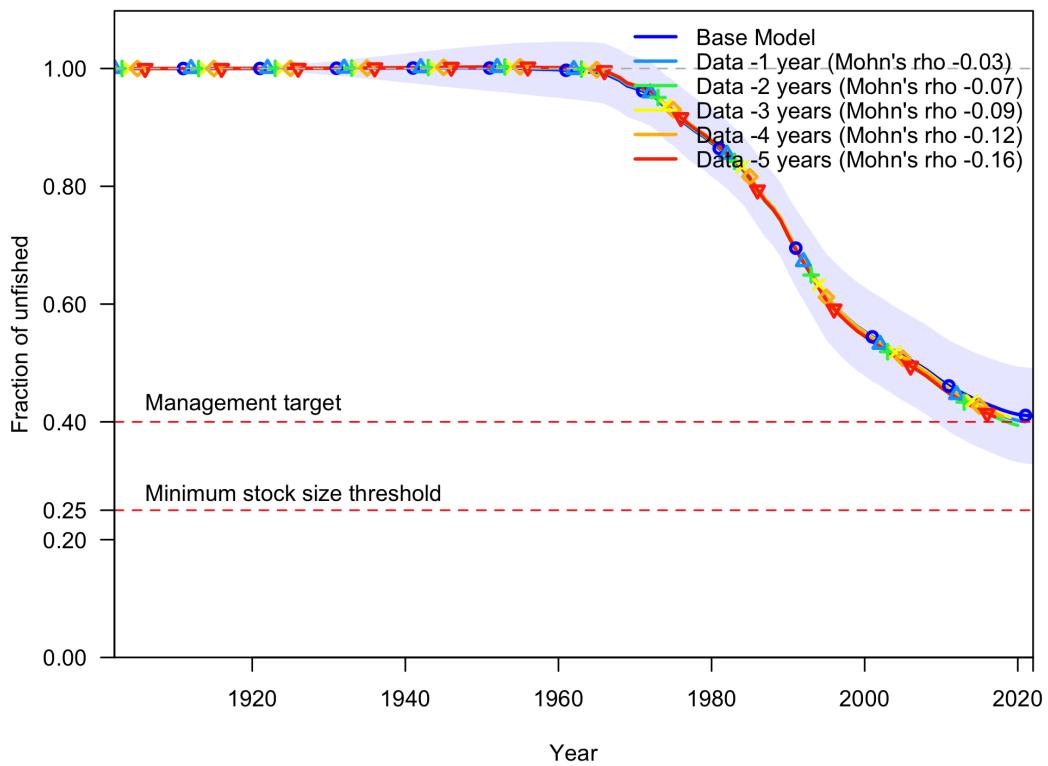


Figure 60: Impact of removing 1-5 years of data on estimated relative spawning output from retrospective analysis. Blue shaded region is the 95% confidence interval around the estimated timeseries from the 2023 base model.

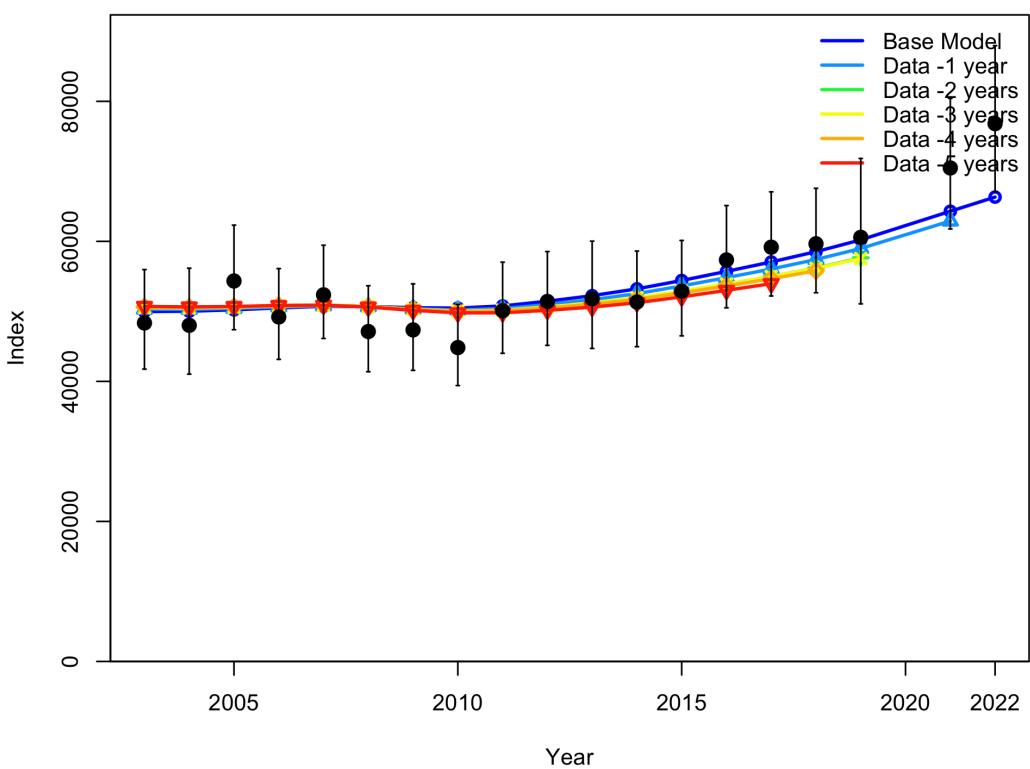


Figure 61: Impact of removing 1-5 years of data on model fit to the WCGBTS indices of abundance.

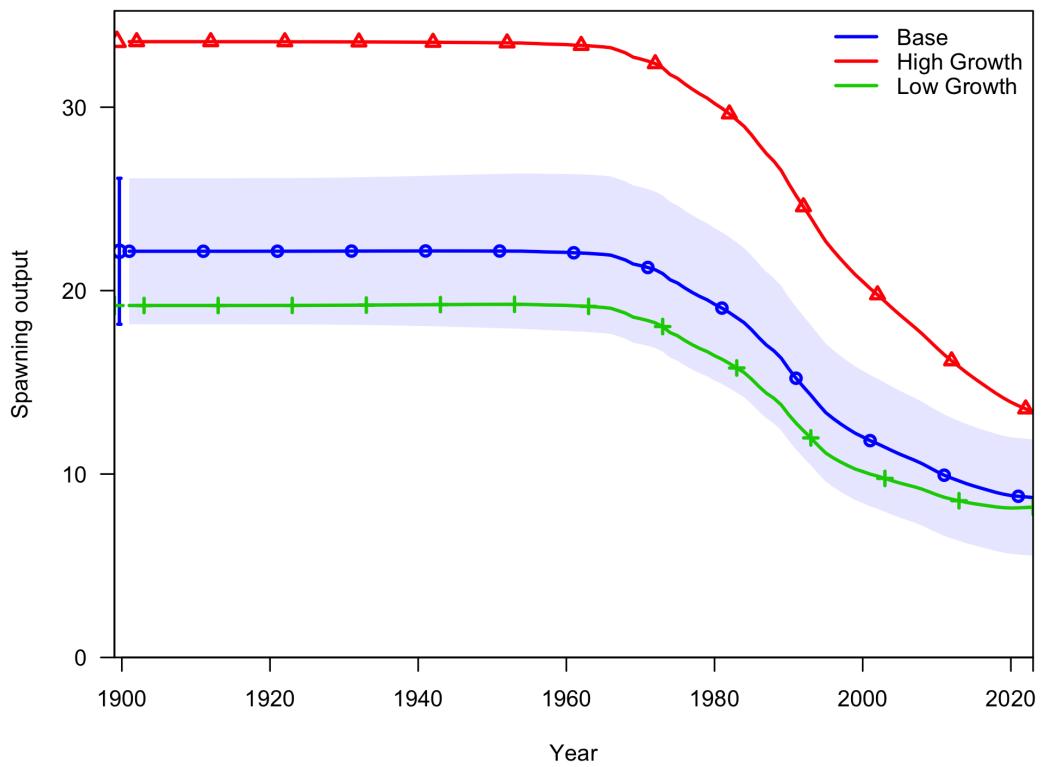


Figure 62: Spawning output comparisons of the base model and high growth and low growth assumptions.

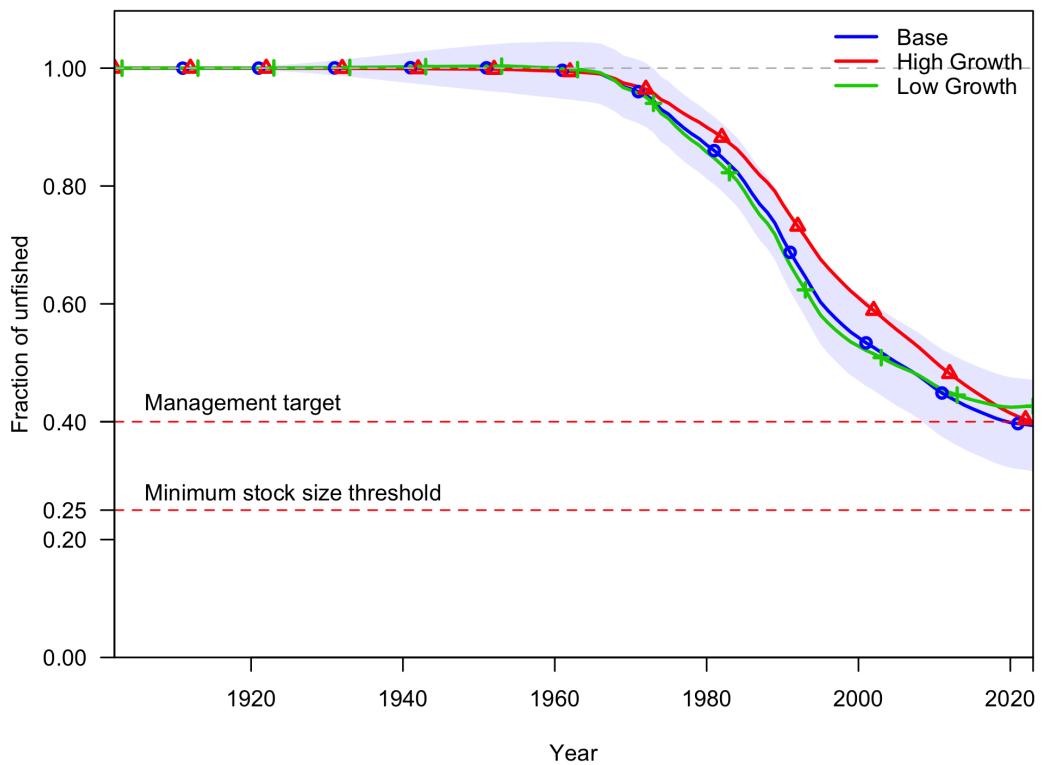


Figure 63: Relative spawning output comparisons of the base model and high growth and low growth assumptions.

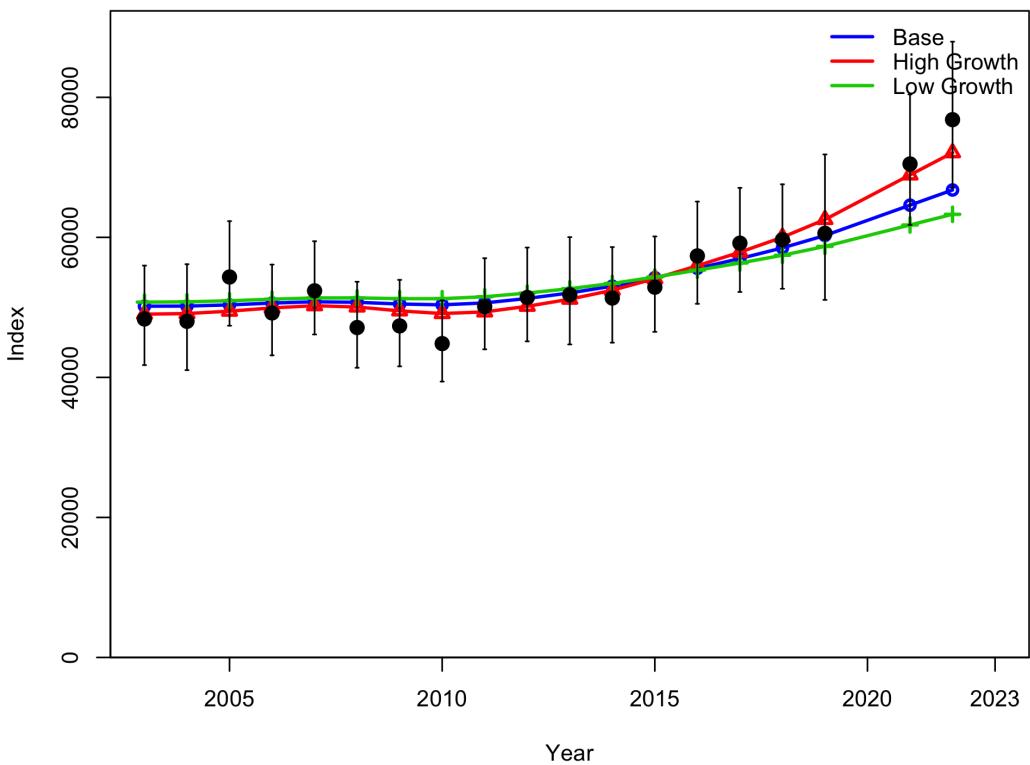


Figure 64: Comparison of fits to combo survey data between the base model and high growth and low growth sensitivities.

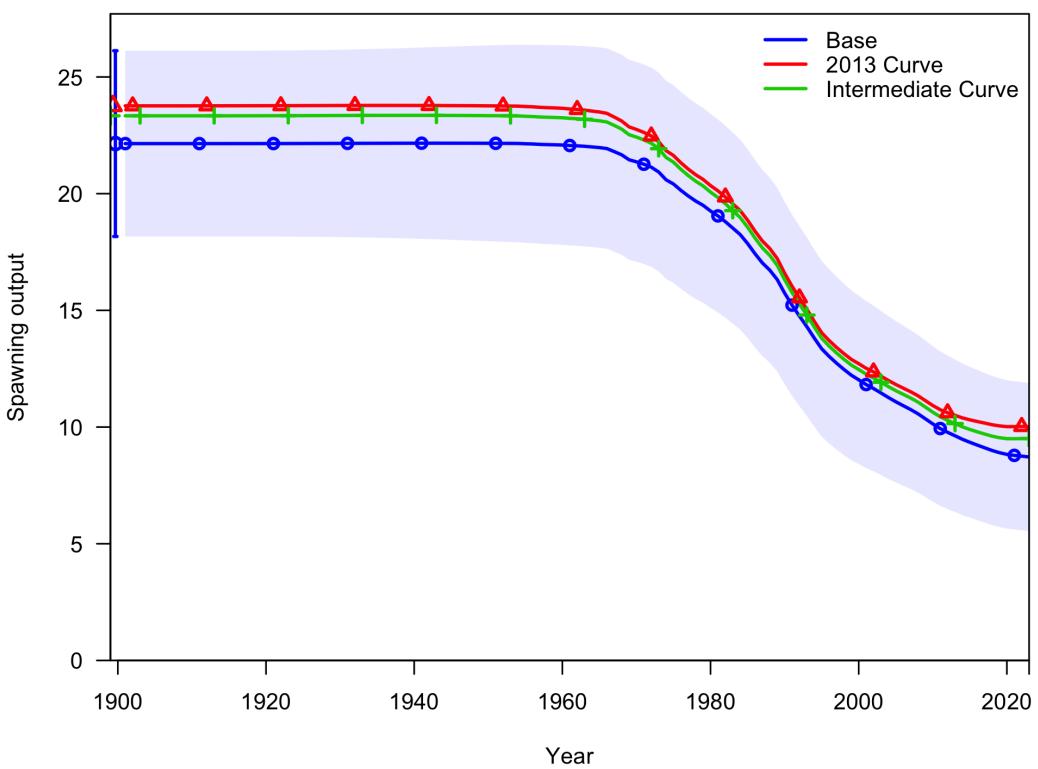


Figure 65: Spawning output comparisons of the base model and maturity sensitivities.

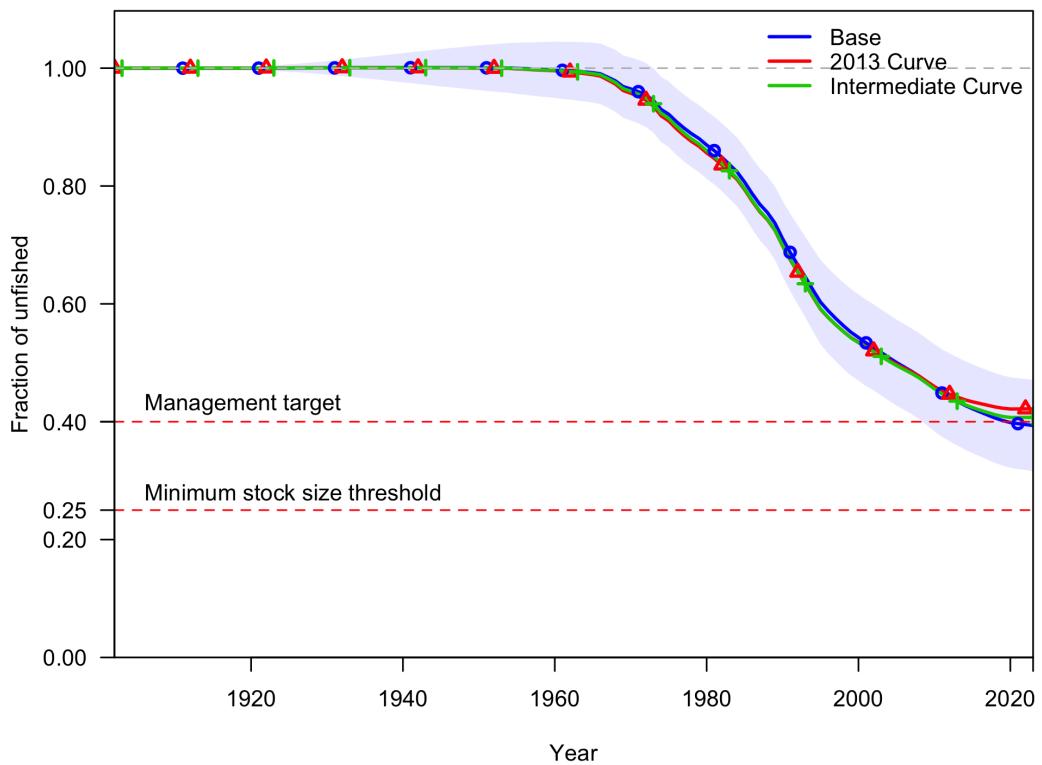


Figure 66: Relative spawning output comparisons of the base model and maturity sensitivities.

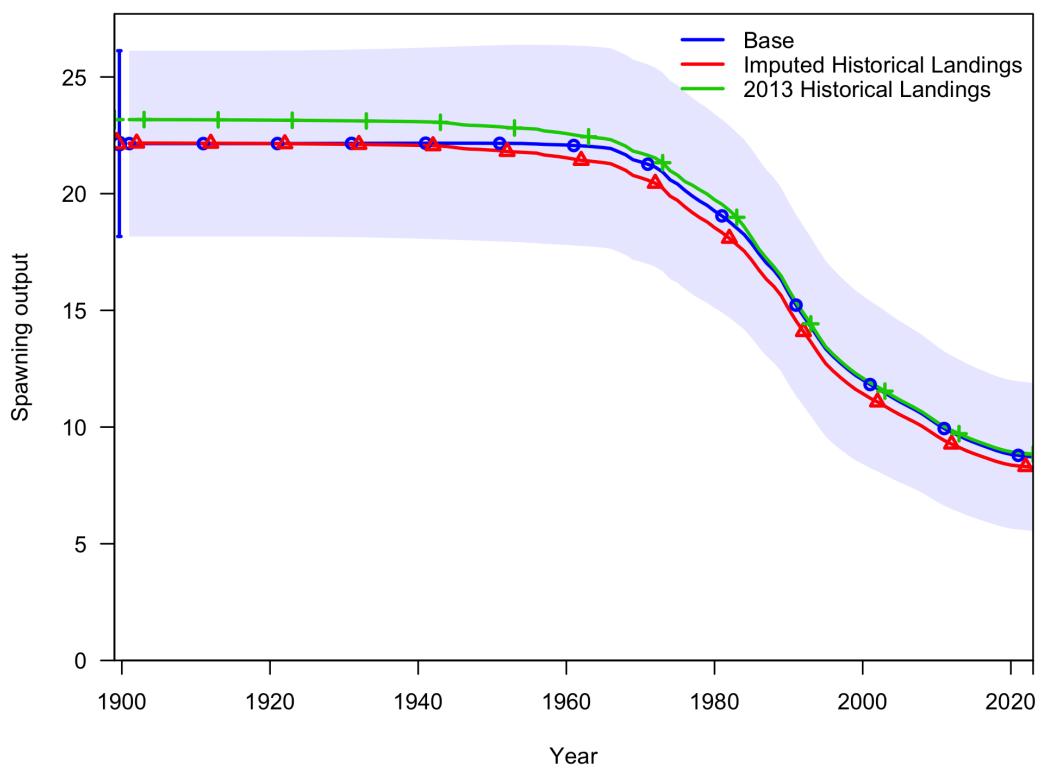


Figure 67: Spawning output comparisons of the base model and landing sensitivities.

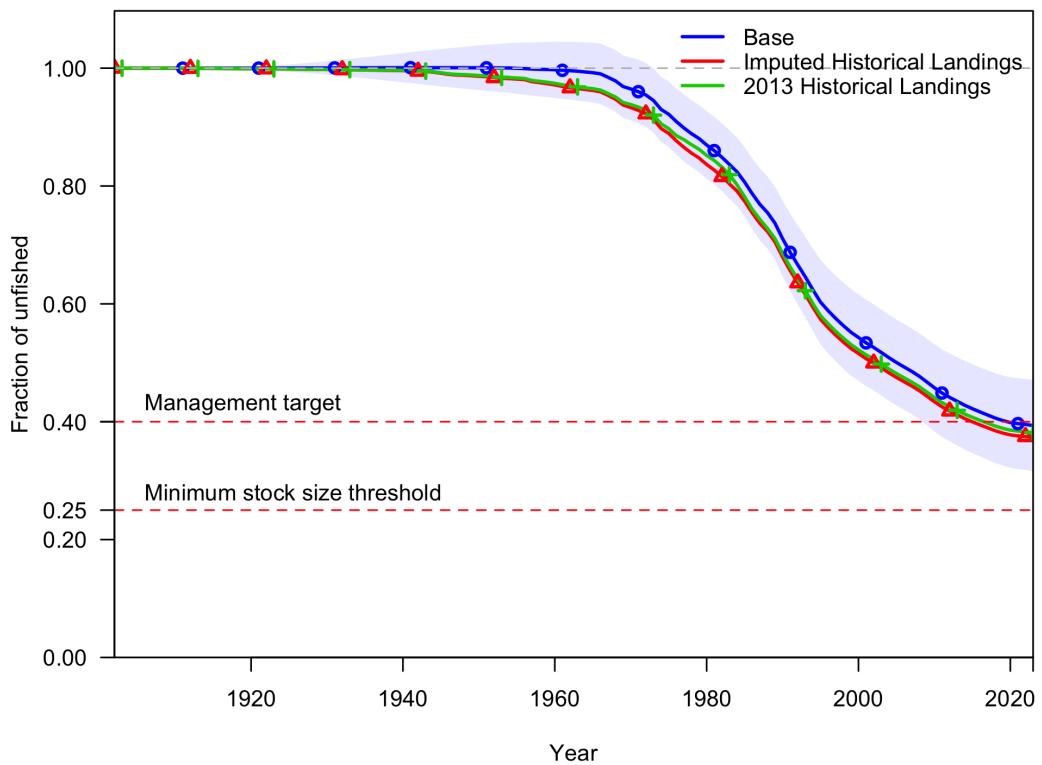


Figure 68: Relative spawning output comparisons of the base model and landing sensitivities.

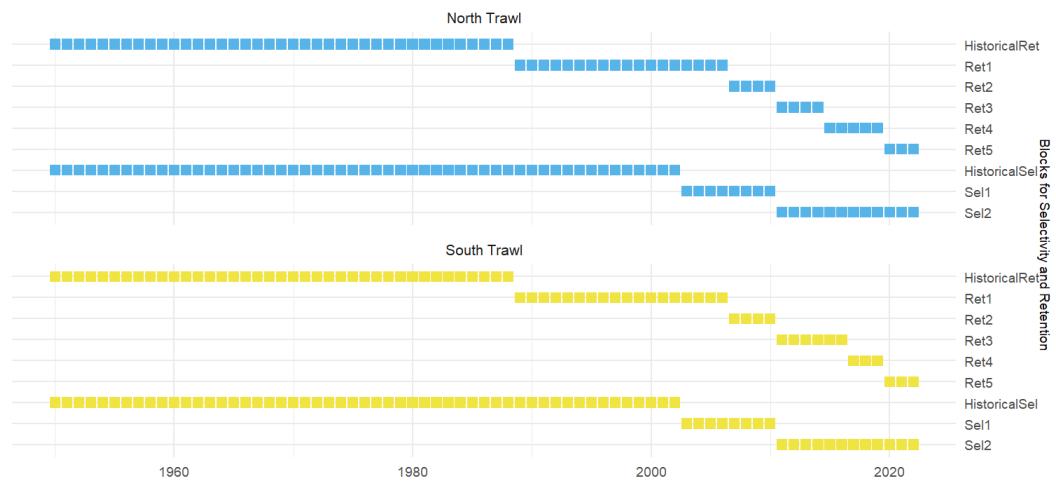


Figure 69: Time blocking for selectivity and retention for North and South trawl fleets.

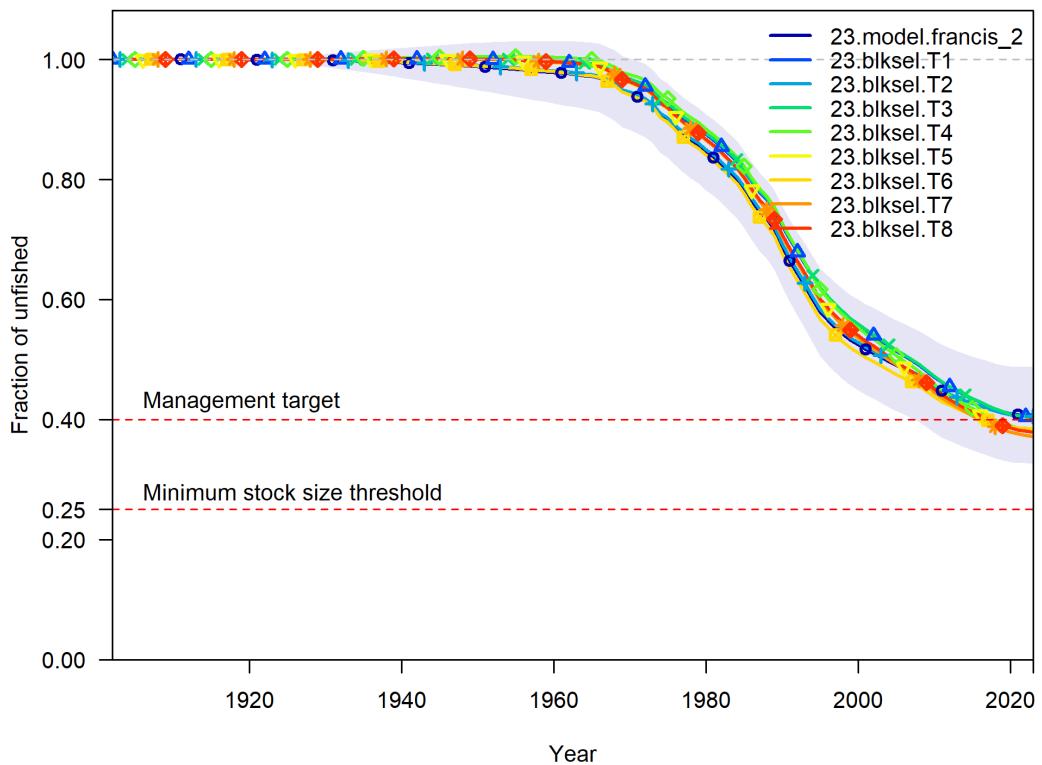


Figure 70: Relative spawning output comparisons of the base model and selectivity sensitivities.

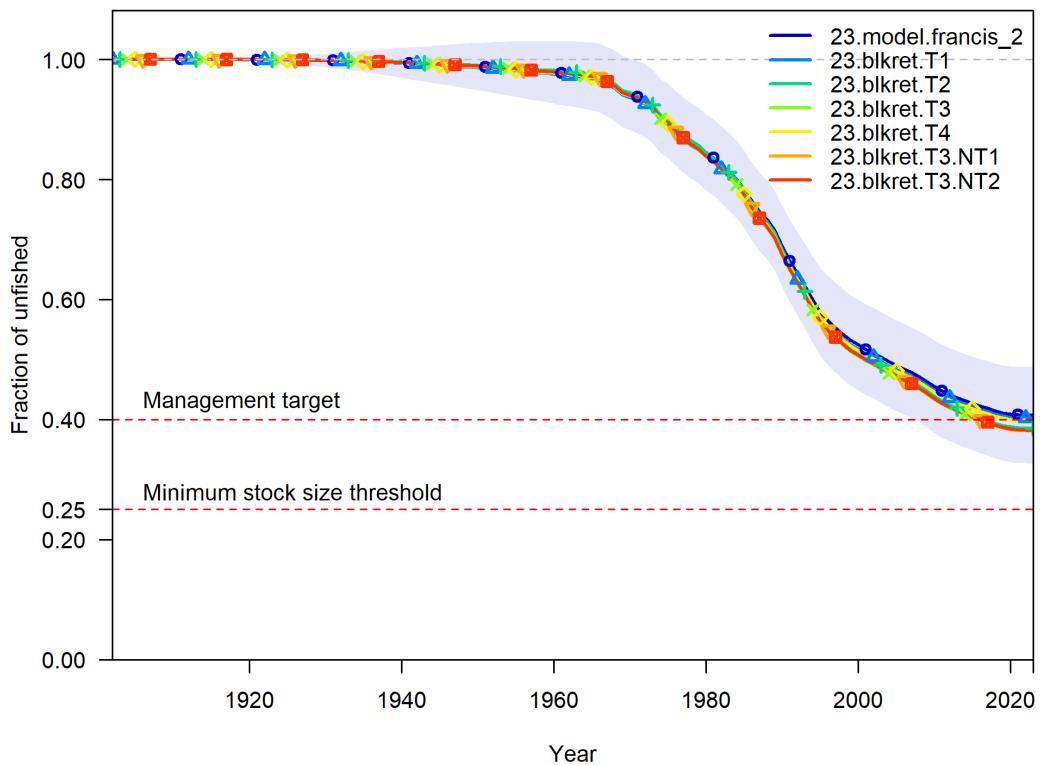


Figure 71: Relative spawning output comparisons of the base model and retention sensitivities.