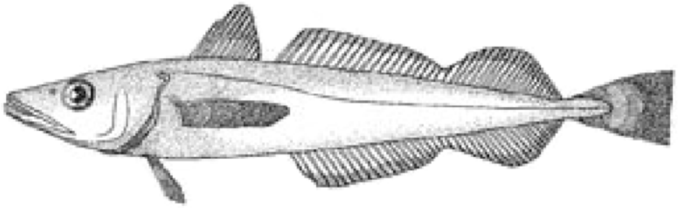
Agenda Item F.2
Attachment 1 ***(Electronic Only)***
March 2023

Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2023

DRAFT for submission to Scientific Review Group[1]



Joint Technical Committee of the Pacific Hake/Whiting Agreement
Between the Governments of the United States and Canada

January 27th, 2023

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This document reports the collaborative efforts of the official U.S. and Canadian members of the Joint Technical Committee, and others that contributed significantly.

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ONE-PAGE SUMMARY

- The stock assessment model for 2023 has the same population dynamics structure as the 2022 model. The model is fit to an acoustic survey index of biomass, an index of age-1 fish, annual commercial catch data, mean weight-at-age data, and age-composition data from the survey and commercial fisheries.

- Updates to the data include: fishery catch and age-composition data from 2022, weight-at-age data for 2022, and minor changes to pre-2022 data.

- Coast-wide catch in 2022 was 320,224 t [t represents metric tons], 6% below the average over the most recent 10 years (340,482 t), out of a total allowable catch (TAC), adjusted for carryovers, of 545,000 t. The U.S. caught 291,337 t (72.4% of their quota) and Canada caught 28,887 t (20.3% of their quota).

- The median estimate of the 2023 relative spawning biomass (female spawning biomass at the start of 2023 divided by that at unfished equilibrium, B_0) is 104% but is highly uncertain (with 95% credible interval from 42% to 300%). The median relative spawning biomass has increased since 2021, due to the estimated above average 2020 cohort entering maturity. The large, but uncertain, size of the 2020 cohort is based on the 2021 age-1 index estimate and the 2022 fishery age-composition data.

- The median estimate of female spawning biomass at the start of 2023 is 1,909,550 t (with 95% credible interval from 757,006 to 5,609,831 t). This is 34% higher than this assessment's median estimate for the 2022 female spawning biomass of 1,423,665 t (with 95% credible interval 716,046–3,081,428 t).

- The estimated probability that female spawning biomass at the start of 2023 is below the $B_{40\%}$ (40% of B_0) reference point is 1.9%, and the probability that the relative fishing intensity exceeded its target in 2022 is 0.1%. The joint probability of both these occurring is 0.1%.

- Based on the default harvest rule, the estimated median catch limit for 2023 is 778,008 t (with 95% credible interval from 301,205 to 2,136,434 t).

- Projections were conducted across a wide-range of catch levels due to high uncertainty in estimates of recent and forecasted recruitment. Projections setting the 2023 and 2024 catches equal to the 2022 coast-wide TAC of 545,000 t show the estimated median relative spawning biomass decreasing from 104% in 2023 to 93% in 2024 to 77% in 2025, with a 16% chance of the female spawning biomass falling below $B_{40\%}$ in 2025. There is an estimated 88% chance of the female spawning biomass declining from 2023 to 2024, and an 85% chance of it declining from 2024 to 2025 for these constant catches.

EXECUTIVE SUMMARY

STOCK

This assessment reports the status of the coastal Pacific Hake (or Pacific whiting, *Merluccius productus*) stock off the west coast of the United States and Canada at the start of 2023. This stock exhibits seasonal migratory behavior, ranging from offshore and generally southern waters during the winter spawning season to coastal areas between northern California and northern British Columbia during the spring, summer, and fall when the fishery is conducted. In years with warmer water the stock tends to move farther to the north during the summer. Older hake tend to migrate farther north than younger fish in all years, with catches in the Canadian zone typically consisting of fish greater than four years old. Separate, and much smaller, populations of hake occurring in the major inlets of the northeast Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California, are not included in this analysis.

CATCHES

Coast-wide fishery landings of Pacific Hake averaged 242,873 t from 1966 to 2022, with a low of 89,930 t in 1980 and a peak of 440,950 t in 2017 (Figure a). Prior to 1966, total removals were negligible compared to the modern fishery. Over the early period (1966–1990) most removals were from foreign or joint-venture fisheries. Across the time series, annual catch in U.S. waters averaged 185,086 t, (76.2% of the total catch) while catch from Canadian waters averaged 57,788 t. Over the last 10 years, 2013–2022 (Table a), the average coast-wide catch was 340,482 t with U.S. and Canadian catches averaging 275,246 t and 65,236 t, respectively. Since 2017, the coast-wide

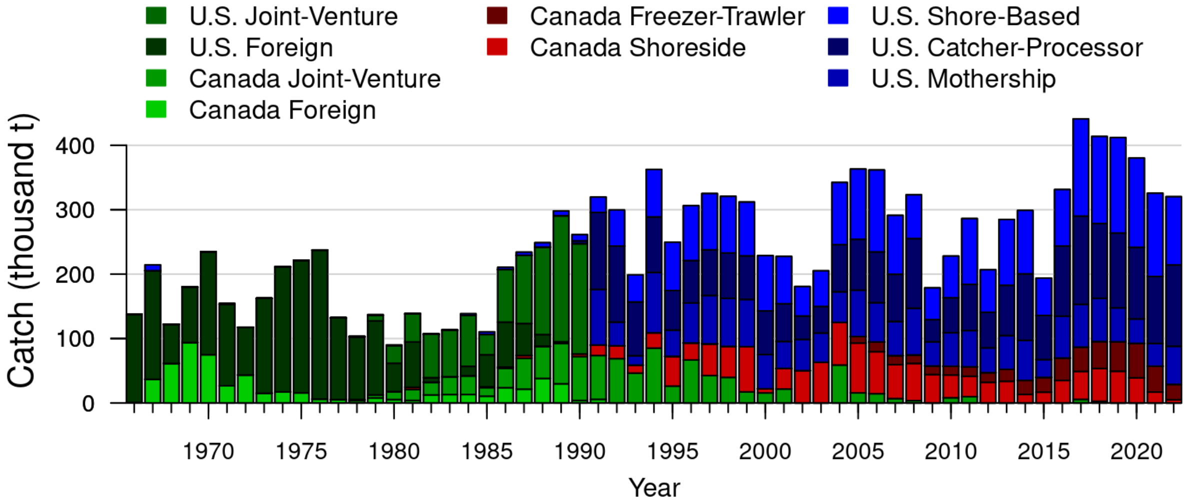

Figure a. Total Pacific Hake catch used in the assessment by sector, 1966–2022. U.S. tribal catches are included in the sectors where they are represented.

Table a. Recent commercial fishery catch (t). Tribal catches are included in the sector totals. Research catch includes landed catch associated with certain research-related activities. Catch associated with surveys and discarded bycatch in fisheries not targeting hake is relatively small and not included in the table or model.

Year	US Mother-ship	US Catcher-Processor	US Shore-Based	US Research	US Total	CAN Joint-Venture	CAN Shoreside	CAN Freezer-Trawler	CAN Total	Total
2013	52,470	77,950	102,141	1,018	233,578	0	33,665	18,584	52,249	285,828
2014	62,102	103,203	98,640	197	264,141	0	13,326	21,792	35,118	299,259
2015	27,665	68,484	58,011	0	154,160	0	16,775	22,887	39,662	193,822
2016	65,036	108,786	87,760	745	262,327	0	35,009	34,724	69,733	332,060
2017	66,428	136,960	150,841	0	354,229	5,608	43,427	37,686	86,721	440,950
2018	67,121	116,073	135,112	0	318,306	2,724	50,747	41,942	95,413	413,719
2019	52,646	116,146	148,210	0	317,002	0	49,275	45,738	95,013	412,015
2020	37,978	111,147	138,688	95	287,908	0	39,077	53,412	92,489	380,397
2021	35,208	104,030	129,319	917	269,473	0	16,952	40,123	57,076	326,549
2022	59,152	126,247	105,938	0	291,337	0	5,050	23,837	28,887	320,224

catch has been declining annually through 2022, when it was 320,224 t out of a total allowable catch (TAC, adjusted for carryovers) of 545,000 t. Attainment in the U.S. was 72.4% of its quota and in Canada it was 20.3%.

In this document, the terms catch and landings are used interchangeably. Estimates of discard within the target fishery are included, but discarding of Pacific Hake in non-target fisheries is not. Discard from all fisheries, including those that do not target hake, is estimated to be less than 1% of landings in recent years. During the last five years, catches were considerably above the long-term average catch (242,873 t), but have been in decline over that period (especially in Canada). Landings between 2001 and 2008 were predominantly comprised of fish from the very large 1999 year class, with the cumulative removal (through 2022) from that cohort estimated at approximately 1.29 million t. Through 2022, the cumulative catch of the 2010, 2014, and 2016 year classes is estimated to be about 1.25 million t, 0.80 million t, and 0.53 million t, respectively. In the 2022 catch, the 2020 cohort was the largest (33%), followed by the 2016 cohort (24%), and then the 2014 cohort (16%).

DATA AND ASSESSMENT

This Joint Technical Committee (JTC) assessment depends on the fishery landings (1966–2022), an acoustic survey biomass index of age-2+ fish (Figure b) and age compositions (1995–2021), a relative index of age-1 fish (Figure c; 1995–2021), fishery age compositions (1975–2022), and mean weight-at-age data (1975–2022). In 2011 the survey biomass index was the lowest in the time series and was followed by the index increasing in 2012, 2013, and again in 2015 before decreasing to near the time series average in 2017. The 2019 estimate is the fourth highest of the series, and the 2021 estimate is near the time series average. Age-composition data from the aggregated fisheries and the acoustic survey, along with the age-1 index, provide data that facilitates estimating relative cohort strength, i.e., strong and weak cohorts. The age-1 index suggests particularly large numbers of age-1 fish in 2009, 2011, 2015, and 2021 (2008, 2010, 2014, and 2020 year classes, respectively), and is not available for most even years (odd year classes). There is not data to inform the size of the 2022 year class.

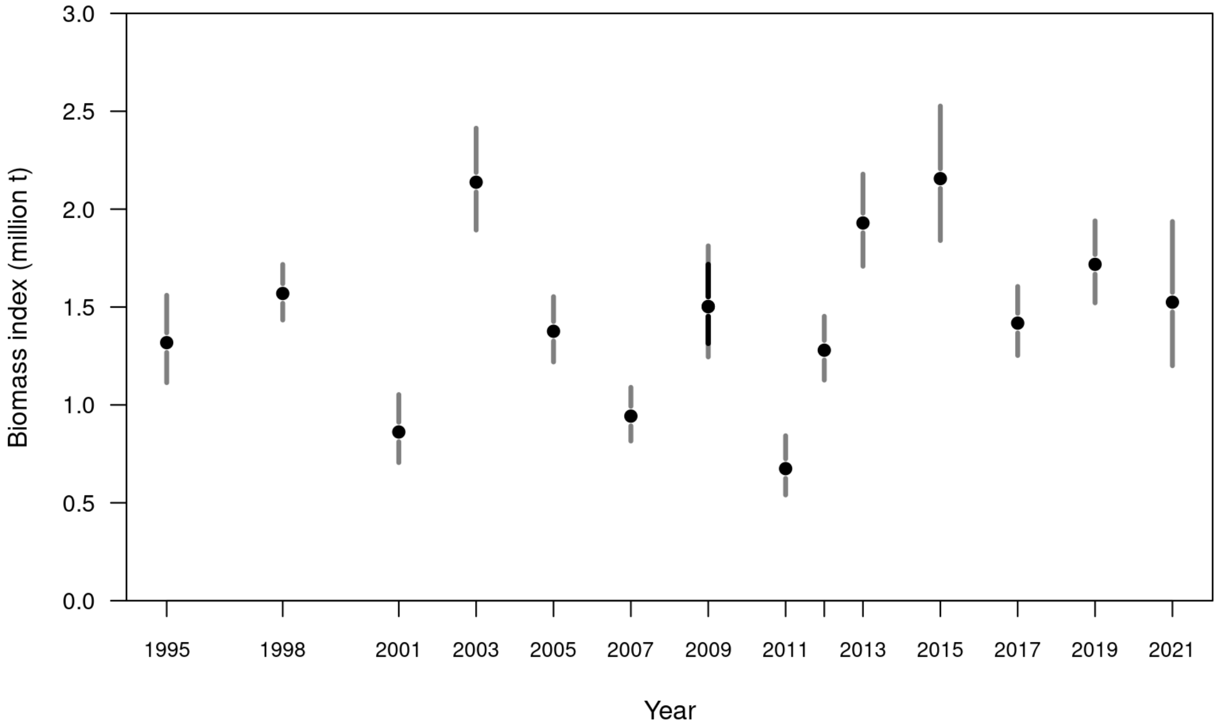

Figure b. Acoustic survey biomass index of age-2+ fish (millions of tons). Approximate 95% confidence intervals are based on sampling variability (intervals without squid/hake apportionment uncertainty in 2009 are displayed in black).

The assessment uses a Bayesian estimation approach, sensitivity analyses, and retrospective investigations to evaluate the potential consequences of parameter uncertainty, alternative structural models, and historical performance of the assessment model, respectively. The Bayesian approach combines prior knowledge about natural mortality, stock-recruitment steepness (a parameter for stock productivity), and several other parameters, with likelihoods for the acoustic survey biomass index, acoustic survey age-composition data, the relative age-1 index, and fishery age-composition data. Integrating the joint posterior distribution over model parameters provides probabilistic inferences about uncertain model parameters and forecasts derived from those parameters; this is done via Markov chain Monte Carlo sampling using the efficient No-U-Turn Sampler (NUTS) that was successfully tested in 2020 and used in subsequent assessments. Sensitivity analyses are used to identify alternative model assumptions that may also be consistent with the data. All models, including bridging, sensitivity, and retrospective models, use a Bayesian framework for estimation. Retrospective analyses identify possible poor performance of the assessment model with respect to future predictions. Past assessments have conducted closed-loop simulations that provide insights into how alternative combinations of survey frequency, assessment model selectivity assumptions, changes in hake distribution, and harvest control rules affect expected management outcomes given repeated application of these procedures over the long-term. The results of past (and ongoing) closed-loop simulations help inform decisions made for this assessment.

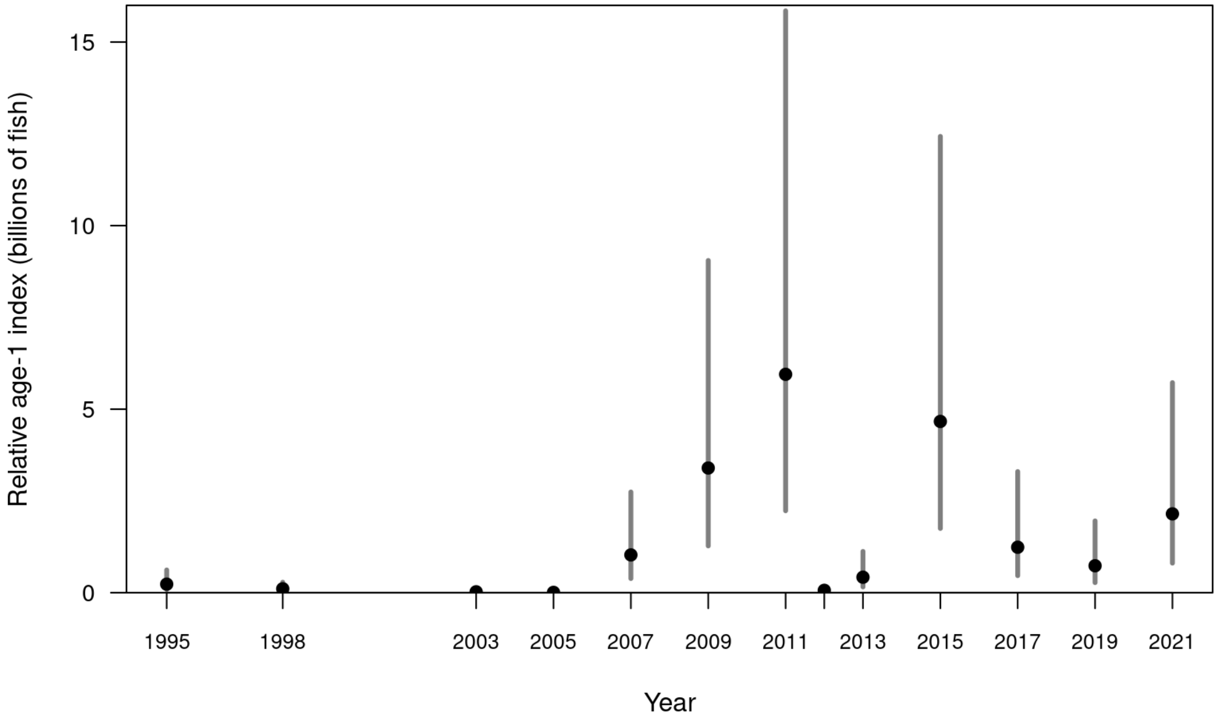

Figure c. Relative index of age-1 fish (numbers of fish) and approximate 95% confidence intervals based on sampling variability. The index is relative because the survey does not attempt to sample all available age-1 fish and the analysis does not include kriging as is done to estimate age-2+ biomass.

This 2023 assessment retained the same general population dynamics structure as the base assessment model from 2022 and again is configured using Stock Synthesis. This includes the continued use (since 2014) of time-varying (rather than fixed) selectivity to maintain flexibility with fishing dynamics given variability in Pacific Hake distribution patterns. The Dirichlet-multinomial estimation approach to weighting composition data was retained, and sensitivity to an alternative data-weighting approach was investigated. Time-varying fecundity, which was introduced in 2019, was retained. Assumptions for the forecast period for weight at age and selectivity continue to be based on conditions during the last five years, as done since the 2020 assessment. The main change from the 2022 assessment is the addition of 2022 data.

STOCK BIOMASS

Results from the base model indicate that since the 1960s, Pacific Hake female spawning biomass has ranged from well below to above unfished equilibrium (Figures d and e). Model estimates suggest that it was below the unfished equilibrium in the 1960s, at the start of the assessment period, due to lower than average recruitment. The stock is estimated to have increased rapidly and was above unfished equilibrium in the mid-1970s and mid-1980s (after two large recruitment events in the early 1980s). It then declined steadily to a low in 1999. This was followed by a brief increase to a peak in 2002 as the very large 1999 year class matured. The 1999 year class largely

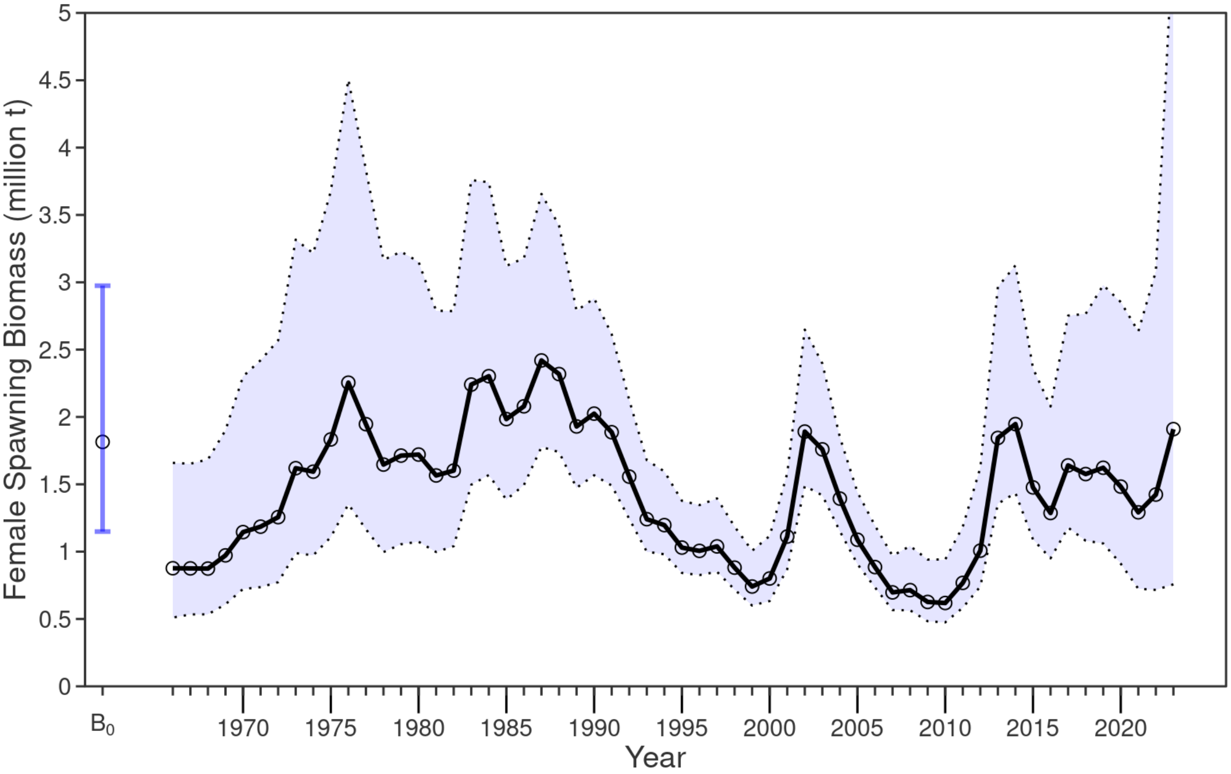

Figure d. Median (solid line) of the posterior distribution for beginning of the year female spawning biomass (B_t in year t; million t) through 2023 (solid line) with 95% posterior credibility intervals (shaded area). The left-most circle with a 95% posterior credibility interval is the estimated unfished equilibrium biomass, B_0.

supported the fishery for several years due to relatively small recruitment events between 2000 and 2007. With the aging 1999 year class, median female spawning biomass declined throughout the late 2000s, reaching a time-series low of 0.619 million t in 2010. Median female spawning biomass is estimated to have peaked again in 2013 and 2014 due to a very large 2010 year class and an above-average 2008 year class. The subsequent decline from 2014 to 2016 is primarily from the 2010 year class surpassing the age at which the gains in weight from growth are greater than the losses in weight from mortality (growth-mortality transition). The 2014 year class is estimated to be large, though not as large as the 1999 and 2010 year classes, increasing the biomass in 2017. The estimated biomass was relatively steady from 2017 to 2019 and then declined in 2020 and 2021 due to the 2014 and 2016 year classes moving through the growth-mortality transition during a period of high catches. The increase in female spawning biomass since 2021 is due to the expected above average 2020 cohort entering maturity and the recent declining trend in catch.

The median estimate of the 2023 relative spawning biomass (female spawning biomass at the start of 2023 divided by that at unfished equilibrium, B_0) is 104%. However, the uncertainty is particularly large this year, with a 95% posterior credibility interval from 42% to 300% (Table b), due to remaining unknowns about the size of the 2020 cohort (e.g., not yet sampled by the acoustic survey). The median estimate of the 2023 female spawning biomass is 1.910 million t (with a 95% posterior credibility interval from 0.757 to 5.610 million t). The current estimate of the 2022 female

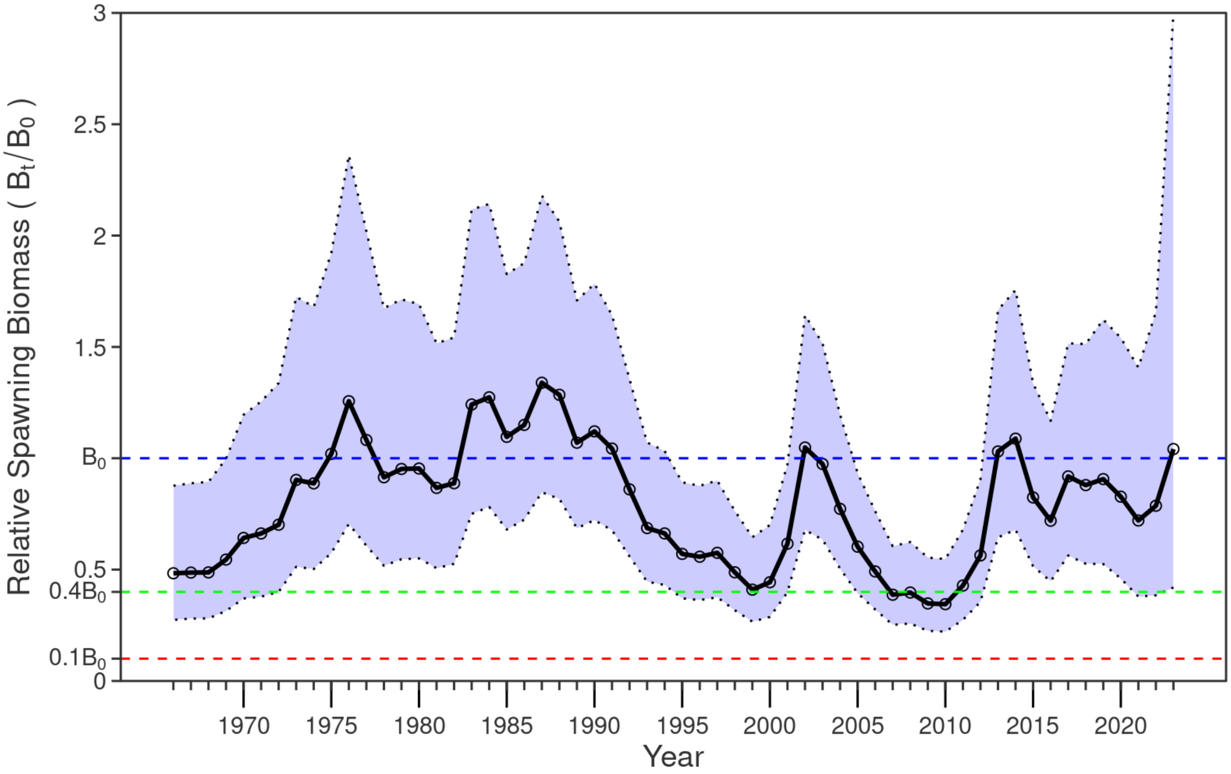

Figure e. Median (solid line) of the posterior distribution for relative spawning biomass (B_t/B_0) through 2023 with 95% posterior credibility intervals (shaded area). Dashed horizontal lines show 10%, 40%, and 100% of the unfished equilibrium (B_0).

spawning biomass is 1.424 (0.716–3.081) million t. This is a higher median but similar credibility interval compared to the 1.171 (0.584–2.585) million t estimated in the 2022 assessment. The increase appears to be due to the addition of 2022 fishery age-composition data, which suggests the 2020 cohort may be larger than the age-1 index alone was indicating in the last assessment.

RECRUITMENT

The addition of 2022 data for this assessment does not substantially change the pattern of recruitment estimated in recent assessments. However, estimates of absolute recruitment for the most recent years can change with new data. For example, this assessment's median estimate of the 2020 recruitment is 6.2 billion fish higher than in the last assessment (a 118% increase). Similarly, estimates for 2019 and 2021 recruitments have changed by -39% (-0.4 billion fish) and -52% (-0.5 billion fish), respectively, but the general notion remains that recent recruitment is highly uncertain.

Pacific Hake have low to moderate recruitment with occasional large year classes (Table c and Figure f). Large year classes in 1980, 1984, and 1999 supported much of the commercial catch from the 1980s to the mid-2000s. From 2000 to 2007, estimated recruitment was at some of the

Table b. Recent trends in estimated beginning of the year female spawning biomass (thousand t) and spawning biomass relative to estimated unfished equilibrium.

Year	Spawning biomass (thousand t)			Relative spawning biomass (B_t/B_0)		
	2.5th percentile	Median	97.5th percentile	2.5th percentile	Median	97.5th percentile
2014	1,435.6	1,947.1	3,124.9	67.9%	108.8%	175.6%
2015	1,090.6	1,476.7	2,361.0	51.5%	82.4%	133.7%
2016	950.3	1,286.9	2,077.9	44.7%	71.9%	116.8%
2017	1,178.4	1,640.3	2,752.4	56.3%	91.9%	151.6%
2018	1,081.2	1,576.0	2,765.0	52.7%	88.0%	151.3%
2019	1,060.6	1,622.7	2,978.6	52.5%	90.6%	162.3%
2020	910.0	1,482.8	2,853.2	46.0%	82.7%	154.1%
2021	724.2	1,291.8	2,634.7	37.9%	72.1%	140.8%
2022	716.0	1,423.7	3,081.4	38.5%	78.7%	165.8%
2023	757.0	1,909.6	5,609.8	42.0%	104.1%	300.2%

Table c. Estimates of recent recruitment (millions of age-0 fish) and recruitment deviations, where deviations below (above) zero indicate recruitment below (above) that estimated from the stock-recruit relationship.

Year	Absolute recruitment (millions)			Recruitment deviations		
	2.5th percentile	Median	97.5th percentile	2.5th percentile	Median	97.5th percentile
2013	137.1	390.3	959.8	-1.950	-0.897	-0.107
2014	5,990.5	9,165.0	16,720.8	1.781	2.264	2.756
2015	8.3	37.7	139.6	-4.636	-3.244	-1.960
2016	3,854.6	6,373.8	12,724.5	1.398	1.932	2.490
2017	1,157.5	2,463.6	5,937.4	0.229	0.960	1.696
2018	185.9	640.8	1,963.5	-1.596	-0.401	0.641
2019	114.9	611.4	2,189.2	-2.100	-0.448	0.726
2020	2,908.4	11,408.9	47,579.7	1.192	2.490	3.822
2021	28.3	450.4	6,911.7	-3.388	-0.726	1.926
2022	41.4	962.6	21,501.9	-3.078	0.007	3.067

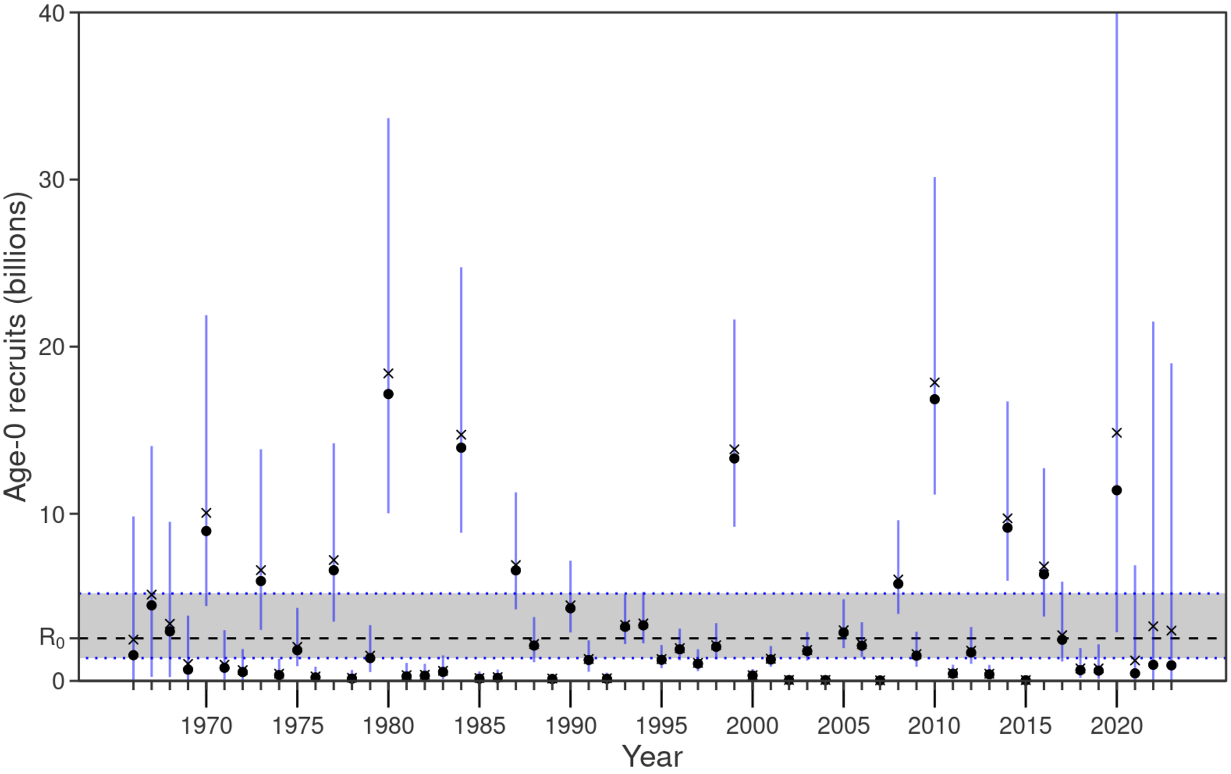

Figure f. Medians (solid circles) and means (×) of the posterior distribution for recruitment (billions of age-0 fish) with 95% posterior credibility intervals (blue, vertical lines). The median of the posterior distribution for mean unfished equilibrium recruitment (R_0) is shown as the horizontal dashed line with the 95% posterior credibility interval shaded between the dotted lines.

lowest values in the time series but this was followed by an above average 2008 year class. The strong 2010 year class comprised 64% of the coast-wide commercial catch in 2014, 32% of the 2016 catch, 23% of the 2018 catch, 15% of the 2020 catch, and 6% of the 2022 catch. The decline from 2014 to 2016 was partly due to the large influx of the 2014 year class (51% of the 2016 catch was age-2 fish from the 2014 year class; this was larger than the proportion of age-2 fish, 41%, from the 2010 year class in 2012). Since 2010, the model currently estimates small 2011, 2012, 2013, 2015, 2018, 2019 and 2021 year classes (median recruitment well below the mean of all median recruitments).

The 2014 and 2016 year classes are both larger than average, with 2014 larger than 2016 but smaller than 2010. With the inclusion of the relative age-1 index, there is information beyond just fishery encounters in the data to estimate the size of the 2020 year class. Collectively, these data indicate that the 2020 year class is likely well above average. The much smaller 2019 year class is informed by the 2021 biomass index and fishery data but is not informed by the relative age-1 index, and the 2021 year class is informed only by 2022 fishery data. There is no information in the data to estimate the sizes of the 2022 and 2023 year classes. Retrospective analyses of year-class strength for young fish have shown the estimates of recent recruitment to be unreliable prior to at least a model age of three (i.e., fish observed at age two) without a survey in the most recent year

Table d. Recent estimates of relative fishing intensity, (1-SPR)/(1-$\text{SPR}_{40\%}$), and exploitation fraction (catch divided by age-2+ biomass).

Year	Relative fishing intensity			Exploitation fraction		
	2.5th percentile	Median	97.5th percentile	2.5th percentile	Median	97.5th percentile
2013	0.393	0.622	0.835	0.041	0.066	0.091
2014	0.366	0.596	0.825	0.042	0.068	0.093
2015	0.251	0.438	0.647	0.037	0.059	0.080
2016	0.452	0.728	0.988	0.053	0.088	0.121
2017	0.470	0.750	1.092	0.071	0.119	0.166
2018	0.418	0.690	1.023	0.054	0.096	0.142
2019	0.417	0.692	0.981	0.056	0.105	0.161
2020	0.348	0.596	0.864	0.060	0.116	0.190
2021	0.296	0.530	0.782	0.056	0.114	0.204
2022	0.274	0.507	0.782	0.023	0.064	0.144

and two (i.e., fish observed at age one) with a survey. While the 2020 cohort was observed by the relative age-1 index in 2021, it will not be observed by the acoustic survey until 2023.

DEFAULT HARVEST POLICY

The default $F_{\text{SPR}=40\%}$–40:10 harvest policy prescribes the maximum rate of fishing mortality to equal $F_{\text{SPR}=40\%}$. This rate gives a spawning potential ratio (SPR) of 40%, meaning that the female spawning biomass per recruit with $F_{\text{SPR}=40\%}$ is 40% of that without fishing. If female spawning biomass is below $B_{40\%}$ (40% of B_0), the policy reduces the TAC linearly until it equals zero at $B_{10\%}$ (10% of B_0). Relative fishing intensity for fishing rate F is $(1-\text{SPR}(F))/(1-\text{SPR}_{40\%})$, where $\text{SPR}_{40\%}$ is the target SPR of 40%; it is reported here interchangeably as a proportion or a percentage.

EXPLOITATION STATUS

The median estimated relative fishing intensity on the stock is below the target of 1.0 for all years (see Table d for recent years and Figure g). Median exploitation fraction (catch divided by biomass of fish of age-2 and above) peaked in 2006 and reached similar levels in 1999 and 2008 (Figure h). Over the last five years, the median estimated exploitation fraction was the highest in 2020 followed closely by 2021 before dropping by nearly half in 2022 (Table d). Median relative fishing intensity is estimated to have declined from 91.0% in 2010 to 43.8% in 2015. It then leveled off around 70% from 2016 to 2019 before declining to 50.7% in 2022. The median exploitation fraction has, on average, increased from a recent low of 0.05 in 2012 to 0.12 in 2020 before dropping back to 2012–2015 levels in 2022. There is a considerable amount of uncertainty around estimates of relative fishing intensity, with the 95% posterior credibility interval reaching above the SPR management target (of 1.0) in 2017 and 2018 over the past decade (Figure g). Exploitation and fishing intensity rates do not always tract well due to a combination of changing age distributions and changing selectivities over time.

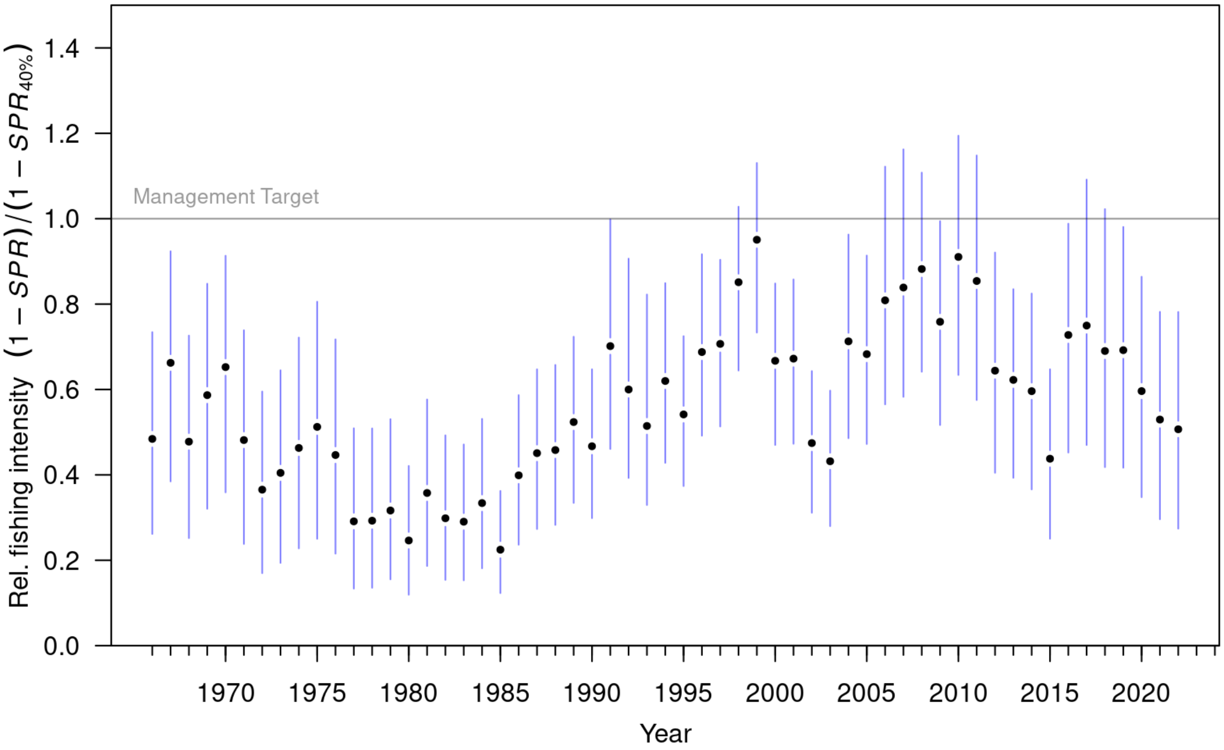

Figure g. Trend in median relative fishing intensity (relative to the SPR management target) through 2022 with 95% posterior credibility intervals. The management target defined in the Joint U.S.-Canada Agreement for Pacific Hake is shown as a horizontal line at 1.0.

MANAGEMENT PERFORMANCE

Over the last decade (2013–2022), the mean coast-wide utilization rate (proportion of catch target removed) has been 67.1% (Table e). Over the last five years (2018 to 2022), the mean utilization rates were 71.4% for the United States and 57.1% for Canada. While relatively stable during this time in the United States, the utilization rate in Canada has been declining since 2020 to a time-series low of 20.3% in 2022. Country-specific quotas (or catch targets) in 2020 and 2021 were specified unilaterally, due to the lack of an agreement on coast-wide 2020 and 2021 TACs. The usual 73.88% and 26.12% allocation of coast-wide TAC, as specified in the Joint U.S.-Canada Agreement for Pacific Hake, was once again implemented in 2022.

Total landings last exceeded the coast-wide quota in 2002 when utilization was 112%, though the fishing intensity was relatively low that year due to the appearance of the 1999 year class.

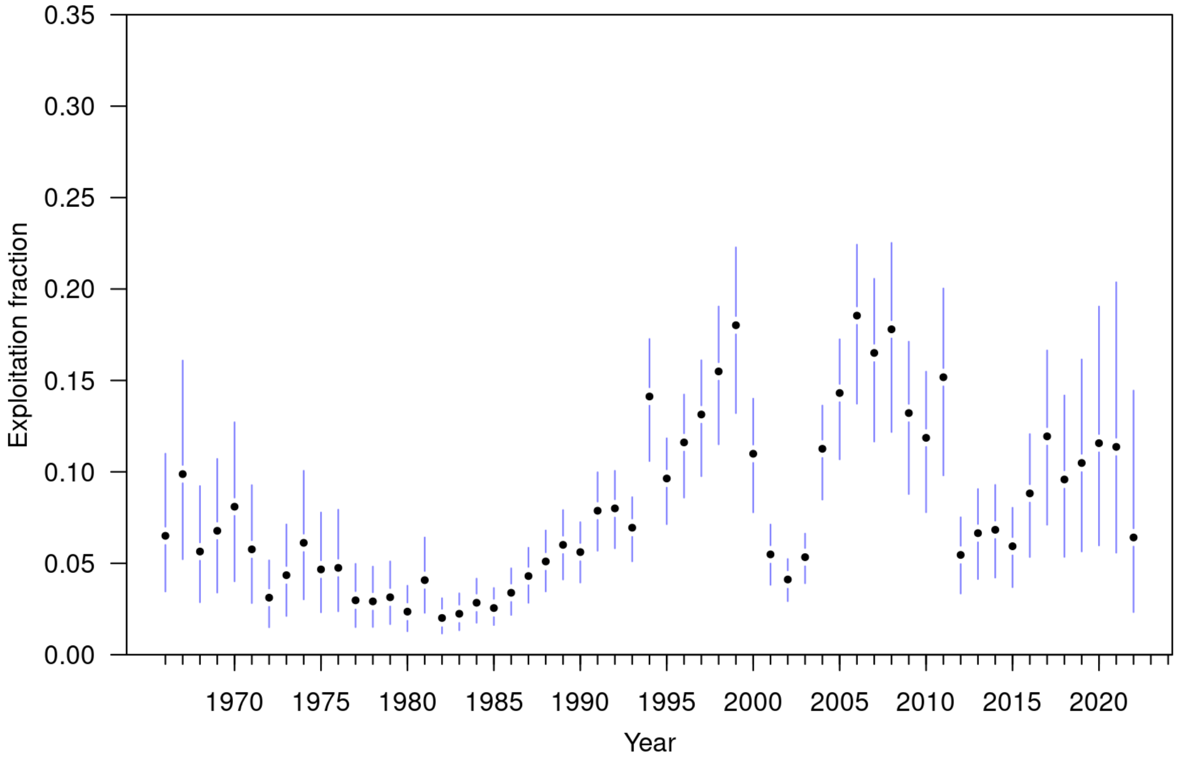

Figure h. Trend in median exploitation fraction (catch divided by age-2+ biomass) through 2022 with 95% posterior credibility intervals.

Table e. Recent trends in Pacific Hake landings and management decisions. Catch targets in 2020 and 2021 were specified unilaterally.

Year	U.S. landings (t)	Canada landings (t)	Total landings (t)	U.S. proportion of total catch	Canada proportion of total catch	U.S. catch target (t)	Canada catch target (t)	Coast-wide catch target (t)	U.S. proportion of catch target removed	Canada proportion of catch target removed	Total proportion of catch target removed
2013	233,578	52,249	285,828	81.7%	18.3%	269,745	95,367	365,112	86.6%	54.8%	78.3%
2014	264,141	35,118	299,259	88.3%	11.7%	316,206	111,794	428,000	83.5%	31.4%	69.9%
2015	154,160	39,662	193,822	79.5%	20.5%	325,072	114,928	440,000	47.4%	34.5%	44.1%
2016	262,327	69,733	332,060	79.0%	21.0%	367,553	129,947	497,500	71.4%	53.7%	66.7%
2017	354,229	86,721	440,950	80.3%	19.7%	441,433	156,067	597,500	80.2%	55.6%	73.8%
2018	318,306	95,413	413,719	76.9%	23.1%	441,433	156,067	597,500	72.1%	61.1%	69.2%
2019	317,002	95,013	412,015	76.9%	23.1%	441,433	156,067	597,500	71.8%	60.9%	69.0%
2020	287,908	92,489	380,397	75.7%	24.3%	424,810	104,480	529,290	67.8%	88.5%	71.9%
2021	269,473	57,076	326,549	82.5%	17.5%	369,400	104,480	473,880	72.9%	54.6%	68.9%
2022	291,337	28,887	320,224	91.0%	9.0%	402,646	142,354	545,000	72.4%	20.3%	58.8%

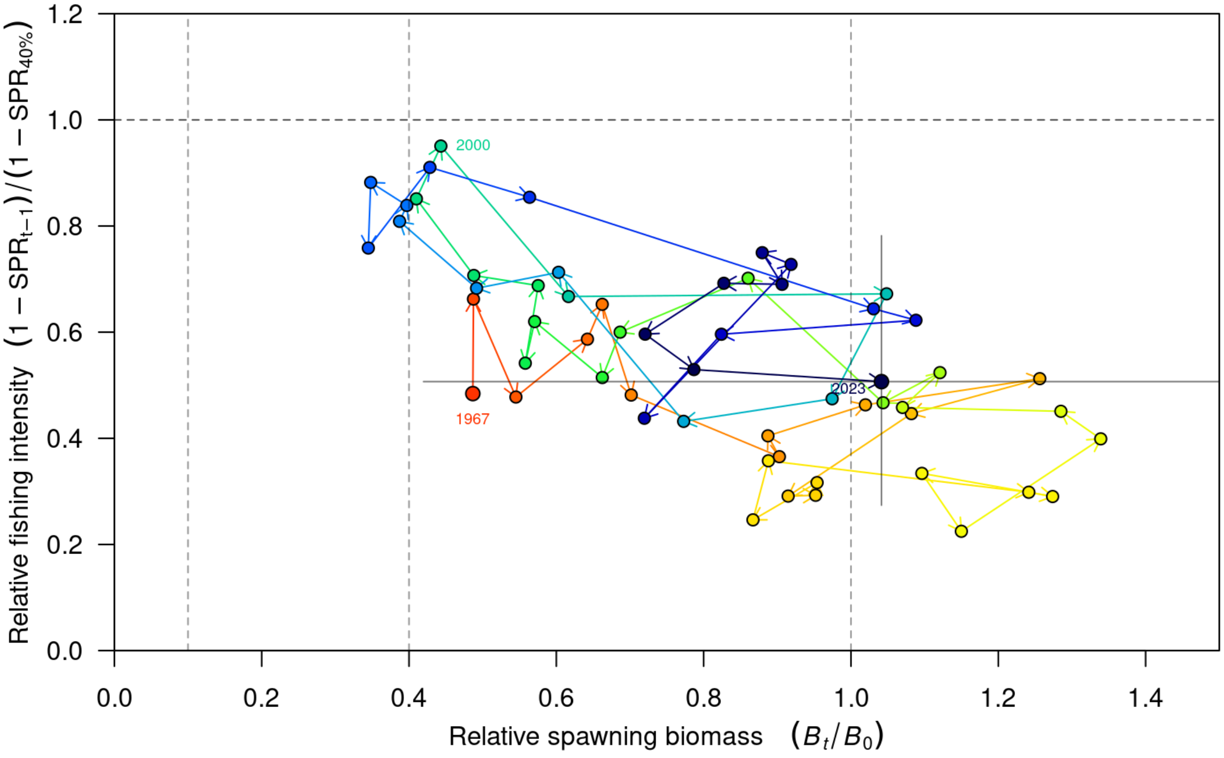

Figure i. Estimated historical path of median relative spawning biomass in year t and corresponding median relative fishing intensity in year $t-1$. Labels show the time series start and end years and the year after the highest relative fishing intensity; labels correspond to year t (i.e., year of the relative spawning biomass). Gray bars span the 95% credibility intervals for 2023 relative spawning biomass (horizontal) and 2022 relative fishing intensity (vertical).

The median relative fishing intensity was below the target in all years (Figures g and i). The median relative spawning biomass was above the $B_{40\%}$ reference point in all years except 2007–2010 (Figures e and i), yet the median relative fishing intensity still remained below the target (Figure i). The targets, $F_{\text{SPR}=40\%}$ and $B_{40\%}$, result in different median population sizes (see Table f), highlighting that there are subtle differences in these conceptual reference points. Between 2007 and 2010, median relative fishing intensity ranged from 76% to 91% and median relative spawning biomass between 0.34 and 0.40. Biomass has risen from the 2010 low with the 2008, 2010, 2014, 2016, and 2020 recruitments, and median relative spawning biomass has been above the reference point of 40% since 2011.

While there is large uncertainty in the estimates of relative fishing intensity and relative spawning biomass, the model estimates a 0.1% joint probability of being both above the target relative fishing intensity in 2022 and below the $B_{40\%}$ relative spawning biomass level at the start of 2023.

Table f. Summary of median and 95% credibility intervals of equilibrium conceptual reference points for the Pacific Hake base assessment model. Equilibrium reference points were computed using 1975–2022 averages for mean weight-at-age and baseline selectivity-at-age (1966–1990; prior to time-varying deviations).

Quantity	2.5^{th} percentile	Median	97.5^{th} percentile
Unfished female spawning biomass (B_0, thousand t)	1,149	1,815	2,975
Unfished recruitment (R_0, millions)	1,364	2,547	5,230
Reference points (equilibrium) based on $F_{\mathrm{SPR}=40\%}$			
Female spawning biomass at $F_{\mathrm{SPR}=40\%}$ ($B_{\mathrm{SPR}=40\%}$, thousand t)	372	642	1,064
SPR at $F_{\mathrm{SPR}=40\%}$	–	40%	–
Exploitation fraction corresponding to $F_{\mathrm{SPR}=40\%}$	16.1%	18.6%	21.2%
Yield associated with $F_{\mathrm{SPR}=40\%}$ (thousand t)	168	309	570
Reference points (equilibrium) based on $B_{40\%}$ (40% of B_0)			
Female spawning biomass ($B_{40\%}$, thousand t)	460	726	1,190
SPR at $B_{40\%}$	40.7%	43.6%	51.8%
Exploitation fraction resulting in $B_{40\%}$	12.3%	16.4%	19.5%
Yield at $B_{40\%}$ (thousand t)	169	302	555
Reference points (equilibrium) based on estimated MSY			
Female spawning biomass (B_{MSY}, thousand t)	283	467	821
SPR at MSY	22.5%	29.9%	47.3%
Exploitation fraction corresponding to SPR at MSY	14.4%	25.9%	35.2%
MSY (thousand t)	175	325	614

REFERENCE POINTS

The term ‘reference points’ is used throughout this document to describe common conceptual summary metrics (Table f). The Agreement specifically identifies $F_{\mathrm{SPR}=40\%}$ as the default harvest rate and $B_{40\%}$ as a point where the 40:10 TAC adjustment is triggered (see the Glossary in Appendix C). The medians of sustainable yields and biomass reference points are similar to what was reported in the 2022 assessment. The probability that female spawning biomass at the beginning of 2023 is below $B_{40\%}$ is $\mathrm{P}(B_{2023} < B_{40\%}) = 1.9\%$, and of being below $B_{25\%}$ is $\mathrm{P}(B_{2023} < B_{25\%}) = 0.1\%$. The probability that the relative fishing intensity was above its target of 1.0 at the end of 2022 is 0.1%.

UNRESOLVED PROBLEMS AND MAJOR UNCERTAINTIES

Measures of uncertainty in the base model underestimate the total uncertainty in the current stock status and projections because they do not account for possible alternative structural models for hake population dynamics and fishery processes (e.g., selectivity) and the scientific basis for prior probability distributions. To address such structural uncertainties, we performed sensitivity analyses to investigate a range of alternative assumptions and present the key ones in the main document.

The Pacific Hake stock displays high recruitment variability relative to other west coast groundfish stocks, resulting in large and rapid biomass changes. This leads to a dynamic fishery that potentially targets strong cohorts and results in time-varying fishery selectivity. This volatility results in a high level of uncertainty in estimates of current stock status and stock projections because, with limited data to estimate incoming recruitment, the cohorts are fished before the assessment can accurately determine how big they are (i.e., cohort strength is typically not well known until it is observed by the fishery and survey, typically at minimum age of three). While the addition of the age-1 index helps inform recent recruitment, the survey is conducted every other year and does not directly address current or future recruitment expectations. In particular, while the model estimates the 2020 cohort as above average in size, its absolute size remains highly uncertain. This uncertainty propagates directly into current and forecasted estimates of female spawning biomass. The upcoming 2023 acoustic survey will provide additional information on the size of the 2020 year-class (as well as inform the 2021 and 2022 year classes), which will lessen uncertainty of estimates of female spawning biomass. Further, the interactions among variance parameters that govern variability in fishery selectivity and recruitment parameters through time, as well as those used in relative data weighting, are not well understood and could propagate uncertainty beyond what is presented in this assessment.

FORECAST DECISION TABLES

The catch limit for 2023 based on the default $F_{\text{SPR}=40\%}$–40:10 harvest policy has a median of 778,008 t with a wide range of uncertainty, the 95% credibility interval being 301,205–2,136,434 t.

Decision tables give the projected population status (relative spawning biomass) and fishing intensity relative to the target under different catch alternatives for the base model (Tables g and h). The tables are organized to show the projected outcome for each potential catch level and year (row) across the quantiles (columns) of the posterior distribution. Tables show results for up to three years of future catch levels based on subsequent estimates of stock status and fishing intensity. Figure j shows the projected relative spawning biomass for several of the catch alternatives. Population dynamics and governing parameters assumed during the forecast period include random recruitment; selectivity, weight-at-age and fecundity averaged over the five most recent years (2018–2022); and all other parameters as constant.

A relative fishing intensity of 1 should indicate fishing at the $F_{\text{SPR}=40\%}$ default harvest rate catch target but the projected median relative fishing intensity can be slightly different than the target because the $F_{\text{SPR}=40\%}$ default harvest-rate catch limit is calculated using baseline selectivity-at-age (1966–1990; prior to time-varying deviations), whereas the forecasted catches are removed using selectivity averaged over the last five years. Recent changes in selectivity will thus be reflected in the determination of fishing relative to the default harvest policy. For example, fishing at the $F_{\text{SPR}=40\%}$ default harvest-rate catch limit (scenario n: default HR) in 2023 results in a median relative fishing intensity of 0.91 (Table h).

Management metrics that were identified as important to the Joint Management Committee and the Advisory Panel in 2012 are presented for 2024, 2025, and 2026 projections (Tables i, j, and k; Figures k, l, and m). These metrics summarize the probability of various outcomes from the base

Table g. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year. Catch alternatives are based on: constant catches (rows a, b, c, d, f, g, i, k, l), including catch similar to 2022 (row f) and to the TAC from 2022 (row l); and non-constant catches that result in annual 10% declines in catch (rows e, h, j), median relative fishing intensity of 100% (row m), median catch estimated via the default harvest policy ($F_{\text{SPR}=40\%}$–40:10, row n), and the fishing intensity that results in the median projected catch remaining the same in 2023 and 2024 (row o).

Catch Alternative			Biomass at start of year	Resulting relative spawning biomass		
				5%	**50%**	**95%**
	Catch year	**Catch (t)**	Start of 2023	0.49	1.04	2.50
a:	2023	0	Start of 2024	0.50	1.07	2.59
	2024	0	Start of 2025	0.48	1.03	2.52
	2025	0	Start of 2026	0.47	1.01	2.54
b:	2023	180,000	Start of 2024	0.46	1.02	2.54
	2024	180,000	Start of 2025	0.40	0.94	2.43
	2025	180,000	Start of 2026	0.36	0.90	2.41
c:	2023	225,000	Start of 2024	0.45	1.01	2.53
	2024	225,000	Start of 2025	0.38	0.92	2.41
	2025	225,000	Start of 2026	0.33	0.87	2.39
d:	2023	270,000	Start of 2024	0.44	1.00	2.52
	2024	270,000	Start of 2025	0.36	0.90	2.39
	2025	270,000	Start of 2026	0.31	0.84	2.36
e:	2023	320,000	Start of 2024	0.42	0.99	2.50
10%	2024	288,000	Start of 2025	0.35	0.89	2.37
reduction	2025	259,200	Start of 2026	0.30	0.83	2.35
f:	2023	325,000	Start of 2024	0.42	0.99	2.50
2022	2024	325,000	Start of 2025	0.34	0.88	2.36
catch	2025	325,000	Start of 2026	0.27	0.81	2.32
g:	2023	350,000	Start of 2024	0.42	0.98	2.49
	2024	350,000	Start of 2025	0.33	0.86	2.35
	2025	350,000	Start of 2026	0.26	0.79	2.30
h:	2023	350,000	Start of 2024	0.42	0.98	2.49
10%	2024	315,000	Start of 2025	0.33	0.87	2.36
reduction	2025	283,500	Start of 2026	0.28	0.81	2.33
i:	2023	380,000	Start of 2024	0.41	0.97	2.48
	2024	380,000	Start of 2025	0.31	0.85	2.33
	2025	380,000	Start of 2026	0.24	0.77	2.28
j:	2023	380,000	Start of 2024	0.41	0.97	2.48
10%	2024	342,000	Start of 2025	0.32	0.86	2.34
reduction	2025	307,800	Start of 2026	0.26	0.80	2.31
k:	2023	430,000	Start of 2024	0.40	0.96	2.46
	2024	430,000	Start of 2025	0.29	0.83	2.31
	2025	430,000	Start of 2026	0.21	0.74	2.24
l:	2023	545,000	Start of 2024	0.37	0.93	2.43
2022	2024	545,000	Start of 2025	0.24	0.77	2.25
TAC	2025	545,000	Start of 2026	0.14	0.67	2.17
m:	2023	778,008	Start of 2024	0.32	0.87	2.37
FI=	2024	733,102	Start of 2025	0.17	0.68	2.14
100%	2025	615,970	Start of 2026	0.11	0.57	2.05
n:	2023	778,008	Start of 2024	0.32	0.87	2.37
default	2024	740,322	Start of 2025	0.17	0.68	2.14
HR	2025	621,315	Start of 2026	0.10	0.57	2.05
o:	2023	748,093	Start of 2024	0.32	0.88	2.38
C2023=	2024	748,071	Start of 2025	0.17	0.68	2.15
C2024	2025	626,326	Start of 2026	0.11	0.57	2.05

Table h. Forecast quantiles of Pacific Hake relative fishing intensity (1-SPR)/(1-$\text{SPR}_{40\%}$), expressed as a proportion, for the 2023–2025 catch alternatives presented in Table g. Values greater than 1 indicate relative fishing intensities greater than the $F_{\text{SPR}=40\%}$ harvest policy calculated using baseline selectivity.

Catch Alternative			**Relative fishing intensity**		
	Catch year	**Catch (t)**	**5%**	**50%**	**95%**
a:	2023	0	0.00	0.00	0.00
	2024	0	0.00	0.00	0.00
	2025	0	0.00	0.00	0.00
b:	2023	180,000	0.20	0.39	0.66
	2024	180,000	0.17	0.36	0.64
	2025	180,000	0.16	0.35	0.66
c:	2023	225,000	0.25	0.46	0.74
	2024	225,000	0.20	0.42	0.73
	2025	225,000	0.19	0.42	0.77
d:	2023	270,000	0.29	0.52	0.81
	2024	270,000	0.24	0.48	0.81
	2025	270,000	0.23	0.49	0.87
e:	2023	320,000	0.33	0.58	0.88
10%	2024	288,000	0.25	0.51	0.85
reduction	2025	259,200	0.22	0.48	0.87
f:	2023	325,000	0.33	0.58	0.88
2022	2024	325,000	0.28	0.55	0.90
catch	2025	325,000	0.27	0.56	0.97
g:	2023	350,000	0.35	0.61	0.91
	2024	350,000	0.30	0.58	0.94
	2025	350,000	0.29	0.59	1.01
h:	2023	350,000	0.35	0.61	0.91
10%	2024	315,000	0.27	0.54	0.90
reduction	2025	283,500	0.24	0.52	0.92
i:	2023	380,000	0.37	0.64	0.94
	2024	380,000	0.32	0.61	0.98
	2025	380,000	0.31	0.63	1.07
j:	2023	380,000	0.37	0.64	0.94
10%	2024	342,000	0.29	0.57	0.94
reduction	2025	307,800	0.26	0.55	0.97
k:	2023	430,000	0.41	0.69	0.99
	2024	430,000	0.35	0.66	1.04
	2025	430,000	0.34	0.69	1.15
l:	2023	545,000	0.48	0.78	1.09
2022	2024	545,000	0.42	0.76	1.17
TAC	2025	545,000	0.41	0.80	1.26
m:	2023	778,008	0.60	0.91	1.22
FI=	2024	733,102	0.52	0.91	1.29
100%	2025	615,970	0.46	0.90	1.31
n:	2023	778,008	0.60	0.91	1.22
default	2024	740,322	0.52	0.91	1.29
HR	2025	621,315	0.47	0.91	1.31
o:	2023	748,093	0.59	0.90	1.21
C2023=	2024	748,071	0.53	0.91	1.29
C2024	2025	626,326	0.47	0.91	1.31

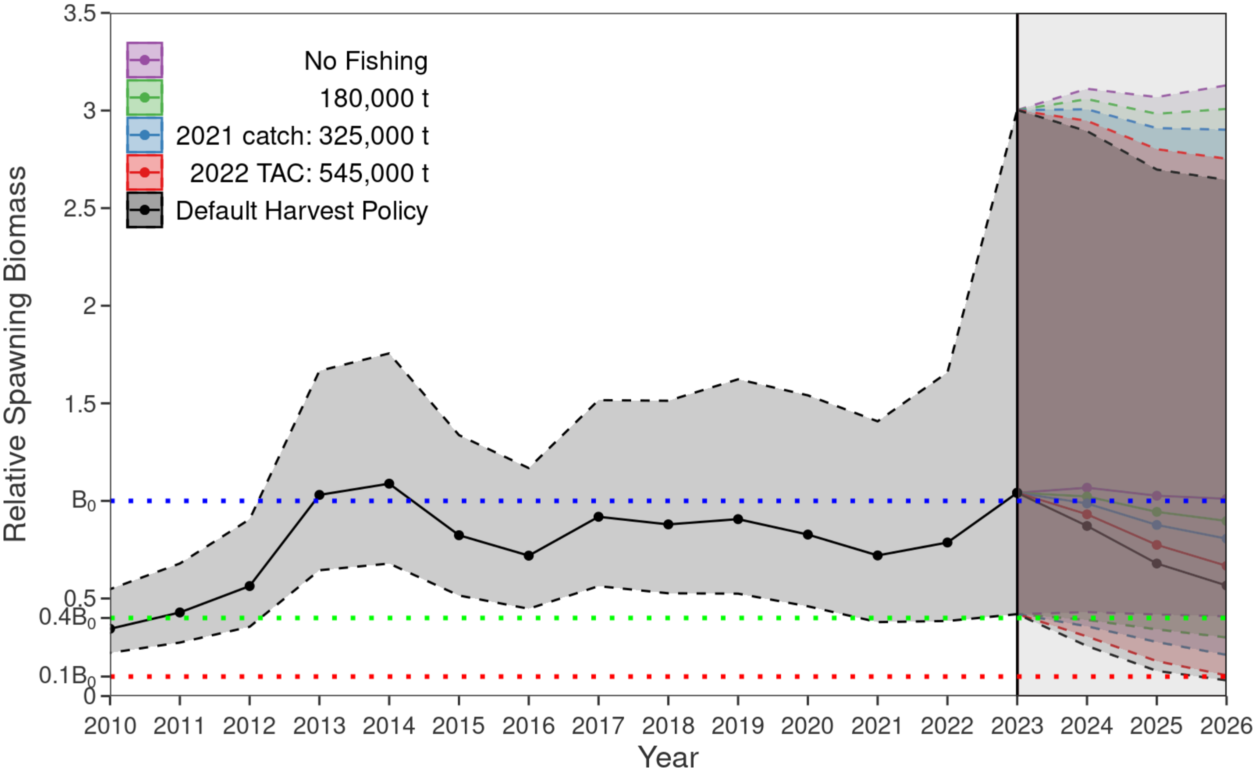

Figure j. Time series of estimated relative spawning biomass to 2023 from the base model, and forecast trajectories to 2026 for several management actions defined in Table g, with 95% posterior credibility intervals.

model given each potential management action. Although not linear, probabilities can be interpolated from these results for intermediate catch values in 2023 (Table i and Figure k). However, interpolation is not appropriate for all catches in 2024 or 2025 because they are conditional on previous year(s) catch levels. This explains why a few probabilities decline (rather than rise) with increased 2024 and 2025 catch levels (Tables j and k and Figures l and m). The predicted relative spawning biomass trajectory through 2026 is shown in Figure j for several of the management actions. With zero catch for the next three years, the biomass has a 50% probability of decreasing from 2023 to 2024 (Table i), a 73% probability of decreasing from 2024 to 2025 (Table j), and a 68% probability of decreasing from 2025 to 2026 (Table k).

The probability of the female spawning biomass decreasing from 2023 to 2024 is above 72% for all non-zero catch levels examined (Table i and Figure k). This probability is 81% for a 2023 catch level similar to that for 2022 (scenario f: 2023 catch). For all explored catches, the maximum probability of female spawning biomass at the start of 2024 dropping below $B_{10\%}$ is 0%, and of dropping below $B_{40\%}$ is 10% (Table i and Figure k). As the large 2010, 2014, and 2016 cohorts continue to age, their biomass is expected to decrease as losses from mortality outweigh increases from growth. The estimated above-average (yet still highly uncertain) 2020 cohort will continue to play a large role in determining female spawning biomass during the forecast years presented here.

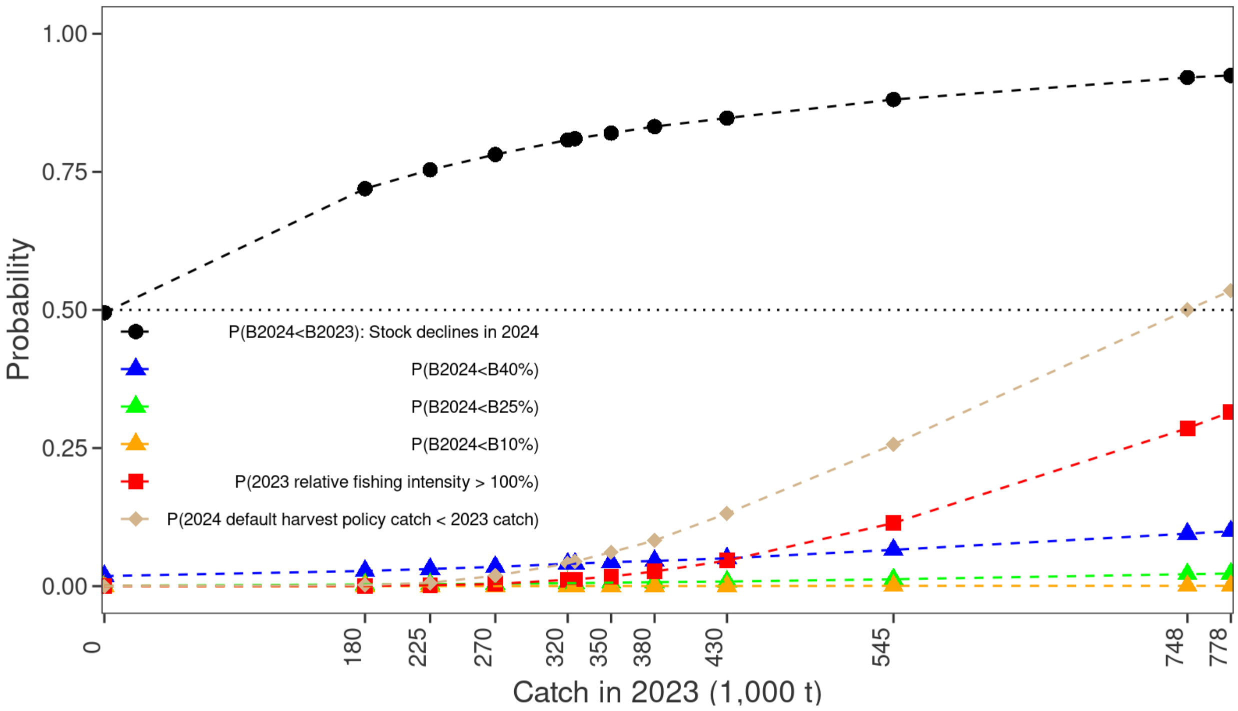

Figure k. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2024 default harvest policy catch for alternative 2023 catch options (explained in Table g) as listed in Table i. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table i. Probabilities related to female spawning biomass, relative fishing intensity, and the 2024 default harvest policy catch for alternative 2023 catch options (explained in Table g).

Catch in 2023	Probability $B_{2024} < B_{2023}$	Probability $B_{2024} < B_{40\%}$	Probability $B_{2024} < B_{25\%}$	Probability $B_{2024} < B_{10\%}$	Probability 2023 relative fishing intensity > 100%	Probability 2024 default harvest policy catch < 2023 catch
a: 0	50%	2%	0%	0%	0%	0%
b: 180,000	72%	3%	0%	0%	0%	0%
c: 225,000	75%	3%	0%	0%	0%	1%
d: 270,000	78%	3%	0%	0%	0%	2%
e: 320,000	81%	4%	1%	0%	1%	4%
f: 325,000	81%	4%	1%	0%	1%	4%
g: 350,000	82%	4%	1%	0%	2%	6%
h: 350,000	82%	4%	1%	0%	2%	6%
i: 380,000	83%	5%	1%	0%	3%	8%
j: 380,000	83%	5%	1%	0%	3%	8%
k: 430,000	85%	5%	1%	0%	5%	13%
l: 545,000	88%	7%	1%	0%	11%	26%
m: 778,008	92%	10%	2%	0%	32%	53%
n: 778,008	92%	10%	2%	0%	32%	53%
o: 748,093	92%	10%	2%	0%	29%	50%

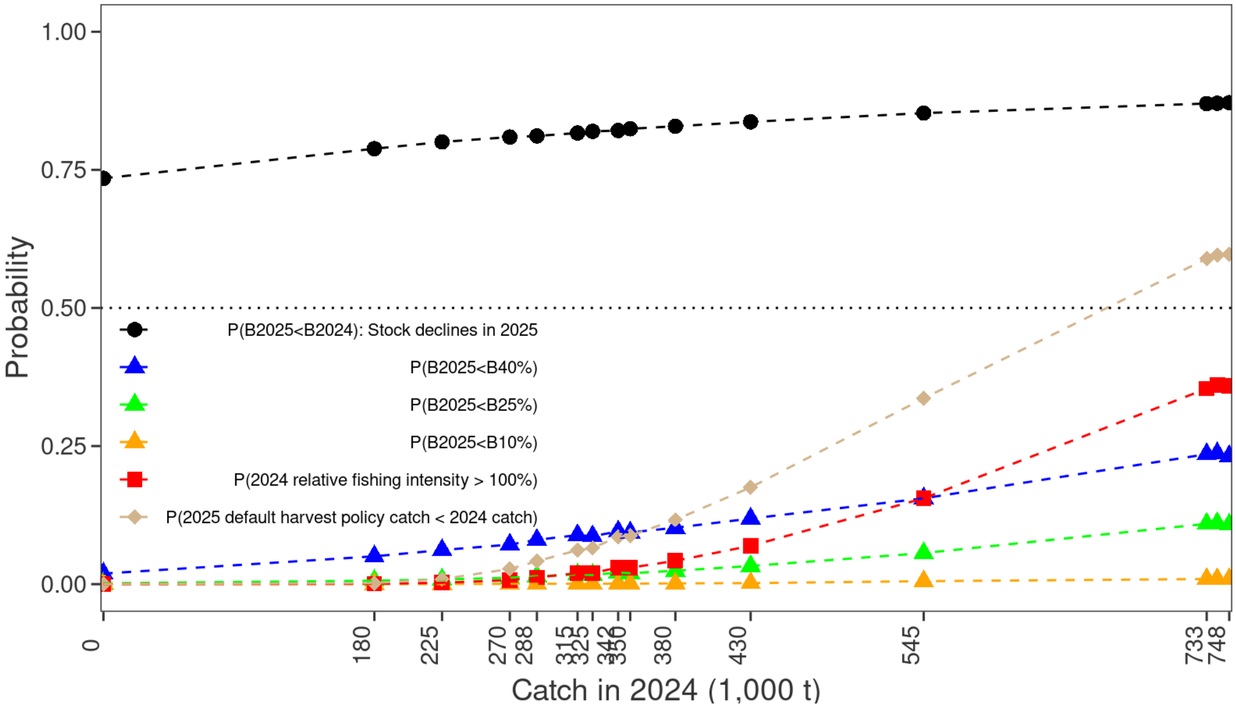

Figure l. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options (including associated 2023 catch; catch options explained in Table g) as listed in Table j. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table j. Probabilities related to female spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options, given the 2023 catch shown in Table i (catch options explained in Table g).

Catch in 2024	**Probability $B_{2025} < B_{2024}$**	**Probability $B_{2025} < B_{40\%}$**	**Probability $B_{2025} < B_{25\%}$**	**Probability $B_{2025} < B_{10\%}$**	**Probability 2024 relative fishing intensity > 100%**	**Probability 2025 default harvest policy catch < 2024 catch**
a: 0	73%	2%	0%	0%	0%	0%
b: 180,000	79%	5%	1%	0%	0%	0%
c: 225,000	80%	6%	1%	0%	0%	1%
d: 270,000	81%	7%	1%	0%	1%	3%
e: 288,000	81%	8%	1%	0%	1%	4%
f: 325,000	82%	9%	2%	0%	2%	7%
g: 350,000	82%	9%	2%	0%	3%	9%
h: 315,000	82%	9%	2%	0%	2%	6%
i: 380,000	83%	10%	2%	0%	4%	12%
j: 342,000	82%	10%	2%	0%	3%	9%
k: 430,000	84%	12%	3%	0%	7%	18%
l: 545,000	85%	16%	6%	1%	16%	34%
m: 733,102	87%	24%	11%	1%	35%	59%
n: 740,322	87%	24%	11%	1%	36%	60%
o: 748,071	87%	23%	11%	1%	36%	60%

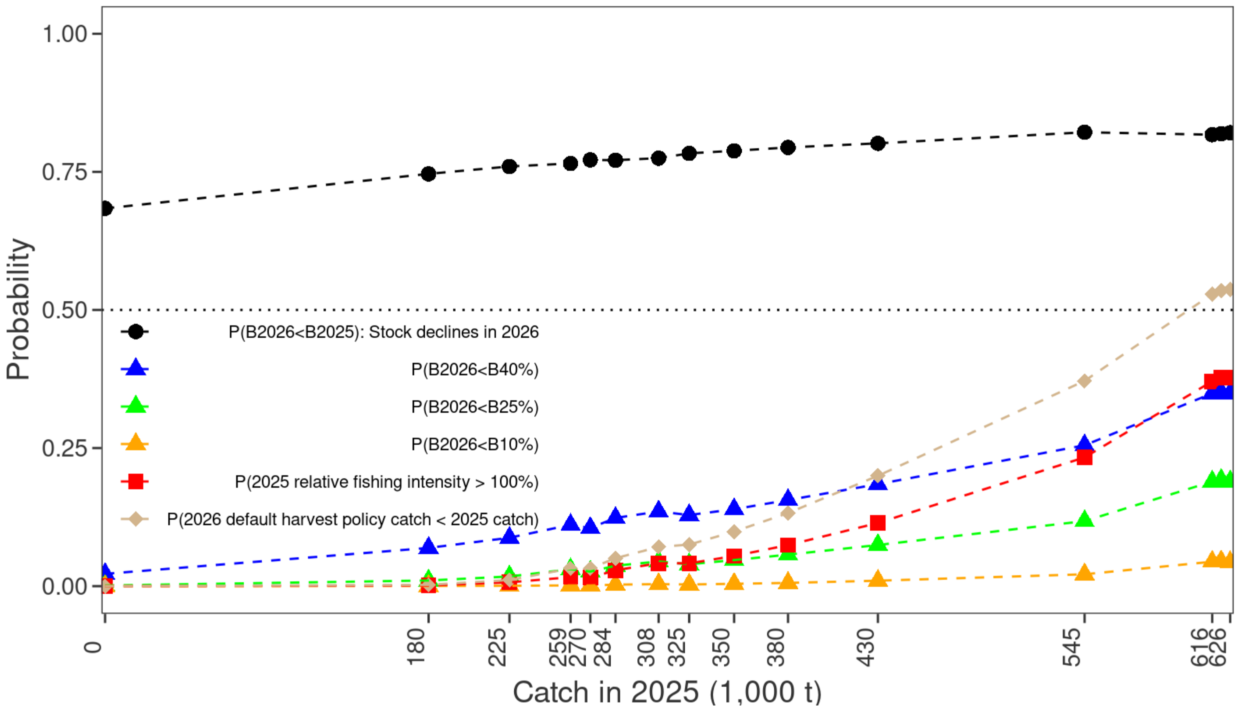

Figure m. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2026 default harvest policy catch for alternative 2025 catch options (including associated 2023 and 2024 catches; catch options explained in Table g) as listed in Table k. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table k. Probabilities related to female spawning biomass, relative fishing intensity, and the 2026 default harvest policy catch for alternative 2025 catch options, given the 2023 and 2024 catches shown in Tables i and j (catch options explained in Table g).

Catch in 2025	**Probability $B_{2026} < B_{2025}$**	**Probability $B_{2026} < B_{40\%}$**	**Probability $B_{2026} < B_{25\%}$**	**Probability $B_{2026} < B_{10\%}$**	**Probability 2025 relative fishing intensity > 100%**	**Probability 2026 default harvest policy catch < 2025 catch**
a: 0	68%	2%	0%	0%	0%	0%
b: 180,000	75%	7%	1%	0%	0%	0%
c: 225,000	76%	9%	2%	0%	1%	1%
d: 270,000	77%	11%	3%	0%	2%	3%
e: 259,200	77%	11%	3%	0%	2%	3%
f: 325,000	78%	13%	4%	0%	4%	8%
g: 350,000	79%	14%	5%	0%	5%	10%
h: 283,500	77%	12%	4%	0%	3%	5%
i: 380,000	79%	16%	6%	1%	7%	13%
j: 307,800	77%	14%	4%	0%	4%	7%
k: 430,000	80%	18%	7%	1%	11%	20%
l: 545,000	82%	26%	12%	2%	23%	37%
m: 615,970	82%	35%	19%	4%	37%	53%
n: 621,315	82%	35%	19%	4%	38%	54%
o: 626,326	82%	35%	19%	4%	38%	54%

RESEARCH AND DATA NEEDS

There are many research projects that could improve the stock assessment for Pacific Hake and lead to improved biological understanding and decision-making. The top three are:

1. Continue to conduct research to evaluate ways to improve recent, current, and future recruitment estimates for use in stock assessment. This could include the development of time series of recruitment indices, time series of informative environmental or ecosystem variables, and models that have predictive skill (e.g., Vestfals et al, under review). Explorations should also consider options for incorporating information on recruitment into the stock assessment model and the Pacific Hake management framework. For example, time series could be included in the stock assessment as a standalone data source (similar to acoustic survey biomass estimates) or the estimation procedure that was used to generate the time series itself could be integrated directly into the stock assessment model. Results from such work should be connected to or in cooperation with ongoing research related to recruitment variability as discussed in Section 3.3. Related, there is a need to streamline and broaden the availability of products from oceanographic models (e.g., Regional Ocean Modeling System) so that they are available stock-wide (spanning the international boundary) and updated on a recurring basis so they can be used as informative links in operational stock assessments. A successful example of this has been the annual production of Pacific Hake distribution forecasts that depend on short-term (i.e., 6–9 month) forecasts of subsurface (i.e., 100 m depth) temperature from J-SCOPE (http://www.nanoos.org/products/j-scope/home.php). The existing management strategy evaluation framework should be used, or further developed, to examine how information on recruitment can inform robust management decisions.

2. Document the existing survey methodologies, protocols, and adaptive survey-design decisions that lead to the development of Pacific Hake biomass and age-composition estimates and the relative age-1 index used in the stock assessment. Such documentation will ensure transparency, enable repeatability, and provide a record of changes in procedures over time. Also, continue to conduct research to improve the estimation of age composition and abundance from data collected during the acoustic survey. This includes, but is not limited to, research on species identification, target verification, target strength, implications of the south-to-north directionality of the survey, alternative technologies to assist in the survey (e.g., artificial intelligence and machine learning), and efficient analysis methods. The latter should include bootstrapping of the acoustic survey time series or related methods that can incorporate relevant uncertainties into the calculations of survey variance. Relevant uncertainties include topics such as the target-strength relationship, subjective scoring of echograms, thresholding methods, and methods to estimate the species-mix that are used to interpret the acoustic backscatter. Continue to work with acousticians and survey personnel from the Northwest Fisheries Science Center (and, more broadly, those involved with the U.S. Re-Envisioning West Coast Surveys Initiative) and Fisheries and Oceans Canada to determine optimal survey designs given constraints, including designs that incorporate ecosystem-based factors and other potential target species (e.g., rockfish, euphausiids, and mesopelagics) for the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey. The existing management strategy evaluation framework should be used, or further developed,

to examine how changes in survey methods can be used to inform robust management decisions.

3. Work with regional partners to develop an annual workflow that provides key metrics, indicators, or other summaries of general ecosystem conditions relevant to the Pacific Hake coast-wide stock. In particular, include those that are potentially associated with Pacific Hake biology and ecology (e.g., recruitment, distribution, predation, prey, and communities). Such information can broaden the context within which a single species stock assessment is interpreted, be used to support model development, refine uncertain assessment conclusions (e.g., productivity), and provide other non-assessment indicators of the system's state to management.

1 INTRODUCTION

The Joint U.S.-Canada Agreement for Pacific Hake (called the Agreement) was signed in 2003, went into force in 2008, and was implemented in 2010. The committees defined by the Agreement were first formed in 2011, and 2012 was the first year for which the process defined by the Agreement was followed, including stock assessment. This is the twelfth annual stock assessment conducted under the Agreement process.

Under the Agreement, Pacific Hake (*Merluccius productus*, also referred to as Pacific whiting) stock assessments are to be prepared by the Joint Technical Committee (JTC) comprised of both U.S. and Canadian scientists and reviewed by the Scientific Review Group (SRG) that consists of representatives from both nations. Additionally, the Agreement calls for both of these bodies to include scientists nominated by an Advisory Panel (AP) of fishery stakeholders.

The primary data sources for this assessment include an acoustic survey, annual fishery catch, mean weight-at-age data, as well as survey and fishery age-composition data. The assessment depends primarily upon an acoustic survey index of biomass time series for information on the scale of the current population. Age-composition data from the aggregated fishery and the acoustic survey provide additional information allowing the model to resolve strong and weak cohorts. The catch is an important source of information regarding changes in abundance and places a lower bound on the available population biomass in each year.

This assessment is fully Bayesian, with the base model incorporating prior information on several key parameters (including informative priors on natural mortality, M, and steepness of the stock-recruit relationship, h) and integrating over parameter uncertainty to provide results that can be probabilistically interpreted. From a range of alternate models investigated by the JTC, a subset of sensitivity analyses are also reported to provide a broad qualitative comparison of structural uncertainty with respect to the base model (Section 3.8). The structural assumptions of this 2023 base model, implemented using version 3.30.20 of the Stock Synthesis software (Methot and Wetzel, 2013), are the same as the 2022 base model (Edwards et al., 2022). All model runs reported in this document are performed in a Bayesian context. Responses to 2022 SRG requests are in Section 3.3 and a Glossary of terms appears in Appendix C.

1.1 STOCK STRUCTURE AND LIFE HISTORY

Pacific Hake is a semi-pelagic schooling species distributed along the west coast of North America, generally ranging in latitude from 25°N to 55°N (see Figure 1 for an overview map). It is among 18 species of hake from four genera (being the majority of the family Merlucciidae), which are found in both hemispheres of the Atlantic and Pacific Oceans (Alheit and Pitcher, 1995; Lloris et al., 2005). The coastal population of Pacific Hake is currently the most abundant groundfish population in the California Current system. Smaller populations of this species occur in the major inlets of the Northeast Pacific Ocean, including the Strait of Georgia, the Puget Sound, and the Gulf of California. Each of these smaller populations are genetically distinct from the coastal population (Vrooman and Paloma, 1977; Iwamoto et al., 2004; King et al., 2012; García-De León et al., 2018). The coastal population is also distinguished from the inshore populations by larger size-at-age and seasonal migratory behavior and from fish off the west coast of Baja California by smaller size-at-age and later spawning (Zamora-García et al., 2020).

The coastal population of Pacific Hake typically ranges from the waters off southern California to northern British Columbia and rarely into southern Alaska, with the northern boundary related to fluctuations in annual migration (Hamel et al., 2015) depending, in part, on water temperature (Malick et al., 2020*a*,*b*). In spring, adult Pacific Hake migrate onshore and northward to feed along the continental shelf and slope from northern California to Vancouver Island. In summer, Pacific Hake often form extensive mid-water aggregations in association with the continental shelf break, with the highest densities located over bottom depths of 200–300 m (Dorn and Methot, 1991, 1992).

Older Pacific Hake exhibit the greatest northern migration each season, with two- and three-year old fish rarely observed in Canadian waters north of southern Vancouver Island. During El Niño events (warm ocean conditions such as in 1998 and 2016), a larger proportion of the population migrates into Canadian waters (Figure 2), due to temperature effects (Malick et al., 2020*a*) and possibly intensified northward transport during the period of active migration (Dorn, 1995; Agostini et al., 2006). In contrast, La Niña conditions (colder water, such as in 2001, 2011, and 2021) result in a southward shift in their distribution, with a much smaller proportion of the population found in Canadian waters, as seen in those surveys (Figure 2). In general, warmer than average thermal habitat conditions for mature Pacific Hake leads to relatively higher biomass further north and relatively lower biomass around the U.S.-Canadian border, while cooler than average conditions leads to relatively higher biomass of immature Pacific Hake generally spread evenly across their distribution (Malick et al., 2020*a*). The distribution of age-1 fish also changes between years (Figure 3).

1.2 ECOSYSTEM CONSIDERATIONS

Pacific Hake are important to ecosystem dynamics in the Eastern Pacific Ocean due to their relatively large total biomass and potentially large role as both prey and predator (Hicks et al., 2013). Ongoing research investigating abiotic (environmental conditions) and biotic (e.g., maturity and diet) drivers of the distribution, recruitment, growth, and survival of Pacific Hake could provide insight into how the population is linked with broader ecosystem considerations. For example, Turley and Rykaczewski (2019) found decreased survival of larval Pacific Hake as storm events increased, contrary to many other species in the southern California Current Ecosystem. An analysis of drivers of recruitment across the maternal preconditioning, egg, and larval phases of Pacific Hake indicated recruitment is associated with eddy kinetic energy, the location of the North Pacific Current bifurcation, and upwelling during maternal preconditioning, as well as associated with northward long-shore transport and the number of days between storm events during larval stages (Vestfals et al., under review). Phillips et al. (2022) suggests temperature dynamically influences the co-occurrence of Pacific Hake and krill (i.e., euphausiids; *Euphausiacea*), which can influence annual Pacific Hake growth and recruitment as the availability of key prey species shifts. Previous research developed an index of abundance for Humboldt Squid (*Dosidicus gigas*) and suggested that the abundance of Pacific Hake decreased with increasing squid abundance (Stewart et al., 2014; Taylor et al., 2015). Many additional research topics relevant to Pacific Hake distribution, recruitment, and growth patterns in relation to oceanographic conditions have been investigated

(Ressler et al., 2007; Hamel et al., 2015; Malick et al., 2020*a*,*b*) but further research on this topic is still needed.

Fitting the assessment model to empirical weight-at-age data allows for time-varying growth without needing a mechanistic relationship or environmental data, which facilitates an ‘Ecosystem Approach to Fisheries Management’ (a priority for DFO and NOAA); see Section 2.4.3. Nonetheless, ongoing research investigating spatiotemporal drivers of weight-at-age will provide more insights into the specific mechanisms affecting changes in growth, which will enable condition-specific prediction capabilities (e.g., assumptions of growth, or weight-at-age, during forecast years).

1.3 MANAGEMENT OF PACIFIC HAKE

Since the implementation of the Magnuson-Stevens Fishery Conservation and Management Act in the U.S. and the declaration of a 200-mile fishery-conservation zone in the U.S. and Canada in the late 1970s, annual quotas (or catch targets) have been used to limit the catch of Pacific Hake in both countries’ zones. Scientists from both countries historically collaborated through the Technical Subcommittee of the Canada-U.S. Groundfish Committee (TSC), and there were informal agreements on the adoption of annual fishing policies. During the 1990s, however, disagreements between the U.S. and Canada on the allotment of the catch limits between U.S. and Canadian fisheries led to quota overruns; the 1991–1992 national quotas summed to 128% of the coast-wide limit, while the 1993–1999 combined quotas were an average of 112% of the limit. The Agreement establishes U.S. and Canadian shares of the coast-wide total allowable catch (TAC) at 73.88% and 26.12%, respectively, and this distribution has largely been adhered to since 2005. However, a bilateral agreement on the coast-wide TAC could not be reached in 2020 or 2021; so, catch targets were set unilaterally during these years for the first time since the inception of the Agreement. Catch shares distributions as specified in the Agreement were once again applied in 2022.

Since 1999, an upper limit on catch has been calculated using an $F_{\text{SPR}=40\%}$ default harvest rate with a 40:10 adjustment. This decreases the catch linearly from the catch at a relative spawning biomass of 40% to zero catch at a relative spawning biomass values of 10% or less (called the default harvest policy in the Agreement); relative spawning biomass is the female spawning biomass divided by that at unfished equilibrium. Further considerations have almost always resulted in catch targets being set lower than the recommended catch limit. Total catch has not exceeded the coast-wide quota since 2002, and harvest rates are likely to have never exceeded the $F_{\text{SPR}=40\%}$ target.

1.3.1 Management of Pacific Hake in the United States

In the U.S. zone, participants in the directed fishery are required to use pelagic trawls with a codend mesh of at least 7.5 cm. Regulations also restrict the area and season of fishing to reduce the bycatch of Chinook Salmon (*Oncorhynchus tshawytscha*), depleted rockfish populations (though all but Yelloweye Rockfish, *Sebastes ruberrimus*, have rebuilt in recent years), and other species as related to their specific harvest specifications. The current allocation agreement, effective since 1997, divides the U.S. harvest into tribal (17.5%) and non-tribal (82.5%, including a small amount set aside for research) components. Starting in 1996, the Makah Tribe has conducted a fishery with the tribal allocation in its “usual and accustomed fishing area”. The non-tribal harvest allocation is divided among catcher-processors (34%), motherships (24%), and the shore-based fleet (42%).

Since 2011, the non-tribal U.S. fishery has been fully rationalized with allocations in the form of Individual Fishing Quotas (IFQs) to the shore-based sector and group shares to cooperatives in the at-sea mothership (MS) and catcher-processor (CP) sectors. The At-Sea Hake Observer Program has been monitoring fishing vessel activity since 1975, originally monitoring foreign and joint-venture vessels. Observer coverage has been 100% on all domestic vessels since 1991 (including the 2020 and 2021 fishing seasons, despite the COVID-19 pandemic).

Shortly after the 1997 allocation agreement was approved by the Pacific Marine Fisheries Commission, fishing companies owning catcher-processor vessels with U.S. west coast groundfish permits established the Pacific Whiting Conservation Cooperative (PWCC). The primary role of the PWCC is to distribute the catcher-processor allocation among its members to achieve greater efficiency and product quality, as well as promoting reductions in waste and bycatch rates relative to the former "derby" fishery in which all vessels competed for a fleet-wide quota. The mothership fleet has also formed a cooperative where bycatch allocations are pooled and shared among the vessels. The individual cooperatives have internal systems of in-season monitoring and spatial closures to avoid and reduce bycatch of salmon and rockfish.

1.3.2 Management of Pacific Hake in Canada

Canadian groundfish managers distribute their portion of the coast-wide TAC as quota to individual license holders. In 2022, Canadian hake fishermen were allocated a TAC of 142,354 t, which did not include any carryover quota. Canadian priority lies with the domestic fishery, but when there is determined to be an excess of fish for which there is not enough domestic processing capacity, fisheries managers give consideration to a Joint-Venture fishery in which foreign processor vessels are allowed to accept codends from Canadian catcher vessels while at sea. The last year a Joint-Venture fishery was conducted was in 2018.

In 2022, all Canadian Pacific Hake trips were subject to 100% observer coverage, by electronic monitoring for both the shoreside component of the domestic fishery and the freezer-trawler component. There were once again no on-board observers available for the entirety of the fishing season. This is expected to be the situation moving forward, with no plans for observers to board any of the Canadian groundfish vessels.

Retention of all catch, with the exception of prohibited species, was mandatory. The retention of groundfish other than Sablefish, Mackerel, Walleye Pollock, and Pacific Halibut on dedicated Pacific Hake trips using electronic monitoring was not allowed to exceed 10% of the landed catch weight. The bycatch allowance for Walleye Pollock was 30% of the total landed weight.

1.4 FISHERIES

The fishery for the coastal population of Pacific Hake occurs along the coasts of northern California, Oregon, Washington, and British Columbia primarily during May-November (Hicks et al., 2013). The fishery is conducted with mid-water trawls and has met the Marine Stewardship Council (MSC) Fisheries Standard to be certified as meeting sustainable fishing benchmarks since 2009. Foreign fleets dominated the fishery until 1991, when domestic fleets began taking the majority of the catch. Catches were occasionally greater than 200,000 t prior to 1986, and since then they have been greater than 200,000 t for all except four years.

According to 2020 statistics, the Pacific Hake fishery was Canada's largest commercial wild fishery (species with the largest catch), representing 14% of Canada's total landings of all species (www.dfo-mpo.gc.ca). Over CA$26 million in wages was estimated to have been paid to employees of the processing industry in British Columbia in 2019, with an exported value of CA$100 million in product mainly to Ukraine, China, Lithuania, and South Africa (DFO, 2021).

In the US, over $75.2 million in wages was estimated to have been paid to employees in 2020 (www.noaa.gov). This includes wages paid to crew and captains fishing on catcher vessels that deliver shoreside and at-sea to motherships, workers in shore-based processing facilities, crew, captains, and workers on catcher-processor vessels, and workers on mothership vessels. The exported value of Pacific Hake was US$127 million in 2020, including to Ukraine, Nigeria, and Italy, which make up about 57% of the total exports (www.noaa.gov). The total economic impacts of the Pacific Hake fishery on the U.S. West Coast in 2020 was US$289 million in income and 3,950 U.S. jobs.

The Joint Management Committee (JMC) determined an adjusted (for carryovers) coast-wide TAC of 545,000 t for 2022. The U.S. catch target was set at 402,646 t and the Canadian catch target at 142,354 t. The historical catch of Pacific Hake for 1966–2022 by nation and fishery sector is shown in Tables 1–3 and Figure 4. Table 3 also shows recent catches in relation to targets (see Section 3.4.2). A brief review of the 2022 fishery is presented here by country. Additional information is available in annual United States and Canada Advisory Panel reports (Appendices E–D).

1.4.1 Fisheries for Pacific Hake in the United States

The U.S. specified catch target (i.e., adjusted for carryovers) of 402,646 t was further divided among the research, tribal, catcher-processor, mothership, and shore-based sectors. After the tribal allocation of 17.5% (70,463 t), and a 750 t allocation for research catch and bycatch in non-groundfish fisheries, the 2022 non-tribal U.S. catch limit of 331,433 t was allocated to the catcher-processor (34%), mothership (24%), and shore-based (42%) commercial sectors. Reallocation of 40,000 t of tribal quota to non-tribal sectors on September 15 resulted in final quotas for the catcher-processor, mothership, and shore-based sectors of 126,287 t, 89,144 t, and 156,002 t, respectively.

The midwater fishery for Pacific Hake began on May 15 for the shore-based and at-sea fisheries. In earlier years, the shore-based midwater fishery began on June 15 north of 42°N latitude, but could fish for Pacific Hake between 40°30'N and 42°N latitudes starting on April 1. Since 2015, the shore-based fishery has been allowed to fish north of 40°30'N latitude starting May 15 and fish south of 40°30'N latitude starting on April 15. Although, only a small amount of the shore-based allocation is released for this early period prior to the main opening. Regulations do not allow at-sea processing or night fishing (midnight to one hour after official sunrise) south of 42°N latitude (the Oregon-California border) at any time during the year.

The total catch of Pacific Hake in U.S. waters was the fourth highest value ever recorded (Table 1) and the U.S. utilization rate (72.4%) continued to be maintained close to what it has been in recent years (see Appendix E for more details). There was 27.6% of the total U.S. adjusted TAC that was not caught. The catcher-processor, mothership, and shore-based fleets caught 100.0%, 66.4%, and

67.2% of their final reallocated quotas, respectively. Tribal landings, which are included in the shoreside sector totals were 1,173 t. Monthly catch rates in the at-sea sector were on average lower than last year except for May, which was slightly higher, and August, which in most years has no catch due to vessels fishing Alaskan pollock at that time (Figure 5). The median fishing depth for the at-sea fleets was deeper than last year but near the average over the last five years (Figure 6). The shore-based fishery had the largest monthly catches during July, August, and September.

In both U.S. at-sea sectors, age-2, age-6, and age-8 fish, associated with the 2020, 2016, and 2014 year classes, were the most common ages. Unlike last year, age-2 fish were seen in appreciable numbers in the catch this year. The reported proportions at age summarize sampling efforts on 455 catcher-processor hauls and 289 mothership hauls (Table 4). For the catcher-processor sector, the four most abundant age classes (by numbers) seen in 2022 were age-2 (49.1%), age-6 (19.3%), age-8 (12.6%), and age-5 (7.9%; Table 5). For the mothership sector, the four most abundant age classes for 2022 were age-2 (42.4%), age-6 (18.4%), age-8 (15.3%), and age-5 (7.0%; Table 6).

Age-samples from 80 shoreside trips showed similar age compositions in the catch compared to the at-sea fisheries, though not nearly as many age-2 fish. The four most abundant age classes for highest occurrences being for 2022 were age-6 (34.4%), age-8 (21.0%), age-5 (11.4%), and age-2 (11.3%); Table 7. Age-composition differences between at-sea and shoreside fleets during the 2022 fishing year were larger than usual due, in part, to seasonal spatiotemporal fleet dynamics. For example, the timing of the at-sea Pacific Hake fishery shifted due to low Bering Sea pollock quotas and stayed south along the Oregon and California border longer than usual (see Appendix E for more details).

1.4.2 Fisheries for Pacific Hake in Canada

The 2022 Canadian Pacific Hake domestic fishery removed 28,887 t from Canadian waters (Table 2), which was 20.3% of the Canadian TAC of 142,354 t. The attainment for Canada was much lower than usual, due to the fishing vessels having a difficult time finding fish in Canadian waters (see Appendix D for more details).

The shoreside component made up of vessels landing fresh round product onshore landed 5,050 t, the lowest on record since 1990. The freezer-trawler component, which freezes headed and gutted product while at sea, landed 23,837 t. There was no Joint-Venture fishery in 2022.

Fishing started in early April and ended in November. The general view of the Canadian fleet is that abundance in Canadian-waters was down in 2022, including areas outside of Southwest Vancouver Island. The freezer trawlers fished in considerably shallower areas than last year and at shallower depths, whereas the shoreside vessels fished their gear at deeper depths than in 2021 (Figure 7). Reports of difficulties finding fish in 2022, and thus additional searching, is perhaps related to these standout differences in fishing depths. The fish caught in Canada appeared to be mostly from three age classes (ages 6, 8, 12, and 5), with very few smaller fish (less than 500 grams) caught.

The most abundant year classes in the Canadian shoreside catch (by numbers) were age-6 (22.8%), age-8 (17.6%), age-5 (14.0%), and age-12 (13.9%); Table 8. The most abundant year classes in the Canadian freezer-trawler catch were age- 6 (22.1%), age-8 (17.8%), age-12 (16.5%), and age-7 (8.0%); Table 9.

2 DATA

Fishery-dependent and fishery-independent data used in this assessment (Figure 8) include the following sources:

- Total catch from all U.S. and Canadian fisheries that target Pacific Hake from 1966 to 2022 (Tables 1–3).
- Fishery age compositions aggregated by year and country-specific sector for the last ten years are available (Tables 5–9) to investigate region-specific trends; age compositions aggregated by year, composed of data from the U.S. fishery (1975–2022) and the Canadian fishery (1985–2022), are used to fit the model (Table 10 and Figure 9).
- Biomass index and age compositions from the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey (1995, 1998, 2001, 2003, 2005, 2007, 2009, 2011, 2012, 2013, 2015, 2017, 2019, 2021; Tables 11, 12, and 13; Figures 9 and 10).
- The relative age-1 index (billions of age-1 fish) derived from the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey (1995, 1998, 2003, 2005, 2007, 2009, 2011, 2012, 2013, 2015, 2017, 2019, 2021; Table 12; Figure 11).
- Mean observed weight-at-age data from fishery and survey catches (1975–2022; Figures 13–15) and, thus, derived fecundity-at-age as well (Figure 12).

The following biological relationships, derived from external analysis of auxiliary data, were input as fixed values in the assessment model:

- Ageing-error matrices based on cross-read and double-blind-read otoliths.
- Proportion of female Pacific Hake mature by age, as developed from recent histological analyses of ovary samples (Table 14 and Figure 12).

Additional data sources not used in this assessment are discussed in Section 2.3.

2.1 FISHERY-DEPENDENT DATA

2.1.1 Total catch

The catch of Pacific Hake for 1966–2022 is summarized by country-specific sectors (Tables 1–3) and modeled as annual coast-wide catches. Catches in U.S. waters prior to 1978 are available only by year from Bailey et al. (1982) and historical assessment documents. Canadian catches prior to 1989 are also unavailable in disaggregated form. The U.S. shore-based landings are from the Pacific Fishery Information Network (PacFIN) database. Foreign and Joint-Venture catches for 1981–1990 and U.S. domestic at-sea catches for 1991–2022 are calculated from the Alaska Fisheries Science Center's North Pacific Groundfish and Halibut Observer (NORPAC) database, which also stores data from the At-Sea Hake Observer Program. Canadian Joint-Venture catches from 1989 are from the Groundfish Biological (GFBio) database. Canadian shore-based landings are from the Groundfish Catch (GFCatch) database for 1989–1995, the Pacific Harvest Trawl (PacHarvTrawl) database for 1996–March 31, 2007, and the Fisheries Operations System (FOS) database for April 2007–present.

Vessels in the U.S. shore-based fishery carry observers and are required to retain all catch and bycatch for sampling by plant observers. All catches from U.S. at-sea vessels, Canadian Joint-Venture vessels, and Canadian freezer trawlers were monitored by at-sea observers from 1996–2019.

In 2020 and 2021 there were no observers on Canadian freezer trawlers due to staffing issues. Due to the ongoing staffing issues, the decision was made to stop providing observers on board all Canadian vessels, for 2022 and all future groundfish trawl trips. This means there is not currently and will not be in the future, any at-sea sampling on board Canadian vessels. Canadian managers, scientists, and the sampling contractor, Archipelago Marine Research Ltd. (AMR) met in early 2022 to solidify a plan to ensure the ongoing sampling of Pacific Hake for Canadian trips. The sampling plan was agreed upon by all parties and consisted of employees aboard Freezer trawlers freezing two bags of approximately 50 whole fish from two tows per trip and delivering them to AMR on return to shore. The bags are stored by AMR until enough have accumulated to sample in bulk, and they sample them over the period of a day or two. This plan ensures that there are individual weights taken for fish from the freezer trawlers, something that was not happening during the at-sea sampling. These weight data give more Canadian input into the weight-at-age matrix. The shoreside vessels continue to make landings with sampling happening on shore at the time of landing.

Canadian trawl catches are monitored autonomously at-sea by cameras onboard vessels. Catch is recorded by dockside samplers within the Groundfish Trawl Dockside Monitoring Program using total catch weights provided by processing plants. Discards are negligible relative to the total fishery catch for all sectors.

For recent catches with haul- or trip-level information, removals by month during the fishing season allowed for the estimation of monthly bycatch rates from observer or dockside information. This information has also allowed a detailed investigation of shifts in fishery timing (see Figure 5 in Taylor et al. 2014).

Minor updates to catches used in previous assessments were made based on the best available information extracted from the aforementioned databases. Tribal catches were available in PacFIN for the U.S. tribal fishery at the time the data were extracted and were cross-checked with numbers based on information provided by the Makah Tribe. The Makah Tribe is also working on providing historical catches such that shore-based catches can be summarized separately from tribal catches since the onset of the fishery.

2.1.2 Fishery biological data

Biological information from the U.S. at-sea fishery was extracted from the NORPAC database. This included sex, length, weight, and age information from the foreign and Joint-Venture fisheries from 1975–1990 and from the domestic at-sea fishery since 1990. Observers collect data by selecting fish randomly from each haul. The number of otoliths collected per haul has varied over time but is currently three fish every third haul.

Biological samples from the U.S. shore-based fishery since 1991 were collected by port samplers located where there are substantial landings of Pacific Hake, primarily Eureka, Newport, Astoria, and Westport. Port samplers routinely take one sample per offload (or trip) consisting of 100 randomly selected fish for individual length and weight, and, from these, typically 20 fish are randomly subsampled for otolith extraction.

When there were observers (1996–2019) aboard Canadian freezer trawler vessels, they collected 50 otoliths and 300 lengths per sample, sampling once per day during trips that on average last approximately seven days. For 2022 and onwards, there are no longer observers on freezer trawlers (Section 2.1.1), so the frozen samples that are delivered for each trip are all sampled for length, weight, sex, and otoliths are taken. There are approximately 100 fish per trip, in two bags of 50. There have been some exceptions to this; due to unforeseen circumstances while at sea, some trips did not bring any samples back and some only brought single bags.

For electronically observed Canadian shoreside trips, port samplers obtain biological data from the landed catch. For each sampled trip, 50 ages and 300 lengths are sampled from the catch. Observed domestic haul-level information is then aggregated to the trip level to be consistent with the unobserved trips that are sampled in ports.

When there has been a Canadian Joint-Venture fishery, length samples are collected every second day of fishing operations, and otoliths are collected once per week. Length and age samples are taken randomly from a given codend. The sampled weight from which biological information is collected must be inferred from length-weight relationships.

The sampling unit for the shore-based fisheries is the trip, while the haul is the primary unit for the at-sea fisheries (Table 4). There is no least common denominator for aggregating at-sea and shore-based fishery samples because detailed haul-level information is not recorded for trips in the shore-based fishery and hauls sampled in the at-sea fishery cannot be aggregated to a comparable trip level. As a result, initial sample sizes are simply the summed hauls and trips for fishery biological data.

Biological data were analyzed based on the sampling protocols used to collect them and expanded to estimate the corresponding statistic from the entire landed catch by fishery and year when sampling occurred. A description of the analytical steps for expanding the age compositions can be found in earlier stock assessment documents (Hicks et al., 2013; Taylor et al., 2014).

The aggregate fishery age-composition data (1975–2022) confirm the well-known pattern of large cohorts born in 1973, 1977, 1980, 1984, 1987, 1999, 2008, 2010, 2014 and 2016 (Table 10 and

Figure 9). Recent age-composition data still easily track the 2010 cohort, as well as the large cohorts born since then (Table 10 and Figure 9). Currently, the 2020 cohort is the largest observed cohort in the U.S. at-sea sector (Tables 5–6), the 2016 cohort is the largest observed cohort in the U.S. shore-based fleet (Table 7), and the 2016 cohort is also the largest observed cohort in both Canadian fleets (Tables 8–9). Age-1 fish were observed by the fishery this year (Table 10) in the U.S. at-sea sector and shore-based fleet. For the combined data in 2022, the 2020 cohort was the largest (33%), followed by the 2016 cohort (24%), and then the 2014 cohort (16%). For the combined data in 2021, the 2016 cohort was the largest (34%), followed by the 2014 cohort (25%), and then the 2017 cohort (13%).

We caution that proportion-at-age data contain information about the relative numbers-at-age, and these can be affected by changing recruitment, selectivity, or fishing mortality, making these data difficult to interpret on their own. For example, the above-average 2005 and 2006 year classes declined in proportion in the 2011 fishery samples but persisted in small proportions for years in the fishery catch, although were much reduced starting in 2011 due to mortality and the overwhelming size of the more recent large cohorts. The assessment model is fit to these data to estimate the absolute sizes of incoming cohorts, which become more precise after they have been observed several times (i.e., encountered by the fishery and survey over several years).

Both the weight- (Figure 15; Section 2.4.3) and length-at-age information suggest that growth of Pacific Hake has fluctuated markedly over time (see Figure 7 in Stewart et al. 2011). This is particularly evident in the frequency of larger fish ($>$ 55 cm) before 1990 and a recent linear shift towards larger fish. Although length-composition data (Section 2.4.4) are not fit explicitly in the base assessment model presented here, the presence of the 2008 and 2010 year classes have been clearly observed in length data from both of the U.S. fishery sectors, and the 2014 year class has been apparent since 2016.

2.1.3 Catch per unit effort

Calculation of a reliable fishery catch-per-unit-effort (CPUE) metric is particularly problematic for Pacific Hake, and it has never been used as a tuning index for the assessment of this stock (see Hicks et al. 2013 for more details).

2.2 FISHERY-INDEPENDENT DATA

2.2.1 Acoustic survey

The Joint U.S. and Canadian Integrated Acoustic and Trawl Survey (Stewart et al., 2011) has been the primary fishery-independent tool used to assess the distribution, abundance, and biology of coastal age-2+ Pacific Hake along the west coasts of the U.S.A. and Canada. The acoustic surveys performed in 1995, 1998, 2001, 2003, 2005, 2007, 2009, 2011, 2012, 2013, 2015, 2017, 2019, and 2021 were used in this assessment (Table 12). The acoustic survey samples transects that represent all waters off the coasts of the U.S.A. and Canada thought to contain all portions of the age-2+ Pacific Hake stock. Observations of age-0 and age-1 Pacific Hake are excluded from the age-2+ index due to largely different schooling behavior relative to older Pacific Hake, concerns about their catchability by the trawl gear, and differences in expected location during the summer months when the survey takes place. Observations of age-1 Pacific Hake are recorded during the survey, and additional analyses, described below, are conducted to develop a relative age-1 index.

The 2021 survey covered U.S. and Canadian waters from Point Conception to north of Haida Gwaii using 108 transects (Figure 2). In the U.S.A., transects were mostly separated by 10 nmi, except 20 nmi spacing was used north of San Francisco Bay to Cape Mendocino and again in northern Washington to account for available ship days at sea. In Canada, transects were separated by 10 nmi along Vancouver Island and then 20 nmi further north. The Bell M. Shimada and the F/V Nordic Pearl worked collaboratively to completed the full extent of the survey in 2021.

Distributions of the backscatter of Pacific Hake plotted for each acoustic survey since 1995 illustrate the variable spatial patterns of age-2+ fish across years (Figure 2). This variability is due in part to changes in the composition of the age-2+ population because older Pacific Hake tend to migrate farther north and partly due to environmental and/or climatic factors. The 1998 acoustic survey is notable because it shows an extremely northward distribution that is thought to be related to the strong 1997-1998 El Niño. In contrast, distribution of Pacific Hake during the 2001 acoustic survey was compressed into the lower latitudes off the coast of Oregon and Northern California. There was a strong La Niña event in 2000. In 2003, 2005, and 2007 the distribution of Pacific Hake did not show an unusual coast-wide pattern despite 2003 and 2007 being characterized as El Niño years. In 2009, 2011, 2012, and 2013 the majority of the distribution of Pacific Hake was again found in U.S. waters, which is more likely due to age-composition than the environment, although 2013 showed some warmer than average sea-surface temperatures. In 2015, sea-surface temperatures were warmer again, resulting in a northern shift in the overall distribution. The distribution of Pacific Hake in 2017 was more latitudinally uniform than observed in 2015. This is likely a result of having large proportions of two cohorts (2010 and 2014 year-classes) in 2017 as opposed to many other years when a single cohort is dominant in the observed samples (Figure 2). Weak 2019 El Niño conditions decreased in their prevalence starting in March of that year, leading to neutral conditions by July. Consequently, the 2019 survey saw Pacific Hake on all survey transects from just north of Morro Bay, California to the northern end of Vancouver Island, with the greatest offshore extent found off of Cape Mendocino. The 2021 survey saw the majority of Pacific Hake in U.S. waters and a continuation of conditions moving towards higher productivity La Niña conditions in the California Current from 2020 to 2021. Ongoing research is looking into relationships between environmental conditions and Pacific Hake distribution and recruitment, that will help to inform the mechanisms behind observations (Malick et al., 2020*b*; Phillips et al., 2023).

During the acoustic surveys, mid-water trawls are made opportunistically to determine the species composition of observed acoustic sign and to obtain the length data necessary to scale the acoustic backscatter into biomass (see Table 12 for the number of trawls in each survey year). Biological samples collected from these trawls are post-stratified, based on similarity in size composition, and the composite length frequency is used to characterize the size distribution of Pacific Hake along each transect and to predict the expected backscattering cross section for Pacific Hake based on the fish-size target-strength (TS) relationship. Any potential biases that might be caused by factors such as alternative TS relationships are partially accounted for in catchability. But, variability in the estimated survey biomass due to uncertainty in TS is not explicitly accounted for in the assessment.

Data from the acoustic survey are analyzed using kriging, which accounts for spatial correlation, to provide an estimate of total biomass as well as an estimate of the year-specific sampling variability due to patchiness of schools of Pacific Hake and irregular transects (Petitgas, 1993; Rivoirard et al., 2000; Mello and Rose, 2005; Simmonds and MacLennan, 2006). Advantages to the kriging approach are discussed in the 2013 stock assessment (Hicks et al., 2013).

For the 2016 assessment (Grandin et al., 2016), the data from all surveys since 1998 were scrutinized and reanalyzed using consistent assumptions, an updated version of the EchoPro software, and a common input-file structure because some previously generated files had spurious off-transect zeros because of how the data were exported. The same analytical procedure was carried out during the reanalysis of 1995 survey data (Berger et al., 2017) and during the preparation of survey data collected since 2017. The assumptions are as follows:

- fixed minimum (k_{min}=3) and maximum (k_{max}=10) number of points used to calculate the value in a cell;
- search radius is three times the length scale that is estimated from the variogram; and
- biomass decays with distance from the end of the transect when extrapolating biomass beyond the western end of a transect, which was refined and supported by the SRG starting with the 2016 assessment (Grandin et al., 2016).

The 2021 survey estimate was scaled by factor of 1.06 to convert EK 80 acoustic data (2021 survey only) to EK 60 acoustic data to standardize the survey time series. The survey team will eventually be converting all pre-2021 EK 60 data to an equivalent EK 80 format. Thus, a full time series of consistently analyzed survey biomass (Table 12 and Figure 10) and age compositions (Table 11 and Figure 9) since 1995 are used to fit the stock assessment model. These data contain many sources of variability (see Stewart et al. 2011) but results from research done in 2010 and 2014 on their representativeness show that trawl sampling and post-stratification is only a small source of variability. Specifically, repeated trawls at different depths and spatial locations on the same aggregation of Pacific Hake were similar and analyses regarding the method used to stratify the data led to similar overall conclusions. Estimates of country-specific age-2+ biomass are also provided (Table 13).

Estimated age-2+ biomass in the survey increased steadily over the four surveys conducted in 2011-2013 and 2015 (Table 12 and Figure 10). It decreased in 2017 to 1.42 million t and then increased to 1.72 million t in 2019 before decreasing again to 1.52 million t in 2021. The 2021 survey age composition was made up of 28%, 21%, 14%, 10%, and 8% from the 2016, 2014, 2017, 2010, and 2019 year classes, respectively. Note that the estimate of biomass does not include age-1 fish and the age compositions used to estimate selectivity of the survey also exclude age-1 fish (Table 11).

A separate relative age-1 index (numbers of fish) was included in the base model in 2022 and was previously explored as a sensitivity since 2013 (Hicks et al., 2013; Johnson et al., 2021; Edwards et al., 2022). The relative index of age-1 fish in this assessment was estimated similarly to previous years, except the estimate of 2021 numbers of age-1 fish was scaled by a factor of 1.06 to account for differences between the EK 60 and EK 80 echosounders (the same approach used for the estimate of age-2+ biomass). The index is a relative index (of numbers) that indicates relative changes between years. The age-1 index confirms the large year classes in 2008, 2010, 2014, 2016, and 2020 (Table 12 and Figure 11). In 2021, some age-1 fish were found in isolated homogeneous pockets but they were more so found to be mixed in with older fish. That same general pattern has occurred since 2015, with the exception of 2019 where age-1 fish were mostly in isolated pockets.

Incorporating the relative age-1 index results in estimates of recruitment strength that are informed on average one year earlier than models without the index (compare the retrospective Figures 54 and G.1 in Johnson et al. 2021). The suite of sensitivity models related to the relative age-1 index explored over the past decade indicate that its use typically provides the model with the correct direction of cohort strength (weak, strong, or neutral). The utility of an informed recruitment signal is far greater than an uninformed recruitment assumption. Whereas the assumption for uniformed recruitment is currently limited to the mean estimated recruitment over a specified range of years. Finally, the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey team supports its use for stock assessment, and the team is committed to continually evaluating and refining approaches to improve survey estimates and related uncertainty. A model without the age-1 index was explored as a sensitivity.

2.3 OTHER DATA NOT USED IN THIS ASSESSMENT

Some data sources were not included in the base model but have been explored, used for sensitivity analyses, or were included in previous stock assessments. Data sources not discussed here have either been discussed at past Pacific Hake assessment review meetings or are discussed in more detail in the 2013 stock assessment document (Hicks et al., 2013). A few are listed below.

- Fishery and survey length compositions.
- Fishery and survey age-at-length compositions.
- Biomass index and age compositions from the following years of the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey 1977, 1980, 1983, 1986, 1989, and 1992.
- Bottom trawl surveys in the U.S.A. and Canada (various years and spatial coverage from 1977–2022).
- Northwest Fisheries Science Center/Southwest Fisheries Science Center/PWCC coast-wide juvenile Pacific Hake and rockfish surveys (2001–2022).
- Bycatch of Pacific Hake in the trawl fishery for Pink Shrimp off the coast of Oregon (2004, 2005, 2007, and 2008).
- Historical biological samples collected in Canada prior to 1990 but currently not available in electronic form.

- Historical biological samples collected in the U.S.A. prior to 1975 but currently not available in electronic form or too incomplete to allow analysis with methods consistent with more current sampling programs.

- California Cooperative Oceanic Fisheries Investigations (CalCOFI) larval Pacific Hake production index, 1951-2006. The data source was previously explored and rejected as a potential index of Pacific Hake female spawning biomass. However, the JTC are exploring new avenues to utilize CalCOFI data based on recently developed methods (see Section 3.3).

- Northwest Fisheries Science Center winter 2016 and 2017 acoustic research surveys of spawning Pacific Hake.

2.4 EXTERNALLY ANALYZED DATA

2.4.1 Maturity and fecundity

Data related to the fecundity relationship were updated for the 2018 assessment (Edwards et al., 2018). The age-based maturity ogive (Table 14 and Figure 12) was developed using histological estimates of functional maturity from 1,947 ovaries that were associated with age estimates. These samples were collected from the acoustic survey, winter and summer acoustic research trips, observers in the U.S. At-Sea Hake Observer Program aboard commercial catcher-processor vessels, and the U.S. West Coast Groundfish Bottom Trawl Survey (Table 15). Samples from south of Point Conception (34.44°N) were excluded from this analysis because they were thought to mature at earlier ages and smaller sizes (see Edwards et al. 2018 for more information). Tissue samples for genetic analyses have been collected from many of the same fish from which ovaries were sampled. It is the hope that these genetic samples may help determine whether the fish south of 34.44°N are from the same stock as the rest of the coastal population. Additional samples are available to update this relationship (including samples collected from Canadian waters since 2018) but have yet to be analyzed.

Time-varying fecundity-at-age was modeled using year-specific weight-at-age values in the calculation of fecundity (Berger et al., 2019). Samples from age-15+ fish were pooled for both the maturity and weight-at-age estimation due to limited sample sizes. Consequently, the age 15+ estimates were applied to ages 15-20 for purposes of modeling the population dynamics (Figure 12).

Some fish at almost every age were found to be functionally immature based on histological criteria. Older, functionally immature fish are a combination of "skip spawners" that will not be spawning in the upcoming year and senescent fish that appear to no longer have viable ovaries. Results from ongoing research investigating the impacts of functionally immature individuals on estimates of female spawning biomass could help refine the fraction of fish mature at each age.

2.4.2 Ageing error

The large inventory of Pacific Hake age determinations includes many duplicate reads of the same otolith, either by more than one laboratory or by more than one age reader within a laboratory. Recent west coast stock assessments have utilized the cross- and double-reads approach to generate an ageing-error matrix describing the imprecision and bias in the observation process as a function of fish age. New data and analyses were used in the 2009 assessment to address an additional process influencing the ageing of Pacific Hake, namely cohort-specific ageing error related to the relative strength of a year-class. This process reflects a tendency for uncertain age determinations to be assigned to predominant year classes. The result is that the presence of strong year classes is inflated in the age data while neighboring year classes are under-represented relative to what would be observed if ageing error were consistent at age across cohorts.

To account for these observation errors in the model, year-specific ageing-error matrices (defined via vectors of standard deviations of observed age at true age) are applied, where the standard deviations of strong year classes are reduced by a constant proportion. For the 2009 and 2010 assessments, this proportion was determined empirically by comparing double-read error rates for strong year classes with rates for other year classes. In 2010, a blind double-read study was conducted using otoliths collected across the years 2003-2009. One read was conducted by a reader who was aware of the year of collection, and therefore of the age of the strong year classes in each sample, while the other read was performed by a reader without knowledge of the year of collection, and therefore with little or no information to indicate which ages would be more prevalent. The results were analyzed via an optimization routine to estimate both ageing error and cohort effect. The resultant ageing error was similar to the ageing error derived from the 2008 analysis. Since 2011, cohort-specific ageing error has been used to reduce the ageing-error standard deviation by a factor of 0.55 for the following largest cohorts: 1980, 1984, 1999, 2010, and 2014. In the 2014 base model (Taylor et al., 2014), the 2008 cohort was also included in this set, but subsequent estimates show this year class to not be as strong as previously thought, and thus, cohort-specific ageing error has not been included for the 2008 cohort since 2015. Also, cohort-specific ageing error does not include the reduction in ageing error for age-1 fish under the assumption that they never represent a large enough proportion of the samples to cause measurement error related to the cohort-effect.

Additional exchanges of otoliths between ageing labs within the U.S.A. and Canada are in process but were not completed in time for this assessment. The additional across-lab double reads will be informative for updating the ageing-error matrix. Unfortunately, increased protocols for moving samples across the border have led to delays.

2.4.3 Weight-at-age

A matrix of empirically derived population weight-at-age means by year (Figures 13–15) is used in the current assessment model to translate numbers-at-age directly to biomass-at-age. Annual mean weight-at-age was calculated from year-specific samples pooled from all fisheries and the acoustic survey for the years 1975 to 2022 (Figures 13–15). Past investigations into calculating weight-at-age for the fishery and survey independently showed little impact on model results. New and historical samples were pulled from all relevant databases such that the derived matrices included the best available data. Samples from winter and research surveys are not included. Samples from the Canadian fishery are subset by area to exclude near-shore samples. Pre-1975 weight-at-age data available in the PacFIN database that were discovered during the 2018 assessment-review process were confirmed to be samples collected within Puget Sound and have not been included in any assessment. Weights from fish ages 15 and above for each year were pooled, and thus, ages 15–20 are assumed to have the same mean weight-at-age. Combinations of age and year with no observations were assumed to change linearly over time between observations at any given age. The number of samples (Figure 14) is generally proportional to the amount of catch, so the combinations of year and age with no samples should have relatively little importance in the overall estimates of the population dynamics.

The biomass at the start of a given year is based on the weight-at-age from the previous year; for example, the biomass at the start of 2022 is calculated using the empirical weight-at-age from 2021 (Figure 13). Prior to 1975, weight-at-age is assumed to be equal to the mean of all available information for each respective age (1975-2022), consistent with the 2022 base model (Figure 13). Both forecast weight-at-age data and forecast selectivity are based on the respective means from the most recent five years (2018–2022), for consistency (Figure 13).

The use of empirical weight-at-age is a convenient method to capture the variability in both the weight-at-length relationship within and among years as well as the variability in length-at-age data, without requiring parametric models to represent these relationships. However, this method requires the assumption that observed values are not biased by strong selectivity at length or weight and that the spatial and temporal patterns of the data sources provide a representative view of the underlying population. Simulations show that, in general, using empirical weight-at-age data when many observations are available results in more accurate estimates of spawning biomass than modeling growth (Kuriyama et al., 2016).

The temporal changes in weight-at-age may be due to ecosystem effects such as prey availability, predator abundance, and ocean temperature (Chittaro et al., 2022). Thus, while not explicitly parameterized in the assessment, such ecosystem effects are somewhat implicitly accounted for, especially compared to assuming time-invariant weight-at-age.

2.4.4 Length-at-age

In the 2006-2010 assessments that attempted to estimate the parameters describing a parametric growth curve, strong patterns were identified in the observed data indicating sexually dimorphic and temporally variable growth. In aggregate, these patterns result in a greater amount of process error for length-at-age data than is easily accommodated with parametric growth models, and attempts to explicitly model size-at-age dynamics (including use of both year-specific and cohort-specific growth) have not been very successful for Pacific Hake. The lack of success was particularly evident in the residuals of the length-frequency data from models prior to 2011. Potential avenues for explicitly modeling variability in length- and weight-at-age data in this model have not been revisited since 2011.

2.5 ESTIMATED PARAMETERS AND PRIOR PROBABILITY DISTRIBUTIONS

Several prior distributions (Table 16) are used to fit the model. The priors that are assumed to be informative are discussed below.

2.5.1 Natural Mortality

Since the 2011 assessment, a combination of the informative prior for natural mortality used in previous Canadian assessments and results from analyses using Hoenig's (1983) method support the use of a lognormal distribution with a median of 0.20 and a standard deviation (in log space) of 0.10. Sensitivity to this prior has been evaluated extensively in many previous assessments of Pacific Hake (see Hicks et al. 2013 for a discussion of the historical treatment of natural mortality and its prior) and is repeated here (see Section 3.8), including increasing the prior standard deviation and using and alternative prior distribution altogether based on a life history meta-analysis (Hamel, 2015; Hamel and Cope, 2022). This method used a lognormal prior distribution with a median of 0.22 (based on a maximum age of 25 for Pacific Hake) and a standard deviation (in log space) of 0.31. Alternative prior distributions for natural mortality typically have a significant impact on the model results. But in the absence of new information on natural mortality there has been little option to update the prior.

2.5.2 Steepness

The prior for the steepness parameter of the stock-recruitment function is based on the median (0.79) and the 20th (0.67) and 80th (0.87) percentiles from Myers et al.'s (1999) meta-analysis of the family Gadidae and has been used in U.S. assessments since 2007. This prior has a beta distribution with parameters 9.76 and 2.80, which translate to a mean of 0.777 and a log-standard deviation of 0.113. Sensitivities to the variance on the prior on steepness were evaluated in the 2012 and 2013 assessments (Stewart et al., 2012; Hicks et al., 2013). Sensitivities to the mean of the prior are explored in this assessment (see Section 3.8).

2.5.3 Variability on fishery selectivity deviations

Time-varying selectivity was introduced in the 2014 assessment (Taylor et al., 2014) and is modeled using annual deviations since 1991 applied to the selectivity-at-age parameters for the fishery. A normal distribution with a fixed standard deviation ($\Phi = 1.4$; see Edwards et al. 2018 for justification) is used as a penalty function to keep deviations from straying far from zero. Selectivity for age-0 fish is fixed at 0.0 and parameters for ages that are estimated represent the change in selectivity from the next youngest age. Beyond the age of 6, age-specific parameters are fixed at zero giving constant selectivity beyond the last estimated value. The condition that maximum selectivity equals 1.0 results in one fewer degree of freedom than the number of estimated parameters. Further testing of alternative methods for parameterizing time-varying selectivity (e.g., Xu et al. 2019) should be investigated in conjunction with the estimation of additional time-varying parameters.

2.5.4 Age composition likelihood

Since 2018, the assessment has used the linear formulation of the Dirichlet-multinomial (D-M) likelihood (Thorson et al., 2017) to fit the age-composition data. Estimated parameters θ_{fish} and θ_{surv} serve to automatically adjust the weight given to the fishery- and the survey-composition data, respectively. As of 2021, Stock Synthesis includes the constant of integration in the likelihood calculation for the D-M model such that likelihoods are comparable across weighting methods.

Integration of weighting the composition data within the assessment increases the efficiency of the assessment process, removes the subjective choice of how many iterations are required, and ensures that the results of model sensitivities, retrospective analyses, and likelihood profiles are automatically tuned, rather than having the age compositions be given the same weight as the base model. Note that the following description holds for both the survey data and the fishery data, with θ equal to θ_{surv} or θ_{fish}.

The likelihood function for the linear parameterization of the D-M likelihood (see Equation 10 of Thorson et al. (2017)) is

$$\mathrm{L}(\boldsymbol{\pi}, \theta | \tilde{\boldsymbol{\pi}}, n) = \frac{\Gamma(n+1)}{\prod_{a=1}^{A_{\max}} \Gamma(n\tilde{\pi}_a + 1)} \frac{\Gamma(\theta n)}{\Gamma(n + \theta n)} \prod_{a=1}^{A_{\max}} \frac{\Gamma(n\tilde{\pi}_a + \theta n \pi_a)}{\Gamma(\theta n \pi_a)}, \quad (1)$$

where $\tilde{\pi}_a$ is the observed proportion at age a, π_a is the corresponding expected proportion at age a estimated by the model, $\tilde{\boldsymbol{\pi}}$ and $\boldsymbol{\pi}$ designate the vectors of these proportions, $A_{\max}$ is the maximum age in the model, and n is the input sample size. The parameter θ is defined as a linear scaling parameter such that θn is the variance-inflation parameter of the D-M distribution. The linear parameterization has been shown to be superior over the saturation parameterization in simulation testing (Fisch et al., 2022), and thus corroborates our decision to continue to use it even though the saturation parameterization is available in Stock Synthesis.

The effective sample size associated with this likelihood is given by

$$n_{\mathrm{eff}} = \frac{1}{1+\theta} + \frac{n\theta}{1+\theta}. \quad (2)$$

The input sample sizes used in this assessment, which are based on the number of trips and/or hauls, are large enough that the first term is insignificant compared to the second term. Consequently, $\theta/(1+\theta)$ can be compared to the sample size multipliers used in the McAllister-Ianelli data-weighting method (McAllister and Ianelli, 1997) that was used for assessments prior to 2018 (Table 17) and as a sensitivity here (see Section 3.8). In short, the McAllister-Ianelli method involves iteratively adjusting multipliers of the input sample sizes passed to the multinomial likelihoods until they are roughly equal to the harmonic mean of the effective sample sizes. The effective sample size is dependent on how well the model expectation matches the observed values. Typically, this process involves no more than four to five iterations.

A uniform prior between -5 and 20 for $\log \theta_{\mathrm{fish}}$ and $\log \theta_{\mathrm{surv}}$ tends to lead to inefficient sampling of $\log \theta_{\mathrm{surv}}$ because many samples occur in a part of the parameter space where the effective sample size multiplier, $\theta_{\mathrm{surv}}/(1+\theta_{\mathrm{surv}})$, is between 0.99 and 1.0 (Berger et al., 2019). In that area, the input sample sizes given the uniform prior have full weight and the likelihood surface is almost completely flat with respect to $\log \theta_{\mathrm{surv}}$. The current prior on $\log \theta_{\mathrm{surv}}$ can be associated with an approximately uniform prior of the weight $\theta_{\mathrm{surv}}/(1+\theta_{\mathrm{surv}})$, where the parameters of the normal distribution were back-calculated from a uniform distribution with the bounds of 0 and 1 (Grandin et al., 2020). The normal prior for both $\log \theta_{\mathrm{fish}}$ and $\log \theta_{\mathrm{surv}}$ has a mean of 0 and a standard deviation of 1.813.

Composition data can also be weighted using the Francis method (T2.6 in Table 2 of Francis, 2011), which is based on variability in the observed ages by year. This method, like the McAllister-Ianelli method, is iterative, where the sample sizes are adjusted such that the fit of the expected mean age should be within the estimated uncertainty at a rate that is consistent with the variability expected given the effective sample sizes. The Francis method is known to be sensitive to outliers and prone to convergence issues when selectivity varies with time. As a result, the Francis method was not included as a sensitivity.

3 ASSESSMENT

3.1 MODELING HISTORY

In spite of the relatively short history of fishing, Pacific Hake have surely been subject to a larger number of stock assessments than any marine species off the west coast of the U.S.A. and Canada. These assessments have included a large variety of age-structured models. Initially, a cohort analysis tuned to fishery CPUE was used (Francis et al., 1982). Later, the cohort analysis was tuned to National Marine Fisheries Service (NMFS) triennial acoustic survey estimates of absolute biomass at age (Hollowed et al., 1988). Since 1989, Stock Synthesis models (or base versions of it) fit to fishery catch-at-age data and acoustic survey estimates of population biomass and age composition have been the primary assessment method.

While the general form of the age-structured assessment has remained similar since 1991, modeling procedures have been modified in a variety of ways. There have been alternative data choices, post-data collection processing routines, data-weighting schemes, structural assumptions for the stock assessment model, MCMC sampling algorithms, and control rules (Table 17). Analysts are constantly trying to improve the caliber and relevance of the assessment by responding to new scientific developments related to statistics and biological dynamics, policy requirements, and different or new insights brought up during the peer review process to ensure a robust stock assessment.

Data processing, filtering, and weighting choices have been modified several times since the first assessment. For example, modifications to the target-strength relationship used to scale acoustic data changed in 1997 (Dorn and Saunders, 1997), and kriging was implemented to account for the spatial correlation in the acoustic data in 2010 (Stewart and Hamel, 2010). While survey data have been the key index for biomass since 1988, surveys that have been used have varied considerably. The Alaska Fisheries Science Center/Northwest Fisheries Science Center West Coast Triennial Shelf Survey was used from 1988 before being discarded from the 2009 assessment (Hamel and Stewart, 2009). Acoustic surveys from the years prior to 1995 were used for assessments in the early 1990s, but Stewart et al. (2011) reviewed these early surveys and deemed that sampling was insufficient to be comparable with more recent data. Several recruitment indices have been considered but ultimately none were identified as adding appreciable contribution to model results (Helser et al., 2002, 2005; Stewart and Hamel, 2010), except for the fishery-independent acoustic-based age-1 index which has been included in the base model since the 2022 assessment. The process for generating fecundity-at-age from weight-at-age data changed in 2019 from using time-invariant to year-specific values. Even where data have been consistently used, the weighting of these data in the statistical likelihood has changed through the use of various emphasis factors (e.g., Dorn 1994; Dorn et al. 1999), a multinomial sample size on age compositions (e.g., Dorn et al. 1999; Helser et al. 2002, 2005; Stewart et al. 2011), internal estimations of effective sample size using the Dirichlet-multinomial distribution (Edwards et al., 2018), and assumptions regarding year-specific survey variance. Since 2021, a more computationally efficient Bayesian MCMC sampler (No-U-Turn Sampler; NUTS; Hoffman and Gelman 2014) was used to estimate posterior distributions (Monnahan and Kristensen, 2018; Monnahan et al., 2019), a change from previous assessments that used the random walk Metropolis Hastings (rwMH) sampler (details described in Johnson et al. 2021). The list of changes discussed above is for illustrative purposes only and represents a small fraction of the different choices analysts have made and that reviewers have required.

The structure of the assessment models has perhaps had the largest number of changes. In terms of spatial models, analysts have considered spatially explicit forms (Dorn, 1994, 1997), spatially implicit forms (Helser et al., 2006), and single-area models (Stewart et al., 2012). Predicted recruitment has been modeled by sampling historical recruitment (e.g., Dorn 1994; Helser et al. 2005), using a stock-recruitment relationship parameterized using maximum sustainable yield (MSY) and the fishing mortality rate estimated to produce the MSY (F_{MSY}; Martell 2010), and using several alternative steepness priors (Stewart et al., 2012; Hicks et al., 2013). Selectivity has also been modeled in several ways: invariant (Stewart et al., 2012; Hicks et al., 2013), time-varying with (Helser et al., 2002) and without (Dorn, 1994; Dorn and Saunders, 1997; Stewart et al., 2012; Hicks et al., 2013) a random walk, alternative levels of allowable deviation through time (Hicks et al., 2013; Berger et al., 2017), age-based (Dorn, 1994; Dorn and Saunders, 1997; Stewart et al., 2012; Hicks et al., 2013), and length-based (Helser and Martell, 2007).

Several harvest control rules have been explored for providing catch limits from stock assessment output. Pacific Hake stock assessments have presented decision makers with constant F, variable F, and the following hybrid control rules: $F_{\text{SPR}=35\%}$, $F_{\text{SPR}=40\%}$, $F_{\text{SPR}=40\%}$–40:10, $F_{\text{SPR}=45\%}$, $F_{\text{SPR}=45\%}$–40:10, and $F_{\text{SPR}=50\%}$ (e.g., Dorn 1996; Hicks et al. 2013). Changes to policies such as the United States' National Standards Guidelines in 2002 and the $F_{\text{SPR}=40\%}$–40:10 harvest control rule in the Agreement (Appendix C) have required specific changes to control rules.

In addition to the examples given above and changes documented in stock assessments, there have been many more investigations conducted at review panel meetings. Starting in 2013, the addition of the MSE (Hicks et al., 2013; Jacobsen et al., 2021) facilitated investigating changes to the modeling procedure in terms of pre-specified objectives that aim for a sustainable coast-wide fishery.

3.2 DESCRIPTION OF BASE MODEL

The 2023 base model has the same population dynamics structure as the 2022 assessment's base model. The statistical-catch-at-age model assumes that the Pacific Hake population is a single coast-wide stock subject to one aggregated fleet with combined male and female population dynamics. Stock Synthesis (Methot and Wetzel, 2013) version 3.30.20 was the modeling platform used. The largest change between the 2022 and 2023 stock assessments is the addition of another year of fishery data into the base model.

The 2023 base model includes a time series (1995 to 2021) of acoustic age-2+ biomass estimates and acoustic estimates of age-1 fish (see Section 2.2.1 for more details on the age-1 index). Maturity is assumed to be time-invariant and the maturity ogive updated in 2018 was retained (see Section 2.4.1). Fecundity is defined as weight-at-age multiplied by the maturity ogive and is time-varying across years with empirical weight-at-age data (1975–2022; see Section 2.4.3). The D-M likelihood approach (Thorson et al., 2017) is again used to estimate the weights associated with age-composition data, rather than iteratively tuning the sample size multiplier as in 2017 and earlier assessments (see Section 2.5.4). Time-varying fishery selectivity is retained in the 2023 base model with the magnitude of the allowable deviations unchanged from the 2022 base model (see Section 2.5.3). The general parameterization of selectivity was retained, although additional parameters were required to estimate an additional year of deviations. The selectivity of the acoustic survey is assumed to be time invariant. Selectivity curves were modeled as non-parametric functions estimating age-specific values for each age beginning at age-2 for the index of age-2+ biomass and age-1 for the fishery until a maximum age of 6, after which all ages are assumed to have the same selectivity. Selectivity for the age-1 index was set to one for age-1 and zero for all other ages.

Prior probability distributions are used for a select few parameters and fixed values are used for several parameters. For the base model, the instantaneous rate of natural mortality (M) is estimated with a lognormal prior having a median of 0.20 and a standard deviation (in log-space) of 0.1 (see Section 2.5.1). The stock-recruitment function is a Beverton-Holt parameterization, with the log of the mean unexploited recruitment ($\log R_0$) freely estimated. This assessment uses the same beta-distributed prior for stock-recruit steepness (h), based on Myers et al. (1999), that has been applied since 2011 (Stewart et al., 2011). Year-specific recruitment deviations were estimated from 1966–2021 as well as the years 2022–2026 for purposes of forecasting. The standard deviation, σ_r, of recruitment variability serves as a recruitment deviation constraint and is fixed at 1.4 in this assessment. This value is based on consistency with the observed variability in the time series of recruitment deviation estimates and is the same as assumed in assessments from 2013 to 2022 (Table 17). Catchabilities associated with the biomass index (q_b) and with the age-1 index (q_1) were calculated analytically as per Ludwig and Walters (1981) for each sample of posterior parameters, resulting in a distribution of catchability for each.

Statistical likelihood functions used for data fitting are typical of many stock assessments. The biomass index was fit via a log-normal likelihood function, using the observed (and extra 2009) sampling variability, estimated via kriging, as year-specific weighting. The age-1 index was also specified as having lognormal error structure. An additional constant and additive standard deviation on the log-scale component is included for both the biomass index and the age-1 index, which were freely estimated to accommodate unaccounted-for sources of process and observation error. A D-M likelihood was applied to age-composition data, with input sample sizes equal to the sum of the number of trips and hauls sampled across all fishing fleets or the number of trawl sets in the research surveys (see Section 2.5.4).

Model results and statistical inference were based on 8,000 MCMC samples (using the `adnuts` R package; Monnahan and Kristensen (2018)) to describe posterior distributions for model parameters and derived quantities. The number of samples used for bridging models, sensitivity models, and retrospective models was also 8,000. Medians (50% quantiles) are reported together with the bounds of 95% credibility intervals calculated as the 2.5% quantile and the 97.5% quantile of posterior distributions from the MCMC samples, to give equal-tailed intervals. A full explanation of the NUTS algorithm and the `adnuts` package, including an analysis with the Pacific Hake stock can be found in Monnahan et al. (2019).

3.3 RESPONSE TO 2022 SCIENTIFIC REVIEW GROUP (SRG) REVIEW

The Scientific Review Group (SRG) meeting was held virtually from February 14-17, 2022.

The following are the 'SRG Recommendations and Conclusions for the Stock Assessment' from the 2022 SRG report and the associated responses from the JTC:

1. **The SRG notes that σ_R is an influential parameter and that determining the choice of σ_R remains a challenge and encourages the JTC to continue to work on the issue.**

Response – Developing best practices for modeling mean unfished equilibrium recruitment (R_0) and recruitment variability (σ_R) remain broad topics of contemporary research. Recent recommendations suggest that the next generation of stock assessment modeling frameworks should concomitantly treat recruitment deviations as a random effect and estimate σ_R (Punt et al., 2020). The JTC continues to conduct, collaborate on, and monitor ongoing research projects concerning approaches for advancing recruitment estimation, as applied to Pacific Hake and in general. Many of these issues are widespread in stock assessment and scientific-based solutions are likely to be the result of medium to long-term research projects. Here, we provide a few updates to our previous response on this topic, including specific advances in research endeavors where applicable.

The JTC continues to participate in collaborative research to investigate the concurrent estimation of multiple variance parameters within stock assessments. For Pacific Hake, this includes the estimation of the variability associated with time-varying selectivity (Φ), σ_R, extra standard deviation parameters on index data, and Dirichlet-multinomial parameters θ_{fish} and θ_{surv}. In this assessment, Φ and σ_R are input as fixed parameters because Stock Synthesis uses penalized likelihood and therefore is not formulated to estimate random effects. Additionally, estimation of these variance parameters using MCMC requires the specification of hyperpriors for which there has been little research. The Laplace approximation (Thorson et al., 2015) was investigated as an alternative means to estimate these parameters. However, estimates from this method were large and simulation shows them to be biased high. Additional research still in its infancy suggests that stock assessment frameworks with the ability to estimate random effects internally are better at estimating autocorrelated processes than random processes. Next steps for the JTC includes fitting Stock Synthesis to these same data sets to determine best practices when variance parameters cannot be estimated and fitting a wide variety of stock assessment frameworks to data when multiple random processes are present in the true dynamics.

The Management Strategy Evaluation (MSE) framework for Pacific Hake creates considerable advantages for examining recruitment. The stock assessment model in the MSE is written in Template Model Builder (TMB), which provides efficient estimation of random effects using the Laplace approximation, while being parameterized to mimic many (but currently not all) of the pertinent *features of Stock Synthesis used in this assessment. Thus, the performance of using restricted maximum likelihood to estimate* σ_R *(Thorson, 2019) can be investigated in terms of management as well as statistical performance. Research projects using the MSE framework are underway to evaluate the robustness of recruitment modeling assumptions and the advantages of including environmentally-driven recruitment indices on management performance and uncertainty. Research (under review) by Dr. Cathleen Vestfals and colleagues at the Northwest Fisheries Science Center has identified specific climate drivers associated with Pacific Hake early life-history stages and recruitment and is being used to select which environmental variables to fit as an index of recruitment within the stock assessment model. Further development of environmentally-driven recruitment indices using updated environmental predictions is also underway. The utility of fitting to a recruitment index will be investigated in terms of forecasting skill and management performance within the MSE by the MSE working group.*

The number of stock assessment frameworks written in TMB or other platforms that allow for the estimation of random effects is increasing. These frameworks, specifically the Woods Hole Assessment Model (WHAM; Stock and Miller 2021) and State-Space Assessment Model (SAM; Nielsen and Berg 2014) are both peer reviewed and currently being used for management. The JTC has fit WHAM to data on Pacific Hake and explored the estimates of several variance parameters that are currently only explored via sensitivity analyses in Stock Synthesis. Next steps include fitting data using SAM and using estimates from both frameworks as inputs to Stock Synthesis.

The JTC is also following work being conducted by the International Council for the Exploration of the Sea (ICES) Methods Working Group which, among other things, is looking at meta-analytical approaches for estimating recruitment parameters. Results from this work could be used to develop informative prior distributions on key recruitment parameters. Deliverables were put on hold as a result of COVID-19 but the project continues to be making progress.

2. **The SRG recommends exploring alternative methods to simulate recruitment in the projections. Although Stock Synthesis currently does not have the capability to characterize a different process other than the assumed lognormal distribution, improvements such as drawing from past observations or using a mixture distribution to simulate recruitment should be considered for modelling platforms in the future.**

Response – The JTC continues to explore approaches to make informed decisions about current and future recruitment in projections. The inclusion, and associated justification, of the age-1 index in the 2022 and 2023 base model is one example of this (see Sections 2.2.1 and 3.2). Additionally, the JTC is working with Dr. Kristin Marshall to further explore the fit of oceanographic and environmental variables identified by Dr. Cathleen Vestfals as being informative about the early life history of Pacific Hake as indices of recruitment within Stock Synthesis. Ongoing research includes expanding the variables (originally only amalgamated from 1980–2010) to 2010 onwards to create a single time series, and investigating relationships leading to better informed recent, current, and potential near-term forecast recruitment estimates.

Available options in Stock Synthesis for recruitment during the projection period are the stock-recruitment curve, the stock-recruitment curve with a multiplier, and the mean across a user-

defined time period. The MSE tool could be used to consider alternative recruitment distributional assumptions as future research. A member of the JTC is on the development team for NOAA's next generation stock assessment modeling platform (Fisheries Integrated Modeling System; FIMS), which ensures features such as recruitment forecast options will be taken into consideration. Plans are for the Pacific Hake stock assessment to be a test model.

The JTC has requested DFO funding to collaborate with Australian, U.S., and Canadian researchers on developing two potential approaches for developing an index of age-0 Pacific Hake. The first approach is based on the method of Suthers et al. (2022), who proposed and simulation-tested a novel method for estimating growth and mortality of fish larvae based on size distributions. In 2022, Suthers visited NOAA's Southwest Fisheries Science Center to start applying the method to CalCOFI data (which include 1.3 million hake larvae) and compare results to estimates of recruitment from the last hake assessment (Edwards et al., 2022). The second approach will apply a method proposed by Hinchliffe et al. (2021) that relates the mortality/growth ratio of larval fish to the slope of the zooplankton size spectrum (which characterises the size distribution of zooplankton) to quantify the recruitment potential of larval Pacific Hake. The proposed work will support collaborations to work on both approaches, will utilise recent improvements in fitting size spectra to data (Edwards et al., 2020), and aims to provide new information on Pacific Hake recruitment.

We also include Figure 30 (as developed in the 2022 assessment) which presents a novel approach to visualise estimates of recruitment, to avoid misunderstanding of how large some recruitment events might be.

3. Pacific Hake dynamics are highly variable even without fishing mortality. **The SRG applauds the efforts of the JTC and the MSE Working Group to add capabilities for specifying dynamic reference points within the assessment and MSE platforms, and encourage those groups to work together and develop a discussion of alternative reference points, including dynamic reference points, for future SRG consideration.**

Response – The JTC agrees that future reference point discussions stemming from simulation work, preferably through the MSE, would be beneficial. In particular, the JTC continues to have interest in exploring the utility of dynamic reference points. The MSE can now utilize dynamic reference points in management procedure scenarios, and Stock Synthesis models can now incorporate dynamic reference point capabilities into routine stock assessment output. In the coming year, the JTC plans to initiate simulations that explore alternative dynamic F-based target reference points coupled with static (equilibrium-based) biomass limit reference points in exploratory harvest control rule scenarios.

Over the past year, the JTC has continued to engage in research activities and outreach related to dynamic reference points broadly, as well as specifically for Pacific Hake. In particular, the JTC conducted a learning session at the summer JMC meting to promote internal awareness and basic understanding of the key concepts, methods, and assumptions associated with dynamic reference point calculations. The JTC also engaged with external partners, the Western and Central Pacific Fisheries Commission science provider (Secretariat of the Pacific Community), to learn from *their experience developing and applying dynamic reference points to operational highly migratory species assessments and management plans. Additionally, the JTC is contributing to, and following, updates to Canadian and United States national guidance documentation on the incorporation of prevailing environmental conditions into stock assessments and subsequent management advice (e.g., defining reference points).*

4. The SRG encourages work to develop a picture of the Pacific Hake reproductive cycle both seasonally and at the life-time scale based on histological and physiological measurements. In addition, the SRG notes that Canadian samples and those from the winter research cruises should be included in the maturity analysis. **The SRG encourages continued sampling and analysis to improve understanding of the Pacific Hake reproductive cycle.**

Response – Pacific Hake ovary samples were not collected over the past year, but plans include more sample collections in the coming years. Including Canadian samples in subsequent maturity analyses still remains a goal, but barriers (lab training, capacity, and moving bio-samples across the broader) still remain. Research is in-progress by Melissa Head (NWFSC) focusing on temporal and spatial trends in hake reproduction. The analysis will include over a decade of maturity samples, spanning much of the U.S. West Coast. The project aims to evaluate how interannual changes affect size and age at maturity across a latitudinal gradient and how the timing of spawning and rate of skip spawning differs spatio-temporally. A presentation summarizing progress to date and future plans is planned for the SRG meeting.

Research being led by Adam Luckenbach at the Northwest Fisheries Science Center looking at physiological indices of fish reproductive and metabolic status is expected to bolster the current practice of using gonadal histology alone for surveyed Pacific Hake and provide important data to more accurately determine the reproductive cycle of females. Data generated to date indicate that two types of lipids, triacylglycerols and phospholipids, in the livers of Pacific Hake are inversely related and predictive of sexual maturity in females. Levels of these lipids are also considerably shifted when aborted, atretic ovarian follicles are observed, suggesting that lipid levels may be predictive of skipped spawning, which can reduce the effective female spawning biomass. Data analyses will continue in 2023. New developments are expected to inform maturity in future Pacific Hake stock assessments.

5. **The SRG also recommends continuing to conduct the following sensitivities: steepness, natural mortality, σ_R , excluding the age-1 index, alternative standard deviations for time-varying selectivity, and down-weighting fishery age-composition data.**

Response – The JTC has conducted all of the requested sensitivities (and many others) and provides summaries in written (Section 3.8), tabular (beginning with Table 33), and graphical (beginning with Figure 41) formats in this document.

6. Based on the preliminary results shown, previous assessments have correctly predicted an increase or decrease in recruitment and spawning biomass in subsequent years, although the projections are usually less definitive than the current base model results. Given that this analysis provides some confidence in the current expectations of continued stock decline, **the SRG recommends that the JTC continue to explore and refine this analysis for future assessments.**

The SRG encourages the JTC to explore, with the JMC and AP, the value of a threshold for specifying the probability of projected declines or increases of the stock in future assessments.

Response – The JTC has again updated this analysis to continue comparing estimates from the current base model with forecasts from previous assessments (Figures 57–64). Related, the JTC is continuing to explore options for improving recruitment estimation and predictions (see Responses 1–4 and 7).

The JTC has not had an opportunity to meet with JMC, AP, or the MSE working group to explicitly explore threshold values for specifying the probability of projected declines or increases of the stock in future assessments. This endeavor is well suited for upcoming MSE-related performance metrics discussions.

7. The SRG notes that there are currently multiple strong cohorts in the stock where previously there was only one strong cohort during the period of sample collection for the ageing error matrix that supports the assessment model. **Based on this observation, the SRG recommends that an ageing error study using samples collected during the past decade be conducted in conjunction with the Committee of Age Reading Experts (CARE).**

Response – An ageing error study in conjunction with CARE has commenced, including planned sample exchanges between United States and Canada ageing labs. However, a full exchange remains on hold due to difficulties with permits to send biological specimens across the border.

8. **The SRG recommends that historical sources of data be investigated to determine whether they can be used to supplement the weight-at-age matrix**, including unaged otolith samples (and associated data) from the 1970s that may be available in the Burke Museum in Seattle.

Response – The JTC has conducted analyses previously showing that small changes to historical data have little relevance to current management quantities of interest. So at this time, the JTC does not expect small amounts of historical weight-at-age data to significantly alter stock assessment results used for management decisions. The JTC has not had the opportunity to visit the Burke Museum in Seattle to ascertain whether Pacific Hake age structures are available and in a usable state.

9. Uncertainty in weight-at-age is not accounted for in the stock assessment and a five-year average of recent observations is used for all years of the projections. **The SRG requests that the JTC explore alternative methods for forecasting weight-at-age and evaluate whether they can improve projections.**

Response – It is important to capture key, mechanistic, and/or stochastic population processes in stock assessment projections to sufficiently characterize levels of prediction uncertainty that are consistent with available information to adequately contextualize metrics used to aid management decisions. Likewise, it is as important to evaluate the basic population-dynamics assumptions used in such projections. Recent, current, and future recruitment are perhaps the most influential sources of uncertainty in stock assessment projections. As a result, the JTC has prioritized re-

search on recruitment, including supporting analyses and other related analyses mentioned in this section. Over the next few years, the JTC plans to work with the MSE working group on a newly funded research project aimed at incorporating environmentally-driven growth into the operating model and testing consequences of climate-driven changes in recruitment, growth, and movement concomitantly.

Empirical weight-at-age data indicate inter-annual variation in Pacific Hake growth, and this variation could be related to individual cohort effects (e.g., large cohorts have a negative growth influence on adjacent cohorts). The JTC has future plans to explicitly evaluate these relationships using random effects models to partition the variance components (year and cohort) in available weight-at-age data and to explore spatial patterns (Indivero et al., 2023). This work could rely or build upon research currently in progress by a graduate student looking at variation in Pacific Hake weight-at-age data. The JTC also plans to explore new weight-at-age forecasting capabilities in Stock Synthesis (once fully tested). A simulation experiment that evaluates the influence of variable weight-at-age data relative to other sources of variance in stock assessment projections (e.g., recruitment) would also be useful. Until this work is completed, the JTC continues to use a recent five-year average in the projection period because it is consistent with recent data (Figures 13 and 15). This assumption is consistent with what is allowable within other commonly used stock assessment frameworks that accommodate time-varying dynamics.

10. The parameter weighting the acoustic survey age samples was often estimated near the upper bound of 1.0 and could not upweight the age samples. Investigations during the SRG meeting showed that the posterior distribution of the parameter may have some probability of upweighting the age samples from the base assessment inputs, although likely had little difference on stock assessment outcomes. **The SRG encourages the JTC to consider methods to determine the maximum input sample size for the survey age compositions. Previous work of Stewart and Hamel (2014) may be useful for this purpose.**

Response – The JTC concurs that determining maximum input sample sizes, as well as relative maximums across years, is a worthwhile endeavor. Determining appropriate input samples sizes for composition data is a long-standing issue with much debate. Progress made for Pacific Hake will undoubtedly provide useful for stock assessment more broadly. The JTC has yet to undertake any specific analyses investigating input sample sizes. Researchers at the Alaska Fisheries Science Center have recently begun similar inquires, indicating that a collaborative approach may be mutually beneficial.

11. The use of high-performance computing (e.g., a dedicated server or cloud computing) allowed for the complete set of assessment results to be characterized using MCMC at a minimal cost. **The SRG recommends future use of high-performance computing to provide complete and thorough assessment results in a timely manner.**

Response – Resources were made available for the JTC to use a new high-performance computing network server with 80 processors to complete all model runs (bridging, base, sensitivity, retrospectives, and forecasts). Another high-performance server unit and two high-performance laptops have also been acquired for completing the Pacific Hake assessment. These resources are *used for data preparation, diagnostic examination, running test models, and exploring alternative model configurations.*

A new server was purchased and used to run all the models and for running the software that builds the document. The server has 80 Intel Xeon Gold CPUs and 128 GB of RAM and is running Ubuntu Linux version 22.04.1 LTS which was the newest stable version at the time of writing. The server was set up with user account for each JTC member, with a remote desktop server (X-Remote Desktop Protocol; XRDP) running for easy access. All connections were through a 4096-bit passwordless Secure SHell (SSH) and the server was otherwise locked down from a security standpoint. The entire server is automatically backed up on a mirrored RAID device once per day, with model input files also backed up to a Google drive. If everything were lost the models could be re-run very quickly and the document regenerated in full.

Scripts were written in the Bash shell scripting language to allow operating system level control and monitoring over parallel model runs. Each run was also parallelized internally with 16 chains per model; that parallelism was controlled from within R using the `future` *and* `furrr` *packages. With each model needing 16 CPUs, the JTC were able to run 4 models at a time, taking up 64 CPUs and leaving 16 available for use in writing and building the document. The total runtime for these models is now on the order of 1-3 hours, depending on the CPU and memory load on the server at the time.*

The server setup allowed all JTC members to work together in a way not possible before. This integrated setup will ensure an ideal workflow in the coming years, with a centralized system housing all model runs and document software.

12. The SRG appreciates the investigation of alternative model structures, including alternative modelling platforms. **The SRG encourages the JTC to continue these types of investigations.**

Response – The JTC continues to explore the implementation of a hake-like assessment in WHAM and SAM, in addition to the custom TMB estimation model used in the MSE, to evaluate the impact of platform-specific configurations, assumptions, and capabilities.

13. **The SRG appreciates the dedication and teamwork displayed by the JTC in producing the best available scientific information and advice on the Pacific Hake stock during the COVID-19 pandemic.**

Response – Teamwork and collaboration is an attribute of great interest and pride within the JTC, and we believe it is fundamental to successfully achieving the science objectives as outlined in the Agreement.

3.4 MODELING RESULTS

3.4.1 Changes from 2022

A set of ‘bridging’ models was constructed to evaluate the component-specific effects of the steps to change from the 2022 base model to the 2023 base model. The steps are:

- Update to the latest version of Stock Synthesis, version 3.30.20, to follow current best practices;
- Add new catch data for 2022 and update historical catches;
- Add weight-at-age data for 2022 and update historical weight-at-age data;
- Add fishery age-composition data for 2022 and update historical fishery age-composition data.

Stock Synthesis version 3.30.20 includes a number of changes since the version used by Edwards et al. (2022). Changes relevant to this assessment include a fix to the forecasting module that ensures weight-at-age information in the first year of the forecast is as specified rather than carried forward from the previous year. This fix was implemented and used in the 2022 assessment for all forecasts provided to management. Additional changes were made to Stock Synthesis to ensure models that use empirical weight-at-age data do not report tables in the output that use growth parameters because even though growth parameters are not used they must still be provided as placeholders in the input files. Adaptations within the Stock Synthesis modeling framework itself had little effect on parameter estimates compared to the 2022 base model and thus no effect on resulting time series (Figure 16).

The update of pre-2022 data occurs because databases are continually updated; this yielded minor adjustments to the data. Samples that were recently aged but not available for the 2022 assessment were included. These changes to pre-2022 data were small enough that they had little impact on the model results and are thus combined with steps that add data from the 2022.

The addition of the 2022 catch data extends the model to the start of 2023. Recruitment estimates and historical stock trajectory were relatively unchanged, and the new data suggest a slight increase in female spawning biomass from 2022 to 2023 (Figure 16). Adding the weight-at-age data for 2022 makes little change, though slightly increases the estimated female spawning biomass (Figure 16).

The final step added the fishery age-composition data for 2022, which shifted the ending year of the deviations in the selectivity parameters from 2021 to 2022. These data had relatively little impact on the historical biomass estimates, but did shift recent recruitment estimates (Figure 16). The estimated 2019 recruitment decreased, while the estimated large 2020 cohort was shifted even larger. The increase in 2020 recruitment contributes to a considerable increase in female spawning biomass by the start of 2023, as these fish are considered mostly mature at the start of 2023. Despite both fishery age compositions and the relative age-1 index pointing towards a strong 2020 cohort, estimates of 2023 female spawning biomass remain highly uncertain, largely due to underlying uncertainty in recent recruitment (Figure 16). Uncertainty related to the 2020 cohort should decrease once these fish have been observed by the acoustic survey and the fishery during 2023.

3.4.2 Assessment model results

Model Fit

Stationarity of the posterior distribution for model parameters was assessed via a suite of standard single-chain and multi-chain diagnostic tests via graphical summaries and interactive web applications (`ShinySTAN`; https://mc-stan.org/users/interfaces/shinystan). Key diagnostic figures are given in Appendix A and now discussed. All estimated parameters showed good mixing during sampling, no evidence for lack of convergence, and acceptable autocorrelation (results for some key parameters are shown in Figures A.1–A.3). Correlation-corrected effective sample sizes were sufficient to summarize the posterior distributions and neither the Geweke nor the Heidelberger and Welch statistics for these parameters exceeded critical values more frequently than expected via random chance (Figure A.4). The Gelman-Rubin multi-chain diagnostic test, which compares within-chain variance to among-chain variance, further indicated that convergence was adequately achieved (examined via `ShinySTAN`). Correlations among key parameters were generally low, with the exception of M and $\log R_0$ (Figure A.5). Estimates of recruitment in 2014 and 2016 were correlated with the derived quantity of catch from the default harvest rule in 2023, as to be expected given the dependencies among these quantities (Figure A.5). An examination of deviations in recruitment (log-scale differences between estimated and expected recruitment values) from recent years (Figure A.6) indicates the highest correlation (0.92) was between the 2014 and 2016 recruitment deviations. This is an increase in correlation relative to the last assessment despite the fact that each cohort has been observed for an additional year.

Regarding the Dirichlet-multinomial parameter θ_{fish}, the estimate (median and 95% credible interval) for $\log\theta_{\text{fish}}$ is -0.629 (-0.826, -0.43), giving an effective sample size multiplier $\theta_{\text{fish}}/(1+\theta_{\text{fish}})$ of 0.348 (0.304, 0.394). The related survey age-composition parameter θ_{surv} has $\log\theta_{\text{surv}}$ estimated as 2.595 (1.42, 4.764), and the resulting effective sample size multiplier $\theta_{\text{surv}}/(1+\theta_{\text{surv}})$ of 0.931 (0.805, 0.992).

The base model fit to the acoustic survey biomass index (Figure 17) remains similar to the 2022 base model, which is not surprising given no new survey information is available for this assessment. For the 2022 base model the 2021 survey biomass estimate resulted in a slight upward shift in the fit to the 2019 survey data points, but the result of a relatively stable biomass trend from 2013–2019 remained unchanged from the previous assessment. At the time, the addition of the 2021 fishery data was the main reason for this change in fit to the 2019 data point. The 2021 survey estimate was lower than in 2019 (second lowest since 2013), and the model fit indicates a slight decline in biomass from 2019 to 2021. The 2001 survey biomass index continues to be well below any model predictions that were evaluated, and no direct cause for this is known. The survey did begin earlier that year than all other surveys between 1995 and 2009 (Table 12), which may explain some portion of the anomaly, along with El Niño conditions and age structure. The underestimation of the 2009 biomass estimate is larger than the underestimation of any other year. The uncertainty of this point (both modeled and actual) is high because of the presence of large numbers of Humboldt Squid during the survey. Humboldt Squid have similar target strength to hake which could introduce bias in the biomass estimate for that year, and which also likely influenced hake population dynamics through predation in that year.

The median posterior density estimates from the fit to the survey were less than the 2015 survey index, greater than the 2017 and 2019 survey indices, and closely fit the 2021 index (Figure 17). This is likely due to slight differences in what the fishery composition data and survey composition data, when considered independently, would otherwise suggest as population trends. Additionally, the population has undergone recent high, but declining, catch levels and produced a couple of above-average cohorts that are now mature.

The base model fit to the index of age-1 fish highlights an overall general confirmation of relative cohort strength (Figure 18). In particular, the 2008 and 2014 cohorts were estimated to be less than the index, while the 1994 and 2016 cohorts were estimated to be larger than indicated by the index. The age-1 fish in 2011 (the large 2010 cohort) was closely fit. Age-1 fish in 2021 (2020 cohort) were estimated slightly above the index value and, being so young, include a large amount of uncertainty. The model indicates that the 2020 cohort may be similar in size to the 2014 cohort, based on information in the age-1 index, age-1 fish caught in the 2021 fishery, and from age-2 fish caught in the 2022 fishery. The high age-1 survey index from 2021 is largely in concurrence with oceanographic conditions, as summarized in NOAA's annual Ecosystem Status Report of the California Current (Harvey et al., 2021). Recruitment is generally impacted by oceanographic conditions both during maternal preconditioning and during egg and larval stages. During maternal preconditioning (spring-fall, 2019) upwelling conditions were variable but near average (Harvey et al., 2020). Weaker upwelling conditions are associated with higher Pacific Hake recruitment during this phase (Vestfals et al., under review). During egg and larval phases (2020), ocean conditions were broadly associated with high productivity across many taxa (Harvey et al., 2021). These conditions were marked by strong winter upwelling which brings nutrients to coastal waters, cooler temperatures, an energy-rich copepod community, and high productivity of krill, a key food source for Pacific Hake (Buckley and Livingston, 1997; Harvey et al., 2021).

Fits to the age-composition data continue to show close correspondence to the dominant and small cohorts observed in the data when the data give a consistent signal (Figure 19). Because of the time-varying fishery selectivity, the fit to commercial age-composition data is particularly good, although models with time-invariant selectivity used in previous years also fit the age compositions well. In the 2022 fishery, the 2020 cohort was the largest (33%), followed by the 2016 cohort (24%), and then the 2014 cohort (16%). Age compositions from the 2021 acoustic survey suggest a similar age structure for older fish. The 2020 cohort has not yet been observed by the acoustic survey. Combined, the 2015–2022 fishery age-composition data and the 2017–2021 acoustic survey age-composition data suggest that 2014 was a strong recruitment year, and the model was able to adequately fit to these observations (Figure 19). The 2016 cohort, which has been observed twice by the survey, still appears to be smaller than the 2014 cohort. The 2021 survey was the first to sample the 2019 cohort, confirming that it was not large (8.0% of the 2021 survey catch). The 2020 cohort, which has been observed twice by the fishery, once by the age-1 index, but not the acoustic survey is currently expected to be above average in size. Residual patterns to the fishery and survey age data do not show patterns that would indicate systematic bias in model predictions (Figure 20).

The median estimates for numbers, biomass, exploitation rate, and catch (in numbers and in biomass) for each age class in each year are given in Tables 18-22. For the major cohorts, the resulting estimated age-specific catch, natural mortality, and surviving biomasses are given in Table 23. For example, the catch weight of the 2014 cohort at age-5 was slightly less than that of the

2010 cohort at age-5 and the resulting surviving biomass of the 2014 cohort was approximately half of the surviving biomass of the 2010 cohort.

Posterior distributions for both steepness and natural mortality are influenced by priors (Figure 21). The posterior for steepness is only slightly updated by the data, as expected given the low level of information available to inform steepness as found in previous hake assessments. The posterior of natural mortality, on the other hand, is shifted to the right of the prior distribution and the prior may be constraining the posterior distribution from shifting further. Broadening the prior distribution by increasing the prior standard deviation for the natural mortality parameter is examined in sensitivity runs (see Section 3.8). Other parameters showed updating from diffuse priors to posterior distributions, including θ_{fish} and θ_{surv} (as outlined in Section 2.5.4).

The 2023 base model specified the same level of variation (standard deviation of $\Phi = 1.4$) associated with time-varying fishery selectivity as the 2022 base model, effectively allowing the model flexibility (i.e., a lower penalty on the overall likelihood) to fit to data that suggests high variability among years for each age. This level of variation led to results that remained consistent with the 2021 acoustic survey biomass estimate and gave reasonable fits to the fishery age-composition data, given that there is considerable uncertainty associated with spatial changes in fish availability (due to movement) and recent variability in oceanographic conditions. Estimated selectivity deviations for age-3 and age-4 fish are larger from 2010 to 2012 than in subsequent years until 2020 when the deviation for age-4 was large again (Figures 22 and 23). The median selectivity peaks at age-4 in 2010, 2012 and 2020 and at age-3 in 2011 suggesting targeting (or generally higher availability) of the younger cohorts in those years. This pattern is consistent with the 2008 cohort appearing strong in the fishery age compositions initially, but decreasing in prominence from 2013 onward (Figure 19). Fishery selectivity on age-2 fish was at its highest in 2016. Fishery selectivity for the most recent year was characteristic by a logistic pattern, where selectivity generally increased smoothly from age 3 to a peak at age 6 and older ages (Figure 23). However, age-2 selectivity was slightly higher than for other younger fish, likely as a result of increased availability of the above-average 2020 cohort. Even though the survey selectivity is time invariant, the posterior shows a broad band of uncertainty between ages 2 and 5 (Figure 24). The decline in survey selectivity between ages 3 and 4 may be an artifact of the interaction between large cohorts and the biennial timing of recent surveys, with the 2010, 2014, and 2016 cohorts occurring in the survey at ages 3 and 5 but not age 4. Fishery selectivity is likewise very uncertain (Figures 23 and 24), but in spite of this uncertainty, changes in year-to-year patterns in the estimates are still evident, particularly for age-2, age-3, and age-4 fish, though these patterns might also reflect time-varying mortality processes.

Stock biomass

The base stock assessment model indicates that, since the 1960s, Pacific Hake female spawning biomass has ranged from well below to above unfished equilibrium (Figures 25 and 26 and Tables 24 and 25). The model estimates that it was below the unfished equilibrium in the 1960s, at the start of the assessment period, due to lower than average recruitment. The stock is estimated to have increased rapidly and was above unfished equilibrium in the mid-1970s and mid-1980s (after two large recruitments in the early 1980s). It then declined steadily to a low in 1999. This was followed by a brief increase to a peak in 2002 as the very large 1999 year class matured. The 1999 year class largely supported the fishery for several years due to relatively small recruitments between 2000 and 2007. With the aging 1999 year class, median female spawning biomass declined throughout the late 2000s, reaching a time-series low of 0.619 million t in 2010. The assessment model estimates that median spawning biomass then peaked again in 2013 and 2014 due to a very large 2010 year class and an above-average 2008 year class. The subsequent decline from 2014 to 2016 is primarily from the 2010 year class surpassing the age at which gains in weight from growth are greater than the loss in weight from mortality (growth-mortality transition). The 2014 year class is estimated to be large, though not as large as the 1999 and 2010 year classes, resulting in an increased biomass in 2017. The estimated biomass was relatively steady from 2017 to 2019, and then declined in 2020 and 2021 due to the 2014 and 2016 year classes moving through the growth-mortality transition during a period of high catches. The increase in spawning biomass since 2021 is due to the expected above average 2020 cohort entering maturity and the recent declining trend in catch.

The median estimate of the 2023 relative spawning biomass (spawning biomass at the start of 2023 divided by that at unfished equilibrium, B_0) is 104%. However, the uncertainty is large, with a 95% posterior credibility interval from 42% to 300% (Tables 24 and 25), due to remaining unknowns about the size of the 2020 cohort (e.g., not yet sampled by the acoustic survey).

The median estimate of the 2023 spawning biomass is 1.910 million t (with a 95% posterior credibility interval from 0.757 to 5.610 million t). The current estimate of the 2022 female spawning biomass is 1.424 (0.716–3.081) million t. This is a somewhat higher median and broader credibility interval than the 1.171 (0.584–2.585) million t estimated in the 2022 assessment, but there is considerable overlap of the credibility intervals. The increase appears to be due to the addition of 2022 fishery age composition data, which suggests the 2020 cohort may be larger than the age-1 index alone was indicating in the last assessment (as outlined in Section 3.4.1).

Recruitment

The new data for this assessment do not significantly change the pattern of recruitment estimated in recent assessments. However, estimates of absolute recruitment for the most recent years can change with new data. For example, this assessment's median estimate of the 2020 recruitment is 6.2 billion fish higher than in the last assessment (a 118% increase). Similarly, estimates for 2019 and 2021 recruitments have changed by -39% (-0.4 billion fish) and -52% (-0.5 billion fish), respectively, but the general notion remains that recent recruitment is highly uncertain.

Pacific Hake appear to have low average recruitment with occasional large year-classes (Figures 27 and 28, Tables 24 and 25). Very large year classes in 1980, 1984, and 1999 supported much of the commercial catch from the 1980s to the mid-2000s. From 2000 to 2007, estimated recruitment was at some of the lowest values in the time series, but this was followed by an above average 2008 year class. The very strong 2010 year class comprised 64% of the coast-wide commercial catch in 2014, 32% of the 2016 catch, 23% of the 2018 catch, 15% of the 2020 catch, and 6% of the 2022 catch. The decline from 2014 to 2016 was partly due to the large influx of the 2014 year class

(51% of the 2016 catch was age-2 fish from the 2014 year class; this was larger than the proportion of age-2 fish, 41%, from the 2010 year class in 2012).

The current assessment also estimates a strong 2014 year class (Figure 29) comprising 51% of the 2016 catch, 38% of the 2017 catch, 27% of the 2018 catch, 33% of the 2019 catch, 31% of the 2020 catch 25% of the 2021 catch, and 16% of the 2022 catch. The 2016 cohort also appears to be above average, comprising 26% of the 2018 catch, 21% of the 2019 catch, 36% of the 2020 catch, and 34% of the 2021 catch, and 24% of the 2022 catch. The absolute size of the 2014 year class has now stabilized after observations across eight years of fishery observations and three acoustic surveys. The 2016 year class is estimated to be above average (similar in size to the 2008 year class) from six years of fishery data and two years of survey data. Since 2020, the model currently estimates small 2011, 2013, 2015, 2018, 2019, and 2021 year classes (median recruitment well below the mean of all median recruitments) and near average 2012 and 2017 year class. With the addition of the age-1 index, there is information beyond just fishery encounters in the data to estimate the size of the 2020 year class. Collectively, these data indicate that the 2020 year class is likely well above average. The much smaller 2019 year class is informed by the 2021 biomass index and fishery data, but has no age-1 index, and the 2021 year class is only informed by fishery data. There is no information in the data to estimate the sizes of the 2022 and 2023 year classes. Retrospective analyses of year class strength for young fish have shown the estimates of recent recruitment to be unreliable prior to at least model age-3 (observed at age-2) without a survey in the most recent year and age-2 (observed at age-1) with a survey. While the 2020 cohort was observed by the age-1 index in 2021, it will not be observed by the acoustic survey until 2023.

From Figure 27 it looks as though the 2014 recruitment could be as large as the 2010 recruitment. However, the assessment model estimates a 0% chance that this could be the case. The overlapping of the credible intervals in Figure 27 is because large MCMC estimates of 2010 recruitment are associated with large estimates of 2014 recruitment (presumably with large estimates of R_0). By scaling all recruitments by the 2010 recruitment, Figure 30 provides an intuitive way to compare recruitment across years (see Appendix H of Edwards et al. 2022 for motivation and full methods). It shows that there have only been two historical recruitment events (1980 and 1984) that might be as large as in 2010, whereas Figure 27 suggests that 1970, 1999 and 2014 could also possibly be larger than in 2010, giving an over-optimistic impression of how often we can expect cohorts the size of the 2010 cohort to occur. The 2020 cohort is still very uncertain but has a 26% chance of exceeding the 2010 cohort, while the 2021 cohort is definitely smaller than the 2010 cohort (Figure 30). Participants in the Pacific Hake process have an intuition that the 2010 is a very large recruitment event – Figure 30 shows how it is the largest for at least 30 years, and that such large cohorts are rarer than is inferred from Figure 27.

The estimated recruitments with uncertainty for each year and the overall stock recruit relationship are provided in Figure 31. Extremely large variability about the expectation and about the joint uncertainty of individual recruitment and spawning biomass pairs are evident. High and low recruitments have been produced throughout the range of observed spawning biomass (Figure 31). The standard deviation of the time series of median recruitment deviation estimates for the years 1970–2021, which are informed by the age compositions and the age-1 index, is 1.72.

Exploitation status

The median estimated relative fishing intensity on the stock is below the $\mathrm{SPR}_{40\%}$ target for all years (Figure 32 and Tables 24 and 25). It was close to the target in 2008 and 2010, but harvest in those years did not exceed the catch limits that were specified, based on the best available science and harvest control rules in place at the time. Exploitation fraction (catch divided by biomass of fish of age-2 and above) has shown relatively similar patterns (Figure 33 and Tables 24 and 25). Although displaying similar patterns, the exploitation fraction does not necessarily correspond to fishing intensity because fishing intensity more directly accounts for the age-structure of both the population and the catch. Median relative fishing intensity is estimated to have declined from 91.0% in 2010 to 43.8% in 2015, and then it leveled off around 70% from 2016 to 2019 before declining to 50.7% in 2022.. The median exploitation fraction has increased from a recent low of 0.05 in 2012 to 0.12 in 2017 where it remained relatively stable before dropping back to 2012–2015 levels in 2022. Although there is a considerable amount of imprecision around these recent estimates due to uncertainty in recruitment and spawning biomass, the 95% posterior credibility interval of relative fishing intensity was below the SPR management target from 2012 through 2016 and again from 2019 to 2022 (Figure 32). The median estimate for 2017 and 2018 is below the management target though the 95% posterior credibility interval does include the target level.

Management performance

Over the last decade (2013–2022), the mean coast-wide utilization rate (i.e., proportion of catch target removed) has been 67.1% and catches have been below coast-wide targets (Table 3). From 2018 to 2022, the mean utilization rates differed between the United States (71.4%) and Canada (57.1%). In 2015, the utilization rate for the coast-wide fishery was the lowest of the previous decade (44.1%) due, in part, to difficulties locating aggregations of fish and possibly economic reasons. Before 2015, the underutilization in the United States was mostly a result of unrealized catch in the tribal apportionment, while reports from stakeholders in Canada suggested that hake were less aggregated in Canada and availability had declined. In 2016, the utilization rate increased but remained below pre-2015 levels, despite the total 2016 catch being one of the highest of the preceding years. This is in large part due to increasing catch targets as biomass continues to increase. While the total utilization rate between 2017–2021 was relatively steady and close to the average over the last decade (67.1%), it decreased in 2022 to 58.8%. This is primarily due to the utilization rate in Canada declining since 2020 to a time-series low of 20.3% in 2022. Country-specific quotas (or catch targets) in 2020 and 2021 were specified unilaterally, due to the lack of an agreement on coast-wide 2020 and 2021 TACs. The usual 73.88% and 26.12% allocation of coast-wide TAC, as specified in the Joint U.S.-Canada Agreement for Pacific Hake, was once again implemented in 2022. Total landings last exceeded the coast-wide quota in 2002 when utilization was 112%.

As noted above, the median relative fishing intensity was below target in all years. The median relative spawning biomass was above the $B_{40\%}$ reference point in all years except 2007–2010 (Table 24 and Figure 26). These are also shown on a phase plot of the joint history of relative spawning biomass and relative fishing intensity (Figure 34). Relative spawning biomass increased from the lows in 2007–2010 with above average recruitment in 2008, 2010, 2014, 2016, 2017, and 2020. Correspondingly, relative fishing intensity has remained well below target, and total catch has been declining since the time series high in 2017. While there is large uncertainty in the 2022 estimates of relative fishing intensity and relative spawning biomass, the model estimates a 0.1% joint probability of being both above the target relative fishing intensity in 2022 and below the $B_{40\%}$ relative spawning biomass level at the start of 2023.

3.5 MODEL UNCERTAINTY

The base assessment model integrates over the substantial uncertainty associated with several important model parameters including: biomass index and age-1 index catchabilities (q_b and q_1, respectively), the magnitude of the stock (via the R_0 parameter for equilibrium recruitment), productivity of the stock (via the steepness parameter, h, of the stock-recruitment relationship), the rate of natural mortality (M), annual selectivity for key ages, recruitment deviations, and survey and fishery data weights (via the Dirichlet-multinomial parameters θ_{fish} and θ_{surv}).

The medians of the key parameters from the posterior distribution are similar to those in last year's base model (Table 26). The largest change was a doubling of the 2020 cohort size. Medians of some of the derived quantities also change somewhat; in particular, recruitment in 2019 and 2015 decreased (39% and 11%, respectively) from those estimated in the 2022 assessment.

The Pacific Hake stock displays a very high degree of recruitment variability, perhaps the largest of any west coast groundfish stock, resulting in large and rapid biomass changes. This volatility, coupled with a dynamic fishery that potentially targets strong cohorts (resulting in time-varying selectivity) will in most circumstances continue to result in highly uncertain estimates of current stock status and even less-certain projections of the stock trajectory. This is particularly true for spawning biomass estimates in 2023 and throughout the current forecast period, because there is considerable uncertainty associated with the size of the 2020 year class, now mostly mature, that propagates into forecasts. Further observations of this year class, including during the 2023 acoustic survey, will help to refine these estimates and reduce uncertainty. The addition of the age-1 index in this assessment will, in some cases, help to reduce this uncertainty (as it currently does in this case; see Figure 45 discussed later). However, further work is needed to improve upon the characterization of uncertainty in the age-1 index itself, which is based on a time invariant assumption about index observation error and catchability.

Uncertainty measures in the base model underestimate the total uncertainty in the current stock status and projections, because they do not account for alternative structural models for hake population dynamics and fishery processes (e.g., recruitment, selectivity, or spatial fleet or population structure), the effects of alternative data-weighting choices, survey catchability, and the scientific basis for prior probability distributions. To address structural uncertainties, the JTC investigated a range of alternative models, and we present the key sensitivity analyses along with other informative sensitivity analyses using full MCMC results (Section 3.8).

The JTC continues to be committed to advancing MSE analyses, by coordinating research with the Pacific Hake MSE Working Group and other scientists in the region engaged in similar research. Incorporating feedback from the Working Group and stakeholders will ensure that operating models will be able to provide insight into the important questions defined by interested parties. Specifically, the development of MSE tools will evaluate major sources of uncertainty relating to data, model structure and the harvest policy for this fishery, and will compare potential methods to address them. In the coming years, this will include a host of research evaluations (see Section 3.3 and Section 4), including evaluating the utility of incorporating environmentally-driven age-0 recruitment indices into the stock assessment.

3.6 REFERENCE POINTS

The term ‘reference points’ is used throughout this document to describe common conceptual summary metrics. The Agreement specifically identifies $F_{\text{SPR}=40\%}$ as the default harvest rate and $B_{40\%}$ as a point where the 40:10 TAC adjustment is triggered (see the Glossary in Appendix C).

We report estimates of the base reference points (e.g., $F_{\text{SPR}=40\%}$, $B_{40\%}$, B_{MSY}, and MSY) with posterior credibility intervals in Table 27. The median of the female spawning biomass at $F_{\text{SPR}=40\%}$ (namely the median of $B_{\text{SPR}=40\%}$) and the median yield at $F_{\text{SPR}=40\%}$ have remained about the same as estimates in the 2022 assessment (Table 26).

As part of the DFO Sustainable Fisheries Framework, DFO (2009) defined a limit reference point as being a biomass below which serious harm is believed to be occurring to the stock, and an upper stock reference point above which the stock is considered to be healthy. These would equate to the Agreement reference points of $B_{10\%}$ and $B_{40\%}$ (the female spawning biomass being 10% and 40%, respectively, of the unfished equilibrium female spawning biomass). The probabilities of the female spawning biomass at the start of 2023 being above each of these points are $\text{P}(B_{2023} > B_{10\%}) = 100\%$ and $\text{P}(B_{2023} > B_{40\%}) = 98.1\%$ [in last year’s assessment the equivalent calculation was $\text{P}(B_{2022} > B_{40\%}) = 90.5\%$], such that the stock is estimated to be in the ‘healthy zone’ (above the upper stock reference point of $B_{40\%}$). Note that a probability of ‘100%’ (or ‘0%‘) is based on the MCMC results, and is not meant to imply that something definitely occurs (or definitely does not occur).

With respect to DFO’s provisional limit reference point of $0.4B_{\text{MSY}}$ and provisional upper stock reference point of $0.8B_{\text{MSY}}$, the probabilities are $\text{P}(B_{2023} > 0.4B_{\text{MSY}}) = 100\%$ and $\text{P}(B_{2023} > 0.8B_{\text{MSY}}) = 99.9\%$ such that the stock is estimated to be in the provisional ‘healthy zone’. For completeness, we note that $\text{P}(B_{2023} > B_{\text{MSY}}) = 99.8\%$

Reference levels of stock status that are used by the U.S. Pacific Fisheries Management Council (PFMC) for Pacific Hake include $B_{40\%}$ and a Minimum Stock Size Threshold (MSST) of $B_{25\%}$. For 2023, the estimated posterior median relative spawning biomass is 104%, such that the spawning biomass is well above $B_{40\%}$ and $B_{25\%}$. The probability that spawning biomass at the beginning of 2023 is above $B_{40\%}$ is $\text{P}(B_{2023} > B_{40\%}) = 98.1\%$ (as noted above), and of being above $B_{25\%}$ is $\text{P}(B_{2023} > B_{25\%}) = 99.9\%$.

3.7 MODEL PROJECTIONS

The catch limit for 2023 based on the default $F_{\text{SPR}=40\%}$–40:10 harvest policy has a median of 778,008 t and a wide range of uncertainty (Figure 35), with the 95% credibility interval being 301,205–2,136,434 t.

Decision tables give projected population status (relative spawning biomass) and relative fishing intensity under different catch alternatives for the base model (Tables 28 and 29). The tables are organized such that the projected outcome for each potential catch level and year (each row) can be evaluated across the quantiles (columns) of the posterior distribution. The tables use the new format demonstrated by Johnson et al. (2021) arising from discussions at the 2021 SRG meeting. Table 28 shows projected relative spawning biomass outcomes, and Table 29 shows projected fishing intensity outcomes relative to the 100% target (based on SPR; see table legend).

Population dynamics and governing parameters assumed during the forecast period include random recruitment; selectivity, weight-at-age and fecundity averaged over the five most recent years (2018–2022); and all estimated parameters constant (at their estimates for each particular MCMC sample).

Relative fishing intensity exceeding 1 (or 100% when shown as a percentage) indicates fishing in excess of the $F_{\text{SPR}=40\%}$ default harvest rate limit. This can happen for the median relative fishing intensity in 2023, 2024 and 2025 because the $F_{\text{SPR}=40\%}$ default harvest-rate catch limit is calculated using baseline selectivity-at-age (1966–1990; prior to time-varying deviations), whereas the forecasted catches under the default harvest-rate are removed using selectivity averaged over the last five years. Recent changes in selectivity could be reflected in the projection of over- or under-fishing relative to the desired $F_{\text{SPR}=40\%}$ rate.

Key management metrics are presented for 2024, 2025 and 2026 projections (Tables 30–32 and Figures 36–39). These metrics summarize the probability of various outcomes from the base model given each potential management action. Although not linear, probabilities can be interpolated from this table for intermediate catch values in 2023 (Table 30 and Figure 37). However, interpolation may not be applicable for all catches in 2024 and 2025 because they are conditional on previous year(s) catch levels. This explains why a few probabilities decline (rather than rise) with increased 2024 and 2025 catch levels in Tables 31 and 32 and Figures 38 and 39.

Figure 36 shows the projected relative spawning biomass trajectory through 2026 for several of these management actions. With zero catch for the next three years, the biomass has a 50% probability of decreasing from 2023 to 2024 (Table 30 and Figure 37), a 73% probability of decreasing from 2024 to 2025 (Table 31 and Figure 38), and a 68% probability of decreasing from 2025 to 2026 (Table 32 and Figure 39).

The probability of the spawning biomass decreasing from 2023 to 2024 is above 72% for all non-zero catch levels examined (Table 30 and Figure 37). It is 81% for the 2023 catch level similar to that for 2022 (catch alternative f). For all explored catches, the maximum probability of the spawning biomass dropping below $B_{10\%}$ at the start of 2024 is near 0%, at the start of 2025 is 1%, and at the start of 2026 is 4% (Tables 30–32 and Figures 37–39). The similar maximum probability of dropping below $B_{40\%}$ at the start of 2024 is 10%, at the start of 2025 is 24%, and at the start of 2026 is 35%. As the large 2010, 2014, and 2016 cohorts continue to age, their biomass is expected to decrease as losses from mortality continue to outweigh increases from growth. The estimated above-average 2020 cohort has already begun to play a large role in determining female spawning biomass during the forecast years presented here.

It should be noted that forecasted biomass is not only influenced by catch levels. As the large 2010 and 2014 cohorts continue to age, their biomass will continue to decrease (Tables 19 and 23) as losses from mortality outweigh increases from growth. The smaller above-average 2016 cohort entered this growth-mortality transition period around 2019 (Tables 19 and 23). The below-average 2015 and 2018 cohorts will contribute much less to forecasted spawning biomass than the larger cohorts. During 2023, the age-3 2020 cohort will likely move through the growth-mortality transition and thus no longer contribute to an increase in total biomass (note that fecundity will increase which will influence the exact change in spawning biomass, Figure 12).

The age composition (in numbers) of the catch in 2023 is projected to be (using MCMC medians) 38% age-3 fish from the 2020 cohort, 17% age-7 fish from the 2016 cohort, 12% age-6 fish from the 2017 cohort, 11% age-9 fish from the 2014 cohort, and only 5% age-13 fish from the large 2010 cohort (Figure 40). However, those estimates are highly uncertain with the 95% credibility interval for the age-3 fraction spanning 11%–74%.

Due to the higher average weight of older fish compared to younger fish, the median expected proportion of the 2023 catch by weight is 32% for the age-3 2020 cohort (compared to 38% by numbers) and 19% for the age-7 2016 cohort (compared to 17% by numbers; Figure 40).

With respect to the DFO reference points, with the largest 2023 catch of 778,008 t given in Table 30, at the start of 2024 the stock is expected to be above the critical zone with a probability of $\mathrm{P}(B_{2024} > B_{10\%}) = 100\%$ and in the healthy zone with a probability of $\mathrm{P}(B_{2024} > B_{40\%}) = 90\%$. With respect to the DFO provisional reference points (based on B_{MSY}), the stock is expected to be above the provisional critical zone with a probability of $\mathrm{P}(B_{2024} > 0.4B_{\mathrm{MSY}}) = 100\%$, in the healthy zone with a probability of $\mathrm{P}(B_{2024} > 0.8B_{\mathrm{MSY}}) = 99\%$, and above B_{MSY} with a probability of $\mathrm{P}(B_{2024} > B_{\mathrm{MSY}}) = 97\%$ for this catch.

With respect to PFMC stock size reference points, a level of 2023 catch consistent with the Agreement default harvest control rule (778,008 t) has a 10% estimated probability of resulting in the biomass going below $B_{40\%}$ at the start of 2024 (and 2% probability of going below $B_{25\%}$; Table 30). If catches in 2023 and 2024 are the same as in 2022 (325,000 t, catch scenario f) then the probability of the biomass going below $B_{40\%}$ is 4% for the start of 2024 and 9% for the start of 2025.

3.8 SENSITIVITY ANALYSES

Sensitivity analyses were conducted to investigate influence of data inputs and structural uncertainty of the base model by investigating how changes to the model affected the estimated values and derived quantities. All sensitivity analyses compared MCMC posteriors that were created using the `adnuts` R package (Monnahan and Kristensen, 2018; Monnahan et al., 2019) to implement the NUTS algorithm with a similar number of posterior samples as the base model. Several key underlying structural model assumptions were identified that have persisted across many previous hake assessments, and thus warrant revisiting annually as a set of reference sensitivity examinations to new base models. Many additional sensitivity runs were conducted when developing and testing the 2023 base model. Here we focus on the main sensitivities which, relative to the base model, are:

1. Consideration of higher standard deviations on the prior distribution for natural mortality;
2. Consideration of an alternative prior distribution (mean and standard deviation) for natural mortality based on the Hamel (2015) and Hamel and Cope (2022) life history meta-analytic method;
3. Consideration of an alternative prior distribution and a fixed value for steepness, to change the resiliency of the stock;
4. Assumption of higher and lower variation about the stock-recruitment curve (σ_r);
5. Removal of the age-1 index as a data source;
6. Downweighting the fishery age-composition data;
7. Consideration of alternative standard deviations for time-varying selectivity;
8. Consideration of an alternative maximum age for fishery and survey selectivity; and
9. Add the constraint that recruitment deviates must sum to zero.

Comparisons of the parameter estimates between the main sensitivity models with those from the base model are shown in Tables 33–34. None of the sensitivities resulted in any substantial departure from the main population dynamics of the base model. All sensitivity models showed large estimated increases in spawning biomass in the early- to mid-2010s that continues to be driven by the 2010, 2014, and 2016 cohorts, followed by several years of steady decline (2019–2021) before increasing again due to the strong 2020 cohort. All sensitivity models indicate that 2023 relative spawning biomass is above $B_{40\%}$. The overall scale of the population was impacted by various alternative assumptions, and the highly uncertain size of the recent cohorts were more variable across sensitivity analyses than earlier cohorts which have been observed for more years.

The standard deviation of the prior distribution on natural mortality was increased from the base model value of 0.1 to 0.2 and 0.3. The median of the MCMC posteriors for natural mortality increased from 0.233 with a 95% credible interval of 0.193–0.277 for the base model (prior standard deviation of 0.1) to 0.308 with a 95% credible interval of 0.240–0.357 for the sensitivity run with the prior standard deviation set to 0.3 (Table 33). The Hamel and Cope (2022) prior model estimated natural mortality at 0.314 with a 95% credible interval of 0.246–0.362 (Table 33). In addition to allowing a higher estimated value for natural mortality, these M sensitivity models increased the overall scale of the population, the estimated stock status relative to B_0 prior to 1990, the uncertainty in spawning biomass on both absolute and relative scales, halved estimated relative fishing intensity in 2022, and doubled equilibrium yield at $B_{\text{SPR}=40\%}$ (Table 33 and Figures 41 and 42).

The mean of the prior distribution on steepness was decreased from 0.777 (base) to 0.5 and, separately, steepness was fixed at 1.0. The decrease in the mean of the prior resulted in a decrease in the MCMC estimate of steepness from a median of 0.808 with a 95% credible interval of 0.559–0.958

to a median of 0.540 with a 95% credible interval of 0.348–0.758 (Table 33). However, neither steepness sensitivity analysis had a large impact on the overall model results (Figures 41 and 42), because Pacific Hake spawning biomass has remained above levels where changes in steepness would appreciably influence stock-recruit dynamics (Figure 31).

The value of σ_r was changed from a value of 1.40 (base) to alternative high (1.60) and low (1.00) states. Both sensitivities resulted standard deviations of the estimates of recruitment deviations from the period with the most informative data that were higher than the input σ_r, i.e., 1.58 and 1.91 when σ_r was 1.00 and 1.60, respectively. However, the high σ_r model had a larger difference between the female spawning biomass at unfished equilibrium and the female spawning biomass at the initial year of the model than the low σ_r model (Figure 42). Similar to previous assessments, estimates of unfished equilibrium recruitment and relative spawning biomass are sensitive to σ_r, whereas absolute estimates of female spawning biomass are relatively insensitive. The method of Methot and Taylor (2011) proposed to tune σ_r was developed in the context of maximum likelihood estimation and not Bayesian inference, where the latter potentially allows for estimating σ_r using random effects, and thus, this proposed tuning method is not used here to tune the fixed input value.

The sensitivity of the base model to the removal of the age-1 index provides a comparative evaluation of how the base model incorporates information about juvenile fish. Compared to the base model, estimates of spawning biomass throughout most of the time series are similar, but do diverge near the end of the time series (Table 33, Figures 43 and 44). The 2023 estimates of relative spawning biomass are 104.1% for the base model (95% credible interval of 42.0–300.2%) and 123.2% for the removal of the age-1 index model (95% credible interval of 36.7–507.0%). This difference is due to the age-1 index providing additional information on recruitment for cohorts associated with recent age-1 indices (i.e., 2018 and 2020 cohorts detected in the 2019 and 2021 age-1 indices). In particular, the base model with the age-1 index suggests that the 2020 year class is estimated to be large, but not as large as the 2021 and 2022 fishery data alone (i.e., removing the age-1 index) would otherwise suggest (Figure 43). Removing the age-1 index led to minor changes in fit to the age-2+ survey biomass index, with 2019 showing a slight improvement and 2021 a deterioration compared to the base model (Figure 46).

The base model includes a Dirichlet-multinomial likelihood component, which uses two estimated parameters to automatically weight each of the fishery and survey age compositions. The base model was compared to a sensitivity model that downweighted the fishery age compositions relative to the survey age compositions. The data weighting used in the sensitivity model was based on the McAllister-Ianelli method. This method requires manual iterative adjustments to the input sample sizes using a derived multiplier. The McAllister-Ianelli method, which was used in assessments prior to 2018 (Table 17), attempts to make the arithmetic mean of the input sample size approximately equal to the harmonic mean of the effective sample size. The McAllister-Ianelli method suggested a weighting factor of 0.14 and 0.46 (ratio of 0.30) for fishery and survey age compositions, respectively. The median estimate from Dirichlet-multinomial method used in the base model was 0.348 and 0.931 (ratio of 0.37). Downweighting fishery composition data using the McAllister-Ianelli method led to minor changes in relative spawning biomass, recruitment estimates, and increased uncertainty in estimates of early recruitments compared to the base model (Figures 44 and 45).

The degree of flexibility of annual variation in the fishery selectivity was tested using three sensitivities which set alternative values of the Φ parameter (Figures 47-51). The consideration of alternative standard deviations (Φ) for time-varying selectivity is discussed earlier in Section 2.5.3. Changing the values of the parameter Φ controlling the flexibility in time-varying selectivity from the base model value of $\Phi = 1.40$ to alternative values of 0.21, 0.70, and 2.10, did not appreciably influence the estimates, or precision, associated with recruitment in 2014, but it did impact more recent recruitments (Figure 49). In particular, recruitment estimates for 2016 and 2020 are linked to the choice of Φ, where the model with the smallest Φ (0.21) estimates the 2016 and 2020 recruitment deviation as the highest of the Φ sensitivity models (Figure 50), leading to a large increase in spawning biomass in recent years compared to the base model (Figure 47). The value $\Phi = 0.21$ also provides the worst fit to the most recent age-2+ survey biomass index (Figure 51).

3.9 RETROSPECTIVE ANALYSES

Retrospective analyses were performed by iteratively removing the terminal years' data (going back 10 years) and estimating the posterior distribution of parameters under the assumptions of the base model. This year's base model shows similar retrospective results to last year's (Figure 53, Edwards et al. 2022). The addition of the age-1 index in last year's base model found estimates of recruitment strength to come closer to the long-term stable estimate by age-2 in some cases compared to the model without the age-1 index (Edwards et al., 2022). However, some cohort recruitments are still over or under-estimated at age-2. Over-estimation can be seen most clearly with the 2014, 2015, 2017, and 2018 cohorts (Figures 53 and 54). The 2014 cohort reached a high deviation after two years, then even higher after three years only to drop back down to a lower value and then stabilize at around age-4 with the addition of more data. A similar pattern can be seen with the smaller 2017 and 2018 cohorts. Even with the addition of new data, the size of the very small 2015 cohort has not fully stabilized. Under-estimation is slight, but apparent, for the 2016 cohort as recruitment estimates have risen since the estimate at age-3. Cohort strength is further informed once at least one year of age-2+ survey biomass index age-composition data are available for a cohort, which for even-numbered recruitment years typically does not occur until the cohort reaches age-3, due to the acoustic survey occurring in odd years; though the age-1 index does provide some information.

The stability of the recruitment estimates seen in this plot is also evident in the uncertainty estimates of each cohort. Uncertainty of the 2016–2019 cohorts has been substantially reduced compared to removing five years of data (Figure 52, bottom figure). However, the uncertainty of the 2020 cohort has actually increased with the addition of another year of fishery data compared to last year's base model. Medians of various quantities of interest are given in Table 36.

Overall, there is little retrospective change to the relative spawning biomass trajectory up to the mid-2010s, and most retrospective change occurs in the final years of the retrospective model with the most years removed (Figure 52). In this assessment, there is very little retrospective bias. Present is slight year-specific positive and negative bias in spawning biomass, some minor adjustments to recruitment deviates, and a slight trend in B_0 as the retrospective year increases.

All of these retrospective differences are well within the range of estimation uncertainty across all retrospective years. There is no indication from retrospective evaluations that the base model is displaying a systematic bias.

A comparison of the actual assessment models used in each year since 1991 is shown in Figure 55. There have been substantial differences in the structural assumptions of the models and, thus, results submitted each year. The variability between model results, especially early on in the time series, is larger than the uncertainty (95% credibility interval) reported from any single model in recent years. Prior to 2004, survey catchability was fixed at 1.0 and this assumption was heavily investigated between 2004 and 2007, leading to variability in model results because of the use of several different, but fixed, values of survey catchability. Since 2008, catchability has been freely estimated by the model. The fixing of survey catchability had the effect of driving the estimate of initial biomass upward, which in turn scaled the entire biomass trajectory up, leading to higher estimates of relative spawning biomass than in more recent assessments. The median estimates of spawning biomass for recent years have remained similar to the previous assessment but declined relative to the 2015–2017 assessments. The difference is most likely related to the recent under-fitting of the 2017 survey estimate of biomass despite the consistency in the structure of the assessment model in recent years. In addition to more information about the 2014 and 2016 cohorts, the 2018 assessment model also included a change in the data weighting method, an update to maturity and fecundity, and a change to selectivity parameterization (Table 17). The uncertainty interval associated with the 2023 assessment brackets the majority of the historical estimates.

The level of uncertainty associated with each assessment's estimate of that year's current spawning biomass (i.e., that used to convey current stock status and inform management advice) changes from assessment to assessment given updates in data and Pacific Hake population structure and dynamics. While uncertainty around the absolute amount of 2023 spawning biomass is the second largest (behind the 2017 assessment) since 2012, the relative amount of dispersion (or variability relative to the stock size; similar to a coefficient of variation) is not inconsistent with previous assessments (Figure 56).

3.10 PERFORMANCE OF PAST PROJECTIONS

Without rigorous simulation experiments it can be difficult to operationally assess the accuracy of projections in stock assessments because the truth is never known with 100% certainty. For Pacific Hake, hindsight comparisons have been conducted since 2021 (Johnson et al., 2021) to evaluate performance of projections provided in decision tables (such as Tables 30 and 31) of past assessments relative to updated assessments. Overall, results indicate that assessment model projections give a relatively good idea of general projected trends and status.

As an example, the 2019 assessment (Berger et al., 2019) gave the estimated probability of the female spawning biomass declining in the subsequent year, i.e., $P(B_{2020} < B_{2019})$, for several possible catches in 2019, such as 0 t, 180,000 t, 350,000 t, 410,000 t etc. Now that we 'know' the catch in 2019 was 412,015 t, we can select the 410,000 t row (close enough to 412,015 t) in the table from the 2019 assessment to give that assessment's $P(B_{2020} < B_{2019}) = 61\%$; Figure 57. We can also calculate this probability from the current assessment model, which implicitly includes the 412,015 t catch from 2019, giving P$(B_{2020} < B_{2019})$ =97%; Figure 57. We extracted similar probabilities from past assessment documents going back to 2012 and calculate analogous probabilities, P$(B_{t+1} < B_t)$, from the current base model (Figure 57); see Edwards et al. (2022) for full methods.

Each assessment correctly predicted whether the stock would increase or decrease the following year (except for 2018 and 2021; Figure 57). Estimates from previous assessments are closer to 50% than those from the current base model (except for 2021; Figure 57), because the current assessment model has more information and thus provides a more definitive probability (closer to 0% or to 100%) than year t's assessment model. It is desirable that the probabilities from the assessment documents are not too definitive (too close to 0% or to 100%), because they are admitting a wide range of uncertainty given unknown recent recruitments.

The 2018 and 2021 assessments 'incorrectly' projected the stock would likely decline the following year (given the catch that subsequently occurred), because the current assessment model estimates a likely increase (Figure 57). In 2018, this occurred because the biomass trend was relatively flat (Figure 25) so even slight changes in biomass could influence binomial outcomes of an 'increase' or 'decrease' in biomass, despite the overall change in biomass not being very substantial. The 2021 assessment (Johnson et al., 2021) had no information on the 2020 cohort and predicted the biomass would probably decline in 2022 even with zero catch in 2021. However, the current assessment estimates that the 2020 cohort was particularly large, which highlights how impactful a realized large deviation from average recruitment (rather than assuming average recruitment) can be on forecasted outcomes. Similarly, the 2012 assessment had no information on the very large 2010 recruitment, and so also over-estimated the probability of decline the following year (Figure 57).

A range of catch alternatives are shown for the current assessment because realized 2023 catches are not yet known (Figure 57). Catching zero fish in 2023 gives the lowest probability that the stock will decline from 2023 to 2024, with any realistic 2023 catch leading to a likely decline in spawning biomass given current information.

A similar approach was used to calculate the probability of the biomass falling below $B_{40\%}$ in the subsequent year, i.e., P$(B_{t+1} < B_{40\%})$; Figure 58. The 2012 assessment was the only one that gave a $>$ 50% chance of the biomass falling below $B_{40\%}$ in the subsequent year, but later data determined that the 2010 year class was indeed substantial and so in hindsight the probability of going below $B_{40\%}$ was 0% (based on the current assessment). Since the 2018 assessment, the estimated probabilities of the biomass falling below $B_{40\%}$ were $>$ 10% and continued to rise (Figure 58), until falling due to the incoming 2020 cohort. Note that the biomass has been relatively high during the time period shown, so 'correctly expecting' the biomass to remain $> B_{40\%}$ may not be a particular high bar to attain.

Restrospective versions of Figures 57 and 58 are calculated using the current base model but with data only up to a certain year (Figures 59–64). While there are some minor exceptions, the retrospective probabilities of decline (colored squares in Figures 59–63) are generally close to the probabilities currently estimated using all available data (blue triangles). An exception is

$P(B_{2016} < B_{2015})$ which is underestimated (compared to the current base model) until data to 2017 are included (the 2015 values in each panel of Figure 60). This is due to the retrospective uncertainty of the 2014 cohort, seen as an increase and then decrease in expected cohort size in Figure 53. The retrospective calculations for $P(B_{t+1} < B_{40\%})$ show little change as more data are added (Figure 64), except for 2015 and 2021 as information becomes available about the strong 2014 and 2020 cohorts. Combined, these results enhance confidence in the projected outcomes from the assessment model.

4 RESEARCH AND DATA NEEDS

There are many research projects that could improve the stock assessment for Pacific Hake. The following prioritized list of topics will lead to improved biological understanding and decision-making:

1. Continue to conduct research to evaluate ways to improve recent, current, and future recruitment estimates for use in stock assessment. This could include the development of time series of recruitment indices, time series of informative environmental or ecosystem variables, and models that have predictive skill (e.g., Vestfals et al, under review). Explorations should also consider options for incorporating information on recruitment into the stock assessment model and the Pacific Hake management framework. For example, time series could be included in the stock assessment as a standalone data source (similar to acoustic survey biomass estimates) or the estimation procedure that was used to generate the time series itself could be integrated directly into the stock assessment model. Results from such work should be connected to or in cooperation with ongoing research related to recruitment variability as discussed in Section 3.3. Related, there is a need to streamline and broaden the availability of products from oceanographic models (e.g., Regional Ocean Modeling System) so that they are available stock-wide (spanning the international boundary) and updated on a recurring basis so they can be used as informative links in operational stock assessments. A successful example of this has been the annual production of Pacific Hake distribution forecasts that depend on short-term (i.e., 6–9 month) forecasts of subsurface (i.e., 100 m depth) temperature from J-SCOPE (http://www.nanoos.org/products/j-scope/home.php). The existing management strategy evaluation framework should be used, or further developed, to examine how information on recruitment can inform robust management decisions.

2. Document the existing survey methodologies, protocols, and adaptive survey-design decisions that lead to the development of Pacific Hake biomass and age-composition estimates and the relative age-1 index used in the stock assessment. Such documentation will ensure transparency, enable repeatability, and provide a record of changes in procedures over time. Also, continue to conduct research to improve the estimation of age composition and abundance from data collected during the acoustic survey. This includes, but is not limited to, research on species identification, target verification, target strength, implications of the south-to-north directionality of the survey, alternative technologies to assist in the survey (e.g., artificial intelligence and machine learning), and efficient analysis methods. The latter should include bootstrapping of the acoustic survey time series or related methods that can incorporate relevant uncertainties into the calculations of survey variance. Rele-

vant uncertainties include topics such as the target-strength relationship, subjective scoring of echograms, thresholding methods, and methods to estimate the species-mix that are used to interpret the acoustic backscatter. Continue to work with acousticians and survey personnel from the Northwest Fisheries Science Center (and, more broadly, those involved with the U.S. Re-Envisioning West Coast Surveys Initiative) and Fisheries and Oceans Canada to determine optimal survey designs given constraints, including designs that incorporate ecosystem-based factors and other potential target species (e.g., rockfish, euphausiids, and mesopelagics) for the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey. The existing management strategy evaluation framework should be used, or further developed, to examine how changes in survey methods can be used to inform robust management decisions.

3. Work with regional partners to develop an annual workflow that provides key metrics, indicators, or other summaries of general ecosystem conditions relevant to the Pacific Hake coast-wide stock. In particular, include those that are potentially associated with Pacific Hake biology and ecology (e.g., recruitment, distribution, predation, prey, and communities). Such information can broaden the context within which a single species stock assessment is interpreted, be used to support model development, refine uncertain assessment conclusions (e.g., productivity), and provide other non-assessment indicators of the system's state to management.

4. Use, build, and expand upon the existing management strategy evaluation framework to evaluate major sources of uncertainty relating to data, model structure, and the harvest policy for this fishery (as needed) and compare potential methods to address them. In particular, utilize and adapt the management strategy evaluation framework to address new and ongoing stock assessment research and data needs through the Pacific Hake Management Strategy Evaluation Working Group, including relevant requests by the Scientific Review Group (see Section 3.3). For example, research investigating links between Pacific Hake biomass, spatial distribution, growth, recruitment, and natural mortality, and how these biological processes vary with ocean conditions and ecosystem variables such as temperature, transport, and prey availability could inform models used in the MSE. Ongoing investigations have the potential to improve the scenarios considered in future work on the management strategy evaluation framework and the basic understanding of drivers of Pacific Hake population dynamics and availability to fisheries and surveys.

5. Complete the ongoing inter-laboratory otolith exchange and use the results to update estimates of ageing error used in the stock assessment. This would include updated information about ageing imprecision and the effects of large cohorts as understood given simulation analyses and blind-source age reads of samples with and without dominant year classes. The last inter-laboratory comparison was done in 2010 ("CARE" exchanges). Related, streamlining procedures that ease the exchange of biological materials (e.g., otoliths) across international borders would increase the efficiency at which research products can be produced.

6. Continue to collect and analyze life-history data, including weight, maturity, and fecundity for Pacific Hake. Explore possible relationships among these life-history traits and correla-

tions with time, empirical growth, and population density. Improve understanding of links between fecundity and size, age, weight, and batch spawning, as well as spatio-temporal variability in the timing of spawning, skip spawning, batch fecundity, and size and age at maturity. Additionally, a more spatially comprehensive maturity analysis that incorporates information from Canadian samples would be advantageous.

7. Explore the operational use of environmental DNA data for characterizing aspects of Pacific Hake population dynamics, such as changes in species distribution or perhaps density, and the incorporation of these data into stock assessments. Recent research demonstrated that environmental DNA provides similar information as the acoustic survey at scales relevant to management, i.e., coast-wide and not just sample-to-sample comparisons (Shelton et al., 2022), but longer time series are needed before the data can be used to inform trends in abundance. Environmental DNA is now available for 2019 and 2021 (two years total). Continuing to extend the time series would allow for its incorporation in future stock assessments as an index of abundance.

8. Explore alternative approaches and related assumptions for parameterizing time-varying fishery selectivity in the assessment. Simulations that evaluate methods for including multiple variance structures, including interactions, tradeoffs, and related assumptions, across multiple processes (e.g., selectivity, recruitment, data weighting) in integrated stock assessment models would be particularly beneficial.

9. Revisit alternative methods for refining existing prior distributions for natural mortality, including the use of meta-analytic methods. Evaluate feasibility of estimating age-specific natural mortality for Pacific Hake.

10. Explore mid-water community dynamics (or predator/prey relationships more generally) to better understand linkages to Pacific Hake distribution, abundance, and growth. For example, weight-at-age data or other mechanistic linkages (e.g., from diet studies) can inform inter-annual variability and trends in growth, which can improve biomass forecasting capabilities for Pacific Hake.

11. Explore the potential to use acoustic data collected from commercial fishing vessels to study Pacific Hake distributions, schooling patterns, and other questions of interest. This could be similar to the “acoustic vessels of opportunity” program on fishing vessels targeting Pollock in Alaska (Stienessen et al., 2019).

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7 TABLES

Table 1. Annual catches of Pacific Hake (t) in U.S. waters by fleet, 1966-2022. Tribal catches are included in the fleet totals. Research catch includes landed catch associated with research-related activities. Catch associated with surveys and discarded bycatch in fisheries not targeting hake is not currently included in the table or model.

Year	Foreign	JV	Mothership	Catcher-Processor	Shore-based	Research	Total
1966	137,000	0	0	0	0	0	137,000
1967	168,700	0	0	0	8,960	0	177,660
1968	60,660	0	0	0	160	0	60,820
1969	86,190	0	0	0	90	0	86,280
1970	159,510	0	0	0	70	0	159,580
1971	126,490	0	0	0	1,430	0	127,920
1972	74,090	0	0	0	40	0	74,130
1973	147,440	0	0	0	70	0	147,510
1974	194,110	0	0	0	0	0	194,110
1975	205,650	0	0	0	0	0	205,650
1976	231,330	0	0	0	220	0	231,550
1977	127,010	0	0	0	490	0	127,500
1978	96,827	860	0	0	690	0	98,377
1979	114,910	8,830	0	0	940	0	124,680
1980	44,023	27,537	0	0	790	0	72,350
1981	70,365	43,557	0	0	838	0	114,760
1982	7,089	67,465	0	0	1,023	0	75,577
1983	0	72,100	0	0	1,051	0	73,151
1984	14,772	78,889	0	0	2,721	0	96,382
1985	49,853	31,692	0	0	3,894	0	85,439
1986	69,861	81,640	0	0	3,432	0	154,932
1987	49,656	105,997	0	0	4,795	0	160,448
1988	18,041	135,781	0	0	6,867	0	160,690
1989	0	195,636	0	0	7,414	0	203,049
1990	0	170,972	0	4,537	9,632	0	185,142
1991	0	0	86,408	119,411	23,970	0	229,789
1992	0	0	36,721	117,981	56,127	0	210,829
1993	0	0	14,558	83,466	42,108	0	140,132
1994	0	0	93,610	86,251	73,616	0	253,477
1995	0	0	40,805	61,357	74,962	0	177,124
1996	0	0	62,098	65,933	85,128	0	213,159
1997	0	0	75,128	70,832	87,416	0	233,376
1998	0	0	74,686	70,377	87,856	0	232,920
1999	0	0	73,440	67,655	83,470	0	224,565
2000	0	0	53,110	67,805	85,854	0	206,770
2001	0	0	41,901	58,628	73,412	0	173,940
2002	0	0	48,404	36,342	45,708	0	130,453
2003	0	0	45,396	41,214	55,335	0	141,945
2004	0	0	47,561	73,176	96,503	0	217,240
2005	0	0	72,178	78,890	109,052	0	260,120
2006	0	0	60,926	78,864	127,165	0	266,955
2007	0	0	52,977	73,263	91,441	0	217,682
2008	0	0	72,440	108,195	67,861	0	248,496
2009	0	0	37,550	34,552	49,222	0	121,324
2010	0	0	52,022	54,284	64,736	0	171,043
2011	0	0	56,394	71,678	102,146	1,042	231,261
2012	0	0	38,512	55,264	65,919	448	160,144
2013	0	0	52,470	77,950	102,141	1,018	233,578
2014	0	0	62,102	103,203	98,640	197	264,141

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Year	Foreign	JV	Mothership	Catcher-Processor	Shore-based	Research	Total
2015	0	0	27,665	68,484	58,011	0	154,160
2016	0	0	65,036	108,786	87,760	745	262,327
2017	0	0	66,428	136,960	150,841	0	354,229
2018	0	0	67,121	116,073	135,112	0	318,306
2019	0	0	52,646	116,146	148,210	0	317,002
2020	0	0	37,978	111,147	138,688	95	287,908
2021	0	0	35,208	104,030	129,319	917	269,473
2022	0	0	59,152	126,247	105,938	0	291,337

Table 2. Annual catches of Pacific Hake (t) in Canadian waters by fleet, 1966-2022.

Year	Foreign	JV	Shoreside	Freezer-Trawler	Total
1966	700	0	0	0	700
1967	36,710	0	0	0	36,710
1968	61,360	0	0	0	61,360
1969	93,850	0	0	0	93,850
1970	75,010	0	0	0	75,010
1971	26,700	0	0	0	26,700
1972	43,410	0	0	0	43,410
1973	15,130	0	0	0	15,130
1974	17,150	0	0	0	17,150
1975	15,700	0	0	0	15,700
1976	5,970	0	0	0	5,970
1977	5,190	0	0	0	5,190
1978	3,450	1,810	0	0	5,260
1979	7,900	4,230	300	0	12,430
1980	5,270	12,210	100	0	17,580
1981	3,920	17,160	3,280	0	24,360
1982	12,480	19,680	0	0	32,160
1983	13,120	27,660	0	0	40,780
1984	13,200	28,910	0	0	42,110
1985	10,530	13,240	1,190	0	24,960
1986	23,740	30,140	1,770	0	55,650
1987	21,450	48,080	4,170	0	73,700
1988	38,080	49,240	830	0	88,150
1989	29,750	62,718	2,562	0	95,029
1990	3,810	68,314	4,021	0	76,144
1991	5,610	68,133	16,174	0	89,917
1992	0	68,779	20,043	0	88,822
1993	0	46,422	12,352	0	58,773
1994	0	85,154	23,776	0	108,930
1995	0	26,191	46,181	0	72,372
1996	0	66,779	26,360	0	93,139
1997	0	42,544	49,227	0	91,771
1998	0	39,728	48,074	0	87,802
1999	0	17,201	70,121	0	87,322
2000	0	15,625	6,382	0	22,007
2001	0	21,650	31,935	0	53,585
2002	0	0	50,244	0	50,244
2003	0	0	63,217	0	63,217
2004	0	58,892	66,175	0	125,067
2005	0	15,695	77,335	9,985	103,014
2006	0	14,319	65,289	15,136	94,744
2007	0	6,780	52,624	14,122	73,526
2008	0	3,592	57,799	13,185	74,576
2009	0	0	44,136	13,223	57,359
2010	0	8,081	35,362	13,573	57,016
2011	0	9,717	31,760	14,596	56,073
2012	0	0	32,147	14,912	47,059
2013	0	0	33,665	18,584	52,249
2014	0	0	13,326	21,792	35,118

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Year	Foreign	JV	Shoreside	Freezer-Trawler	Total
2015	0	0	16,775	22,887	39,662
2016	0	0	35,009	34,724	69,733
2017	0	5,608	43,427	37,686	86,721
2018	0	2,724	50,747	41,942	95,413
2019	0	0	49,275	45,738	95,013
2020	0	0	39,077	53,412	92,489
2021	0	0	16,952	40,123	57,076
2022	0	0	5,050	23,837	28,887

Table 3. Pacific Hake landings and management decisions. A dash (–) indicates the management decision was either not specified or was unknown to the authors at the time of this assessment.

Year	U.S. landings (t)	Canada landings (t)	Total landings (t)	U.S. proportion of total catch	Canada proportion of total catch	U.S. catch target (t)	Canada catch target (t)	Coast-wide catch target (t)	U.S. proportion of catch target removed	Canada proportion of catch target removed	Total proportion of catch target removed
1966	137,000	700	137,700	99.5%	0.5%	–	–	–	–	–	–
1967	177,660	36,710	214,370	82.9%	17.1%	–	–	–	–	–	–
1968	60,820	61,360	122,180	49.8%	50.2%	–	–	–	–	–	–
1969	86,280	93,850	180,130	47.9%	52.1%	–	–	–	–	–	–
1970	159,580	75,010	234,590	68.0%	32.0%	–	–	–	–	–	–
1971	127,920	26,700	154,620	82.7%	17.3%	–	–	–	–	–	–
1972	74,130	43,410	117,540	63.1%	36.9%	–	–	–	–	–	–
1973	147,510	15,130	162,640	90.7%	9.3%	–	–	–	–	–	–
1974	194,110	17,150	211,260	91.9%	8.1%	–	–	–	–	–	–
1975	205,650	15,700	221,350	92.9%	7.1%	–	–	–	–	–	–
1976	231,550	5,970	237,520	97.5%	2.5%	–	–	–	–	–	–
1977	127,500	5,190	132,690	96.1%	3.9%	–	–	–	–	–	–
1978	98,377	5,260	103,637	94.9%	5.1%	130,000	–	–	75.7%	–	–
1979	124,680	12,430	137,110	90.9%	9.1%	198,900	35,000	–	62.7%	35.5%	–
1980	72,350	17,580	89,930	80.5%	19.5%	175,000	35,000	–	41.3%	50.2%	–
1981	114,760	24,360	139,120	82.5%	17.5%	175,000	35,000	–	65.6%	69.6%	–
1982	75,577	32,160	107,737	70.1%	29.9%	175,000	35,000	–	43.2%	91.9%	–
1983	73,151	40,780	113,931	64.2%	35.8%	175,000	45,000	–	41.8%	90.6%	–
1984	96,382	42,110	138,492	69.6%	30.4%	175,000	45,000	270,000	55.1%	93.6%	51.3%
1985	85,439	24,960	110,399	77.4%	22.6%	175,000	50,000	212,000	48.8%	49.9%	52.1%
1986	154,932	55,650	210,582	73.6%	26.4%	295,800	75,000	405,000	52.4%	74.2%	52.0%
1987	160,448	73,700	234,148	68.5%	31.5%	195,000	75,000	264,000	82.3%	98.3%	88.7%
1988	160,690	88,150	248,840	64.6%	35.4%	232,000	98,000	327,000	69.3%	89.9%	76.1%
1989	203,049	95,029	298,079	68.1%	31.9%	225,000	98,000	323,000	90.2%	97.0%	92.3%
1990	185,142	76,144	261,286	70.9%	29.1%	196,000	73,500	245,000	94.5%	103.6%	106.6%
1991	229,789	89,917	319,705	71.9%	28.1%	228,000	98,000	253,000	100.8%	91.8%	126.4%
1992	210,829	88,822	299,650	70.4%	29.6%	208,800	90,000	232,000	101.0%	98.7%	129.2%
1993	140,132	58,773	198,905	70.5%	29.5%	142,000	61,000	178,000	98.7%	96.3%	111.7%
1994	253,477	108,930	362,407	69.9%	30.1%	260,000	110,000	325,000	97.5%	99.0%	111.5%
1995	177,124	72,372	249,495	71.0%	29.0%	178,400	76,500	223,000	99.3%	94.6%	111.9%
1996	213,159	93,139	306,299	69.6%	30.4%	212,000	91,000	265,000	100.5%	102.4%	115.6%
1997	233,376	91,771	325,147	71.8%	28.2%	232,000	99,400	290,000	100.6%	92.3%	112.1%
1998	232,920	87,802	320,722	72.6%	27.4%	232,000	80,000	290,000	100.4%	109.8%	110.6%
1999	224,565	87,322	311,887	72.0%	28.0%	232,000	90,300	290,000	96.8%	96.7%	107.5%
2000	206,770	22,007	228,777	90.4%	9.6%	232,000	90,300	290,000	89.1%	24.4%	78.9%
2001	173,940	53,585	227,525	76.4%	23.6%	190,400	81,600	238,000	91.4%	65.7%	95.6%
2002	130,453	50,244	180,697	72.2%	27.8%	129,600	–	162,000	100.7%	–	111.5%

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Year	U.S. landings (t)	Canada landings (t)	Total landings (t)	U.S. proportion of total catch	Canada proportion of total catch	U.S. catch target (t)	Canada catch target (t)	Coast-wide catch target (t)	U.S. proportion of catch target removed	Canada proportion of catch target removed	Total proportion of catch target removed
2003	141,945	63,217	205,162	69.2%	30.8%	148,200	–	228,000	95.8%	–	90.0%
2004	217,240	125,067	342,307	63.5%	36.5%	250,000	–	514,441	86.9%	–	66.5%
2005	260,120	103,014	363,135	71.6%	28.4%	269,069	95,128	364,197	96.7%	108.3%	99.7%
2006	266,955	94,744	361,699	73.8%	26.2%	269,545	95,297	364,842	99.0%	99.4%	99.1%
2007	217,682	73,526	291,207	74.8%	25.2%	242,591	85,767	328,358	89.7%	85.7%	88.7%
2008	248,496	74,576	323,072	76.9%	23.1%	269,545	95,297	364,842	92.2%	78.3%	88.6%
2009	121,324	57,359	178,683	67.9%	32.1%	135,939	48,061	184,000	89.2%	119.3%	97.1%
2010	171,043	57,016	228,059	75.0%	25.0%	193,935	68,565	262,500	88.2%	83.2%	86.9%
2011	231,261	56,073	287,334	80.5%	19.5%	290,903	102,848	393,751	79.5%	54.5%	73.0%
2012	160,144	47,059	207,203	77.3%	22.7%	186,036	65,773	251,809	86.1%	71.5%	82.3%
2013	233,578	52,249	285,828	81.7%	18.3%	269,745	95,367	365,112	86.6%	54.8%	78.3%
2014	264,141	35,118	299,259	88.3%	11.7%	316,206	111,794	428,000	83.5%	31.4%	69.9%
2015	154,160	39,662	193,822	79.5%	20.5%	325,072	114,928	440,000	47.4%	34.5%	44.1%
2016	262,327	69,733	332,060	79.0%	21.0%	367,553	129,947	497,500	71.4%	53.7%	66.7%
2017	354,229	86,721	440,950	80.3%	19.7%	441,433	156,067	597,500	80.2%	55.6%	73.8%
2018	318,306	95,413	413,719	76.9%	23.1%	441,433	156,067	597,500	72.1%	61.1%	69.2%
2019	317,002	95,013	412,015	76.9%	23.1%	441,433	156,067	597,500	71.8%	60.9%	69.0%
2020	287,908	92,489	380,397	75.7%	24.3%	424,810	104,480	529,290	67.8%	88.5%	71.9%
2021	269,473	57,076	326,549	82.5%	17.5%	369,400	104,480	473,880	72.9%	54.6%	68.9%
2022	291,337	28,887	320,224	91.0%	9.0%	402,646	142,354	545,000	72.4%	20.3%	58.8%

Table 4. Annual summary of U.S. and Canadian fishery sampling included in this stock assessment by fleet. Majority of values are reported as number of hauls but U.S. shore-based and Canadian shoreside fleets are reported as the number of trips. A dash (–) indicates there was no sampled catch. The number of fish with otoliths sampled per haul has varied over time but is typically small.

	U.S.						**Canada**			
Year	**Foreign (hauls)**	**Joint-Venture (hauls)**	**Mother-ship (hauls)**	**Combined Mother-ship Catcher-processor (hauls)**	**Catcher-processor (hauls)**	**Shore-based (trips)**	**Foreign (hauls)**	**Joint-Venture (hauls)**	**Shoreside (trips)**	**Freezer Trawlers (hauls)**
1975	13	–	–	–	–	–	–	–	–	–
1976	142	–	–	–	–	–	–	–	–	–
1977	320	–	–	–	–	–	–	–	–	–
1978	336	5	–	–	–	–	–	–	–	–
1979	99	17	–	–	–	–	–	–	–	–
1980	191	30	–	–	–	–	–	–	–	–
1981	113	41	–	–	–	–	–	–	–	–
1982	52	118	–	–	–	–	–	–	–	–
1983	–	117	–	–	–	–	–	–	–	–
1984	49	74	–	–	–	–	–	–	–	–
1985	37	19	–	–	–	–	–	–	–	–
1986	88	32	–	–	–	–	–	–	–	–
1987	22	34	–	–	–	–	–	–	–	–
1988	39	42	–	–	–	–	–	3	–	–
1989	–	77	–	–	–	–	–	3	–	–
1990	–	143	–	–	–	15	–	5	–	–
1991	–	–	–	116	–	26	–	18	–	–
1992	–	–	–	164	–	46	–	33	–	–
1993	–	–	–	108	–	36	–	25	3	–
1994	–	–	–	143	–	50	–	41	1	–
1995	–	–	–	61	–	51	–	35	3	–
1996	–	–	–	123	–	35	–	28	1	–
1997	–	–	–	127	–	65	–	27	1	–
1998	–	–	–	149	–	64	–	21	9	–
1999	–	–	–	389	–	80	–	14	26	–
2000	–	–	–	413	–	91	–	25	1	–
2001	–	–	–	429	–	82	–	28	1	–
2002	–	–	–	342	–	71	–	–	36	–
2003	–	–	–	358	–	78	–	–	21	–
2004	–	–	–	381	–	72	–	20	28	–
2005	–	–	–	499	–	58	–	11	31	14
2006	–	–	–	549	–	83	–	21	21	46
2007	–	–	–	524	–	68	–	1	7	29
2008	–	–	324	–	356	63	–	–	20	31
2009	–	–	316	–	278	65	–	–	7	19
2010	–	–	443	–	331	75	–	–	8	17
2011	–	–	481	–	506	81	–	2	4	7
2012	–	–	299	–	332	76	–	–	43	101
2013	–	–	409	–	474	96	–	–	10	105
2014	–	–	423	–	557	68	–	–	28	79
2015	–	–	203	–	431	84	–	–	6	74
2016	–	–	502	–	671	76	–	–	75	116
2017	–	–	353	–	684	112	–	–	75	76
2018	–	–	403	–	549	92	–	–	44	91
2019	–	–	286	–	494	129	–	–	37	104
2020	–	–	186	–	389	99	–	–	32	–
2021	–	–	186	–	409	124	–	–	–	2
2022	–	–	289	–	455	80	–	–	23	16

Table 5. Recent age-proportion data used in the assessment for the U.S. Catcher-Processor fleet. Proportions are calculated from numbers of individuals in each age group. Age 15 is an accumulator group.

Year	Number of fish	Number of hauls	Age (% of total for each year)														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
2013	1,402	474	0.10	0.51	72.04	7.12	13.80	1.50	1.19	1.44	0.84	0.36	0.24	0.10	0.07	0.44	0.24
2014	1,652	557	0.00	4.13	5.17	71.41	5.98	8.89	0.89	2.03	0.89	0.44	0.09	0.00	0.00	0.09	0.00
2015	1,263	431	3.49	1.66	7.55	3.45	76.45	3.20	2.16	0.33	0.77	0.52	0.00	0.12	0.12	0.00	0.15
2016	1,995	671	0.40	52.87	2.37	5.57	2.23	31.31	1.56	2.06	0.73	0.20	0.44	0.20	0.00	0.04	0.00
2017	2,026	684	1.75	0.87	50.75	2.36	4.99	3.08	28.79	3.01	2.11	1.17	0.25	0.58	0.17	0.00	0.12
2018	1,162	549	5.42	35.76	1.05	26.03	2.14	2.65	2.69	19.36	2.50	1.25	0.28	0.40	0.29	0.10	0.07
2019	1,190	494	0.00	6.84	25.00	1.35	39.00	1.48	4.09	1.81	17.40	1.15	0.84	0.45	0.05	0.16	0.38
2020	909	389	0.00	0.19	7.90	40.75	1.16	31.65	1.85	1.61	1.80	11.14	0.68	1.08	0.00	0.05	0.13
2021	1,206	409	3.88	0.62	2.82	13.37	36.29	1.66	22.87	1.90	1.99	1.64	10.94	1.37	0.43	0.16	0.07
2022	956	455	0.98	49.10	1.31	1.73	7.85	19.27	0.72	12.55	1.41	0.88	0.51	2.27	1.10	0.29	0.02

Table 6. Recent age-proportion data used in the assessment for the U.S. Mothership fleet. Proportions are calculated from numbers of individuals in each age group. Age 15 is an accumulator group.

Year	Number of fish	Number of hauls	Age (% of total for each year)														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
2013	1,215	409	0.00	1.19	83.16	4.52	7.51	0.25	0.96	1.18	0.13	0.19	0.15	0.05	0.23	0.35	0.14
2014	1,252	423	0.00	5.01	3.50	74.63	4.75	7.51	1.01	1.28	1.00	0.52	0.11	0.08	0.00	0.14	0.47
2015	601	203	1.81	0.65	10.41	4.77	71.42	4.00	4.13	1.07	0.63	0.83	0.29	0.00	0.00	0.00	0.00
2016	1,495	502	0.53	59.25	1.45	5.10	2.44	26.82	1.54	1.92	0.38	0.32	0.09	0.15	0.00	0.00	0.00
2017	1,054	353	7.78	0.77	51.20	2.21	3.41	1.28	27.73	1.88	1.96	0.49	0.08	0.81	0.19	0.16	0.06
2018	818	403	17.23	26.16	1.93	27.24	0.69	2.31	1.75	16.91	3.32	1.00	0.52	0.33	0.20	0.34	0.06
2019	824	286	0.00	15.17	20.36	0.94	36.52	1.24	4.01	1.61	16.51	1.46	1.08	0.44	0.50	0.15	0.01
2020	509	186	0.00	0.00	8.81	40.36	2.56	28.39	1.59	2.20	2.18	11.30	1.34	0.85	0.42	0.00	0.00
2021	545	186	0.00	0.43	1.78	11.57	37.92	2.18	22.34	1.27	1.98	2.77	13.83	2.40	0.67	0.21	0.67
2022	609	289	1.66	42.42	1.94	2.59	7.04	18.36	0.82	15.31	2.05	0.39	0.30	4.25	1.85	0.53	0.46

Table 7. Recent age-proportion data used in the assessment for the U.S. Shore-Based fleet. Proportions are calculated from numbers of individuals in each age group. Age 15 is an accumulator group.

Year	Number of fish	Number of trips	Age (% of total for each year)														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
2013	1,915	96	0.00	0.36	79.28	5.93	9.79	0.67	1.38	1.01	0.36	0.37	0.13	0.04	0.09	0.31	0.27
2014	1,355	68	0.00	2.14	3.38	63.99	8.26	15.10	1.30	2.40	1.67	0.63	0.23	0.00	0.20	0.20	0.50
2015	1,680	84	6.12	1.34	7.42	4.91	67.24	4.05	5.06	0.78	1.05	1.28	0.24	0.17	0.00	0.00	0.32
2016	1,518	76	0.11	65.44	1.41	3.25	1.55	22.03	1.60	2.70	0.72	0.29	0.31	0.26	0.14	0.10	0.08
2017	2,235	112	3.68	0.71	35.37	2.63	3.66	2.50	43.03	2.89	2.12	1.66	0.64	0.53	0.27	0.11	0.20
2018	1,834	92	7.72	27.85	1.75	31.45	1.24	2.40	2.61	19.08	2.65	1.32	0.86	0.49	0.40	0.15	0.05
2019	2,566	129	0.00	15.79	22.48	0.93	32.19	1.86	3.29	1.74	16.71	1.28	1.61	0.90	0.54	0.31	0.37
2020	1,974	99	0.00	0.02	8.34	34.50	1.35	32.07	1.24	2.29	1.57	15.88	1.06	0.88	0.43	0.06	0.32
2021	2,480	124	0.17	0.26	1.97	12.69	34.48	2.73	25.94	1.92	2.80	2.08	11.12	2.27	0.85	0.22	0.50
2022	1,600	80	0.46	11.29	1.11	1.90	11.35	34.36	1.60	21.02	2.26	1.39	1.17	9.17	1.65	0.78	0.47

Table 8. Recent age-proportion data used in the assessment for the Canadian Shoreside fleet. Proportions are calculated from numbers of individuals in each age group. Age 15 is an accumulator group.

Year	Number of fish	Number of trips	Age (% of total for each year)														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
2013	226	10	0.00	0.00	1.40	4.79	4.30	2.28	26.20	7.96	4.54	14.17	0.51	2.84	4.34	24.81	1.87
2014	279	28	0.00	0.00	0.19	15.02	12.71	24.00	9.01	14.61	8.84	1.86	4.42	0.57	0.45	0.86	7.47
2015	296	6	2.78	0.00	1.12	2.64	63.52	8.10	11.53	1.31	5.61	1.85	0.00	0.53	0.00	0.34	0.67
2016	554	75	0.00	12.59	0.64	6.99	6.41	54.59	6.06	8.29	1.81	1.11	0.24	0.50	0.36	0.06	0.36
2017	750	75	6.95	0.33	7.80	1.72	3.00	7.29	48.08	13.27	6.95	1.33	1.25	1.19	0.14	0.15	0.55
2018	476	44	0.50	5.15	1.91	22.50	1.23	4.48	5.93	35.33	12.43	4.43	2.61	1.05	0.96	1.23	0.24
2019	327	37	0.00	13.24	11.41	2.87	30.26	1.91	4.36	2.71	26.38	2.28	3.26	0.83	0.51	0.00	0.00
2020	1,438	32	0.00	0.04	9.59	19.80	1.37	30.16	2.71	3.49	2.56	24.07	2.86	2.12	0.22	0.48	0.54
2022	635	23	0.00	0.00	0.13	1.36	14.04	22.81	6.53	17.60	4.87	4.22	4.65	13.94	5.75	2.31	1.80

Table 9. Recent age-proportion data used in the assessment for the Canadian freezer-trawler fleet. Proportions are calculated from numbers of individuals in each age group. Age 15 is an accumulator group.

Year	**Number of fish**	**Number of hauls**	**Age (% of total for each year)**														
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15+**
2013	1,332	105	0.00	0.00	2.82	5.95	18.32	5.87	18.85	13.07	5.45	5.54	2.06	2.70	4.14	11.52	3.73
2014	1,056	79	0.00	0.00	0.99	13.40	10.12	24.79	5.38	14.12	7.62	4.71	3.13	1.41	1.91	2.06	10.37
2015	755	74	0.00	0.28	2.60	2.68	58.93	12.33	11.55	3.16	3.80	2.20	0.81	0.63	0.15	0.25	0.61
2016	886	116	0.17	5.06	1.99	4.30	6.92	57.49	9.01	8.21	2.06	2.33	1.28	0.52	0.14	0.11	0.43
2017	760	76	0.00	0.57	7.35	2.42	5.46	5.09	49.91	12.31	9.76	2.38	2.47	1.36	0.21	0.19	0.50
2018	1,225	91	0.10	4.76	0.71	17.77	2.47	3.97	5.14	45.39	9.46	5.26	2.37	1.14	0.64	0.56	0.26
2019	912	104	0.04	18.25	15.20	3.64	19.11	2.69	3.97	4.52	22.89	5.41	2.41	1.14	0.38	0.36	0.00
2021	100	2	0.00	0.00	0.00	17.21	24.00	6.79	27.39	2.87	2.87	9.48	5.39	1.13	0.00	2.87	0.00
2022	421	16	0.00	0.00	0.00	0.25	6.20	22.15	8.02	17.76	7.55	4.38	6.08	16.52	7.45	2.87	0.76

Table 10. Aggregated fishery age-proportion data used in the base model. Proportions are calculated from numbers of individuals in each age group where the contributions from each fleet are weighted by the catch in that fleet. Sample sizes are sum of hauls and trips from individual fleets (shown in preceding tables) as described in Section 2.1.2. Age 15 is an accumulator group for comparing observed and expected proportions.

Year	**Number of samples**	**Age (% of total for each year)**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15+**
1975	13	4.61	33.85	7.43	1.25	25.40	5.55	8.03	10.54	0.95	0.60	0.87	0.45	0.00	0.48	0.00
1976	142	0.09	1.34	14.47	6.74	4.10	24.58	9.77	8.90	12.10	5.43	4.30	4.08	1.07	2.36	0.69
1977	320	0.00	8.45	3.68	27.47	3.59	9.11	22.68	7.60	6.54	4.02	3.55	2.31	0.57	0.31	0.12
1978	341	0.47	1.11	6.51	6.31	26.42	6.09	8.87	21.50	9.78	4.71	4.68	2.34	0.52	0.35	0.34
1979	116	0.00	6.49	10.24	9.38	5.72	17.67	10.26	17.37	12.76	4.18	2.88	0.96	1.65	0.00	0.45
1980	221	0.15	0.54	30.09	1.85	4.49	8.16	11.23	5.01	8.94	11.08	9.46	2.63	3.79	1.52	1.07
1981	154	19.49	4.03	1.40	26.73	3.90	5.55	3.38	14.67	3.77	3.19	10.18	2.31	0.50	0.16	0.72
1982	170	0.00	32.05	3.52	0.49	27.35	1.53	3.68	3.89	11.76	3.27	3.61	7.65	0.24	0.30	0.66
1983	117	0.00	0.00	34.14	4.00	1.82	23.46	5.13	5.65	5.30	9.38	3.91	3.13	2.26	1.13	0.69
1984	123	0.00	0.00	1.39	61.90	3.62	3.85	16.78	2.85	1.51	1.24	3.34	0.92	0.59	1.44	0.56
1985	57	0.92	0.11	0.35	7.24	66.75	8.41	5.60	7.11	2.04	0.53	0.65	0.25	0.00	0.00	0.03
1986	120	0.00	15.34	5.38	0.53	0.76	43.63	6.90	8.15	8.26	2.19	2.82	1.83	3.13	0.46	0.61
1987	56	0.00	0.00	29.58	2.90	0.14	1.01	53.26	0.40	1.25	7.09	0.00	0.74	1.86	1.76	0.00
1988	84	0.00	0.65	0.07	32.28	0.98	1.45	0.66	46.05	1.35	0.84	10.48	0.79	0.05	0.07	4.28
1989	80	0.00	5.62	2.43	0.29	50.21	1.26	0.29	0.08	35.19	1.80	0.40	2.32	0.08	0.00	0.04
1990	163	0.00	5.19	20.56	1.89	0.59	31.35	0.51	0.20	0.04	31.90	0.30	0.07	6.41	0.00	0.99
1991	160	0.00	3.46	20.37	19.63	2.52	0.79	28.26	1.18	0.14	0.18	18.69	0.42	0.00	3.61	0.74
1992	243	0.46	4.24	4.30	13.05	18.59	2.27	1.04	33.93	0.77	0.08	0.34	18.05	0.41	0.04	2.43
1993	172	0.00	1.05	23.24	3.26	12.98	15.67	1.50	0.81	27.42	0.67	0.09	0.12	12.00	0.05	1.13
1994	235	0.00	0.04	2.83	21.39	1.27	12.63	18.69	1.57	0.57	29.91	0.26	0.28	0.02	9.63	0.91
1995	147	0.62	1.28	0.47	6.31	28.97	1.15	8.05	20.27	1.58	0.22	22.42	0.44	0.45	0.04	7.74
1996	186	0.00	18.28	16.24	1.51	7.74	18.14	1.00	4.91	10.98	0.58	0.35	15.72	0.01	0.11	4.44
1997	220	0.00	0.74	29.47	24.95	1.47	7.84	12.49	1.80	3.98	6.67	1.28	0.22	6.08	0.73	2.28
1998	243	0.02	4.78	20.34	20.29	26.60	2.87	5.41	9.31	0.92	1.56	3.90	0.35	0.09	2.94	0.63
1999	509	0.06	10.24	20.36	17.98	20.06	13.20	2.69	3.93	4.01	0.99	1.54	2.14	0.39	0.33	2.07
2000	530	1.00	4.22	10.94	14.29	12.88	21.06	13.12	6.55	4.65	2.51	2.07	2.31	1.29	0.72	2.41
2001	540	0.00	17.34	16.25	14.25	15.68	8.56	12.10	5.99	1.78	2.23	1.81	0.70	1.42	0.68	1.21
2002	449	0.00	0.03	50.64	14.93	9.69	5.72	4.44	6.58	3.55	0.87	0.84	1.04	0.24	0.47	0.95
2003	456	0.00	0.10	1.39	67.79	11.66	3.35	5.01	3.20	3.15	2.12	0.88	0.44	0.54	0.13	0.23
2004	501	0.00	0.02	5.34	6.13	68.29	8.11	2.18	4.13	2.51	1.27	1.07	0.35	0.27	0.16	0.17
2005	613	0.02	0.57	0.46	6.56	5.38	68.72	7.95	2.36	2.91	2.21	1.18	1.09	0.25	0.09	0.25
2006	720	0.33	2.81	10.44	1.67	8.57	4.88	59.04	5.28	1.72	2.38	1.13	1.01	0.43	0.14	0.19
2007	629	0.78	11.52	3.81	15.70	1.59	6.89	3.81	43.95	5.08	1.71	2.20	1.66	0.48	0.19	0.64

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Year	Number of samples	Age (% of total for each year)														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15+**
2008	794	0.75	9.88	30.51	2.40	14.41	1.02	3.61	3.15	28.07	3.04	1.14	0.73	0.52	0.31	0.44
2009	685	0.64	0.56	31.00	27.36	3.33	10.59	1.30	2.28	2.23	16.20	2.46	0.85	0.59	0.28	0.33
2010	874	0.03	25.22	3.38	35.41	21.49	2.29	2.93	0.43	0.58	0.98	5.81	0.93	0.29	0.10	0.15
2011	1,081	2.67	8.72	70.86	2.63	6.34	4.37	1.12	0.80	0.29	0.37	0.12	1.32	0.17	0.10	0.11
2012	851	0.18	40.91	11.55	33.04	2.49	5.10	2.52	1.13	0.66	0.23	0.33	0.35	0.86	0.28	0.38
2013	1,094	0.03	0.54	70.30	5.91	10.48	1.12	3.42	2.06	0.90	1.37	0.26	0.33	0.53	2.28	0.46
2014	1,155	0.00	3.28	3.81	64.44	6.94	12.07	1.59	3.10	1.82	0.81	0.46	0.12	0.19	0.27	1.11
2015	798	3.63	1.14	6.88	3.94	70.01	4.94	5.08	0.95	1.55	1.08	0.20	0.20	0.06	0.05	0.27
2016	1,440	0.29	50.72	1.72	4.82	2.80	31.69	2.53	3.22	0.85	0.49	0.38	0.26	0.08	0.06	0.09
2017	1,300	3.76	0.73	38.38	2.38	4.12	3.12	36.85	4.41	3.10	1.33	0.61	0.72	0.21	0.09	0.20
2018	1,179	7.35	25.54	1.50	27.01	1.51	2.81	3.04	22.70	4.32	1.90	0.94	0.55	0.41	0.32	0.09
2019	1,050	0.00	13.19	20.84	1.57	33.00	1.77	3.80	2.16	18.66	1.84	1.60	0.73	0.37	0.22	0.24
2020	706	0.00	0.08	8.39	35.66	1.43	31.27	1.66	2.18	1.83	14.65	1.17	1.09	0.26	0.10	0.24
2021	721	1.42	0.37	1.99	13.37	34.17	2.81	24.65	1.96	2.43	2.94	10.64	1.83	0.58	0.53	0.31
2022	863	0.89	33.21	1.29	1.86	8.70	23.74	1.50	15.95	2.19	1.18	1.04	5.67	1.84	0.66	0.30

Table 11. Survey age-proportion data used in the base model. Proportions are calculated from numbers of individuals in each age group. Age 15 is an accumulator group.

Year	Number of samples	Age (% of total for each year)													
		2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15+**
1995	69	20.48	3.26	1.06	19.33	1.03	4.03	16.37	1.44	0.72	24.86	0.24	1.67	0.21	5.32
1998	105	6.83	8.03	17.03	17.25	1.77	11.37	10.79	1.73	4.19	7.60	1.27	0.34	9.74	2.06
2001	57	50.61	10.95	15.12	7.86	3.64	3.84	2.60	1.30	1.34	0.65	0.68	0.87	0.15	0.39
2003	71	23.06	1.63	43.40	13.07	2.71	5.14	3.43	1.82	2.44	1.44	0.49	0.43	0.42	0.52
2005	47	19.07	1.23	5.10	4.78	50.66	6.99	2.50	3.99	2.45	1.71	0.74	0.48	0.14	0.16
2007	69	28.29	2.16	11.64	1.38	5.01	3.25	38.64	3.92	1.94	1.70	0.83	0.77	0.34	0.12
2009	72	0.55	29.34	40.22	2.29	8.22	1.25	1.79	1.93	8.32	3.63	1.44	0.28	0.48	0.26
2011	46	27.62	56.32	3.71	2.64	2.94	0.70	0.78	0.38	0.66	0.97	2.10	0.76	0.31	0.11
2012	94	62.12	9.78	16.70	2.26	2.92	1.94	1.01	0.50	0.23	0.27	0.66	0.98	0.51	0.12
2013	67	2.17	74.98	5.63	8.68	0.95	2.20	2.59	0.71	0.35	0.10	0.13	0.36	0.77	0.38
2015	78	7.45	9.19	4.38	58.99	4.88	7.53	1.69	1.68	1.64	0.95	0.16	0.29	0.24	0.92
2017	58	0.49	52.72	2.80	3.70	3.31	26.02	4.13	2.91	1.14	0.91	0.87	0.42	0.33	0.25
2019	75	10.72	27.24	1.51	31.32	2.50	3.18	2.68	16.12	2.28	0.96	0.36	0.38	0.47	0.28
2021	65	8.03	5.78	14.04	28.24	3.49	20.90	3.06	2.05	1.95	9.92	1.50	0.31	0.22	0.50

Table 12. Summary of the acoustic surveys from 1995 to 2021.

Year	Start date	End date	Vessels	Age-2+ biomass index (million t)	Sampling CV age-2+	Number of hauls with age samples	Age-1 index (billions of fish)	Sampling CV age-1
1995	1-Jul	1-Sep	Miller Freeman Ricker	1.318	0.086	69	0.232	0.500
1998	6-Jul	27-Aug	Miller Freeman Ricker	1.569	0.046	105	0.107	0.500
2001	15-Jun	18-Aug	Miller Freeman Ricker	0.862	0.102	57	–	–
2003	29-Jun	1-Sep	Ricker	2.138	0.062	71	0.024	0.500
2005	20-Jun	19-Aug	Miller Freeman	1.376	0.062	47	0.009	0.500
2007	20-Jun	21-Aug	Miller Freeman	0.943	0.074	69	1.029	0.500
2009	30-Jun	7-Sep	Miller Freeman Ricker	1.502	0.096	72	3.396	0.500
2011	26-Jun	10-Sep	Bell Shimada Ricker	0.675	0.113	46	5.949	0.500
2012	23-Jun	7-Sep	Bell Shimada Ricker F/V Forum Star	1.279	0.065	94	0.064	0.500
2013	13-Jun	11-Sep	Bell Shimada Ricker	1.929	0.062	67	0.422	0.500
2015	15-Jun	14-Sep	Bell Shimada Ricker	2.156	0.081	78	4.665	0.500
2017	22-Jun	13-Sep	Bell Shimada Nordic Pearl	1.418	0.063	58	1.238	0.500
2019	13-Jun	15-Sep	Bell Shimada Nordic Pearl	1.718	0.062	75	0.734	0.500
2021	27-Jun	24-Sep	Bell Shimada Nordic Pearl	1.525	0.122	65	2.147	0.500

Table 13. Summary of the acoustic survey age-2+ biomass attributed to each country.

Year	U.S. Age-2+ biomass (million t)	U.S. sampling CV age-2+	U.S. percentage of biomass	Canada Age-2+ biomass (million t)	Canada sampling CV age-2+	Canada percentage of biomass
1995	1.061	0.084	80.47%	0.257	0.271	19.53%
1998	0.606	0.093	38.62%	0.963	0.047	61.38%
2001	0.793	0.088	92.03%	0.069	0.777	7.97%
2003	1.678	0.063	78.51%	0.459	0.174	21.49%
2005	0.707	0.096	51.40%	0.669	0.076	48.60%
2007	0.683	0.085	72.43%	0.260	0.149	27.57%
2009	1.104	0.106	73.50%	0.398	0.210	26.50%
2011	0.602	0.104	89.27%	0.072	0.607	10.73%
2012	1.141	0.059	89.16%	0.139	0.342	10.84%
2013	1.805	0.054	93.57%	0.124	0.568	6.43%
2015	1.698	0.085	78.77%	0.458	0.214	21.23%
2017	1.028	0.073	72.52%	0.390	0.126	27.48%
2019	1.527	0.054	88.89%	0.191	0.334	11.11%
2021	1.459	0.103	95.67%	0.066	1.641	4.33%

Table 14. Information on maturity and fecundity used in this assessment as shown in Figure 12. The sample sizes refer to the subset of samples in Table 15 for which age readings and histological estimates of maturity have been completed. The mean weight (kg) is based on a much larger set of samples. Mean fecundity is the product of maturity and mean weight but note that year-specific fecundities from 1975–2022 were used in the stock assessment. The values reported for ages 15 and above represent the average across all samples in this range.

Age	**Number of samples**	**Maturity ogive**	**Mean weight**	**Mean fecundity**
0	0	0.000	0.017	0.000
1	122	0.000	0.094	0.000
2	276	0.261	0.257	0.067
3	348	0.839	0.383	0.321
4	333	0.961	0.485	0.466
5	299	0.920	0.532	0.490
6	221	0.928	0.581	0.539
7	81	0.926	0.646	0.598
8	70	0.957	0.712	0.681
9	36	0.944	0.769	0.726
10	51	0.980	0.854	0.837
11	26	0.962	0.925	0.890
12	18	1.000	0.964	0.964
13	24	0.958	1.060	1.015
14	22	0.955	1.003	0.958
15	8	0.900	1.031	0.928
16	9	0.900	1.031	0.928
17	2	0.900	1.031	0.928
18	1	0.900	1.031	0.928
19	0	0.900	1.031	0.928
20	0	0.900	1.031	0.928

Table 15. Number of Pacific Hake ovaries collected for histological analysis. The maturity ogive was determined from a subset of these samples (up to and including 2017; see Edwards et al. 2018).

Year	**NWFSC Trawl Survey**	**CAN Acoustic Survey/ Research (Summer)**	**U.S. Acoustic Survey/ Research (Summer)**	**U.S. Acoustic Survey/ Research (Winter)**	**U.S. At-Sea Hake Observer Program (Spring)**	**U.S. At-Sea Hake Observer Program (Fall)**	**OR Dept. Fish & Wildlife**	**Total**
2009	263	0	0	0	0	0	0	**263**
2012	71	0	199	0	0	0	0	**270**
2013	70	0	254	0	104	103	0	**531**
2014	276	0	0	0	105	142	0	**523**
2015	293	0	193	0	98	112	0	**696**
2016	277	0	26	309	96	162	0	**870**
2017	109	0	65	134	93	113	0	**514**
2018	147	0	64	0	0	0	7	**218**
2019	60	15	92	0	0	0	0	**167**
2020	0	0	0	0	0	0	0	**0**
2021	0	0	69	0	0	0	0	**69**
2022	0	0	0	0	0	0	0	**0**
Total	**1,566**	**15**	**962**	**443**	**496**	**632**	**7**	**4,121**

Table 16. Summary of estimated model parameters and priors in the base model. The beta prior is parameterized with a mean and standard deviation. The lognormal prior is parameterized with the median and standard deviation in log space.

Parameter	Number of parameters	Bounds (low, high)	Prior (Mean, SD) single value = fixed
Stock Dynamics			
Log (R_0)	1	(13, 17)	Uniform
Steepness (h)	1	(0.2, 1)	Beta (0.78, 0.11)
Recruitment variability (σ_r)	–	–	1.4
Log recruitment deviations: 1946–2022	77	(-6, 6)	Lognormal (0, σ_r)
Natural mortality (M)	1	(0.05, 0.4)	Lognormal (-1.61, 0.10)
Data Source			
Acoustic Survey			
Additional variance for survey log (SE)	1	(0.05, 1.2)	Uniform
Non-parametric age-based selectivity: ages 3–6	4	(-5, 9)	Uniform
Age-1 Survey			
Additional variance for age-1 index log (SE)	1	(0.05, 1.2)	Uniform
Fishery			
Non-parametric age-based selectivity: ages 2–6	5	(-5, 9)	Uniform
Selectivity deviations (1991–2022, ages 2–6)	160	(-10, 10)	Normal (0, 1.4)
Data weighting			
Dirichlet-multinomial fishery likelihood, $\log(\theta_{fish})$	2	(-5, 20)	Normal (0, 1.813)
Dirichlet-multinomial survey likelihood, $\log(\theta_{survey})$	2	(-5, 20)	Normal (0, 1.813)

Table 17. Annual changes in the modeling framework used to assess Pacific Hake since 2011. Methods used to weight the age-composition data (Comp Method), i.e., McAllister-Ianelli (MI) and Dirichlet-multinomial (D-M) approaches, are explained in the main text. The MCMC column gives the number of Markov chain Monte Carlo samples used to describe model results and produce statistical inference.

Year	Framework	Survey	Comp Method	MCMC	Change
2011	SS3 3-20, TINSS	yes	MI (0.100, 0.890)	999	Increased compatibility of SS and TINSS, except for age-composition likelihood
2012	SS3 3-23b	yes	MI (0.120, 0.940)	999	One framework for base model; TINSS changed to CCAM
2013	SS3 3-24j	no	MI (0.120, 0.940)	999	Developed MSE
2014	SS3 3-24s	yes	MI (0.120, 0.940)	999	Time-varying fishery selectivity
2015	SS3 3-24u	no	MI (0.120, 0.940)	999	No major changes
2016	SS3 3-24u	yes	MI (0.110, 0.510)	999	Re-analyzed 1998-2015 acoustic-survey data; Removed 1995 survey data
2017	SS3 3-24u	no	MI (0.140, 0.410)	999	Added 1995 survey data; Increased allowable selectivity variation to 0.20
2018	SS3 3-30-10-00	yes	D-M (0.450, 0.920)	2,000	Used D-M to weight age compositions; Updated maturity and fecundity; Stopped transforming selectivity parameters
2019	SS3 3-30-10-00	no	D-M (0.363, 0.919)	2,000	Change to time-varying fecundity
2020	SS3 3-30-14-08	yes	D-M (0.364, 0.912)	2,000	Normal prior for D-M parameters; remove sum to zero constraint for recruitment deviations
2021	SS3 3-30-16-03	no	D-M (0.361, 0.911)	8,250	No U-turn MCMC Sampling (adnuts)
2022	SS3 3-30-16-03	yes	D-M (0.363, 0.930)	12,005	Add relative age-1 index
2023	SS3 3-30-20-00	no	D-M (0.348, 0.930)	8,000	No major changes

Table 18. Estimated numbers-at-age at the beginning of the year from the base model (posterior medians; million).

Year									Age												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20+**
1966	1,538	1,406	875	465	285	187	132	105	85	74	59	51	43	35	29	24	19	16	13	10	34
1967	4,521	1,222	1,115	684	356	214	138	94	74	60	52	42	36	30	24	21	17	14	11	9	42
1968	2,959	3,599	971	862	507	256	150	90	61	49	39	34	27	24	20	16	14	11	9	7	42
1969	675	2,353	2,861	757	661	381	189	106	64	43	35	28	24	19	17	14	11	10	8	6	42
1970	8,967	535	1,867	2,227	570	485	276	128	72	43	29	23	19	16	13	11	9	8	7	5	38
1971	786	7,107	424	1,447	1,664	410	342	182	84	47	29	19	15	12	11	9	7	6	5	4	33
1972	528	624	5,619	331	1,107	1,248	304	243	129	60	34	20	14	11	9	8	6	5	4	4	30
1973	5,973	421	494	4,411	257	846	944	224	178	95	44	25	15	10	8	6	6	5	4	3	27
1974	347	4,729	334	388	3,398	194	636	683	163	129	69	32	18	11	7	6	5	4	3	3	24
1975	1,838	275	3,743	262	297	2,550	144	453	486	116	92	49	22	13	8	5	4	3	3	2	22
1976	205	1,456	218	2,932	202	225	1,918	104	328	353	84	66	35	16	9	6	4	3	2	2	19
1977	6,619	162	1,154	171	2,269	155	170	1,414	77	241	259	62	49	26	12	7	4	3	2	2	17
1978	134	5,249	129	910	134	1,754	119	129	1,068	58	183	196	47	37	20	9	5	3	2	2	15
1979	1,362	106	4,164	102	710	104	1,354	90	98	810	44	139	149	35	28	15	7	4	2	2	14
1980	17,165	1,082	84	3,279	79	549	80	1,022	68	74	612	33	105	112	27	21	11	5	3	2	13
1981	271	13,601	860	66	2,565	61	424	61	780	52	56	466	25	80	86	20	16	9	4	2	12
1982	308	215	10,767	677	51	1,969	47	316	45	580	38	42	347	19	59	64	15	12	6	3	12
1983	535	244	170	8,482	528	40	1,512	35	238	34	438	29	32	261	14	45	48	11	9	5	12
1984	13,954	424	194	134	6,624	410	31	1,149	27	181	26	333	22	24	199	11	34	37	9	7	14
1985	132	11,071	337	153	105	5,122	315	23	868	20	137	19	251	17	18	150	8	26	28	6	17
1986	181	105	8,774	265	120	81	3,964	240	18	662	15	104	15	191	13	14	114	6	20	21	20
1987	6,614	143	83	6,897	206	92	62	2,959	179	13	494	11	78	11	143	9	10	85	5	15	31
1988	2,113	5,240	113	65	5,326	157	70	45	2,178	132	10	364	8	57	8	105	7	8	63	3	34
1989	113	1,676	4,156	89	50	4,054	119	51	33	1,592	96	7	266	6	42	6	77	5	6	46	29
1990	4,348	89	1,326	3,244	68	37	3,005	84	36	24	1,129	68	5	189	4	30	4	55	4	4	53
1991	1,251	3,442	71	1,041	2,495	51	28	2,188	61	26	17	823	50	4	137	3	22	3	40	3	42
1992	126	993	2,722	53	719	1,859	37	20	1,571	44	19	12	591	36	3	98	2	15	2	28	32
1993	3,237	99	786	2,130	37	506	1,369	25	14	1,092	30	13	9	410	25	2	68	2	11	2	42
1994	3,324	2,563	79	618	1,594	26	362	986	18	10	786	22	9	6	295	18	1	49	1	8	32
1995	1,262	2,631	2,029	62	477	1,127	17	229	623	12	6	497	14	6	4	187	11	1	31	1	25
1996	1,889	1,001	2,083	1,598	48	362	787	11	152	414	8	4	330	9	4	3	124	7	1	21	17
1997	1,029	1,500	791	1,562	1,169	34	261	496	7	95	260	5	3	208	6	2	2	78	5	0	24
1998	2,042	816	1,190	621	1,093	789	23	164	310	4	60	163	3	2	130	4	2	1	49	3	15
1999	13,314	1,618	646	919	393	752	470	14	103	194	3	37	102	2	1	82	2	1	1	31	11
2000	322	10,546	1,283	469	606	225	475	288	9	63	119	2	23	63	1	1	50	1	1	0	26
2001	1,277	255	8,350	1,006	341	434	153	300	182	5	40	75	1	14	40	1	0	32	1	0	17
2002	47	1,012	201	6,565	742	229	292	101	198	120	4	26	50	1	10	26	0	0	21	1	11
2003	1,779	37	803	158	5,072	544	161	207	71	141	85	3	19	35	1	7	19	0	0	15	8
2004	46	1,409	30	635	124	3,811	393	114	148	51	100	61	2	13	25	0	5	13	0	0	17
2005	2,895	36	1,115	23	471	75	2,653	262	76	98	34	67	41	1	9	17	0	3	9	0	11
2006	2,105	2,292	29	878	17	330	46	1,708	169	49	63	22	43	26	1	6	11	0	2	6	7

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Year	**Age**																				
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20+**
2007	26	1,669	1,811	21	624	11	202	28	1,033	102	30	38	13	26	16	0	3	7	0	1	8
2008	5,808	20	1,321	1,377	13	412	7	120	16	615	61	18	23	8	15	9	0	2	4	0	5
2009	1,507	4,599	16	1,003	920	9	249	4	67	9	342	34	10	13	4	9	5	0	1	2	3
2010	16,852	1,197	3,637	12	706	640	6	160	3	43	6	220	22	6	8	3	6	3	0	1	3
2011	430	13,338	948	2,767	8	393	407	4	108	2	29	4	148	15	4	5	2	4	2	0	3
2012	1,699	342	10,554	731	1,652	5	269	285	3	76	1	20	3	104	10	3	4	1	3	2	2
2013	390	1,345	270	8,158	535	1,118	4	192	203	2	54	1	14	2	74	7	2	3	1	2	3
2014	9,165	310	1,064	212	6,049	394	813	2	129	137	1	36	1	10	1	50	5	1	2	1	3
2015	38	7,258	245	826	152	4,459	286	563	2	89	95	1	25	0	7	1	34	3	1	1	3
2016	6,374	30	5,728	192	626	112	3,272	213	419	1	66	70	1	19	0	5	1	26	3	1	3
2017	2,464	5,048	23	4,104	142	448	77	2,320	151	297	1	47	50	0	13	0	4	0	18	2	3
2018	641	1,953	3,952	16	2,939	98	314	51	1,525	99	195	1	31	33	0	9	0	2	0	12	3
2019	611	508	1,509	2,907	11	2,119	71	209	34	1,016	66	129	0	21	22	0	6	0	2	0	10
2020	11,409	485	401	1,118	2,138	8	1,442	46	136	22	664	43	85	0	13	14	0	4	0	1	7
2021	450	9,037	383	316	862	1,453	5	947	30	89	14	436	28	55	0	9	9	0	2	0	5
2022	963	355	7,159	301	245	632	974	3	627	20	59	9	289	18	37	0	6	6	0	2	3
2023	931	761	282	5,494	234	188	467	638	2	410	13	38	6	189	12	24	0	4	4	0	3

Table 19. Estimated biomass-at-age at the beginning of the year from the base model (posterior medians; thousand t).

Year	Age																			
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	21	139	229	179	139	101	77	69	60	58	50	46	40	36	29	24	20	17	13	11	35
1967	61	121	292	264	174	115	81	61	53	47	44	38	35	31	24	21	17	14	12	9	43
1968	40	355	254	332	247	138	88	59	43	38	33	31	26	25	20	16	14	11	9	8	43
1969	9	232	749	292	323	205	111	69	45	34	29	25	23	20	17	14	12	10	8	7	43
1970	121	53	489	858	278	261	161	84	51	33	25	21	18	17	13	12	10	8	7	5	39
1971	11	701	111	558	813	221	200	119	60	37	24	17	15	13	11	9	8	6	5	4	34
1972	7	62	1,472	128	540	671	178	159	91	46	28	18	13	11	9	8	6	5	5	4	31
1973	81	42	129	1,700	125	455	551	146	126	73	37	22	14	10	8	7	6	5	4	3	28
1974	5	467	88	150	1,659	104	372	447	115	100	58	29	17	11	7	6	5	4	3	3	25
1975	101	43	1,118	96	182	1,608	113	396	470	105	89	83	34	24	15	14	11	9	8	6	59
1976	11	144	51	1,463	105	156	1,541	96	396	470	122	109	64	30	18	15	10	8	7	6	52
1977	364	14	463	84	1,354	104	129	1,182	75	263	311	78	66	43	24	15	9	6	5	4	36
1978	7	381	16	427	71	1,057	76	95	899	57	201	245	62	54	34	21	12	7	5	4	35
1979	66	8	1,004	26	413	71	1,040	81	90	840	53	173	228	55	50	30	14	8	5	3	27
1980	776	87	18	1,485	31	269	41	670	49	65	650	39	135	146	34	29	16	7	4	2	18
1981	11	1,461	184	23	1,350	24	223	33	582	37	46	486	28	107	128	25	19	10	5	3	14
1982	12	25	2,654	226	16	1,098	19	169	26	447	27	36	368	18	61	74	18	14	7	3	14
1983	19	31	23	2,892	195	13	786	18	147	24	385	27	33	270	19	66	71	17	13	7	18
1984	448	56	32	33	2,904	169	13	675	15	122	18	316	25	25	254	20	64	69	16	13	27
1985	4	1,926	75	38	43	2,794	170	13	608	13	92	17	189	16	12	128	7	22	24	6	15
1986	5	16	2,439	77	36	30	2,151	137	11	543	14	123	18	263	21	22	184	10	32	34	33
1987	147	21	11	2,614	57	26	22	1,709	107	8	377	11	72	14	172	13	15	121	7	21	44
1988	40	734	21	20	2,498	57	25	22	1,365	88	6	334	8	59	8	164	11	12	98	5	54
1989	2	233	1,137	28	15	2,091	52	21	17	1,036	65	4	242	4	35	7	90	6	6	54	33
1990	68	12	323	1,136	27	19	1,656	52	24	12	863	57	11	224	4	43	6	80	5	6	78
1991	20	471	20	385	1,147	26	15	1,293	44	22	19	591	32	4	165	8	51	7	94	6	99
1992	2	135	630	18	341	992	21	12	1,006	29	12	9	435	30	3	101	2	16	2	29	33
1993	50	13	195	721	15	230	676	13	7	600	16	16	9	252	15	1	47	1	7	1	29
1994	51	305	24	224	712	12	190	562	11	6	498	11	6	4	207	13	1	37	1	6	24
1995	19	292	544	21	233	605	11	143	411	9	4	370	11	5	3	150	9	1	25	1	20
1996	29	102	599	636	22	193	445	7	90	263	5	3	223	7	6	2	93	6	0	16	13
1997	16	139	281	675	577	18	143	289	4	58	164	4	2	148	4	2	1	68	4	0	21
1998	31	68	250	223	552	408	12	104	189	3	47	116	2	1	97	3	1	1	39	2	12
1999	202	221	162	318	167	396	262	8	63	137	2	30	77	2	1	67	2	1	1	25	9
2000	5	2,003	494	222	349	149	341	210	7	53	97	2	20	59	1	1	47	1	1	0	24
2001	19	13	2,394	487	223	288	114	259	156	5	38	74	1	15	39	1	0	31	1	0	16
2002	1	77	72	2,996	432	171	211	79	181	103	3	24	42	1	10	27	1	0	22	1	12
2003	27	4	205	69	2,650	320	121	144	53	116	66	2	17	28	0	7	19	0	0	15	8
2004	1	152	6	277	59	2,027	255	81	97	36	81	52	1	13	22	0	4	12	0	0	15
2005	43	4	290	10	239	40	1,507	166	50	69	27	54	33	1	10	16	0	3	9	0	11
2006	31	303	11	402	9	189	27	1,021	111	34	46	16	33	17	1	5	10	0	2	5	7

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Year	**Age**																				
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20+**
2007	0	74	414	9	335	6	123	18	669	72	23	29	11	23	13	0	3	6	0	1	7
2008	82	3	322	562	8	262	5	82	12	443	45	14	19	6	14	8	0	2	3	0	5
2009	20	307	4	343	433	5	167	3	50	8	263	27	10	11	4	9	5	0	1	2	3
2010	217	130	846	4	306	339	4	133	3	44	6	192	18	7	6	3	5	3	0	1	3
2011	5	1,126	233	891	3	202	242	3	92	2	28	4	157	15	5	5	2	3	2	0	3
2012	20	44	2,264	259	676	3	176	197	2	69	1	19	3	103	10	3	4	1	2	1	2
2013	4	174	78	2,933	251	571	2	137	149	2	54	1	18	2	79	8	2	3	1	2	3
2014	95	32	393	97	2,901	212	467	2	85	98	1	42	1	9	1	53	5	2	2	1	3
2015	0	551	61	323	68	2,099	158	335	1	61	68	1	24	0	7	1	43	4	1	2	3
2016	59	5	1,396	70	235	47	1,521	107	215	1	44	49	0	18	0	7	1	37	4	1	4
2017	21	708	7	1,648	69	236	43	1,285	88	194	1	34	40	0	11	0	3	0	17	2	2
2018	9	365	1,400	8	1,478	52	173	31	899	63	125	0	21	24	0	9	0	2	0	13	3
2019	12	34	436	1,299	6	1,134	41	126	22	665	45	94	0	17	17	0	5	0	1	0	9
2020	228	49	138	534	1,086	4	823	27	82	14	429	30	54	0	12	13	0	4	0	1	6
2021	9	1,201	116	166	529	890	3	626	20	68	11	317	20	41	0	8	8	0	2	0	4
2022	19	51	2,626	150	139	410	623	2	428	14	44	8	244	15	32	0	5	5	0	1	3
2023	18	96	94	2,648	127	109	281	407	1	282	9	28	4	149	10	22	0	4	4	0	3

Table 20. Estimated exploitation-fraction-at-age (catch-at-age divided by biomass-at-age at the beginning of the year) presented as a percentage for each year from the base model (posterior medians; percentage of age class removed by fishing).

Year										Age											
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	0.00	0.74	4.93	8.21	9.91	10.61	15.83	14.14	13.04	11.95	10.98	10.26	9.75	8.84	9.30	8.98	8.98	8.98	8.98	8.98	8.98
1967	0.00	1.25	8.22	13.67	16.35	17.48	25.62	22.88	21.10	19.33	17.77	16.61	15.77	14.31	15.05	14.52	14.52	14.52	14.52	14.52	14.52
1968	0.00	0.73	4.82	8.05	9.69	10.43	15.46	13.81	12.74	11.67	10.73	10.03	9.52	8.64	9.09	8.77	8.77	8.77	8.77	8.77	8.77
1969	0.00	1.01	6.71	11.17	13.34	14.35	21.14	18.88	17.41	15.95	14.66	13.70	13.02	11.80	12.42	11.98	11.98	11.98	11.98	11.98	11.98
1970	0.00	1.20	8.01	13.35	15.91	17.02	25.01	22.34	20.61	18.88	17.35	16.21	15.40	13.97	14.69	14.18	14.18	14.18	14.18	14.18	14.18
1971	0.00	0.73	4.89	8.19	9.85	10.58	15.71	14.03	12.94	11.85	10.90	10.18	9.67	8.77	9.23	8.91	8.91	8.91	8.91	8.91	8.91
1972	0.00	0.49	3.31	5.56	6.70	7.23	10.77	9.62	8.87	8.13	7.47	6.98	6.63	6.02	6.33	6.11	6.11	6.11	6.11	6.11	6.11
1973	0.00	0.57	3.80	6.41	7.69	8.28	12.36	11.04	10.18	9.33	8.57	8.01	7.61	6.90	7.26	7.01	7.01	7.01	7.01	7.01	7.01
1974	0.00	0.69	4.62	7.75	9.32	10.02	14.89	13.30	12.27	11.24	10.33	9.66	9.17	8.32	8.75	8.44	8.44	8.44	8.44	8.44	8.44
1975	0.00	0.36	3.41	6.90	6.25	7.24	9.34	8.42	7.60	8.10	7.58	4.34	4.90	3.87	3.76	2.68	2.68	2.68	2.68	2.68	2.68
1976	0.00	0.48	3.58	4.19	6.13	5.45	7.63	6.69	5.08	4.60	4.23	3.72	3.39	3.30	3.14	2.23	2.23	2.23	2.23	2.23	2.23
1977	0.00	0.36	1.37	2.77	3.48	3.67	5.30	4.81	4.14	3.70	3.35	3.17	2.98	2.45	2.01	1.89	1.89	1.89	1.89	1.89	1.89
1978	0.00	0.39	3.94	2.66	3.60	3.76	5.77	4.99	4.38	3.76	3.36	2.96	2.78	2.49	2.12	1.58	1.58	1.58	1.58	1.58	1.58
1979	0.00	0.43	2.39	5.53	3.75	3.78	5.51	4.75	4.63	4.08	3.53	3.39	2.76	2.72	2.36	2.13	2.13	2.13	2.13	2.13	2.13
1980	0.00	0.32	2.14	2.49	4.39	4.17	6.47	5.10	4.68	3.82	3.15	2.88	2.59	2.57	2.63	2.39	2.39	2.39	2.39	2.39	2.39
1981	0.00	0.39	3.46	5.34	5.30	8.41	10.25	9.86	7.21	7.47	6.54	5.17	4.90	4.00	3.61	4.44	4.44	4.44	4.44	4.44	4.44
1982	0.00	0.28	2.41	4.41	7.17	4.77	10.77	8.11	7.58	5.62	6.19	5.02	4.09	4.62	4.21	3.70	3.70	3.70	3.70	3.70	3.70
1983	0.00	0.22	3.75	3.70	5.20	6.97	7.18	7.42	6.04	5.29	4.24	4.01	3.60	3.62	2.82	2.52	2.52	2.52	2.52	2.52	2.52
1984	0.00	0.24	3.43	5.59	4.87	6.17	9.49	7.03	7.12	6.11	5.89	4.34	3.63	4.03	3.22	2.20	2.20	2.20	2.20	2.20	2.20
1985	0.00	0.16	2.15	4.70	4.44	3.94	6.52	6.29	5.01	5.56	5.23	4.09	4.66	3.71	5.19	4.09	4.09	4.09	4.09	4.09	4.09
1986	0.00	0.26	2.57	6.08	8.89	8.59	9.62	9.12	8.13	6.36	5.55	4.40	4.38	3.80	3.11	3.23	3.23	3.23	3.23	3.23	3.23
1987	0.00	0.34	6.31	5.70	11.80	13.63	17.54	11.00	10.63	9.97	8.32	6.47	6.87	5.12	5.28	4.49	4.49	4.49	4.49	4.49	4.49
1988	0.00	0.39	5.04	7.70	7.57	11.50	19.16	14.00	10.90	10.23	10.18	7.44	7.28	6.66	6.73	4.36	4.36	4.36	4.36	4.36	4.36
1989	0.00	0.54	4.80	10.32	16.73	11.30	21.37	23.07	18.14	14.40	13.92	14.88	10.30	14.02	11.32	8.01	8.01	8.01	8.01	8.01	8.01
1990	0.00	0.41	4.11	7.05	9.28	8.64	13.16	11.64	10.87	13.69	9.49	8.73	3.30	6.11	7.13	4.94	4.94	4.94	4.94	4.94	4.94
1991	0.00	0.57	10.24	30.25	11.72	11.53	15.35	14.13	11.57	9.82	7.59	11.61	13.03	8.19	6.92	3.50	3.50	3.50	3.50	3.50	3.50
1992	0.00	0.43	4.53	16.46	20.42	11.58	18.96	17.76	17.21	16.89	17.42	15.28	14.99	12.97	11.31	10.74	10.74	10.74	10.74	10.74	10.74
1993	0.00	0.28	2.60	14.29	18.28	18.11	16.62	16.35	16.81	14.94	16.08	6.49	8.00	13.37	13.68	11.97	11.97	11.97	11.97	11.97	11.97
1994	0.00	0.25	1.92	5.19	21.33	21.70	34.19	31.56	28.93	32.14	28.37	37.10	27.72	24.65	25.65	24.13	24.13	24.13	24.13	24.13	24.13
1995	0.00	0.30	1.72	4.28	6.64	19.79	22.24	23.15	21.93	19.14	21.69	19.43	18.09	15.90	21.26	18.07	18.07	18.07	18.07	18.07	18.07
1996	0.00	1.33	15.62	16.77	13.83	12.70	32.34	28.07	30.68	28.72	30.21	24.36	27.05	22.54	12.30	24.34	24.34	24.34	24.34	24.34	24.34
1997	0.00	0.39	2.08	24.10	26.55	18.20	34.21	31.98	31.86	30.73	29.54	21.61	31.38	26.21	28.19	21.46	21.46	21.46	21.46	21.46	21.46
1998	0.00	0.98	9.48	49.39	22.90	42.40	34.25	29.23	30.50	27.62	23.68	26.01	23.45	23.98	24.93	23.35	23.35	23.35	23.35	23.35	23.35
1999	0.00	0.75	29.03	43.21	56.98	33.97	36.02	35.02	32.79	28.53	30.16	25.11	26.55	22.83	27.30	24.50	24.50	24.50	24.50	24.50	24.50
2000	0.00	0.14	2.50	15.27	14.69	19.09	25.26	24.91	24.05	21.64	22.22	20.57	21.19	19.31	20.73	19.42	19.42	19.42	19.42	19.42	19.42
2001	0.00	0.68	2.33	12.33	20.64	20.05	19.77	17.12	17.26	16.78	15.34	15.09	14.69	14.07	14.88	15.12	15.12	15.12	15.12	15.12	15.12
2002	0.00	0.22	0.91	4.81	11.70	13.17	12.70	11.77	10.05	10.71	10.47	10.17	10.96	10.96	8.50	8.77	8.77	8.77	8.77	8.77	8.77
2003	0.00	0.10	0.72	2.53	8.88	13.32	11.91	13.00	12.04	10.91	11.70	10.08	9.71	11.39	10.69	9.03	9.03	9.03	9.03	9.03	9.03
2004	0.00	0.44	5.69	12.52	39.85	20.34	21.45	19.65	21.12	19.60	17.27	16.20	18.01	14.32	16.09	15.51	15.51	15.51	15.51	15.51	15.51
2005	0.00	0.20	1.75	5.91	20.08	32.62	29.51	26.46	25.60	23.86	21.06	20.69	20.68	22.06	14.64	17.33	17.33	17.33	17.33	17.33	17.33

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Year										**Age**											
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20+**
2006	0.00	0.86	10.64	19.82	24.21	35.03	35.84	35.42	32.29	30.27	29.18	29.34	27.32	32.19	33.10	22.18	22.18	22.18	22.18	22.18	22.18
2007	0.00	2.03	15.54	26.44	27.56	22.95	36.83	35.35	34.54	31.71	28.96	29.33	27.49	25.71	27.93	25.72	25.72	25.72	25.72	25.72	25.72
2008	0.00	1.53	14.87	34.31	23.45	33.19	38.61	38.88	37.35	36.76	35.40	32.84	31.25	34.18	30.01	31.81	31.81	31.81	31.81	31.81	31.81
2009	0.00	0.72	6.12	28.55	23.18	14.96	25.34	23.82	22.76	20.65	22.13	20.87	16.74	19.97	17.72	16.43	16.43	16.43	16.43	16.43	16.43
2010	0.00	0.45	14.43	33.14	61.67	32.83	20.00	15.77	12.16	12.81	13.74	15.02	15.44	11.70	18.28	14.59	14.59	14.59	14.59	14.59	14.59
2011	0.00	1.69	8.93	68.59	33.63	23.24	17.00	14.99	11.85	10.88	10.34	9.41	9.55	9.84	9.58	10.98	10.98	10.98	10.98	10.98	10.98
2012	0.00	0.82	9.96	19.10	31.66	16.59	13.35	12.69	11.27	9.66	9.10	9.09	9.09	8.86	8.83	9.30	9.30	9.30	9.30	9.30	9.30
2013	0.00	0.22	2.38	15.83	13.05	14.01	20.85	18.22	17.86	15.70	13.07	12.14	10.61	11.67	12.22	12.38	12.38	12.38	12.38	12.38	12.38
2014	0.00	0.62	4.66	17.53	12.94	13.30	19.78	18.44	17.23	15.83	16.34	9.75	11.19	11.96	11.74	10.73	10.73	10.73	10.73	10.73	10.73
2015	0.00	2.47	4.86	9.61	12.68	13.83	9.52	8.86	7.80	7.66	7.34	6.32	5.53	5.17	4.84	4.22	4.22	4.22	4.22	4.22	4.22
2016	0.00	3.04	33.91	16.04	22.55	23.51	19.94	18.36	18.08	16.85	14.01	13.19	15.65	9.69	6.39	6.37	6.37	6.37	6.37	6.37	6.37
2017	0.00	4.86	21.43	21.20	21.83	18.98	27.15	27.52	26.25	23.25	24.87	21.16	19.07	19.66	18.71	16.34	16.34	16.34	16.34	16.34	16.34
2018	0.00	11.60	17.55	15.35	15.91	11.36	25.77	23.03	24.12	22.24	22.11	21.03	20.65	19.65	15.85	13.29	13.29	13.29	13.29	13.29	13.29
2019	0.00	1.71	19.56	14.06	16.00	23.24	26.67	25.50	23.91	23.63	22.48	21.26	22.08	18.86	19.56	17.55	17.55	17.55	17.55	17.55	17.55
2020	0.00	0.18	0.95	4.93	24.68	17.18	26.61	25.75	25.10	22.82	23.49	21.83	24.02	18.31	17.39	16.26	16.26	16.26	16.26	16.26	16.26
2021	0.00	0.44	1.80	3.20	10.01	22.33	21.98	22.16	22.15	19.19	19.07	20.14	20.40	19.79	21.06	16.69	16.69	16.69	16.69	16.69	16.69
2022	0.00	0.57	7.27	2.00	3.83	8.67	24.01	21.50	22.54	21.53	20.57	18.26	18.21	18.61	17.70	17.86	17.86	17.86	17.86	17.86	17.86

Table 21. Estimated catch-at-age in numbers for each year from the base model (posterior medians; thousands).

Year	Age																				
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20+**
1966	0	965	11,102	14,692	13,872	10,810	12,492	9,840	7,920	6,968	5,637	4,762	3,957	3,162	2,706	2,180	1,823	1,483	1,187	937	3,121
1967	0	1,440	23,951	35,756	28,488	20,142	20,887	14,320	11,102	8,984	7,897	6,391	5,431	4,487	3,626	3,095	2,477	2,081	1,706	1,369	6,398
1968	0	2,511	12,002	27,046	24,121	14,408	13,683	8,172	5,587	4,370	3,577	3,111	2,509	2,137	1,755	1,421	1,225	976	819	664	3,761
1969	0	2,294	50,898	32,696	43,528	29,348	23,591	13,041	7,878	5,349	4,209	3,380	2,982	2,369	2,016	1,696	1,353	1,168	938	786	5,150
1970	0	621	39,164	116,983	43,753	44,809	40,170	18,582	10,485	6,250	4,234	3,363	2,689	2,378	1,897	1,610	1,355	1,082	928	747	5,498
1971	0	5,229	5,387	46,271	81,621	23,419	32,245	16,510	7,656	4,347	2,611	1,748	1,399	1,117	991	784	666	564	446	384	2,978
1972	0	294	48,929	7,101	36,739	49,972	19,501	15,540	8,024	3,718	2,112	1,265	851	677	543	483	380	324	274	219	1,853
1973	0	232	4,989	109,226	9,555	38,227	70,026	16,141	12,990	6,753	3,124	1,779	1,072	711	570	458	403	322	272	231	1,961
1974	0	3,306	4,094	11,622	155,208	10,423	56,240	61,478	14,253	11,461	5,935	2,748	1,561	934	624	498	399	353	283	240	2,108
1975	0	154	38,318	6,619	11,572	116,861	10,635	33,994	37,086	8,535	6,849	3,603	1,665	941	565	377	301	242	214	170	1,580
1976	0	706	1,852	61,232	6,525	8,603	118,131	6,417	20,560	22,439	5,171	4,157	2,168	1,007	571	342	226	182	146	129	1,153
1977	0	50	6,365	2,332	47,216	3,825	6,952	57,224	3,106	9,972	10,837	2,496	2,016	1,051	486	276	165	110	88	71	671
1978	0	1,527	641	11,376	2,554	39,901	4,421	4,831	39,692	2,148	6,913	7,509	1,735	1,394	725	338	192	115	76	61	555
1979	0	34	24,167	1,426	15,543	2,691	57,343	3,852	4,193	34,486	1,866	5,957	6,518	1,511	1,211	634	293	166	99	66	576
1980	0	278	376	37,091	1,352	11,322	2,676	34,282	2,303	2,510	20,589	1,110	3,567	3,891	900	720	376	175	99	59	415
1981	0	5,819	6,398	1,197	71,865	2,026	22,944	3,283	41,985	2,820	3,070	25,220	1,352	4,355	4,757	1,107	888	462	215	122	632
1982	0	70	64,215	9,934	1,142	52,573	2,015	13,756	1,961	25,174	1,695	1,836	15,100	814	2,618	2,850	666	527	275	128	498
1983	0	68	857	107,469	10,169	897	56,633	1,309	8,930	1,275	16,318	1,098	1,184	9,787	526	1,695	1,836	431	342	178	451
1984	0	131	1,093	1,849	141,996	10,399	1,251	47,538	1,098	7,469	1,072	13,699	917	996	8,196	441	1,422	1,545	360	286	590
1985	0	3,045	1,592	1,808	1,872	110,599	11,021	807	30,446	701	4,797	688	8,781	591	638	5,255	281	906	983	231	614
1986	0	40	63,265	4,643	3,221	2,556	206,990	12,464	906	34,435	794	5,427	777	9,937	663	722	5,954	318	1,027	1,108	1,050
1987	0	69	709	149,980	6,756	3,584	3,878	188,016	11,329	825	31,273	724	4,933	706	9,005	602	654	5,399	289	926	1,975
1988	0	2,855	1,066	1,486	190,000	6,535	4,730	3,088	148,790	8,978	650	24,729	570	3,893	560	7,134	476	518	4,264	229	2,331
1989	0	1,257	54,771	2,807	2,410	236,655	11,055	4,762	3,085	149,118	8,974	654	24,817	572	3,903	561	7,155	479	521	4,287	2,649
1990	0	49	13,335	80,508	2,511	1,636	217,493	6,034	2,590	1,686	81,654	4,918	358	13,570	314	2,137	306	3,905	261	283	3,810
1991	0	2,783	1,910	116,951	136,512	2,841	2,299	183,464	5,019	2,181	1,416	68,876	4,135	301	11,439	264	1,792	257	3,293	219	3,476
1992	0	573	29,199	2,894	70,352	115,444	3,988	2,178	173,447	4,785	2,072	1,345	65,154	3,917	285	10,809	249	1,698	244	3,111	3,495
1993	0	32	5,028	104,079	2,638	42,100	112,619	2,050	1,125	89,712	2,483	1,068	694	33,535	2,014	146	5,560	128	875	125	3,428
1994	0	777	431	11,626	153,665	2,414	64,836	177,418	3,259	1,777	141,178	3,911	1,680	1,094	52,843	3,180	232	8,778	202	1,383	5,638
1995	0	874	9,433	841	15,392	120,836	2,461	32,974	90,146	1,646	897	71,998	1,987	856	558	26,960	1,613	118	4,472	103	3,567
1996	0	1,354	94,445	107,511	2,940	23,786	144,122	2,061	27,608	75,628	1,376	757	60,304	1,676	720	467	22,561	1,354	99	3,747	3,109
1997	0	565	5,865	163,712	154,197	3,224	48,468	92,196	1,316	17,642	48,336	887	484	38,637	1,065	456	297	14,495	866	63	4,407
1998	0	669	24,050	110,557	127,606	174,343	4,108	29,961	57,237	824	10,894	30,028	546	300	24,003	662	284	185	8,997	537	2,788
1999	0	1,698	47,568	137,513	95,683	134,780	94,351	2,811	20,539	39,002	560	7,481	20,446	375	206	16,317	450	193	126	6,116	2,275
2000	0	2,947	12,613	34,394	51,813	28,700	86,135	52,090	1,536	11,387	21,601	308	4,146	11,335	210	113	9,028	249	108	70	4,652
2001	0	86	56,656	60,807	46,586	57,759	22,486	44,309	26,927	793	5,851	11,111	160	2,135	5,831	108	58	4,657	128	55	2,439
2002	0	167	638	145,326	50,868	22,749	26,724	9,167	18,157	11,065	326	2,394	4,563	66	874	2,393	44	24	1,914	53	1,028
2003	0	3	1,485	1,698	236,274	42,994	14,364	18,546	6,379	12,652	7,669	228	1,660	3,175	46	607	1,670	31	17	1,330	756
2004	0	680	340	34,925	24,014	414,056	54,330	15,636	20,298	6,977	13,840	8,417	247	1,817	3,484	50	666	1,832	33	18	2,288
2005	0	8	5,174	572	48,625	13,068	444,264	43,673	12,652	16,350	5,613	11,102	6,754	200	1,468	2,794	40	536	1,470	27	1,861
2006	0	2,677	1,114	80,221	2,227	66,468	9,579	361,334	35,575	10,282	13,305	4,575	9,050	5,494	162	1,196	2,268	33	436	1,194	1,540
2007	0	1,546	65,113	2,332	92,978	1,398	44,891	6,137	230,920	22,713	6,558	8,509	2,927	5,775	3,511	104	766	1,456	21	279	1,752
2008	0	42	48,751	193,671	1,775	87,365	1,849	31,560	4,301	162,868	16,021	4,623	5,973	2,056	4,070	2,466	73	538	1,021	15	1,433
2009	0	2,251	227	98,566	100,857	802	42,114	661	11,304	1,539	58,320	5,716	1,657	2,142	736	1,453	882	26	194	365	520
2010	0	592	122,938	1,192	189,514	111,822	739	21,016	328	5,627	768	29,166	2,844	824	1,061	364	726	440	13	96	442
2011	0	19,520	21,533	612,699	1,067	47,671	41,192	382	10,846	169	2,906	395	15,017	1,467	426	548	188	375	228	7	280
2012	0	358	226,062	49,819	213,886	427	23,596	25,087	232	6,594	103	1,764	239	9,142	896	258	334	115	228	138	176
2013	0	384	1,858	464,076	32,848	80,846	455	25,139	26,485	248	7,016	109	1,880	253	9,710	947	272	354	121	242	332
2014	0	192	18,646	17,234	375,582	28,750	92,397	270	14,643	15,534	145	4,085	64	1,099	149	5,656	556	160	207	71	337
2015	0	13,921	3,011	31,490	8,816	291,719	14,978	29,840	86	4,693	4,966	47	1,312	20	351	48	1,822	178	51	66	132
2016	0	145	473,376	11,254	53,969	11,398	303,358	19,575	38,606	112	6,135	6,490	61	1,707	27	459	62	2,362	232	67	259
2017	0	35,136	1,585	350,032	15,092	45,482	11,568	353,724	22,749	44,986	130	7,134	7,547	71	1,990	31	534	73	2,755	271	383
2018	0	43,488	247,320	1,162	235,116	5,940	44,457	7,090	217,054	13,976	27,621	80	4,382	4,640	44	1,218	19	328	45	1,688	402
2019	0	584	86,119	184,078	945	264,528	10,909	32,236	5,131	157,058	10,118	20,005	58	3,168	3,354	32	884	14	237	32	1,515
2020	0	82	1,321	27,343	270,124	732	219,649	6,960	20,668	3,277	100,544	6,471	12,802	37	2,033	2,146	20	566	9	152	993
2021	0	5,762	2,156	5,485	53,816	199,384	742	138,924	4,420	13,049	2,082	63,636	4,090	8,092	23	1,278	1,358	13	357	6	724
2022	0	333	191,230	3,035	5,559	36,889	150,433	516	96,501	3,066	9,078	1,435	44,293	2,836	5,620	16	892	944	9	248	506

Table 22. Estimated catch-at-age in biomass for each year from the base model (posterior medians; t).

Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	0	95	2,908	5,661	6,775	5,813	7,296	6,436	5,615	5,394	4,746	4,291	3,753	3,308	2,690	2,246	1,878	1,528	1,223	966	3,215
1967	0	142	6,273	13,777	13,913	10,830	12,200	9,367	7,871	6,954	6,649	5,758	5,152	4,693	3,605	3,188	2,552	2,144	1,757	1,410	6,592
1968	0	248	3,143	10,421	11,781	7,747	7,992	5,345	3,961	3,382	3,012	2,803	2,380	2,235	1,745	1,464	1,262	1,006	844	684	3,875
1969	0	226	13,330	12,598	21,259	15,781	13,779	8,530	5,586	4,140	3,544	3,045	2,828	2,478	2,004	1,748	1,394	1,203	967	810	5,306
1970	0	61	10,257	45,074	21,369	24,094	23,463	12,155	7,434	4,837	3,565	3,030	2,551	2,487	1,886	1,659	1,396	1,115	956	769	5,664
1971	0	516	1,411	17,828	39,864	12,592	18,834	10,799	5,428	3,364	2,198	1,575	1,327	1,168	985	808	686	582	460	395	3,068
1972	0	29	12,814	2,736	17,943	26,870	11,391	10,165	5,689	2,878	1,778	1,139	808	708	540	497	392	333	282	226	1,909
1973	0	23	1,307	42,085	4,667	20,554	40,902	10,558	9,210	5,227	2,631	1,603	1,016	743	567	471	415	332	280	238	2,020
1974	0	326	1,072	4,478	75,804	5,604	32,850	40,213	10,105	8,871	4,997	2,476	1,481	977	620	513	411	364	292	247	2,172
1975	0	24	11,446	2,421	7,109	73,693	8,373	29,704	35,892	7,745	6,644	6,101	2,497	1,788	1,104	1,035	826	665	587	467	4,336
1976	0	70	437	30,555	3,385	5,967	94,954	5,881	24,802	29,923	7,496	6,862	3,917	1,871	1,116	938	620	498	400	354	3,163
1977	0	4	2,552	1,147	28,164	2,571	5,273	47,845	3,022	10,848	13,001	3,170	2,718	1,723	971	589	353	235	188	151	1,433
1978	0	111	82	5,346	1,354	24,044	2,826	3,573	33,429	2,108	7,603	9,356	2,306	2,064	1,262	790	448	267	177	142	1,297
1979	0	3	5,824	369	9,047	1,848	44,022	3,432	3,827	35,758	2,236	7,436	9,989	2,345	2,174	1,256	580	329	197	132	1,142
1980	0	22	80	16,799	530	5,552	1,383	22,468	1,643	2,194	21,878	1,290	4,601	5,058	1,143	1,006	525	245	139	82	579
1981	0	625	1,367	410	37,830	797	12,055	1,793	31,338	2,032	2,527	26,262	1,486	5,858	7,100	1,342	1,077	561	260	148	766
1982	0	8	15,829	3,314	357	29,309	810	7,343	1,120	19,379	1,186	1,583	16,002	762	2,691	3,332	778	616	322	150	583
1983	0	9	116	36,647	3,757	294	29,449	658	5,518	900	14,360	1,021	1,226	10,091	695	2,512	2,721	638	506	264	668
1984	0	17	179	461	62,251	4,277	544	27,914	637	5,048	751	13,032	1,042	1,022	10,497	829	2,674	2,905	677	538	1,109
1985	0	530	353	454	762	60,321	5,932	450	21,324	442	3,220	591	6,615	559	431	4,505	241	776	843	198	526
1986	0	6	17,588	1,349	974	955	112,313	7,129	582	28,268	747	6,437	925	13,650	1,113	1,165	9,611	513	1,657	1,788	1,694
1987	0	10	98	56,843	1,882	1,029	1,404	108,579	6,769	525	23,886	711	4,563	876	10,834	852	925	7,643	409	1,310	2,796
1988	0	400	199	449	89,091	2,395	1,686	1,506	93,217	5,997	436	22,709	535	3,990	569	11,165	745	810	6,674	358	3,648
1989	0	175	14,991	876	706	122,067	4,849	1,935	1,594	97,061	6,045	412	22,596	383	3,233	656	8,378	560	610	5,020	3,102
1990	0	7	3,247	28,194	1,014	847	119,904	3,759	1,729	894	62,441	4,087	788	16,100	319	3,135	449	5,729	383	416	5,589
1991	0	380	526	43,237	62,768	1,460	1,250	108,372	3,618	1,853	1,557	49,487	2,648	306	13,785	630	4,271	613	7,846	522	8,283
1992	0	78	6,763	1,005	33,368	61,578	2,320	1,353	111,110	3,125	1,311	971	47,914	3,330	277	11,103	256	1,744	250	3,195	3,590
1993	0	4	1,250	35,220	1,045	19,109	55,577	1,029	549	49,261	1,266	1,348	711	20,574	1,207	100	3,809	88	600	86	2,348
1994	0	92	129	4,216	68,673	1,080	34,116	101,129	2,026	995	89,521	1,897	1,091	798	37,059	2,371	173	6,544	151	1,031	4,203
1995	0	97	2,530	287	7,505	64,853	1,601	20,605	59,469	1,244	599	53,603	1,589	779	380	21,590	1,292	94	3,581	82	2,856
1996	0	138	27,162	42,811	1,374	12,647	81,444	1,341	16,446	48,114	832	568	40,742	1,359	1,070	350	16,941	1,017	74	2,813	2,334
1997	0	52	2,085	70,756	76,035	1,766	26,430	53,778	770	10,710	30,524	766	288	27,502	705	397	258	12,600	753	55	3,831
1998	0	56	5,046	39,712	64,441	90,240	2,224	19,007	34,794	553	8,529	21,404	432	232	17,851	526	225	147	7,145	427	2,214
1999	0	232	11,901	47,511	40,675	70,962	52,544	1,610	12,564	27,418	372	5,977	15,445	330	151	13,358	368	158	103	5,007	1,862
2000	0	560	4,858	16,303	29,875	18,937	61,810	37,916	1,158	9,540	17,624	271	3,546	10,644	183	106	8,429	233	101	65	4,343
2001	0	4	16,243	29,449	30,407	38,381	16,795	38,234	23,036	698	5,634	10,877	161	2,240	5,788	106	57	4,549	126	54	2,382
2002	0	13	229	66,312	29,626	16,944	19,321	7,151	16,590	9,484	286	2,162	3,823	55	945	2,506	46	25	2,003	55	1,077
2003	0	0	379	739	123,453	25,302	10,845	12,832	4,764	10,433	5,894	203	1,538	2,506	39	605	1,664	30	17	1,325	753
2004	0	73	70	15,227	11,541	220,237	35,201	11,059	13,354	4,948	11,140	7,221	190	1,764	3,009	45	596	1,642	30	16	2,050
2005	0	1	1,347	247	24,730	7,049	252,431	27,671	8,287	11,491	4,469	8,998	5,477	152	1,681	2,703	39	519	1,422	26	1,801
2006	0	354	427	36,701	1,190	38,153	5,661	216,042	23,337	7,194	9,658	3,303	7,016	3,615	104	1,142	2,166	31	416	1,140	1,471
2007	0	69	14,872	974	49,929	789	27,263	3,884	149,544	16,024	5,065	6,490	2,381	5,025	2,812	90	666	1,266	18	243	1,523
2008	0	6	11,895	78,998	999	55,608	1,270	21,517	3,053	117,444	11,997	3,732	5,067	1,594	3,595	2,054	61	449	851	12	1,194
2009	0	150	53	33,680	47,514	511	28,225	471	8,436	1,266	44,754	4,652	1,682	1,821	705	1,502	912	27	200	378	537
2010	0	64	28,595	348	82,097	59,288	487	17,546	355	5,782	736	25,558	2,424	927	764	328	655	397	12	86	399
2011	0	1,648	5,291	197,228	413	24,513	24,509	258	9,256	157	2,843	425	15,900	1,508	449	505	173	346	210	6	258
2012	0	46	48,490	17,616	87,565	209	15,484	17,328	180	5,982	99	1,701	230	9,041	889	243	315	108	215	130	166
2013	0	50	534	166,835	15,429	41,264	285	18,012	19,360	206	7,008	117	2,313	283	10,373	999	287	373	128	255	350
2014	0	20	6,884	7,876	180,166	15,473	53,045	166	9,650	11,144	101	4,757	65	1,043	144	5,984	588	170	219	75	357
2015	0	1,057	744	12,297	3,919	137,341	8,285	17,749	58	3,228	3,565	39	1,249	21	382	60	2,276	222	64	83	165
2016	0	24	115,362	4,099	20,271	4,768	141,001	9,880	19,793	62	4,060	4,558	36	1,632	39	668	91	3,435	337	97	377
2017	0	4,930	494	140,573	7,330	23,942	6,493	195,857	13,206	29,489	80	5,138	6,030	55	1,621	29	498	68	2,569	253	357
2018	0	8,132	87,650	538	118,240	3,182	24,531	4,377	127,975	8,935	17,763	54	3,018	3,359	39	1,303	21	351	48	1,806	430
2019	0	40	24,914	82,246	494	141,522	6,326	19,548	3,318	102,779	6,960	14,550	41	2,598	2,651	28	779	12	209	28	1,334
2020	0	8	456	13,065	137,277	411	125,464	4,108	12,514	2,183	65,072	4,506	8,101	31	1,777	2,007	19	530	8	142	928
2021	0	766	652	2,874	33,021	122,063	494	91,801	2,923	9,959	1,599	46,282	2,937	5,989	16	1,122	1,191	11	313	5	635
2022	0	48	70,143	1,513	3,145	23,934	96,247	368	65,775	2,187	6,780	1,207	37,370	2,341	4,876	14	767	811	8	213	436

Table 23. Calculations showing changes in biomass at each age due to natural mortality and fishing for recent strong cohorts. Start Biomass is the biomass at the beginning of the year, Catch Weight is the catch for the cohort for the year, M is the biomass attributed to natural mortality, and Surviving Biomass is what survives to the end of the year. Surviving Biomass does not equal the Start Biomass in the following year because the empirical weights-at-age change between years. Estimated quantities are posterior medians.

	1999 cohort				2010 cohort				2014 cohort				2016 cohort			
Age	**Start Biomass 000s t**	**Catch Weight 000s t**	**M 000s t**	**Surviving Biomass 000s t**	**Start Biomass 000s t**	**Catch Weight 000s t**	**M 000s t**	**Surviving Biomass 000s t**	**Start Biomass 000s t**	**Catch Weight 000s t**	**M 000s t**	**Surviving Biomass 000s t**	**Start Biomass 000s t**	**Catch Weight 000s t**	**M 000s t**	**Surviving Biomass 000s t**
0	202.4	0.0	42.1	160.3	217.4	0.0	45.3	172.1	95.3	0.0	19.8	75.5	58.6	0.0	12.2	46.4
1	2,002.7	0.6	416.6	1,585.6	1,125.8	1.6	233.3	890.8	550.9	1.1	115.1	434.8	708.2	4.9	148.9	554.4
2	2,393.8	16.2	495.4	1,882.1	2,263.9	48.5	465.5	1,749.9	1,396.0	115.4	280.6	1,000.1	1,400.5	87.7	282.6	1,030.2
3	2,995.5	66.3	614.7	2,314.6	2,932.8	166.8	591.6	2,174.4	1,648.0	140.6	327.3	1,180.1	1,298.8	82.2	261.5	955.1
4	2,650.4	123.5	535.5	1,991.5	2,901.5	180.2	582.1	2,139.2	1,477.8	118.2	293.9	1,065.6	1,086.4	137.3	210.7	738.4
5	2,027.3	220.2	396.1	1,410.9	2,099.5	137.3	421.9	1,540.3	1,133.6	141.5	220.9	771.2	889.5	122.1	170.9	596.6
6	1,507.2	252.4	284.6	970.2	1,520.7	141.0	301.2	1,078.5	823.4	125.5	157.2	540.7	623.5	96.2	118.9	408.4
7	1,020.9	216.0	187.5	617.4	1,284.7	195.9	244.3	844.6	625.5	91.8	119.2	414.5	407.1			
8	668.7	149.5	121.1	398.0	899.4	128.0	172.6	598.8	427.6	65.8	82.3	279.6				
9	443.2	117.4	78.9	246.9	664.6	102.8	127.5	434.2	281.9							
10	262.8	44.8	49.5	168.5	429.5	65.1	82.1	282.3								
11	192.4	25.6	37.1	129.8	317.2	46.3	61.0	209.9								
12	156.8	15.9	30.8	110.1	243.5	37.4	46.6	159.6								
13	102.8	9.0	20.6	73.2	149.0											
14	79.1	10.4	15.3	53.4												
15	52.9	6.0	10.4	36.5												
16	43.1	2.3	8.8	32.1												
17	37.3	3.4	7.4	26.5												
18	17.0	2.6	3.3	11.1												
19	12.8	1.8	0.4	10.5												
20	8.7															

Table 24. Time series of median posterior population estimates from the base model. Relative spawning biomass is spawning biomass relative to the unfished equilibrium (B_0). Total biomass includes females and males of ages 0 and above. Age-2+ biomass includes females and males ages 2 and above. Exploitation fraction is total catch divided by total age-2+ biomass. Relative fishing intensity is (1-SPR)/(1-SPR$_{40\%}$) such that values below 100% are below the target rate. A dash (–) indicates a quantity requiring 2023 catch which has not taken place yet.

Year	Female spawning biomass (thousand t)	Relative spawning biomass	Total biomass (thousand t)	Age-2+ biomass (thousand t)	Age-0 recruits (millions)	Relative fishing intensity	Exploitation fraction
1966	877	48.4%	2,331	2,117	1,538	48.4%	6.5%
1967	876	48.7%	2,414	2,170	4,521	66.2%	9.9%
1968	874	48.7%	2,575	2,165	2,959	47.8%	5.6%
1969	972	54.5%	2,918	2,658	675	58.7%	6.8%
1970	1,145	64.2%	3,094	2,898	8,967	65.2%	8.1%
1971	1,185	66.2%	3,397	2,683	786	48.2%	5.8%
1972	1,256	70.2%	3,839	3,766	528	36.5%	3.1%
1973	1,620	90.3%	3,869	3,738	5,973	40.5%	4.4%
1974	1,594	88.7%	3,924	3,452	347	46.3%	6.1%
1975	1,833	102.0%	4,892	4,744	1,838	51.2%	4.7%
1976	2,255	125.6%	5,162	5,000	205	44.6%	4.8%
1977	1,947	108.2%	4,834	4,459	6,619	29.1%	3.0%
1978	1,647	91.5%	3,940	3,553	134	29.3%	2.9%
1979	1,713	95.2%	4,442	4,364	1,362	31.7%	3.1%
1980	1,721	95.4%	4,680	3,818	17,165	24.6%	2.4%
1981	1,566	86.7%	4,885	3,411	271	35.8%	4.1%
1982	1,602	88.8%	5,405	5,360	308	29.8%	2.0%
1983	2,240	124.1%	5,140	5,088	535	29.0%	2.2%
1984	2,303	127.4%	5,380	4,874	13,954	33.4%	2.8%
1985	1,984	109.6%	6,255	4,323	132	22.5%	2.6%
1986	2,079	115.0%	6,244	6,217	181	39.9%	3.4%
1987	2,420	133.9%	5,616	5,444	6,614	45.1%	4.3%
1988	2,318	128.5%	5,660	4,880	2,113	45.8%	5.1%
1989	1,929	107.0%	5,203	4,961	113	52.4%	6.0%
1990	2,025	112.1%	4,738	4,655	4,348	46.7%	5.6%
1991	1,887	104.4%	4,552	4,060	1,251	70.2%	7.9%
1992	1,557	86.0%	3,879	3,744	126	60.0%	8.0%
1993	1,241	68.7%	2,931	2,863	3,237	51.5%	6.9%
1994	1,197	66.2%	2,920	2,566	3,324	62.0%	14.1%
1995	1,030	57.1%	2,899	2,589	1,262	54.2%	9.6%
1996	1,006	55.8%	2,772	2,638	1,889	68.8%	11.6%
1997	1,039	57.5%	2,632	2,475	1,029	70.7%	13.1%
1998	881	48.8%	2,171	2,070	2,042	85.1%	15.5%
1999	741	41.0%	2,158	1,731	13,314	95.1%	18.0%
2000	801	44.3%	4,093	2,082	322	66.7%	11.0%
2001	1,112	61.6%	4,180	4,147	1,277	67.2%	5.5%
2002	1,891	104.8%	4,471	4,393	47	47.4%	4.1%
2003	1,759	97.4%	3,876	3,846	1,779	43.2%	5.3%
2004	1,394	77.3%	3,194	3,039	46	71.3%	11.3%
2005	1,088	60.3%	2,587	2,538	2,895	68.3%	14.3%
2006	885	49.2%	2,287	1,950	2,105	80.9%	18.5%
2007	697	38.7%	1,839	1,764	26	83.9%	16.5%
2008	714	39.7%	1,900	1,815	5,808	88.2%	17.8%
2009	626	34.8%	1,679	1,352	1,507	75.9%	13.2%
2010	619	34.5%	2,272	1,923	16,852	91.0%	11.9%
2011	768	42.8%	3,024	1,893	430	85.4%	15.2%
2012	1,007	56.4%	3,861	3,796	1,699	64.4%	5.5%
2013	1,844	103.1%	4,479	4,299	390	62.2%	6.6%
2014	1,947	108.8%	4,508	4,381	9,165	59.6%	6.8%
2015	1,477	82.4%	3,817	3,268	38	43.8%	5.9%

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Year	Female spawning biomass (thousand t)	Relative spawning biomass	Total biomass (thousand t)	Age-2+ biomass (thousand t)	Age-0 recruits (millions)	Relative fishing intensity	Exploitation fraction
2016	1,287	71.9%	3,829	3,764	6,374	72.8%	8.8%
2017	1,640	91.9%	4,417	3,693	2,464	75.0%	11.9%
2018	1,576	88.0%	4,699	4,317	641	69.0%	9.6%
2019	1,623	90.6%	3,981	3,929	611	69.2%	10.5%
2020	1,483	82.7%	3,628	3,288	11,409	59.6%	11.6%
2021	1,292	72.1%	4,286	2,873	450	53.0%	11.4%
2022	1,424	78.7%	5,164	4,993	963	50.7%	6.4%
2023	1,910	104.1%	4,833	4,514	931	–	–

Table 25. Time-series of 95% posterior credibility intervals for the quantities shown in Table 24. A dash (–) indicates a quantity requiring 2023 catch which has not taken place yet.

Year	Female spawning biomass (thousand t)	Relative spawning biomass	Total biomass (thousand t)	Age-2+ biomass (thousand t)	Age-0 recruits (millions)	(1-SPR) / (1-SPR$_{40\%}$)	Exploitation fraction
1966	510 - 1,659	27.4 - 87.7%	1,484 - 4,314	1,253 - 3,982	64 - 9,843	26.2 - 73.4%	3.5 - 11.0%
1967	534 - 1,653	28.0 - 88.8%	1,562 - 4,529	1,332 - 4,106	239 - 14,052	38.5 - 92.4%	5.2 - 16.1%
1968	534 - 1,684	28.1 - 89.4%	1,648 - 5,013	1,325 - 4,258	229 - 9,519	25.2 - 72.6%	2.9 - 9.2%
1969	609 - 1,901	31.4 - 99.8%	1,870 - 5,828	1,682 - 5,302	42 - 3,903	32.1 - 84.8%	3.4 - 10.7%
1970	723 - 2,301	37.0 - 119.5%	1,955 - 6,311	1,846 - 5,842	4,479 - 21,884	35.9 - 91.3%	4.0 - 12.7%
1971	737 - 2,421	37.8 - 125.5%	2,083 - 7,066	1,667 - 5,474	70 - 3,037	23.8 - 73.9%	2.8 - 9.3%
1972	773 - 2,568	40.0 - 133.8%	2,330 - 8,010	2,278 - 7,828	59 - 1,902	17.0 - 59.5%	1.5 - 5.2%
1973	989 - 3,316	51.3 - 172.5%	2,354 - 7,935	2,282 - 7,673	3,055 - 13,863	19.4 - 64.5%	2.1 - 7.1%
1974	973 - 3,215	50.3 - 168.0%	2,377 - 8,003	2,100 - 6,979	42 - 1,322	22.8 - 72.2%	3.0 - 10.1%
1975	1,108 - 3,676	57.5 - 192.2%	2,938 - 9,922	2,845 - 9,547	882 - 4,368	25.0 - 80.6%	2.3 - 7.8%
1976	1,352 - 4,505	70.5 - 236.1%	3,085 - 10,348	2,995 - 10,008	26 - 849	21.6 - 71.7%	2.4 - 7.9%
1977	1,166 - 3,835	60.8 - 202.0%	2,895 - 9,624	2,670 - 8,793	3,545 - 14,219	13.4 - 50.9%	1.5 - 5.0%
1978	997 - 3,166	51.7 - 167.4%	2,390 - 7,604	2,150 - 6,834	17 - 654	13.6 - 50.9%	1.5 - 4.8%
1979	1,055 - 3,227	54.7 - 171.4%	2,738 - 8,327	2,686 - 8,201	528 - 3,332	15.5 - 53.0%	1.7 - 5.1%
1980	1,074 - 3,152	55.0 - 169.2%	2,916 - 8,623	2,383 - 7,003	10,030 - 33,674	11.9 - 42.1%	1.3 - 3.8%
1981	997 - 2,788	50.6 - 151.6%	3,121 - 8,724	2,170 - 6,078	30 - 1,077	18.7 - 57.7%	2.3 - 6.4%
1982	1,041 - 2,786	52.6 - 154.2%	3,509 - 9,375	3,485 - 9,290	48 - 1,023	15.4 - 49.3%	1.2 - 3.1%
1983	1,497 - 3,759	75.0 - 211.7%	3,433 - 8,619	3,393 - 8,526	97 - 1,525	15.3 - 47.1%	1.3 - 3.4%
1984	1,569 - 3,743	78.1 - 214.2%	3,675 - 8,763	3,327 - 7,918	8,859 - 24,752	18.1 - 53.1%	1.7 - 4.2%
1985	1,386 - 3,122	68.0 - 182.7%	4,357 - 10,062	3,024 - 6,810	17 - 569	12.3 - 36.2%	1.6 - 3.7%
1986	1,494 - 3,179	72.4 - 187.7%	4,470 - 9,709	4,456 - 9,681	23 - 676	23.6 - 58.7%	2.2 - 4.7%
1987	1,777 - 3,656	84.7 - 218.0%	4,117 - 8,516	4,001 - 8,250	4,283 - 11,285	27.3 - 64.7%	2.8 - 5.9%
1988	1,740 - 3,422	81.7 - 206.3%	4,215 - 8,443	3,661 - 7,191	1,121 - 3,817	28.3 - 65.7%	3.5 - 6.8%
1989	1,474 - 2,789	68.6 - 170.9%	3,956 - 7,584	3,767 - 7,245	18 - 427	33.4 - 72.4%	4.1 - 7.9%
1990	1,567 - 2,880	72.2 - 178.4%	3,667 - 6,740	3,605 - 6,620	2,893 - 7,191	29.9 - 64.7%	3.9 - 7.2%
1991	1,491 - 2,615	67.7 - 164.3%	3,573 - 6,369	3,204 - 5,622	546 - 2,423	46.1 - 99.8%	5.7 - 10.0%
1992	1,244 - 2,126	55.9 - 135.5%	3,087 - 5,352	2,979 - 5,148	17 - 489	39.3 - 90.6%	5.8 - 10.1%
1993	1,000 - 1,679	44.6 - 107.1%	2,357 - 3,993	2,309 - 3,896	2,211 - 5,174	32.9 - 82.2%	5.1 - 8.6%
1994	980 - 1,596	43.1 - 103.3%	2,374 - 3,950	2,099 - 3,422	2,247 - 5,315	42.8 - 84.9%	10.6 - 17.3%
1995	842 - 1,378	37.1 - 89.2%	2,349 - 3,948	2,108 - 3,495	759 - 2,151	37.4 - 72.5%	7.1 - 11.8%
1996	826 - 1,346	36.3 - 87.6%	2,256 - 3,746	2,152 - 3,565	1,232 - 3,128	49.2 - 91.7%	8.6 - 14.2%
1997	851 - 1,395	37.6 - 90.0%	2,139 - 3,552	2,019 - 3,331	581 - 1,889	51.3 - 90.4%	9.8 - 16.1%
1998	719 - 1,186	31.8 - 76.4%	1,765 - 2,945	1,684 - 2,788	1,306 - 3,453	64.4 - 102.8%	11.5 - 19.0%
1999	600 - 1,007	26.6 - 64.6%	1,712 - 3,026	1,400 - 2,361	9,223 - 21,624	73.3 - 113.1%	13.2 - 22.3%
2000	633 - 1,116	28.7 - 70.1%	3,102 - 6,012	1,634 - 2,938	99 - 708	47.0 - 84.8%	7.8 - 14.0%
2001	869 - 1,581	39.8 - 97.3%	3,222 - 6,009	3,194 - 5,955	850 - 2,085	47.3 - 85.8%	3.8 - 7.1%
2002	1,488 - 2,648	67.8 - 164.2%	3,511 - 6,292	3,452 - 6,169	15 - 131	31.1 - 64.3%	2.9 - 5.2%
2003	1,418 - 2,397	63.4 - 151.6%	3,121 - 5,299	3,098 - 5,249	1,222 - 2,922	28.0 - 59.7%	3.9 - 6.6%
2004	1,151 - 1,849	50.4 - 119.6%	2,626 - 4,278	2,512 - 4,035	13 - 151	48.6 - 96.3%	8.5 - 13.6%
2005	907 - 1,441	39.4 - 93.4%	2,140 - 3,479	2,105 - 3,399	1,964 - 4,887	47.2 - 91.4%	10.7 - 17.3%
2006	734 - 1,193	32.1 - 76.2%	1,862 - 3,166	1,613 - 2,635	1,429 - 3,508	56.5 - 112.2%	13.7 - 22.4%
2007	566 - 969	25.2 - 60.5%	1,475 - 2,613	1,416 - 2,498	7 - 92	58.3 - 116.2%	11.7 - 20.6%
2008	564 - 1,042	25.8 - 62.4%	1,497 - 2,797	1,434 - 2,653	4,010 - 9,616	64.2 - 110.8%	12.2 - 22.5%
2009	483 - 941	22.5 - 55.4%	1,287 - 2,569	1,044 - 2,033	844 - 2,940	51.7 - 99.4%	8.8 - 17.1%
2010	475 - 941	22.2 - 54.8%	1,712 - 3,537	1,473 - 2,927	11,149 - 30,142	63.4 - 119.4%	7.8 - 15.5%
2011	584 - 1,185	27.4 - 67.9%	2,227 - 4,884	1,435 - 2,929	171 - 965	57.5 - 114.8%	9.8 - 20.0%
2012	741 - 1,624	35.5 - 90.6%	2,803 - 6,301	2,757 - 6,193	1,024 - 3,223	40.5 - 92.1%	3.3 - 7.5%
2013	1,356 - 2,966	64.5 - 166.6%	3,282 - 7,249	3,154 - 6,909	137 - 960	39.3 - 83.5%	4.1 - 9.1%
2014	1,436 - 3,125	67.9 - 175.6%	3,310 - 7,314	3,222 - 7,096	5,991 - 16,721	36.6 - 82.5%	4.2 - 9.3%
2015	1,091 - 2,361	51.5 - 133.7%	2,795 - 6,199	2,411 - 5,247	8 - 140	25.1 - 64.7%	3.7 - 8.0%
2016	950 - 2,078	44.7 - 116.8%	2,792 - 6,340	2,752 - 6,215	3,855 - 12,724	45.2 - 98.8%	5.3 - 12.1%
2017	1,178 - 2,752	56.3 - 151.6%	3,109 - 7,597	2,650 - 6,203	1,158 - 5,937	47.0 - 109.2%	7.1 - 16.6%
2018	1,081 - 2,765	52.7 - 151.3%	3,149 - 8,452	2,918 - 7,731	186 - 1,963	41.8 - 102.3%	5.4 - 14.2%
2019	1,061 - 2,979	52.5 - 162.3%	2,579 - 7,401	2,551 - 7,297	115 - 2,189	41.7 - 98.1%	5.6 - 16.1%
2020	910 - 2,853	46.0 - 154.1%	2,185 - 7,026	1,998 - 6,364	2,908 - 47,580	34.8 - 86.4%	6.0 - 19.0%
2021	724 - 2,635	37.9 - 140.8%	2,263 - 9,406	1,603 - 5,853	28 - 6,912	29.6 - 78.2%	5.6 - 20.4%
2022	716 - 3,081	38.5 - 165.8%	2,312 - 14,200	2,216 - 13,740	41 - 21,502	27.4 - 78.2%	2.3 - 14.4%
2023	757 - 5,610	42.0 - 300.2%	1,915 - 14,503	1,753 - 13,669	46 - 19,005	–	–

Table 26. Select parameters, derived quantities, and reference point posterior median estimates for the (2023) base model compared to the previous assessment's (2022) base model.

	Base model	2022 Base model
Parameters		
Natural mortality (M)	0.233	0.233
Unfished recruitment (R_0, millions)	2,547	2,535
Steepness (h)	0.808	0.810
Additional biomass index SD	0.286	0.292
Catchability: biomass index (q_b)	0.833	0.824
Additional age-1 index SD	0.375	0.373
Catchability: age-1 index (q_1)	0.398	0.422
Dirichlet-multinomial fishery (log θ_{fish})	-0.629	-0.564
Dirichlet-multinomial survey (log θ_{surv})	2.595	2.591
Derived Quantities		
2010 recruitment (millions)	16,852	17,156
2014 recruitment (millions)	9,165	9,312
2016 recruitment (millions)	6,374	6,418
2020 recruitment (millions)	11,409	5,224
Unfished female spawning biomass (B_0, thousand t)	1,815	1,813
2009 relative spawning biomass	34.8%	35.0%
2023 relative spawning biomass	104.1%	–
Reference Points based on $F_{\text{SPR}=40\%}$		
2022 rel. fishing intensity: (1-SPR)/(1-SPR$_{40\%}$)	50.7%	–
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	642	645
SPR at $F_{\text{SPR}=40\%}$	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.6%	18.5%
Yield at $B_{\text{SPR}=40\%}$ (thousand t)	309	309

Table 27. Summary of median and 95% credibility intervals of equilibrium conceptual reference points for the base assessment model. Equilibrium reference points were computed using 1975–2022 averages for mean weight-at-age and baseline selectivity-at-age (1966–1990; prior to time-varying deviations.)

Quantity	**2.5th percentile**	**Median**	**97.5th percentile**
Unfished female spawning biomass (B_0, thousand t)	1,149	1,815	2,975
Unfished recruitment (R_0, millions)	1,364	2,547	5,230
Reference points (equilibrium) based on $F_{\mathbf{SPR}=40\%}$			
Female spawning biomass at $F_{\mathrm{SPR}=40\%}$ ($B_{\mathrm{SPR}=40\%}$, thousand t)	372	642	1,064
SPR at $F_{\mathrm{SPR}=40\%}$	–	40%	–
Exploitation fraction corresponding to $F_{\mathrm{SPR}=40\%}$	16.1%	18.6%	21.2%
Yield associated with $F_{\mathrm{SPR}=40\%}$ (thousand t)	168	309	570
Reference points (equilibrium) based on $B_{40\%}$ (40% of B_0)			
Female spawning biomass ($B_{40\%}$, thousand t)	460	726	1,190
SPR at $B_{40\%}$	40.7%	43.6%	51.8%
Exploitation fraction resulting in $B_{40\%}$	12.3%	16.4%	19.5%
Yield at $B_{40\%}$ (thousand t)	169	302	555
Reference points (equilibrium) based on estimated MSY			
Female spawning biomass (B_{MSY}, thousand t)	283	467	821
SPR at MSY	22.5%	29.9%	47.3%
Exploitation fraction corresponding to SPR at MSY	14.4%	25.9%	35.2%
MSY (thousand t)	175	325	614

Table 28. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year. Catch alternatives are based on: constant catches (rows a, b, c, d, f, g, i, k, l), including catch similar to 2022 (row f) and to the TAC from 2022 (row l); and non-constant catches that result in annual 10% declines in catch (rows e, h, j), median relative fishing intensity of 100% (row m), median catch estimated via the default harvest policy ($F_{\text{SPR}=40\%}$–40:10, row n), and the fishing intensity that results in the median projected catch remaining the same in 2023 and 2024 (row o).

Catch Alternative			**Biomass at start of year**	**Resulting relative spawning biomass**		
				5%	**50%**	**95%**
	Catch year	**Catch (t)**	Start of 2023	0.49	1.04	2.50
a:	2023	0	Start of 2024	0.50	1.07	2.59
	2024	0	Start of 2025	0.48	1.03	2.52
	2025	0	Start of 2026	0.47	1.01	2.54
b:	2023	180,000	Start of 2024	0.46	1.02	2.54
	2024	180,000	Start of 2025	0.40	0.94	2.43
	2025	180,000	Start of 2026	0.36	0.90	2.41
c:	2023	225,000	Start of 2024	0.45	1.01	2.53
	2024	225,000	Start of 2025	0.38	0.92	2.41
	2025	225,000	Start of 2026	0.33	0.87	2.39
d:	2023	270,000	Start of 2024	0.44	1.00	2.52
	2024	270,000	Start of 2025	0.36	0.90	2.39
	2025	270,000	Start of 2026	0.31	0.84	2.36
e:	2023	320,000	Start of 2024	0.42	0.99	2.50
10%	2024	288,000	Start of 2025	0.35	0.89	2.37
reduction	2025	259,200	Start of 2026	0.30	0.83	2.35
f:	2023	325,000	Start of 2024	0.42	0.99	2.50
2022	2024	325,000	Start of 2025	0.34	0.88	2.36
catch	2025	325,000	Start of 2026	0.27	0.81	2.32
g:	2023	350,000	Start of 2024	0.42	0.98	2.49
	2024	350,000	Start of 2025	0.33	0.86	2.35
	2025	350,000	Start of 2026	0.26	0.79	2.30
h:	2023	350,000	Start of 2024	0.42	0.98	2.49
10%	2024	315,000	Start of 2025	0.33	0.87	2.36
reduction	2025	283,500	Start of 2026	0.28	0.81	2.33
i:	2023	380,000	Start of 2024	0.41	0.97	2.48
	2024	380,000	Start of 2025	0.31	0.85	2.33
	2025	380,000	Start of 2026	0.24	0.77	2.28
j:	2023	380,000	Start of 2024	0.41	0.97	2.48
10%	2024	342,000	Start of 2025	0.32	0.86	2.34
reduction	2025	307,800	Start of 2026	0.26	0.80	2.31
k:	2023	430,000	Start of 2024	0.40	0.96	2.46
	2024	430,000	Start of 2025	0.29	0.83	2.31
	2025	430,000	Start of 2026	0.21	0.74	2.24
l:	2023	545,000	Start of 2024	0.37	0.93	2.43
2022	2024	545,000	Start of 2025	0.24	0.77	2.25
TAC	2025	545,000	Start of 2026	0.14	0.67	2.17
m:	2023	778,008	Start of 2024	0.32	0.87	2.37
FI=	2024	733,102	Start of 2025	0.17	0.68	2.14
100%	2025	615,970	Start of 2026	0.11	0.57	2.05
n:	2023	778,008	Start of 2024	0.32	0.87	2.37
default	2024	740,322	Start of 2025	0.17	0.68	2.14
HR	2025	621,315	Start of 2026	0.10	0.57	2.05
o:	2023	748,093	Start of 2024	0.32	0.88	2.38
C2023=	2024	748,071	Start of 2025	0.17	0.68	2.15
C2024	2025	626,326	Start of 2026	0.11	0.57	2.05

Table 29. Forecast quantiles of Pacific Hake relative fishing intensity (1-SPR)/(1-SPR$_{40\%}$), expressed as a proportion, for the 2023–2025 catch alternatives presented in Table 28. Values greater than 1 indicate relative fishing intensities greater than the $F_{\text{SPR}=40\%}$ harvest policy calculated using baseline selectivity.

Catch Alternative			**Relative fishing intensity**		
	Catch year	**Catch (t)**	**5%**	**50%**	**95%**
a:	2023	0	0.00	0.00	0.00
	2024	0	0.00	0.00	0.00
	2025	0	0.00	0.00	0.00
b:	2023	180,000	0.20	0.39	0.66
	2024	180,000	0.17	0.36	0.64
	2025	180,000	0.16	0.35	0.66
c:	2023	225,000	0.25	0.46	0.74
	2024	225,000	0.20	0.42	0.73
	2025	225,000	0.19	0.42	0.77
d:	2023	270,000	0.29	0.52	0.81
	2024	270,000	0.24	0.48	0.81
	2025	270,000	0.23	0.49	0.87
e:	2023	320,000	0.33	0.58	0.88
10%	2024	288,000	0.25	0.51	0.85
reduction	2025	259,200	0.22	0.48	0.87
f:	2023	325,000	0.33	0.58	0.88
2022	2024	325,000	0.28	0.55	0.90
catch	2025	325,000	0.27	0.56	0.97
g:	2023	350,000	0.35	0.61	0.91
	2024	350,000	0.30	0.58	0.94
	2025	350,000	0.29	0.59	1.01
h:	2023	350,000	0.35	0.61	0.91
10%	2024	315,000	0.27	0.54	0.90
reduction	2025	283,500	0.24	0.52	0.92
i:	2023	380,000	0.37	0.64	0.94
	2024	380,000	0.32	0.61	0.98
	2025	380,000	0.31	0.63	1.07
j:	2023	380,000	0.37	0.64	0.94
10%	2024	342,000	0.29	0.57	0.94
reduction	2025	307,800	0.26	0.55	0.97
k:	2023	430,000	0.41	0.69	0.99
	2024	430,000	0.35	0.66	1.04
	2025	430,000	0.34	0.69	1.15
l:	2023	545,000	0.48	0.78	1.09
2022	2024	545,000	0.42	0.76	1.17
TAC	2025	545,000	0.41	0.80	1.26
m:	2023	778,008	0.60	0.91	1.22
FI=	2024	733,102	0.52	0.91	1.29
100%	2025	615,970	0.46	0.90	1.31
n:	2023	778,008	0.60	0.91	1.22
default	2024	740,322	0.52	0.91	1.29
HR	2025	621,315	0.47	0.91	1.31
o:	2023	748,093	0.59	0.90	1.21
C2023=	2024	748,071	0.53	0.91	1.29
C2024	2025	626,326	0.47	0.91	1.31

Table 30. Probabilities related to spawning biomass, relative fishing intensity, and the 2024 default harvest policy catch for alternative 2023 catch options (catch options explained in Table 28).

Catch in 2023	**Probability $B_{2024} < B_{2023}$**	**Probability $B_{2024} < B_{40\%}$**	**Probability $B_{2024} < B_{25\%}$**	**Probability $B_{2024} < B_{10\%}$**	**Probability 2023 relative fishing intensity > 100%**	**Probability 2024 default harvest policy catch < 2023 catch**
a: 0	50%	2%	0%	0%	0%	0%
b: 180,000	72%	3%	0%	0%	0%	0%
c: 225,000	75%	3%	0%	0%	0%	1%
d: 270,000	78%	3%	0%	0%	0%	2%
e: 320,000	81%	4%	1%	0%	1%	4%
f: 325,000	81%	4%	1%	0%	1%	4%
g: 350,000	82%	4%	1%	0%	2%	6%
h: 350,000	82%	4%	1%	0%	2%	6%
i: 380,000	83%	5%	1%	0%	3%	8%
j: 380,000	83%	5%	1%	0%	3%	8%
k: 430,000	85%	5%	1%	0%	5%	13%
l: 545,000	88%	7%	1%	0%	11%	26%
m: 778,008	92%	10%	2%	0%	32%	53%
n: 778,008	92%	10%	2%	0%	32%	53%
o: 748,093	92%	10%	2%	0%	29%	50%

Table 31. Probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options, given the 2023 catch level shown in Table 30 (catch options explained in Table 28).

Catch in 2024	**Probability $B_{2025} < B_{2024}$**	**Probability $B_{2025} < B_{40\%}$**	**Probability $B_{2025} < B_{25\%}$**	**Probability $B_{2025} < B_{10\%}$**	**Probability 2024 relative fishing intensity > 100%**	**Probability 2025 default harvest policy catch < 2024 catch**
a: 0	73%	2%	0%	0%	0%	0%
b: 180,000	79%	5%	1%	0%	0%	0%
c: 225,000	80%	6%	1%	0%	0%	1%
d: 270,000	81%	7%	1%	0%	1%	3%
e: 288,000	81%	8%	1%	0%	1%	4%
f: 325,000	82%	9%	2%	0%	2%	7%
g: 350,000	82%	9%	2%	0%	3%	9%
h: 315,000	82%	9%	2%	0%	2%	6%
i: 380,000	83%	10%	2%	0%	4%	12%
j: 342,000	82%	10%	2%	0%	3%	9%
k: 430,000	84%	12%	3%	0%	7%	18%
l: 545,000	85%	16%	6%	1%	16%	34%
m: 733,102	87%	24%	11%	1%	35%	59%
n: 740,322	87%	24%	11%	1%	36%	60%
o: 748,071	87%	23%	11%	1%	36%	60%

Table 32. Probabilities related to spawning biomass, relative fishing intensity, and the 2026 default harvest policy catch for alternative 2025 catch options, given the 2023 and 2024 catch levels shown in Tables 30 and 31 (catch options explained in Table 28).

Catch in 2025	Probability $B_{2026} < B_{2025}$	Probability $B_{2026} < B_{40\%}$	Probability $B_{2026} < B_{25\%}$	Probability $B_{2026} < B_{10\%}$	Probability 2025 relative fishing intensity > 100%	Probability 2026 default harvest policy catch < 2025 catch
a: 0	68%	2%	0%	0%	0%	0%
b: 180,000	75%	7%	1%	0%	0%	0%
c: 225,000	76%	9%	2%	0%	1%	1%
d: 270,000	77%	11%	3%	0%	2%	3%
e: 259,200	77%	11%	3%	0%	2%	3%
f: 325,000	78%	13%	4%	0%	4%	8%
g: 350,000	79%	14%	5%	0%	5%	10%
h: 283,500	77%	12%	4%	0%	3%	5%
i: 380,000	79%	16%	6%	1%	7%	13%
j: 307,800	77%	14%	4%	0%	4%	7%
k: 430,000	80%	18%	7%	1%	11%	20%
l: 545,000	82%	26%	12%	2%	23%	37%
m: 615,970	82%	35%	19%	4%	37%	53%
n: 621,315	82%	35%	19%	4%	38%	54%
o: 626,326	82%	35%	19%	4%	38%	54%

Table 33. Posterior medians for select parameters, derived quantities, reference points, and negative log likelihoods for the base model and some sensitivity runs (described in Section 3.8). A dash (–) indicates that the parameter or derived quantity was not estimated in the model.

	Base model	Steepness Mean Prior Low (0.5)	Steepness Fix 1.0	Sigma R 1.0	Sigma R 1.6	Natural Mortality (SD=0.2)	Natural Mortality (SD=0.3)	Natural Mortality (Hamel/Cope prior)
Parameters								
Natural mortality (M)	0.233	0.237	0.232	0.230	0.234	0.289	0.308	0.314
Unfished recruitment (R_0, millions)	2,547	2,696	2,479	1,875	3,058	5,556	7,600	8,327
Steepness (h)	0.808	0.540	–	0.811	0.812	0.793	0.792	0.792
Additional biomass index SD	0.286	0.288	0.286	0.283	0.287	0.298	0.303	0.307
Catchability: biomass index (q_b)	0.833	0.817	0.836	0.839	0.831	0.552	0.467	0.446
Additional age-1 index SD	0.375	0.373	0.375	0.360	0.390	0.362	0.356	0.354
Catchability: age-1 index (q_1)	0.398	0.387	0.396	0.380	0.402	0.230	0.187	0.178
Dirichlet-multinomial fishery (log θ_{fish})	-0.629	-0.635	-0.630	-0.689	-0.616	-0.631	-0.631	-0.633
Dirichlet-multinomial survey (log θ_{surv})	2.595	2.577	2.595	2.571	2.599	2.599	2.601	2.594
Derived Quantities								
2010 recruitment (millions)	16,852	17,517	16,780	16,412	17,068	32,797	42,683	47,132
2014 recruitment (millions)	9,165	9,449	9,113	8,984	9,268	16,578	21,126	23,074
2016 recruitment (millions)	6,374	6,604	6,332	6,303	6,423	11,506	14,721	15,930
Unfished female spawning biomass (B_0, thousand t)	1,815	1,864	1,781	1,371	2,180	2,612	3,134	3,323
2009 relative spawning biomass	34.8%	34.8%	35.3%	45.7%	29.3%	38.1%	39.7%	39.9%
2023 relative spawning biomass	104.1%	104.2%	107.8%	119.6%	92.8%	118.7%	120.8%	121.2%
2022 rel. fishing intensity: (1-SPR)/(1-$\text{SPR}_{40\%}$)	50.7%	49.3%	50.7%	52.1%	50.3%	29.9%	23.9%	22.3%
Reference Points based on $F_{\text{SPR}=40\%}$								
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	642	422	713	489	772	909	1,077	1,147
SPR at $F_{\text{SPR}=40\%}$	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.6%	18.8%	18.5%	18.4%	18.6%	21.9%	22.9%	23.2%
Yield at $B_{\text{SPR}=40\%}$ (thousand t)	309	204	342	232	372	542	690	749
Negative log likelihoods								
Total	2,156.87	2,158.45	2,166.56	2,159.85	2,159.24	2,156.87	2,156.87	2,156.91
Survey	-6.23	-6.26	-6.22	-5.80	-6.24	-6.23	-6.23	-6.23
Survey age compositions	1,793.57	1,793.61	1,793.55	1,800.42	1,791.76	1,793.56	1,793.55	1,793.58
Fishery age compositions	289.08	289.07	289.09	289.72	288.92	289.08	289.07	289.10
Recruitment	62.47	63.61	62.15	56.56	67.06	62.49	62.51	62.44
Parameter priors	0.96	1.38	10.97	0.94	0.98	0.96	0.97	0.98
Parameter deviations	16.93	16.94	16.93	17.93	16.67	16.92	16.91	16.94

Table 34. Posterior medians for select parameters, derived quantities, reference points, and negative log likelihoods for the base model and further sensitivity runs (described in Section 3.8). A dash (–) indicates that the parameter or derived quantity was not estimated in the model.

	Base model	Remove Age 1 Index	Downweight Fishery Comps
Parameters			
Natural mortality (M)	0.233	0.233	0.235
Unfished recruitment (R_0, millions)	2,547	2,449	2,740
Steepness (h)	0.808	0.810	0.812
Additional biomass index SD	0.286	0.280	0.288
Catchability: biomass index (q_b)	0.833	0.864	0.846
Additional age-1 index SD	0.375	–	0.324
Catchability: age-1 index (q_1)	0.398	–	0.376
Dirichlet-multinomial fishery (log θ_{fish})	-0.629	-0.628	–
Dirichlet-multinomial survey (log θ_{surv})	2.595	2.629	–
Derived Quantities			
2010 recruitment (millions)	16,852	16,109	17,177
2014 recruitment (millions)	9,165	8,513	9,391
2016 recruitment (millions)	6,374	5,736	6,696
Unfished female spawning biomass (B_0, thousand t)	1,815	1,756	1,927
2009 relative spawning biomass	34.8%	35.3%	31.7%
2023 relative spawning biomass	104.1%	123.2%	92.2%
2022 rel. fishing intensity: (1-SPR)/(1-$\text{SPR}_{40\%}$)	50.7%	55.5%	51.9%
Reference Points based on $F_{\text{SPR}=40\%}$			
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	642	622	688
SPR at $F_{\text{SPR}=40\%}$	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.6%	18.6%	18.7%
Yield at $B_{\text{SPR}=40\%}$ (thousand t)	309	298	334
Negative log likelihoods			
Total	2,156.87	2,152.68	206.56
Survey	-6.23	-8.93	-7.67
Survey age compositions	1,793.57	1,792.59	112.52
Fishery age compositions	289.08	288.68	37.54
Recruitment	62.47	62.65	54.73
Parameter priors	0.96	0.98	-0.03
Parameter deviations	16.93	16.63	9.43

Table 35. Posterior medians for select parameters, derived quantities, reference points, and negative log likelihoods for the base model and further sensitivity runs (described in Section 3.8). A dash (–) indicates that the parameter or derived quantity was not estimated in the model.

	Base model	Phi t.v. selectivity (0.21)	Phi t.v. selectivity (0.70)	Phi t.v. selectivity (2.10)
Parameters				
Natural mortality (M)	0.233	0.218	0.230	0.236
Unfished recruitment (R_0, millions)	2,547	2,368	2,482	2,621
Steepness (h)	0.808	0.811	0.809	0.806
Additional biomass index SD	0.286	0.311	0.287	0.289
Catchability: biomass index (q_b)	0.833	0.838	0.845	0.807
Additional age-1 index SD	0.375	0.494	0.441	0.340
Catchability: age-1 index (q_1)	0.398	0.383	0.394	0.389
Dirichlet-multinomial fishery (log θ_{fish})	-0.629	-0.923	-0.681	-0.615
Dirichlet-multinomial survey (log θ_{surv})	2.595	2.622	2.592	2.612
Derived Quantities				
2010 recruitment (millions)	16,852	15,963	16,373	17,675
2014 recruitment (millions)	9,165	9,727	9,030	9,562
2016 recruitment (millions)	6,374	7,986	6,371	6,684
Unfished female spawning biomass (B_0, thousand t)	1,815	1,891	1,821	1,821
2009 relative spawning biomass	34.8%	30.8%	34.0%	35.8%
2023 relative spawning biomass	104.1%	151.1%	129.7%	97.0%
2022 rel. fishing intensity: (1-SPR)/(1-SPR$_{40\%}$)	50.7%	49.5%	51.6%	49.4%
Reference Points based on $F_{\text{SPR=40\%}}$				
Female spawning biomass at $F_{\text{SPR=40\%}}$ ($B_{\text{SPR=40\%}}$, thousand t)	642	675	647	646
SPR at $F_{\text{SPR=40\%}}$	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.6%	17.7%	18.4%	18.8%
Yield at $B_{\text{SPR=40\%}}$ (thousand t)	309	304	307	315
Negative log likelihoods				
Total	2,156.87	2,280.96	2,186.94	2,144.51
Survey	-6.23	-3.02	-4.91	-6.60
Survey age compositions	1,793.57	1,883.53	1,810.66	1,785.73
Fishery age compositions	289.08	289.10	289.34	289.20
Recruitment	62.47	62.20	63.35	61.71
Parameter priors	0.96	1.16	0.99	0.95
Parameter deviations	16.93	47.96	27.45	13.45

Table 36. Posterior medians from the base model for select parameters, derived quantities, reference point estimates, and negative log likelihoods for retrospective analyses. Some values are implied since they occur after the ending year of the respective retrospective analysis. A dash (–) indicates that the parameter or derived quantity was not output by the model.

	Base model	-1 year	-2 years	-3 years	-4 years	-5 years
Parameters						
Natural mortality (M)	0.233	0.233	0.231	0.231	0.230	0.230
Unfished recruitment (R_0, millions)	2,547	2,583	2,437	2,422	2,433	2,382
Steepness (h)	0.808	0.808	0.809	0.805	0.808	0.810
Additional biomass index SD	0.286	0.288	0.314	0.306	0.323	0.322
Catchability: biomass index (q_b)	0.833	0.823	0.830	0.867	0.902	0.921
Additional age-1 index SD	0.375	0.375	0.315	0.288	0.306	0.319
Catchability: age-1 index (q_1)	0.398	0.414	0.394	0.394	0.389	0.383
Dirichlet-multinomial fishery (log θ_{fish})	-0.629	-0.578	-0.583	-0.553	-0.538	-0.550
Dirichlet-multinomial survey (log θ_{surv})	2.595	2.586	2.409	2.417	2.166	2.152
Derived Quantities						
2010 recruitment (millions)	16,852	17,195	17,080	16,106	15,067	14,653
2014 recruitment (millions)	9,165	9,334	10,020	10,351	10,266	10,541
2016 recruitment (millions)	6,374	6,371	5,443	4,951	4,645	4,781
Unfished female spawning biomass (B_0, thousand t)	1,815	1,836	1,766	1,759	1,774	1,748
2009 relative spawning biomass	34.8%	35.1%	36.4%	35.9%	34.6%	34.5%
2023 relative spawning biomass	104.1%	81.4%	63.3%	64.5%	76.0%	69.3%
2022 rel. fishing intensity: (1-SPR)/(1-SPR$_{40\%}$)	50.7%	57.6%	58.1%	58.0%	53.0%	56.6%
Reference Points based on $F_{\text{SPR}=40\%}$						
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	642	649	625	621	625	619
SPR at $F_{\text{SPR}=40\%}$	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.6%	18.6%	18.5%	18.5%	18.4%	18.4%
Yield at $B_{\text{SPR}=40\%}$ (thousand t)	309	313	299	296	298	294

8 FIGURES

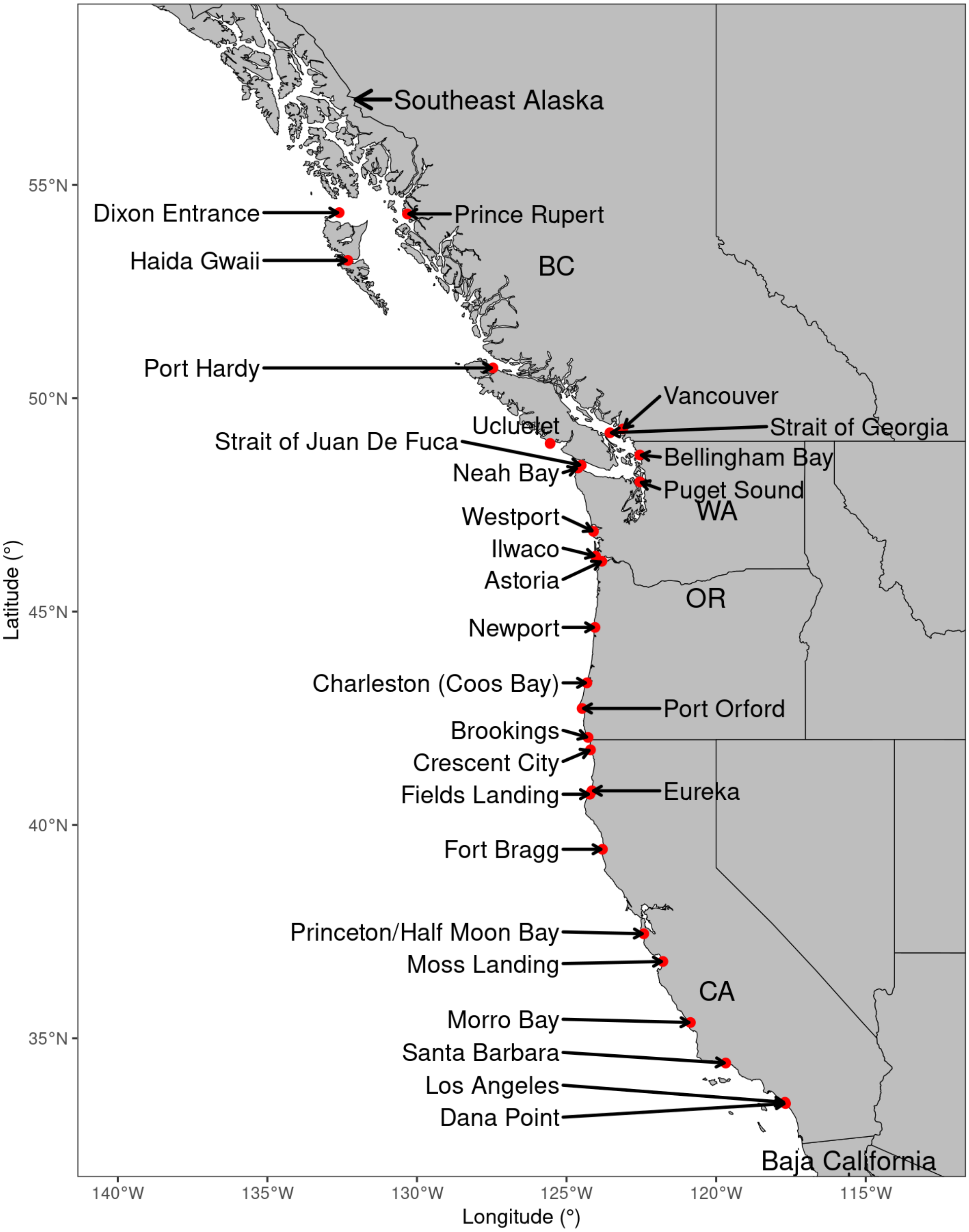


Figure 1. Overview map of the area in the Northeast Pacific Ocean occupied by Pacific Hake. Common areas referred to in this document are shown.

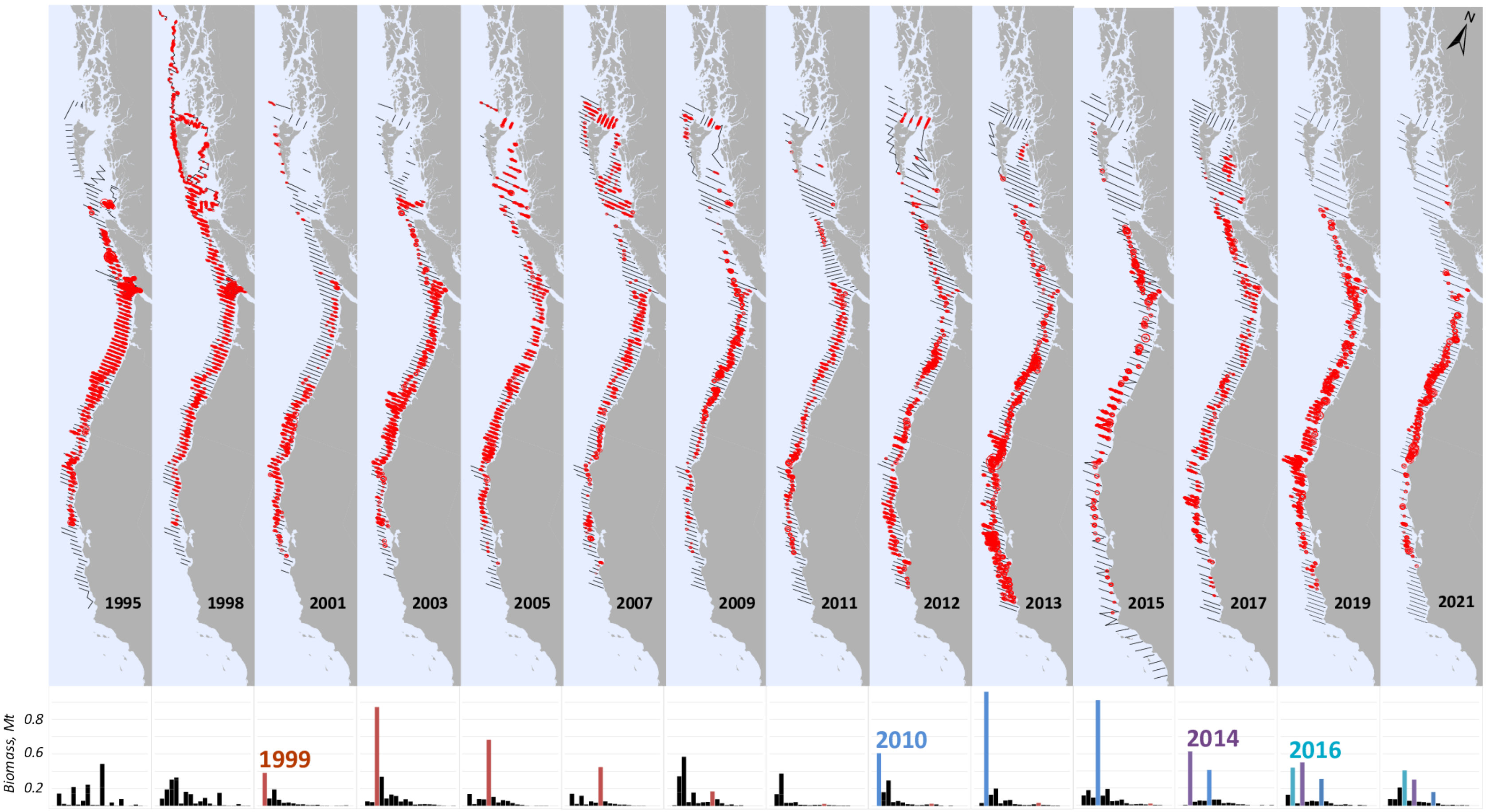


Figure 2. Spatial distribution of acoustic backscatter attributable to age-2 and older Pacific Hake from the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey 1995–2021. Area of the circle is roughly proportional to observed backscatter. Barplots show survey-estimated biomass for ages 2 to 20, with major cohorts highlighted in color. Figure produced by Julia Clemons (NOAA).

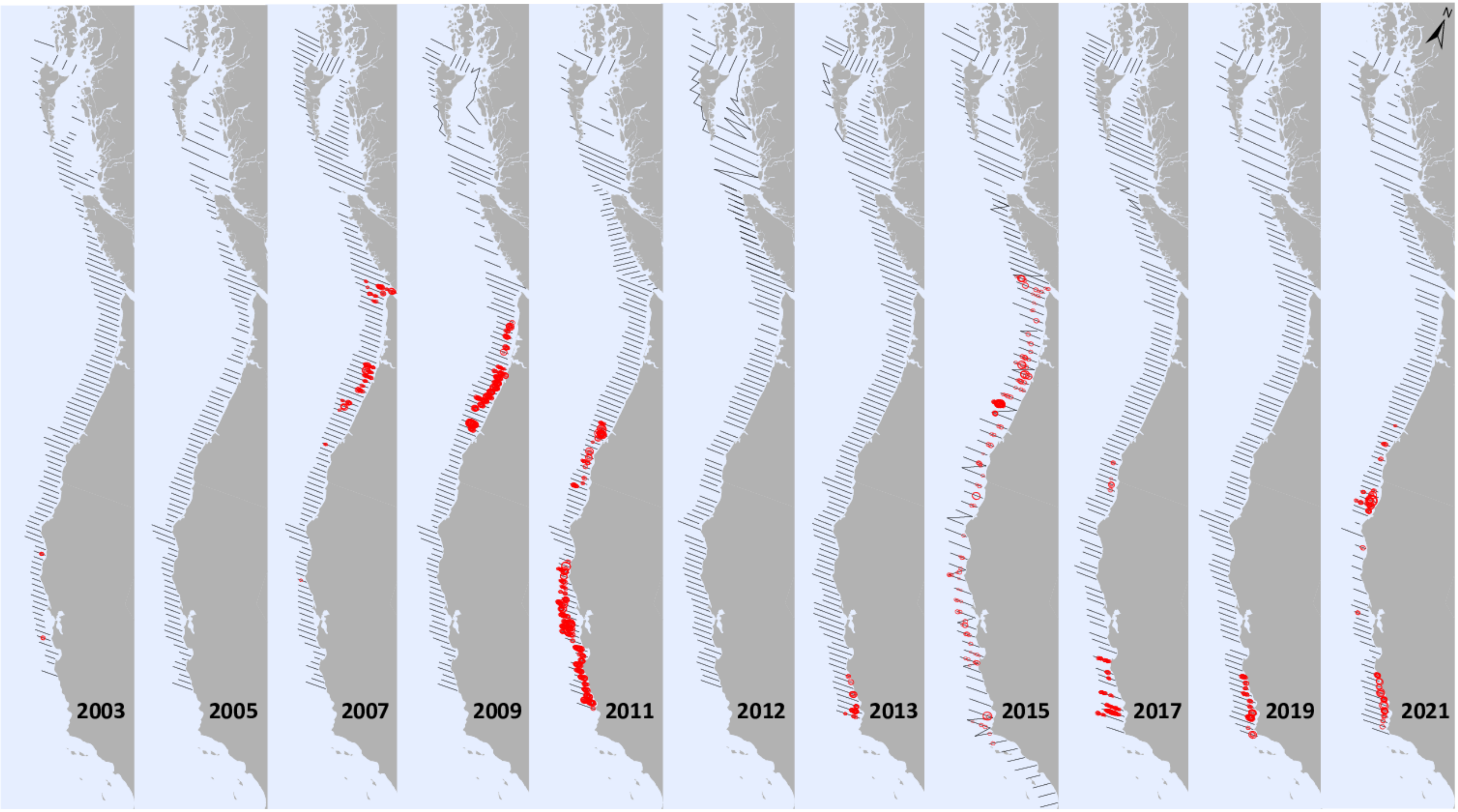


Figure 3. Spatial distribution of acoustic backscatter attributable to age-1 Pacific Hake from the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey 2003–2021. Age-1 Pacific Hake are not fully sampled during the acoustic survey and were not explicitly considered during establishment of the survey sampling design. Area of the circle is roughly proportional to observed backscatter. Figure produced by Julia Clemons (NOAA).

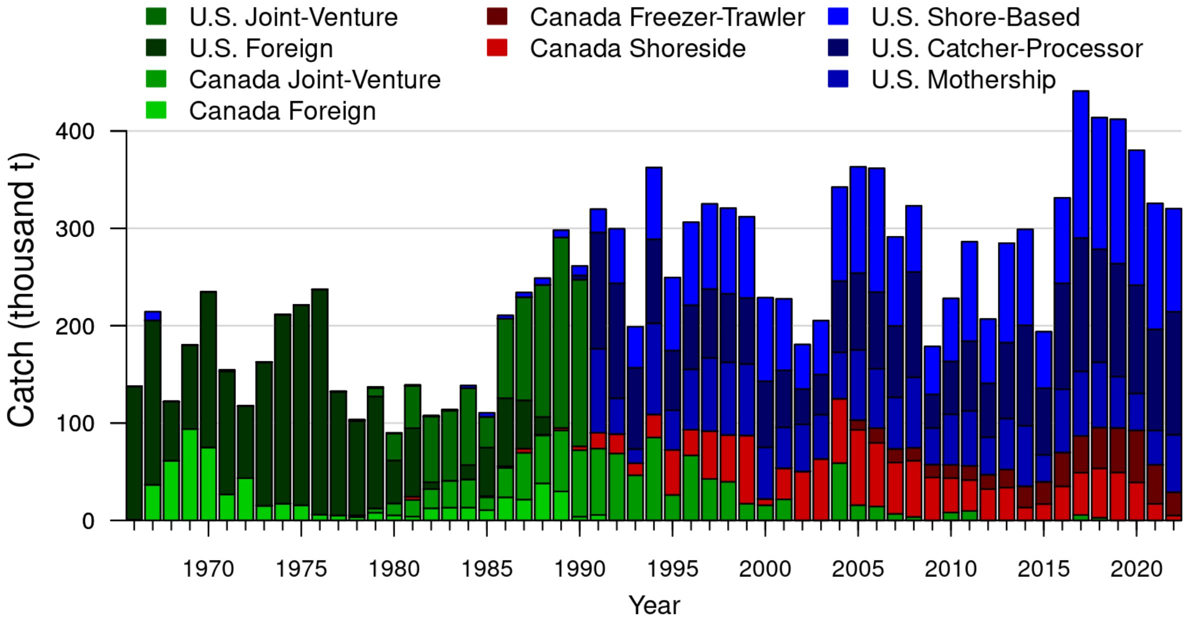


Figure 4. Total Pacific Hake catch used in the assessment by sector, 1966–2022. U.S. tribal catches are included in the appropriate sector.

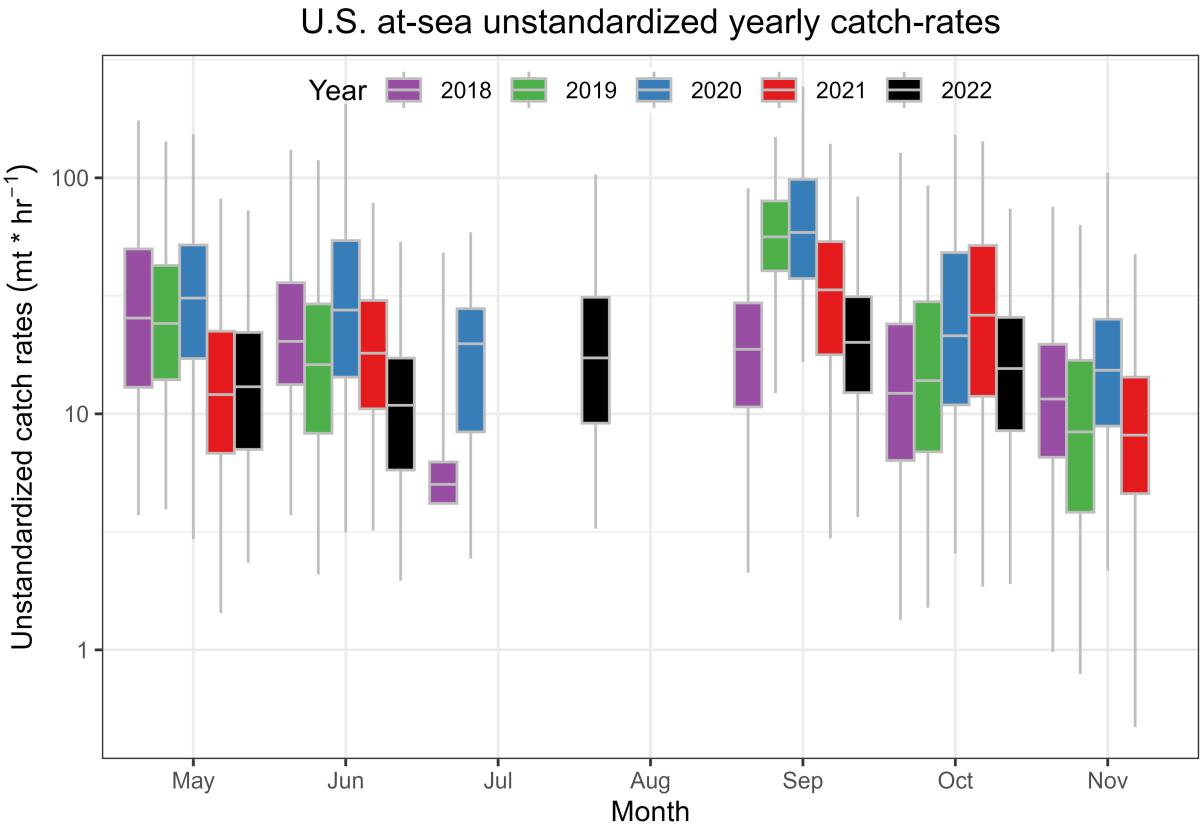


Figure 5. Unstandardized (raw) catch-rates (t/hr) of Pacific Hake catches by tow in the U.S. at-sea fleet from 2018–2022.

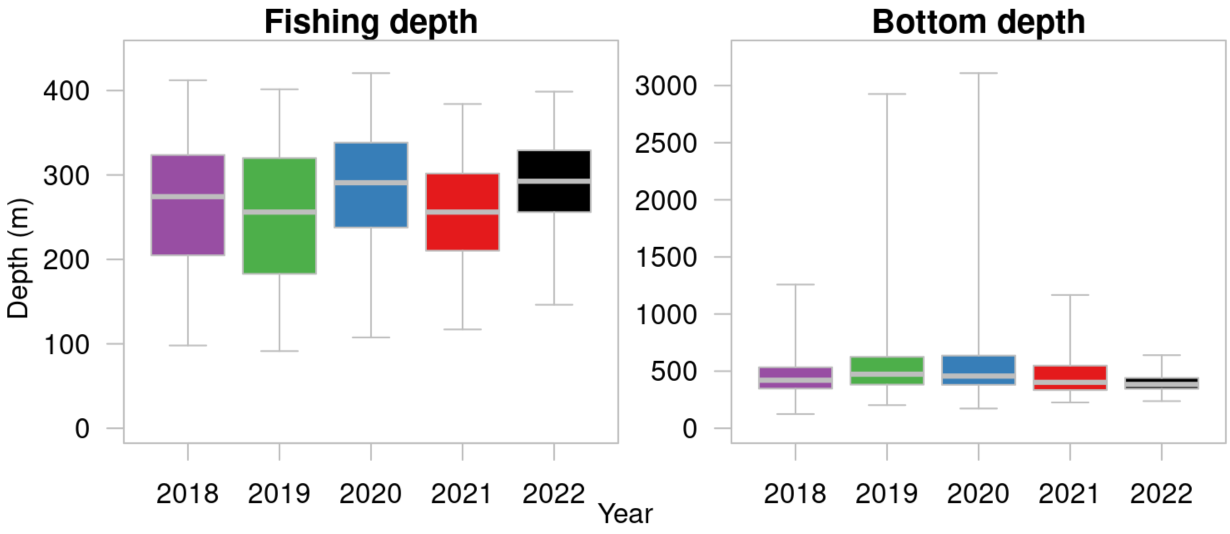


Figure 6. Distribution of fishing depths (left) and bottom depths (right), in meters, of hauls targeting Pacific Hake in the U.S. Catcher-Processor and Mothership sectors from 2018–2022. Horizontal lines in each box represent the median depth and boxes encompass the middle 50% of the data. Whiskers encompass the 95% quantiles.

Figure 7. Distribution of fishing depths (left) and bottom depths (right), in meters, of hauls targeting Pacific Hake in the Canadian fleets from 2018–2022. Horizontal lines in each box represent the median depth and boxes encompass the middle 50% of the data. Whiskers encompass the 95% quantiles.

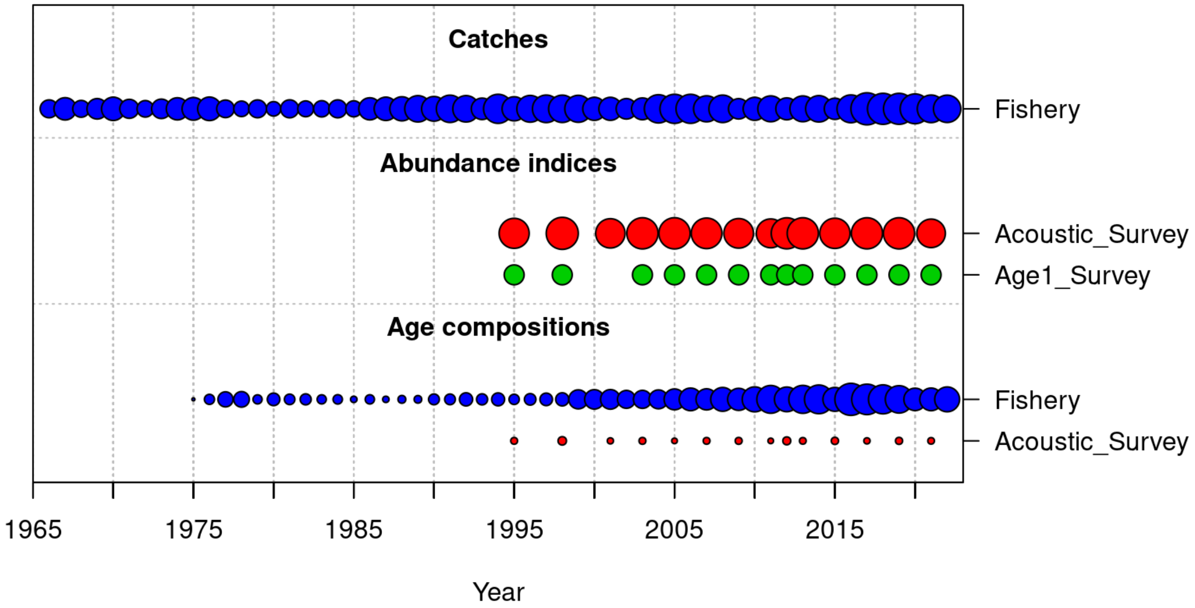


Figure 8. Overview of data used in this assessment. Circle areas are proportional to total catch for the fishery data, precision for the indices, and total sample size for the age compositions (and cannot be compared across data types). Additionally, mean weight-at-age data (1975–2022; not depicted here but see Figure 14 for sample sizes) are used to account for time-varying growth.

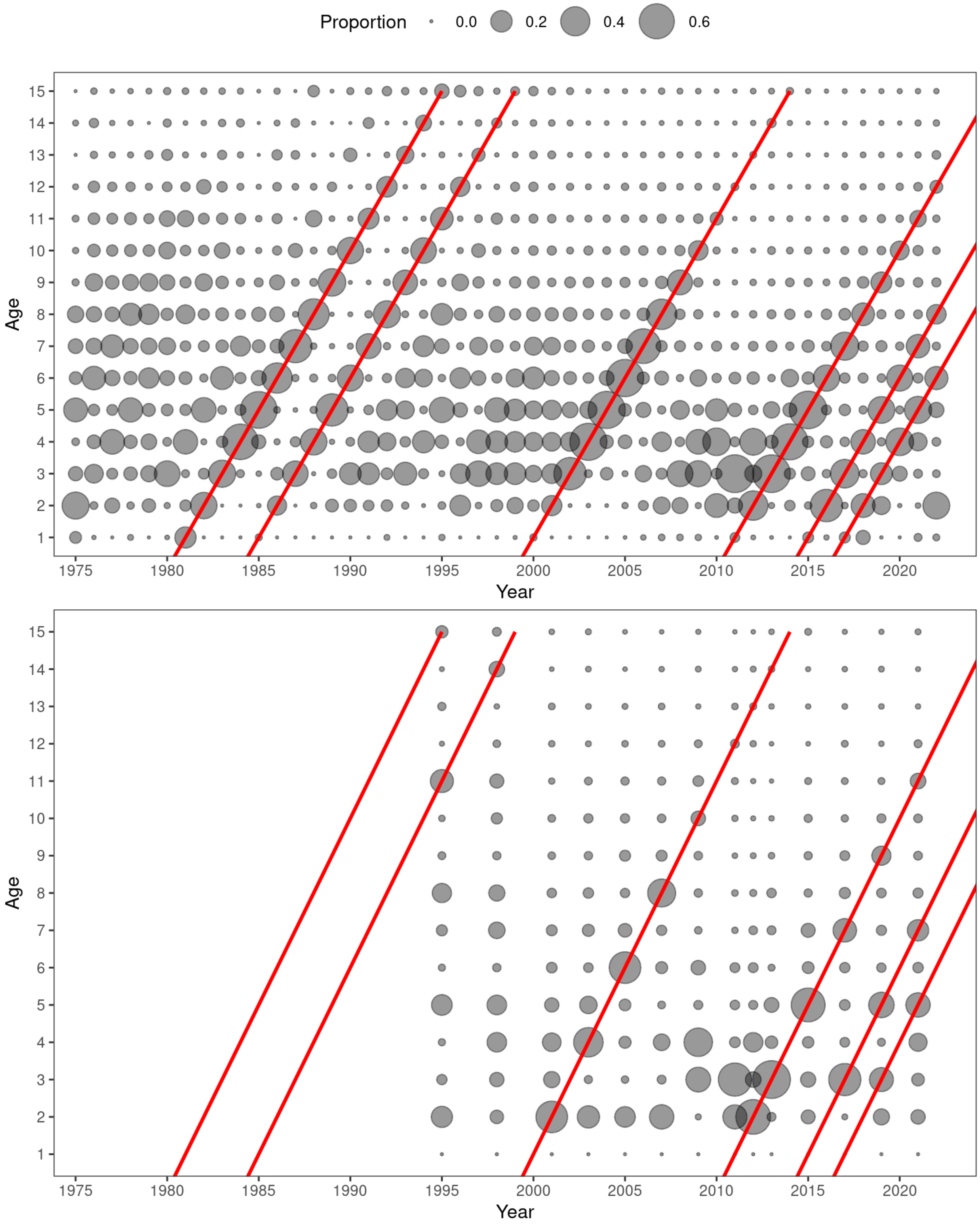


Figure 9. Age compositions for the aggregate fishery (top, all sectors combined) and acoustic survey (bottom) for the years 1975–2022. Proportions in each year sum to 1.0 and area of the bubbles are proportional to the proportion and consistent in both panels (see key at top). The largest bubble in the fishery data is 0.71 for age 3 in 2011 and in the survey data is 0.75 for age 3 in 2013. Red lines track large cohorts.

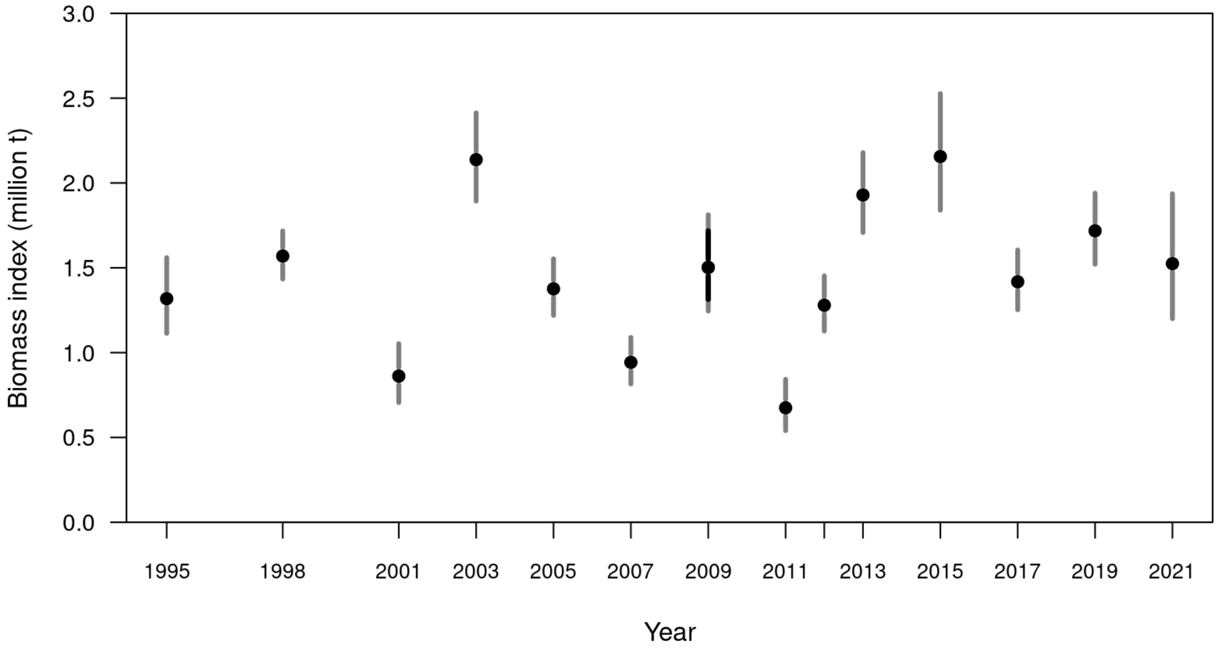


Figure 10. Acoustic survey biomass index of age-2+ fish (millions of tons, Table 12). Approximate 95% confidence intervals are based on sampling variability (intervals without squid/hake apportionment uncertainty in 2009 are displayed in black).

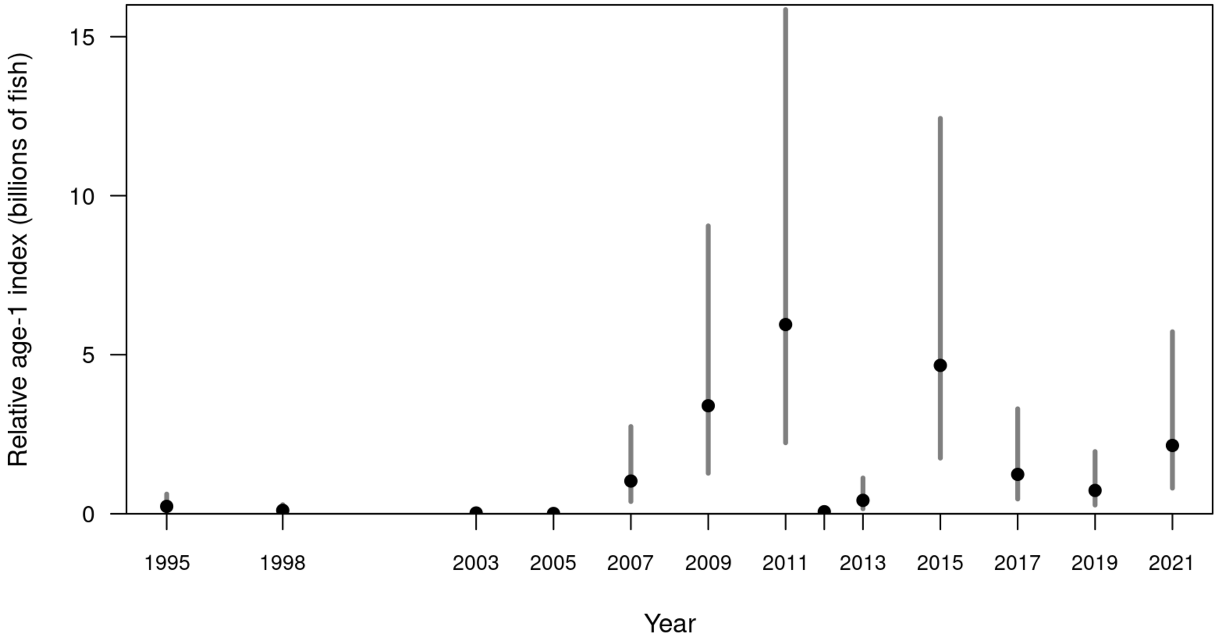


Figure 11. Relative age-1 index (numbers of fish, Table 12) and approximate 95% confidence intervals based on sampling variability. The index is relative because the survey does not attempt to catch all available age-1 fish and the analysis does not include kriging unlike estimates of age-2+ survey biomass.

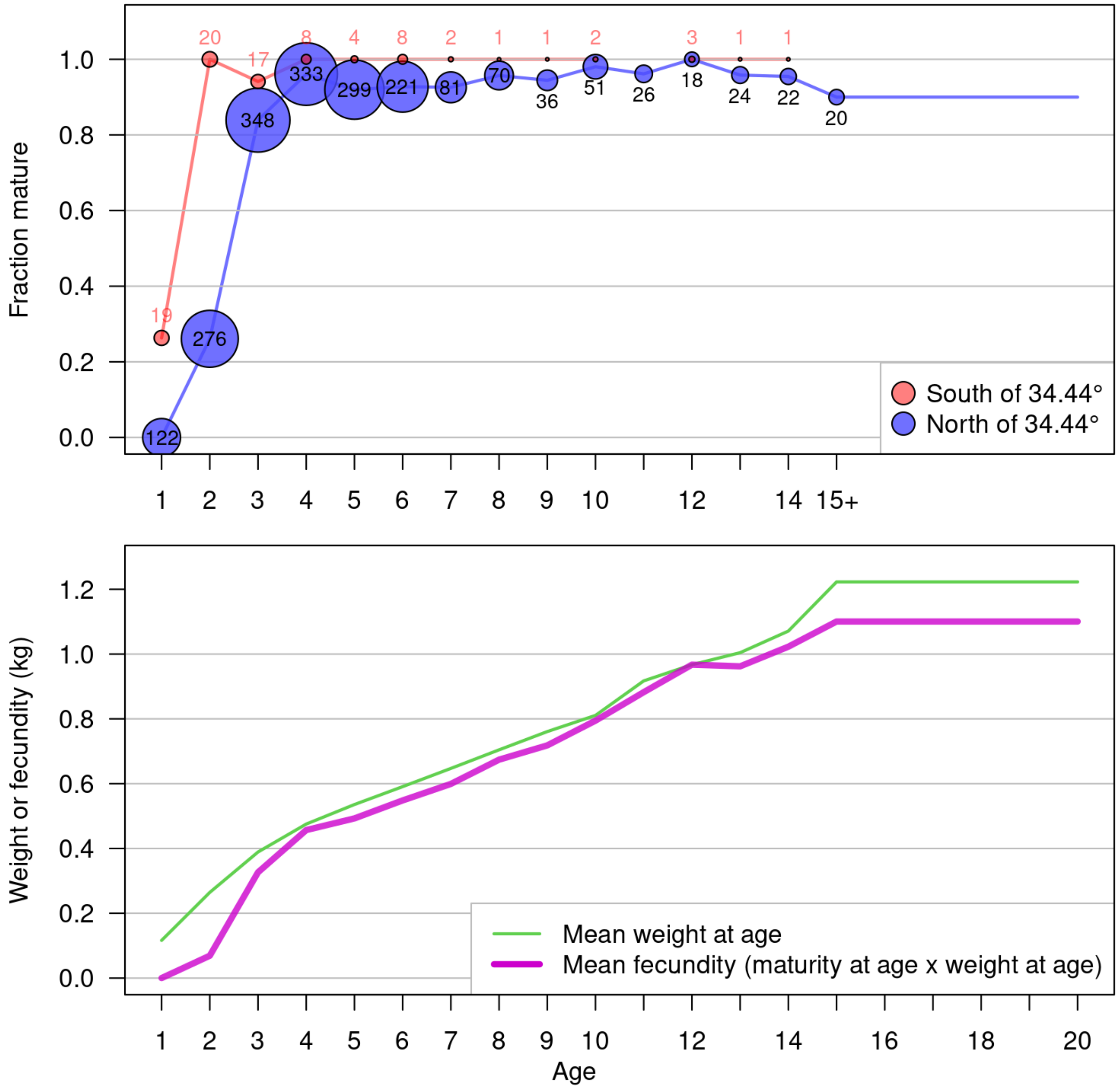
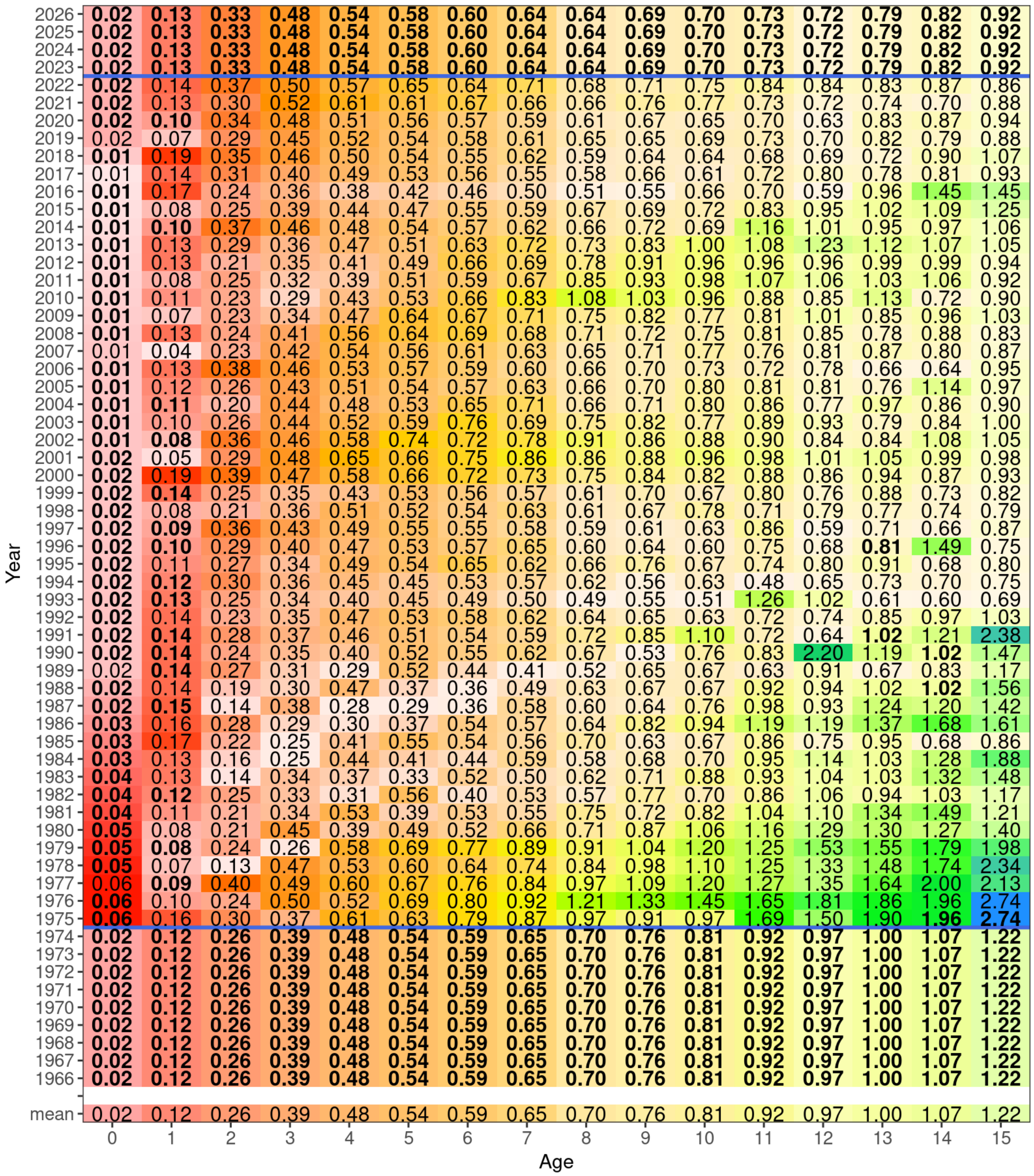
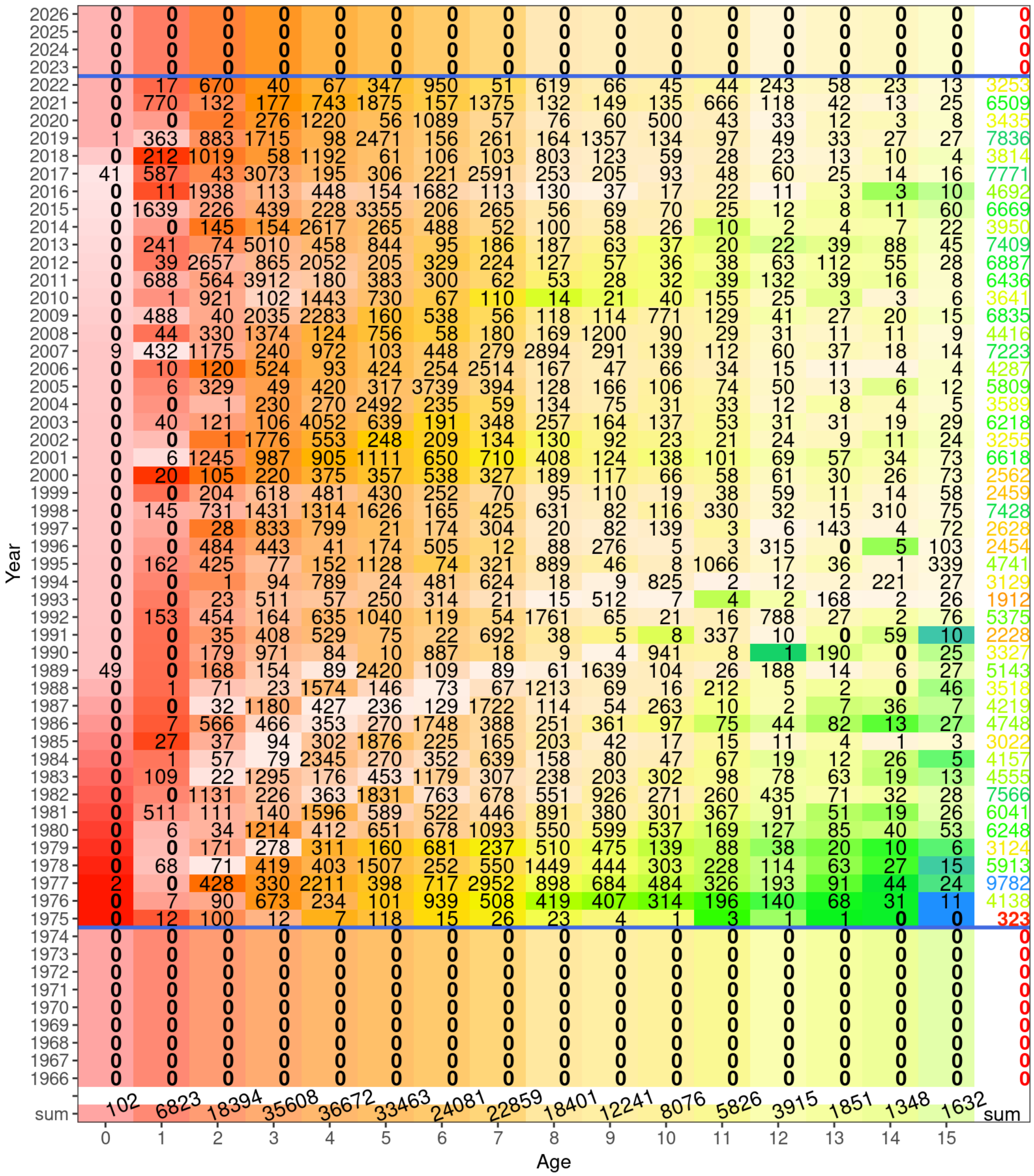


Figure 12. Fraction of fish that are mature at each age north and south of 34.44°N (upper panel) and the fecundity relationship (lower panel). The fecundity relationship (purple line) is the product of the weight-at-age and the maturity-at-age for the samples collected from North of 34.44°N (blue line in upper plot) averaged across 1975 to 2022.



Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2026	**0.02**	**0.13**	**0.33**	**0.48**	**0.54**	**0.58**	**0.60**	**0.64**	**0.64**	**0.69**	**0.70**	**0.73**	**0.72**	**0.79**	**0.82**	**0.92**
2025	**0.02**	**0.13**	**0.33**	**0.48**	**0.54**	**0.58**	**0.60**	**0.64**	**0.64**	**0.69**	**0.70**	**0.73**	**0.72**	**0.79**	**0.82**	**0.92**
2024	**0.02**	**0.13**	**0.33**	**0.48**	**0.54**	**0.58**	**0.60**	**0.64**	**0.64**	**0.69**	**0.70**	**0.73**	**0.72**	**0.79**	**0.82**	**0.92**
2023	**0.02**	**0.13**	**0.33**	**0.48**	**0.54**	**0.58**	**0.60**	**0.64**	**0.64**	**0.69**	**0.70**	**0.73**	**0.72**	**0.79**	**0.82**	**0.92**
2022	**0.02**	0.14	0.37	0.50	0.57	0.65	0.64	0.71	0.68	0.71	0.75	0.84	0.84	0.83	0.87	0.86
2021	**0.02**	0.13	0.30	0.52	0.61	0.61	0.67	0.66	0.66	0.76	0.77	0.73	0.72	0.74	0.70	0.88
2020	**0.02**	**0.10**	0.34	0.48	0.51	0.56	0.57	0.59	0.61	0.67	0.65	0.70	0.63	0.83	0.87	0.94
2019	0.02	0.07	0.29	0.45	0.52	0.54	0.58	0.61	0.65	0.65	0.69	0.73	0.70	0.82	0.79	0.88
2018	**0.01**	0.19	0.35	0.46	0.50	0.54	0.55	0.62	0.59	0.64	0.64	0.68	0.69	0.72	0.90	1.07
2017	0.01	0.14	0.31	0.40	0.49	0.53	0.56	0.55	0.58	0.66	0.61	0.72	0.80	0.78	0.81	0.93
2016	**0.01**	0.17	0.24	0.36	0.38	0.42	0.46	0.50	0.51	0.55	0.66	0.70	0.59	0.96	1.45	1.45
2015	**0.01**	0.08	0.25	0.39	0.44	0.47	0.55	0.59	0.67	0.69	0.72	0.83	0.95	1.02	1.09	1.25
2014	**0.01**	**0.10**	0.37	0.46	0.48	0.54	0.57	0.62	0.66	0.72	0.69	1.16	1.01	0.95	0.97	1.06
2013	**0.01**	0.13	0.29	0.36	0.47	0.51	0.63	0.72	0.73	0.83	1.00	1.08	1.23	1.12	1.07	1.05
2012	**0.01**	0.13	0.21	0.35	0.41	0.49	0.66	0.69	0.78	0.91	0.96	0.96	0.96	0.99	0.99	0.94
2011	**0.01**	0.08	0.25	0.32	0.39	0.51	0.59	0.67	0.85	0.93	0.98	1.07	1.06	1.03	1.06	0.92
2010	**0.01**	0.11	0.23	0.29	0.43	0.53	0.66	0.83	1.08	1.03	0.96	0.88	0.85	1.13	0.72	0.90
2009	**0.01**	0.07	0.23	0.34	0.47	0.64	0.67	0.71	0.75	0.82	0.77	0.81	1.01	0.85	0.96	1.03
2008	**0.01**	0.13	0.24	0.41	0.56	0.64	0.69	0.68	0.71	0.72	0.75	0.81	0.85	0.78	0.88	0.83
2007	0.01	0.04	0.23	0.42	0.54	0.56	0.61	0.63	0.65	0.71	0.77	0.76	0.81	0.87	0.80	0.87
2006	**0.01**	0.13	0.38	0.46	0.53	0.57	0.59	0.60	0.66	0.70	0.73	0.72	0.78	0.66	0.64	0.95
2005	**0.01**	0.12	0.26	0.43	0.51	0.54	0.57	0.63	0.66	0.70	0.80	0.81	0.81	0.76	1.14	0.97
2004	**0.01**	**0.11**	0.20	0.44	0.48	0.53	0.65	0.71	0.66	0.71	0.80	0.86	0.77	0.97	0.86	0.90
2003	**0.01**	0.10	0.26	0.44	0.52	0.59	0.76	0.69	0.75	0.82	0.77	0.89	0.93	0.79	0.84	1.00
2002	**0.01**	**0.08**	0.36	0.46	0.58	0.74	0.72	0.78	0.91	0.86	0.88	0.90	0.84	0.84	1.08	1.05
2001	**0.02**	0.05	0.29	0.48	0.65	0.66	0.75	0.86	0.86	0.88	0.96	0.98	1.01	1.05	0.99	0.98
2000	**0.02**	0.19	0.39	0.47	0.58	0.66	0.72	0.73	0.75	0.84	0.82	0.88	0.86	0.94	0.87	0.93
1999	**0.02**	**0.14**	0.25	0.35	0.43	0.53	0.56	0.57	0.61	0.70	0.67	0.80	0.76	0.88	0.73	0.82
1998	**0.02**	0.08	0.21	0.36	0.51	0.52	0.54	0.63	0.61	0.67	0.78	0.71	0.79	0.77	0.74	0.79
1997	**0.02**	**0.09**	0.36	0.43	0.49	0.55	0.55	0.58	0.59	0.61	0.63	0.86	0.59	0.71	0.66	0.87
1996	**0.02**	**0.10**	0.29	0.40	0.47	0.53	0.57	0.65	0.60	0.64	0.60	0.75	0.68	**0.81**	1.49	0.75
1995	**0.02**	0.11	0.27	0.34	0.49	0.54	0.65	0.62	0.66	0.76	0.67	0.74	0.80	0.91	0.68	0.80
1994	**0.02**	**0.12**	0.30	0.36	0.45	0.45	0.53	0.57	0.62	0.56	0.63	0.48	0.65	0.73	0.70	0.75
1993	**0.02**	**0.13**	0.25	0.34	0.40	0.45	0.49	0.50	0.49	0.55	0.51	1.26	1.02	0.61	0.60	0.69
1992	**0.02**	0.14	0.23	0.35	0.47	0.53	0.58	0.62	0.64	0.65	0.63	0.72	0.74	0.85	0.97	1.03
1991	**0.02**	**0.14**	0.28	0.37	0.46	0.51	0.54	0.59	0.72	0.85	1.10	0.72	0.64	**1.02**	1.21	2.38
1990	**0.02**	**0.14**	0.24	0.35	0.40	0.52	0.55	0.62	0.67	0.53	0.76	0.83	2.20	1.19	**1.02**	1.47
1989	0.02	**0.14**	0.27	0.31	0.29	0.52	0.44	0.41	0.52	0.65	0.67	0.63	0.91	0.67	0.83	1.17
1988	**0.02**	0.14	0.19	0.30	0.47	0.37	0.36	0.49	0.63	0.67	0.67	0.92	0.94	1.02	**1.02**	1.56
1987	**0.02**	**0.15**	0.14	0.38	0.28	0.29	0.36	0.58	0.60	0.64	0.76	0.98	0.93	1.24	1.20	1.42
1986	**0.03**	0.16	0.28	0.29	0.30	0.37	0.54	0.57	0.64	0.82	0.94	1.19	1.19	1.37	1.68	1.61
1985	**0.03**	0.17	0.22	0.25	0.41	0.55	0.54	0.56	0.70	0.63	0.67	0.86	0.75	0.95	0.68	0.86
1984	**0.03**	0.13	0.16	0.25	0.44	0.41	0.44	0.59	0.58	0.68	0.70	0.95	1.14	1.03	1.28	1.88
1983	**0.04**	0.13	0.14	0.34	0.37	0.33	0.52	0.50	0.62	0.71	0.88	0.93	1.04	1.03	1.32	1.48
1982	**0.04**	**0.12**	0.25	0.33	0.31	0.56	0.40	0.53	0.57	0.77	0.70	0.86	1.06	0.94	1.03	1.17
1981	**0.04**	0.11	0.21	0.34	0.53	0.39	0.53	0.55	0.75	0.72	0.82	1.04	1.10	1.34	1.49	1.21
1980	**0.05**	0.08	0.21	0.45	0.39	0.49	0.52	0.66	0.71	0.87	1.06	1.16	1.29	1.30	1.27	1.40
1979	**0.05**	**0.08**	0.24	0.26	0.58	0.69	0.77	0.89	0.91	1.04	1.20	1.25	1.53	1.55	1.79	1.98
1978	**0.05**	0.07	0.13	0.47	0.53	0.60	0.64	0.74	0.84	0.98	1.10	1.25	1.33	1.48	1.74	2.34
1977	0.06	**0.09**	0.40	0.49	0.60	0.67	0.76	0.84	0.97	1.09	1.20	1.27	1.35	1.64	2.00	2.13
1976	**0.06**	0.10	0.24	0.50	0.52	0.69	0.80	0.92	1.21	1.33	1.45	1.65	1.81	1.86	1.96	2.74
1975	**0.06**	0.16	0.30	0.37	0.61	0.63	0.79	0.87	0.97	0.91	0.97	1.69	1.50	1.90	**1.96**	**2.74**
1974	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1973	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1972	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1971	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1970	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1969	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1968	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1967	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
1966	**0.02**	**0.12**	**0.26**	**0.39**	**0.48**	**0.54**	**0.59**	**0.65**	**0.70**	**0.76**	**0.81**	**0.92**	**0.97**	**1.00**	**1.07**	**1.22**
mean	0.02	0.12	0.26	0.39	0.48	0.54	0.59	0.65	0.70	0.76	0.81	0.92	0.97	1.00	1.07	1.22

Figure 13. Empirical weight-at-age (kg) values used for the base model. Colors correspond to the values, with red being the lightest fish (across all years and ages) and blue being the heaviest fish. For each age, the most transparent cells indicate the lightest fish of that age. Data are only available from 1975–2022. Values based on assumptions for the pre-1975 and forecast years are shown outside the blue lines. Bold values between 1975–2022 represent unavailable data such that weights were interpolated or extrapolated from adjacent ages or years. The bottom row (mean) is the sample-weighted mean weight-at-age over all years of data.



Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	sum
2026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2022	0	17	670	40	67	347	950	51	619	66	45	44	243	58	23	13	3253
2021	0	770	132	177	743	1875	157	1375	132	149	135	666	118	42	13	25	6509
2020	0	0	2	276	1220	56	1089	57	76	60	500	43	33	12	3	8	3435
2019	1	363	883	1715	98	2471	156	261	164	1357	134	97	49	33	27	27	7836
2018	0	212	1019	58	1192	61	106	103	803	123	59	28	23	13	10	4	3814
2017	41	587	43	3073	195	306	221	2591	253	205	93	48	60	25	14	16	7771
2016	0	11	1938	113	448	154	1682	113	130	37	17	22	11	3	3	10	4692
2015	0	1639	226	439	228	3355	206	265	56	69	70	25	12	8	11	60	6669
2014	0	0	145	154	2617	265	488	52	100	58	26	10	2	4	7	22	3950
2013	0	241	74	5010	458	844	95	186	187	63	37	20	22	39	88	45	7409
2012	0	39	2657	865	2052	205	329	224	127	57	36	38	63	112	55	28	6887
2011	0	688	564	3912	180	383	300	62	53	28	32	39	132	39	16	8	6436
2010	0	1	921	102	1443	730	67	110	14	21	40	155	25	3	3	6	3641
2009	0	488	40	2035	2283	160	538	56	118	114	771	129	41	27	20	15	6835
2008	0	44	330	1374	124	756	58	180	169	1200	90	29	31	11	11	9	4416
2007	9	432	1175	240	972	103	448	279	2894	291	139	112	60	37	18	14	7223
2006	0	10	120	524	93	424	254	2514	167	47	66	34	15	11	4	4	4287
2005	0	6	329	49	420	317	3739	394	128	166	106	74	50	13	6	12	5809
2004	0	0	1	230	270	2492	235	59	134	75	31	33	12	8	4	5	3589
2003	0	40	121	106	4052	639	191	348	257	164	137	53	31	31	19	29	6218
2002	0	0	1	1776	553	248	209	134	130	92	23	21	24	9	11	24	3255
2001	0	6	1245	987	905	1111	650	710	408	124	138	101	69	57	34	73	6618
2000	0	20	105	220	375	357	538	327	189	117	66	58	61	30	26	73	2562
1999	0	0	204	618	481	430	252	70	95	110	19	38	59	11	14	58	2459
1998	0	145	731	1431	1314	1626	165	425	631	82	116	330	32	15	310	75	7428
1997	0	0	28	833	799	21	174	304	20	82	139	3	6	143	4	72	2628
1996	0	0	484	443	41	174	505	12	88	276	5	3	315	0	5	103	2454
1995	0	162	425	77	152	1128	74	321	889	46	8	1066	17	36	1	339	4741
1994	0	0	1	94	789	24	481	624	18	9	825	2	12	2	221	27	3129
1993	0	0	23	511	57	250	314	21	15	512	7	4	2	168	2	26	1912
1992	0	153	454	164	635	1040	119	54	1761	65	21	16	788	27	2	76	5375
1991	0	0	35	408	529	75	22	692	38	5	8	337	10	0	59	10	2228
1990	0	0	179	971	84	10	887	18	9	4	941	8	1	190	0	25	3327
1989	49	0	168	154	89	2420	109	89	61	1639	104	26	188	14	6	27	5143
1988	0	1	71	23	1574	146	73	67	1213	69	16	212	5	2	0	46	3518
1987	0	0	32	1180	427	236	129	1722	114	54	263	10	2	7	36	7	4219
1986	0	7	566	466	353	270	1748	388	251	361	97	75	44	82	13	27	4748
1985	0	27	37	94	302	1876	225	165	203	42	17	15	11	4	1	3	3022
1984	0	1	57	79	2345	270	352	639	158	80	47	67	19	12	26	5	4157
1983	0	109	22	1295	176	453	1179	307	238	203	302	98	78	63	19	13	4555
1982	0	0	1131	226	363	1831	763	678	551	926	271	260	435	71	32	28	7566
1981	0	511	111	140	1596	589	522	446	891	380	301	367	91	51	19	26	6041
1980	0	6	34	1214	412	651	678	1093	550	599	537	169	127	85	40	53	6248
1979	0	0	171	278	311	160	681	237	510	475	139	88	38	20	10	6	3124
1978	0	68	71	419	403	1507	252	550	1449	444	303	228	114	63	27	15	5913
1977	2	0	428	330	2211	398	717	2952	898	684	484	326	193	91	44	24	9782
1976	0	7	90	673	234	101	939	508	419	407	314	196	140	68	31	11	4138
1975	0	12	100	12	7	118	15	26	23	4	1	3	1	1	0	0	323
1974	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1970	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1968	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1967	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1966	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
sum	102	6823	18394	35608	36672	33463	24081	22859	18401	12241	8076	5826	3915	1851	1348	1632	

Figure 14. Sample sizes of empirical weight-at-age measurements used to calculate mean weight-at-age fit in the base model. Colors and transparency are identical to Figure 13 and based on mean values. Sample sizes of zero highlight years for which data are not available, i.e., pre 1975 and post 2022. The total sample sizes for each age used in the mean over all data years are shown at the bottom and year-specific sample sizes are shown to the right using the same color scale with red indicating small sample sizes and blue indicating the large sample sizes.

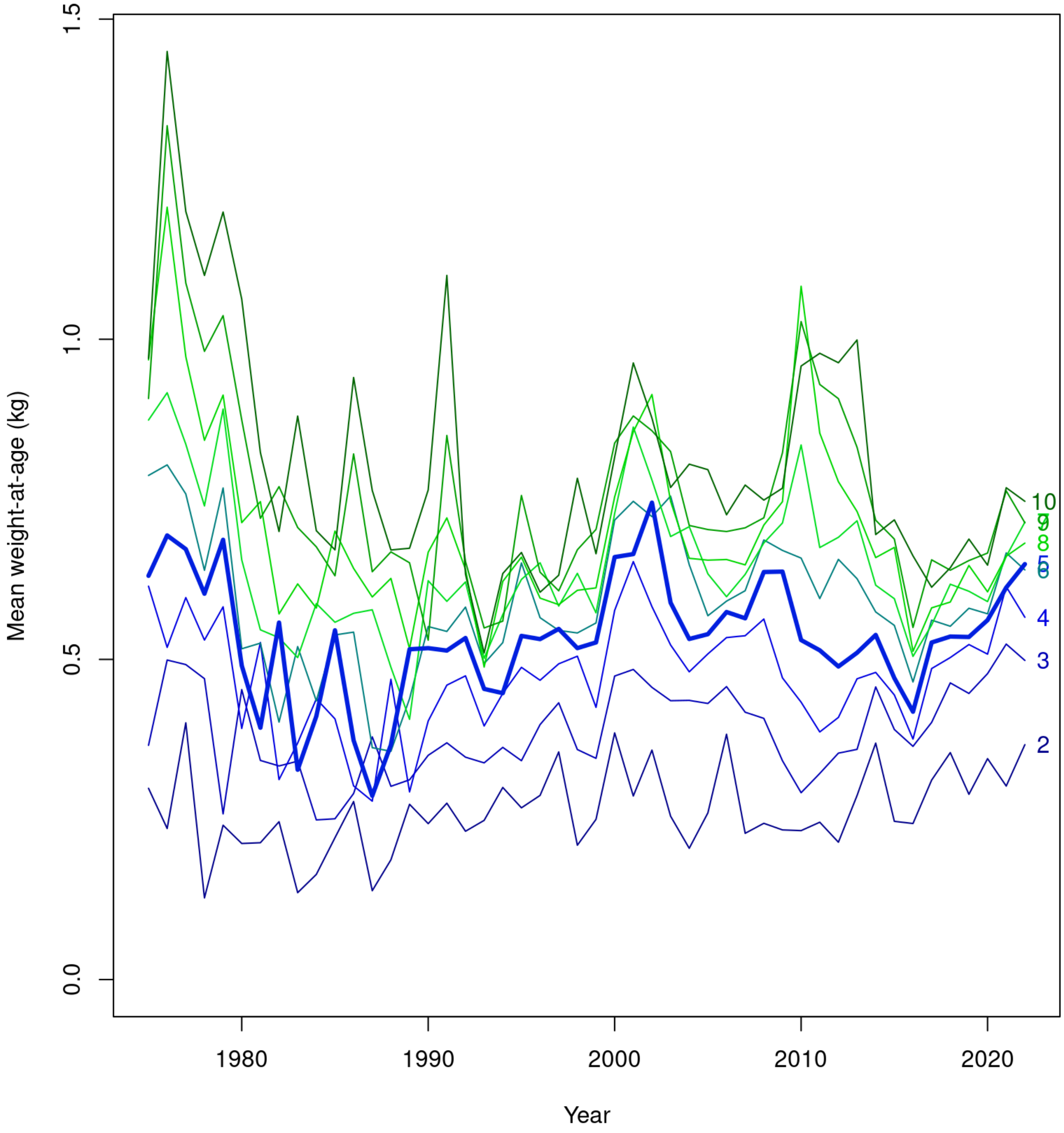


Figure 15. Empirical mean weight-at-age (kg) values for ages 2–10 used for the base model, as in Figure 13 but shown as time series. Blue lines are for the youngest ages and green lines are for the oldest ages shown, with age-5 highlighted in bold as a visual aid.

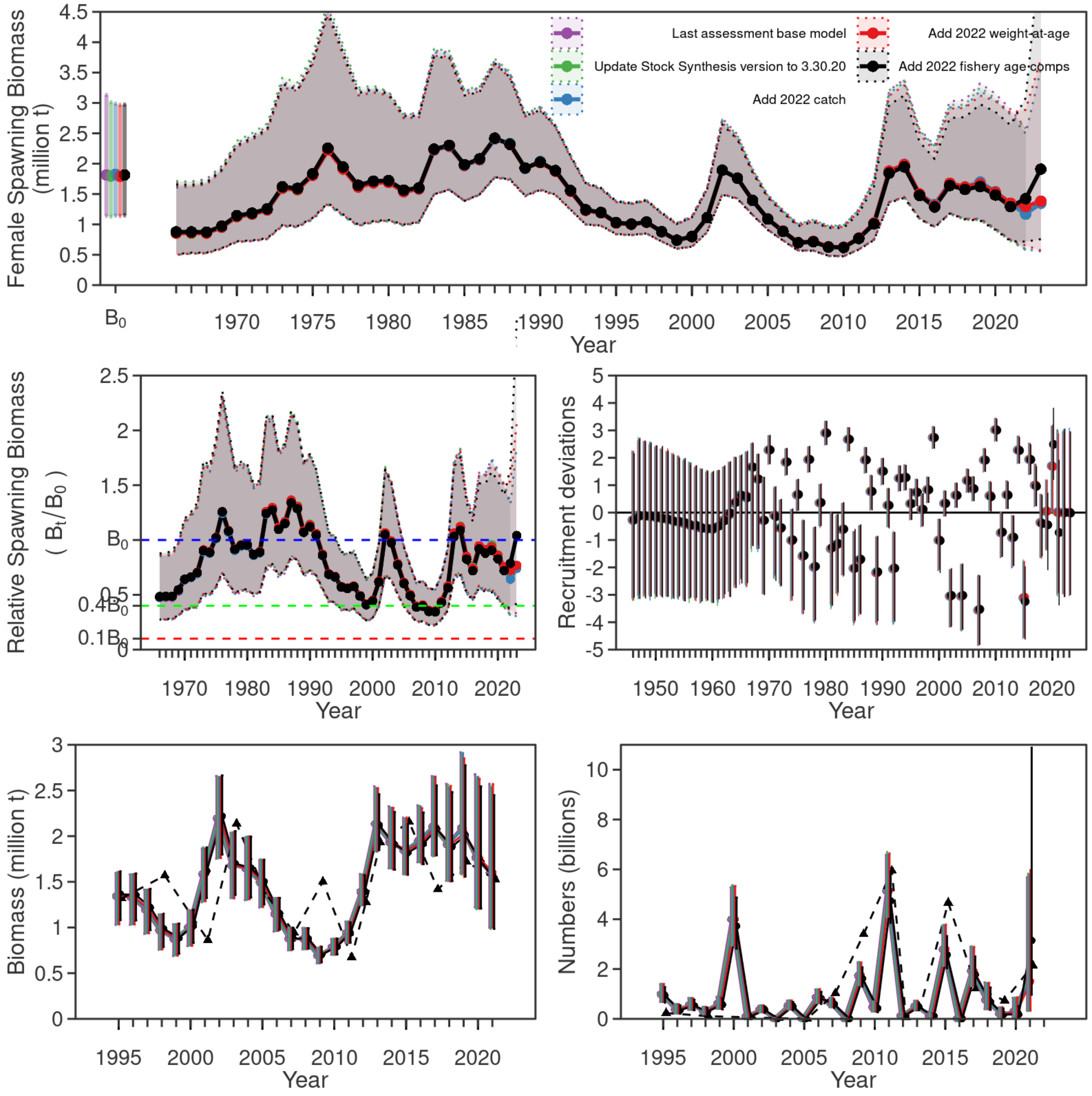


Figure 16. Bridging models showing the sequential steps made to the base model from the 2022 base model to the 2023 base model. In order the steps are: update the Stock Synthesis model code version, add 2022 catch, add 2022 weight-at-age, and add 2022 fishery age compositions. The final model is the base model for 2023. Panels are spawning biomass (upper panel), relative spawning biomass (spawning biomass in each year relative to the unfished equilibrium spawning biomass, middle left), recruitment deviation (middle right), age-2+ survey biomass index (lower left), and age-1 index (lower right), with triangles representing the observed survey indices.

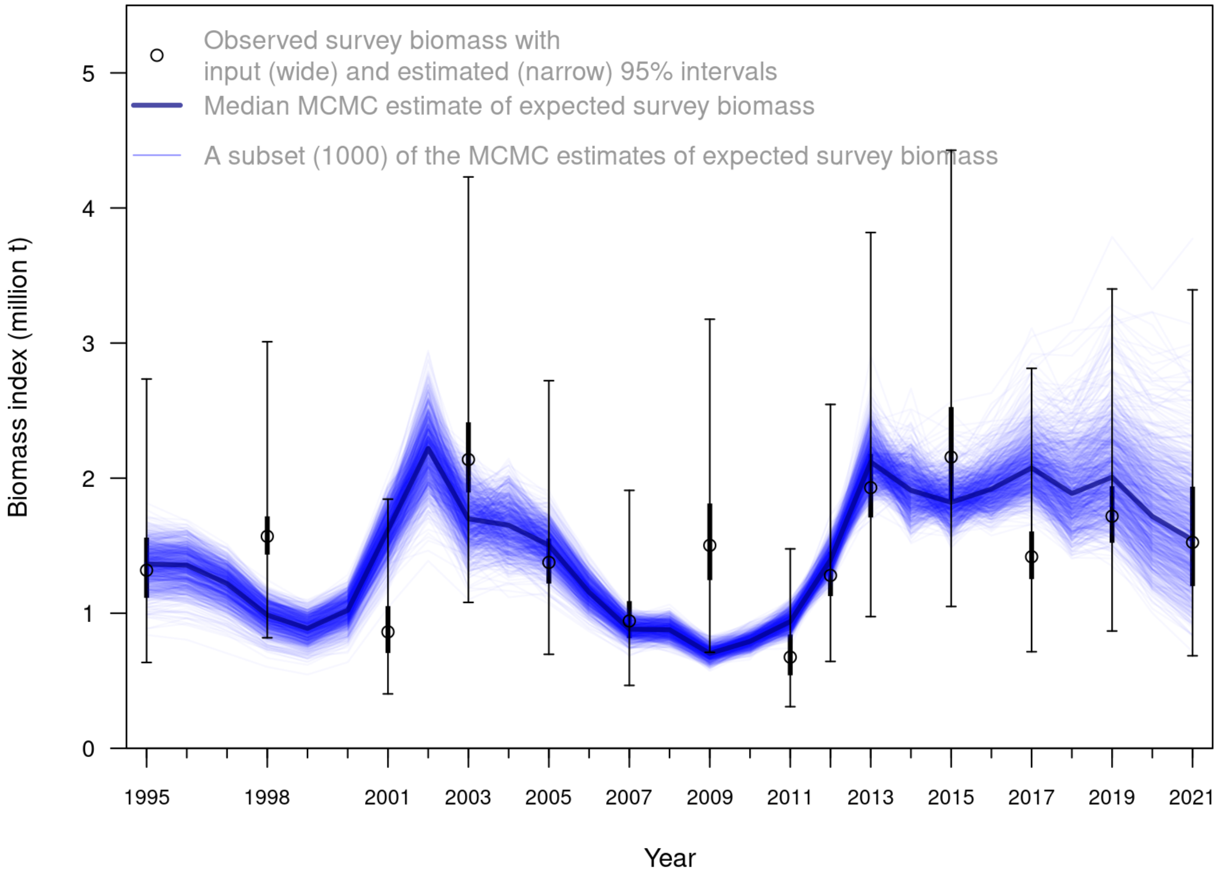


Figure 17. Fits (colored lines) to the acoustic survey (points) with input 95% intervals around the observations. The thin blue lines are the results of a random subset of individual MCMC samples. Thicker uncertainty intervals around observed survey points indicate 95% log-normal uncertainty intervals estimated by the kriging method and are used as input to the assessment model. Thinner uncertainty intervals indicate estimated 95% uncertainty intervals that account for the model estimate of additional uncertainty.

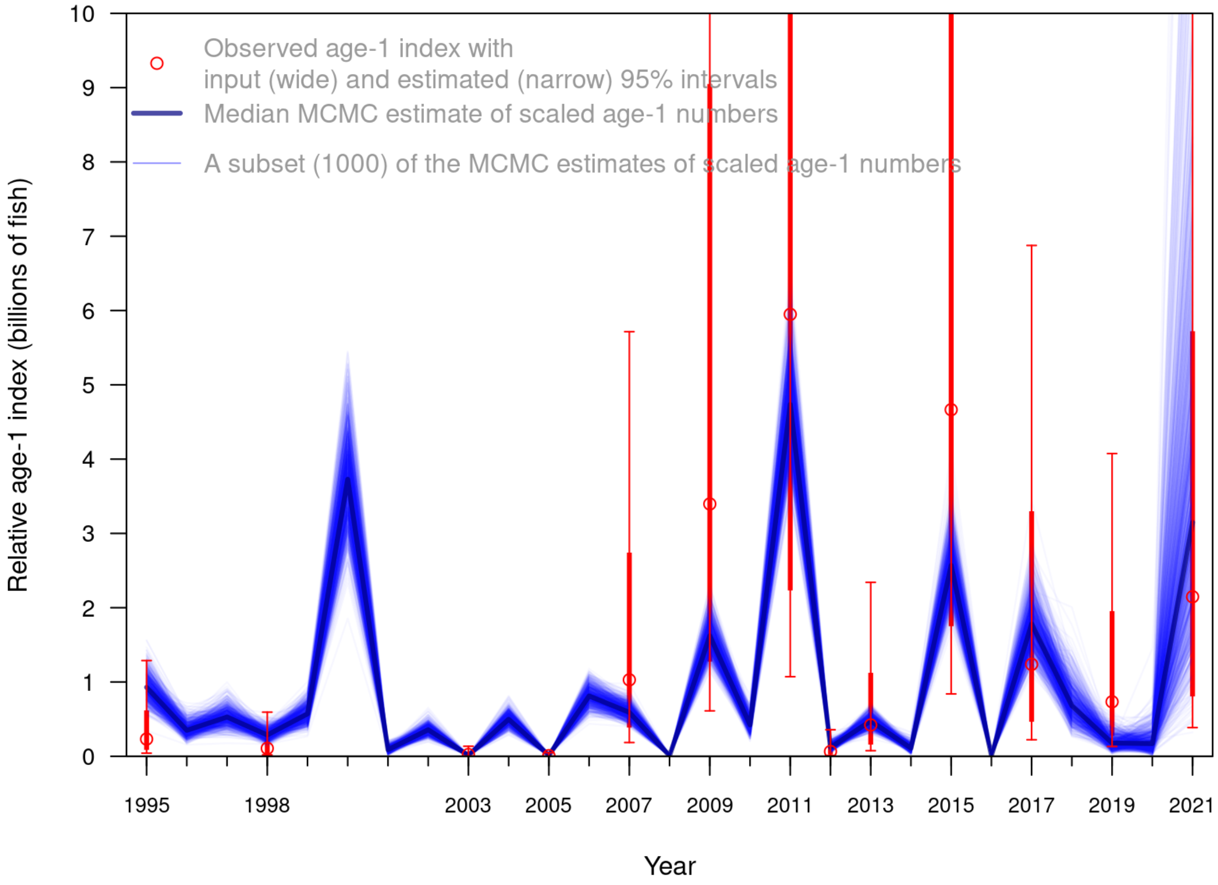
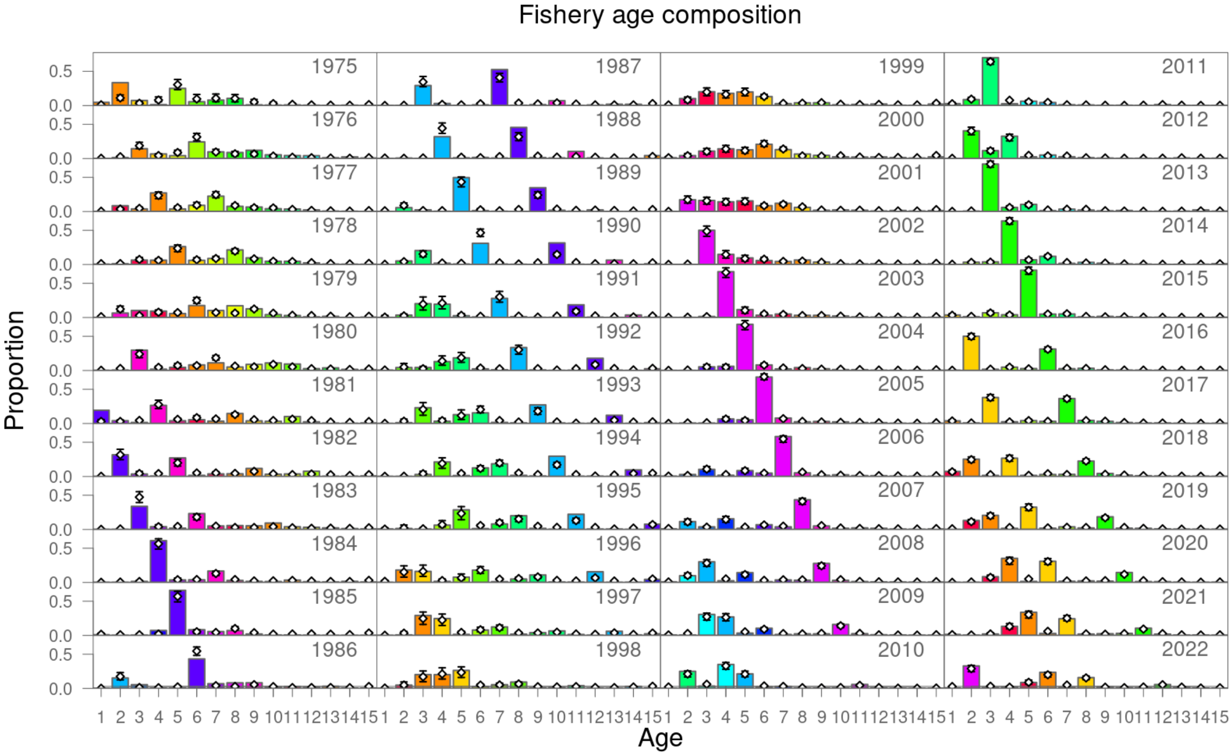


Figure 18. Fits (colored lines) to the relative age-1 index estimated from the acoustic survey (points) with input 95% intervals around the observations. The thin blue lines are the results of a random subset of individual MCMC samples. Thicker uncertainty intervals around observed survey points indicate 95% log-normal uncertainty intervals based on sampling variability and are used as input to the assessment model. Thinner uncertainty intervals indicate estimated 95% uncertainty intervals that account for the model estimate of additional uncertainty.



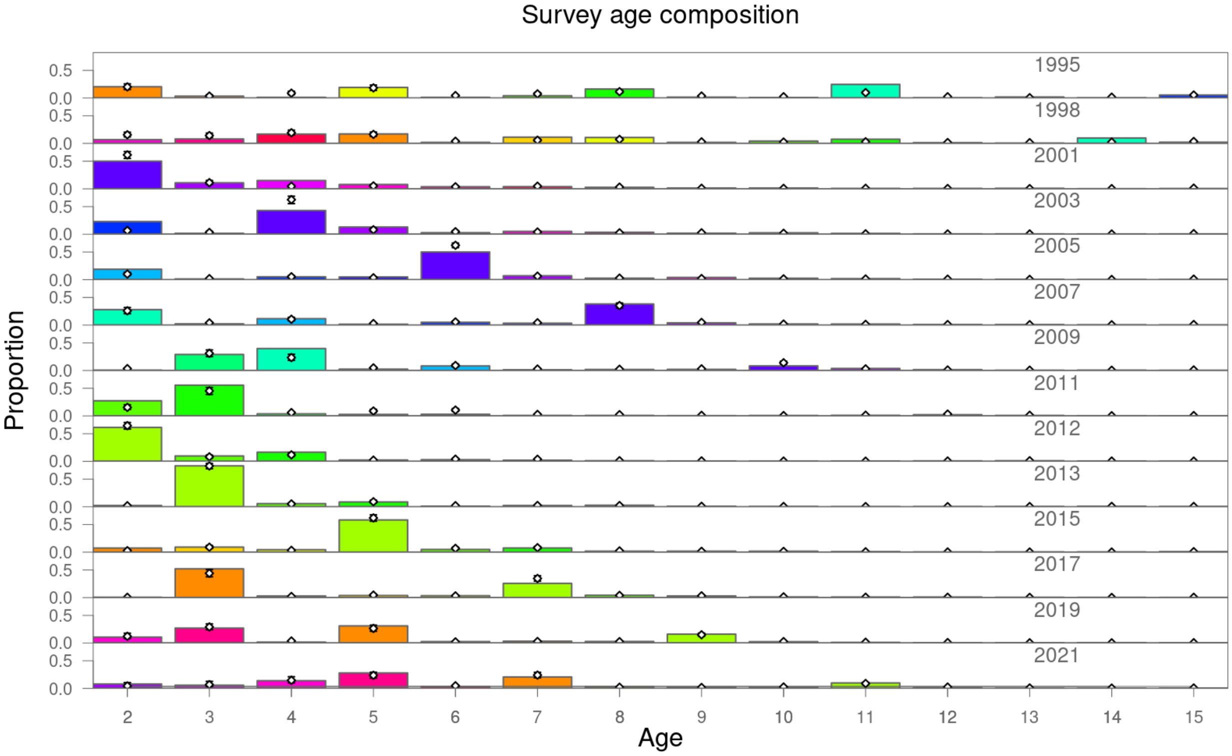


Figure 19. Base model fits to the observed fishery (top) and acoustic survey (bottom) age-composition data. Colored bars show observed proportions with colors following each cohort across years. Points with intervals indicate median expected proportions and 95% credibility intervals from the MCMC calculations.

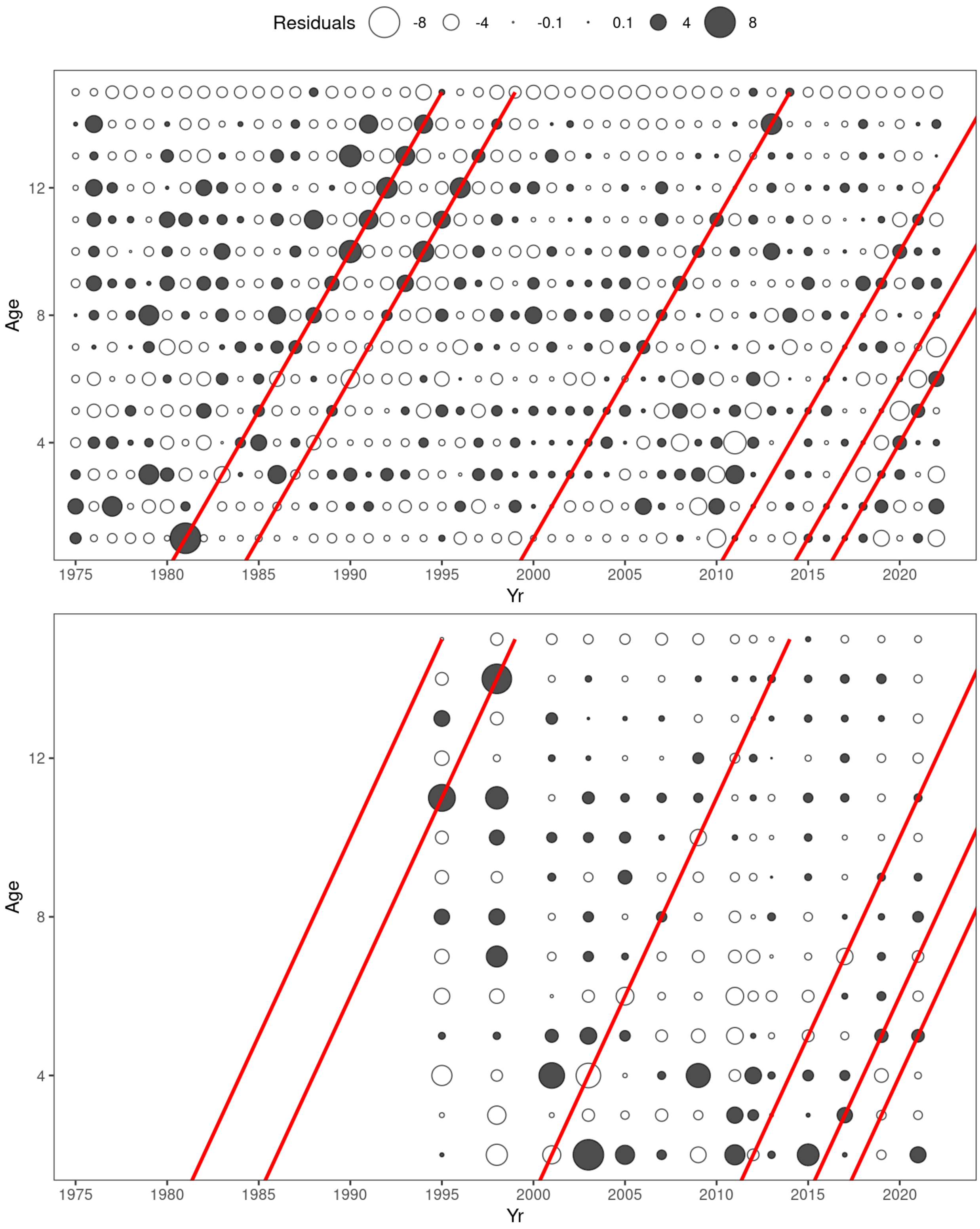


Figure 20. Pearson residuals for base model fits to the age-composition data for the medians of the MCMC posteriors. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected). Red lines track cohorts from years of large recruitment events.

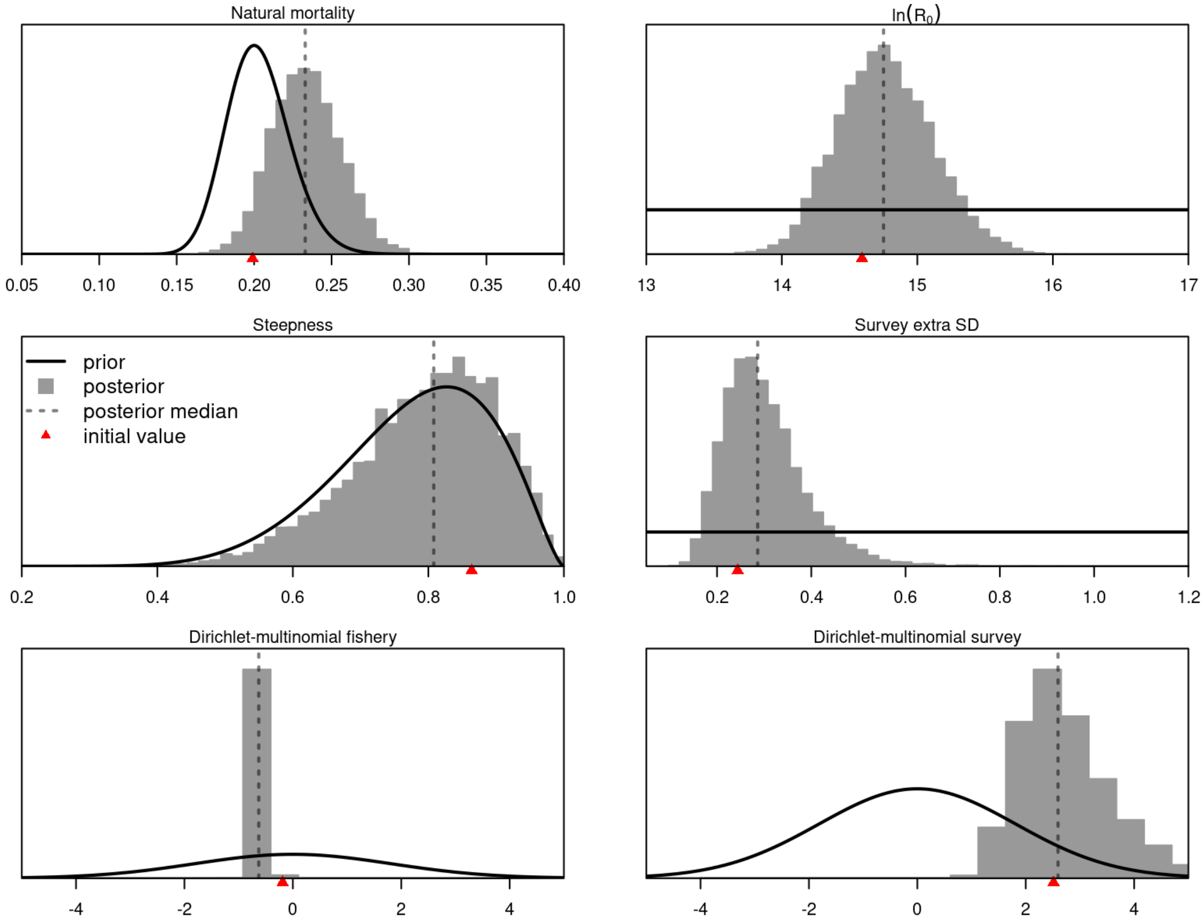


Figure 21. Prior (black lines) and posterior (gray histograms) distributions for key parameters in the base model. The parameters are: natural mortality (M), equilibrium log recruitment ($\log R_0$), steepness (h), the additional process-error standard deviation for the acoustic survey, and the Dirichlet-multinomial parameters for the fishery (θ_{fish}) and the survey (θ_{surv}).

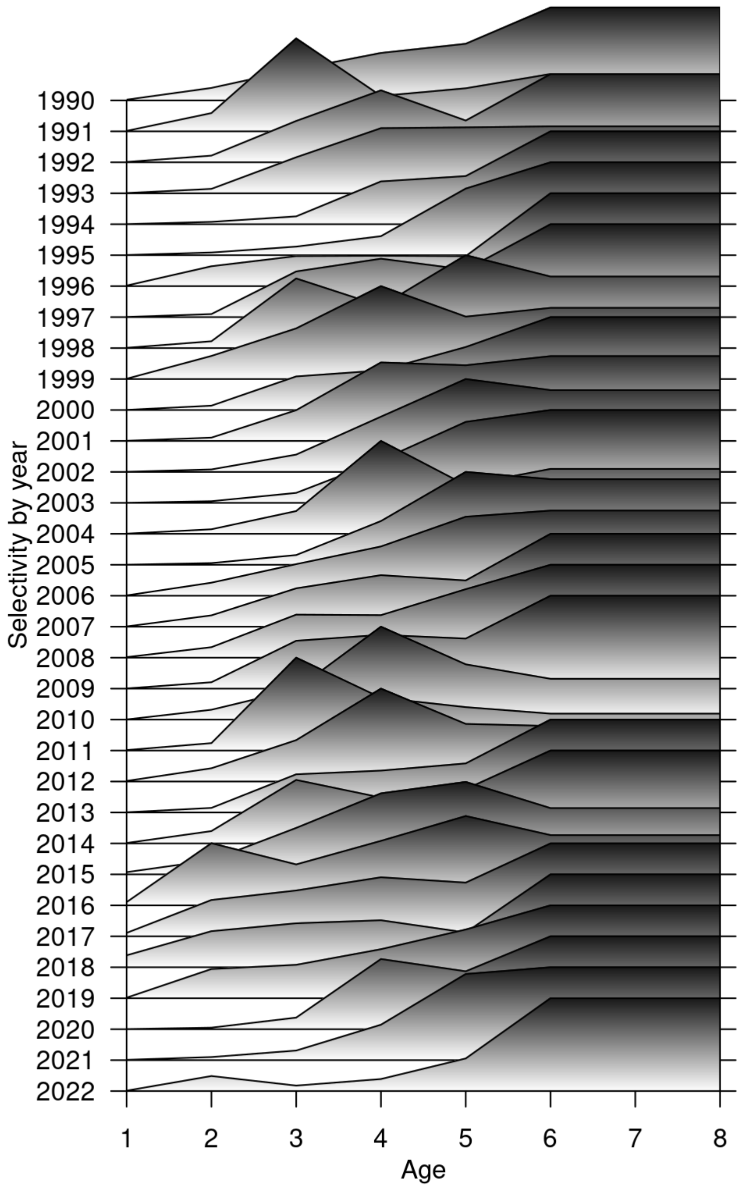


Figure 22. Mountains plot of median fishery selectivity in each year for the base model. Range of selectivity is scaled to be between 0 to 1 in each year.

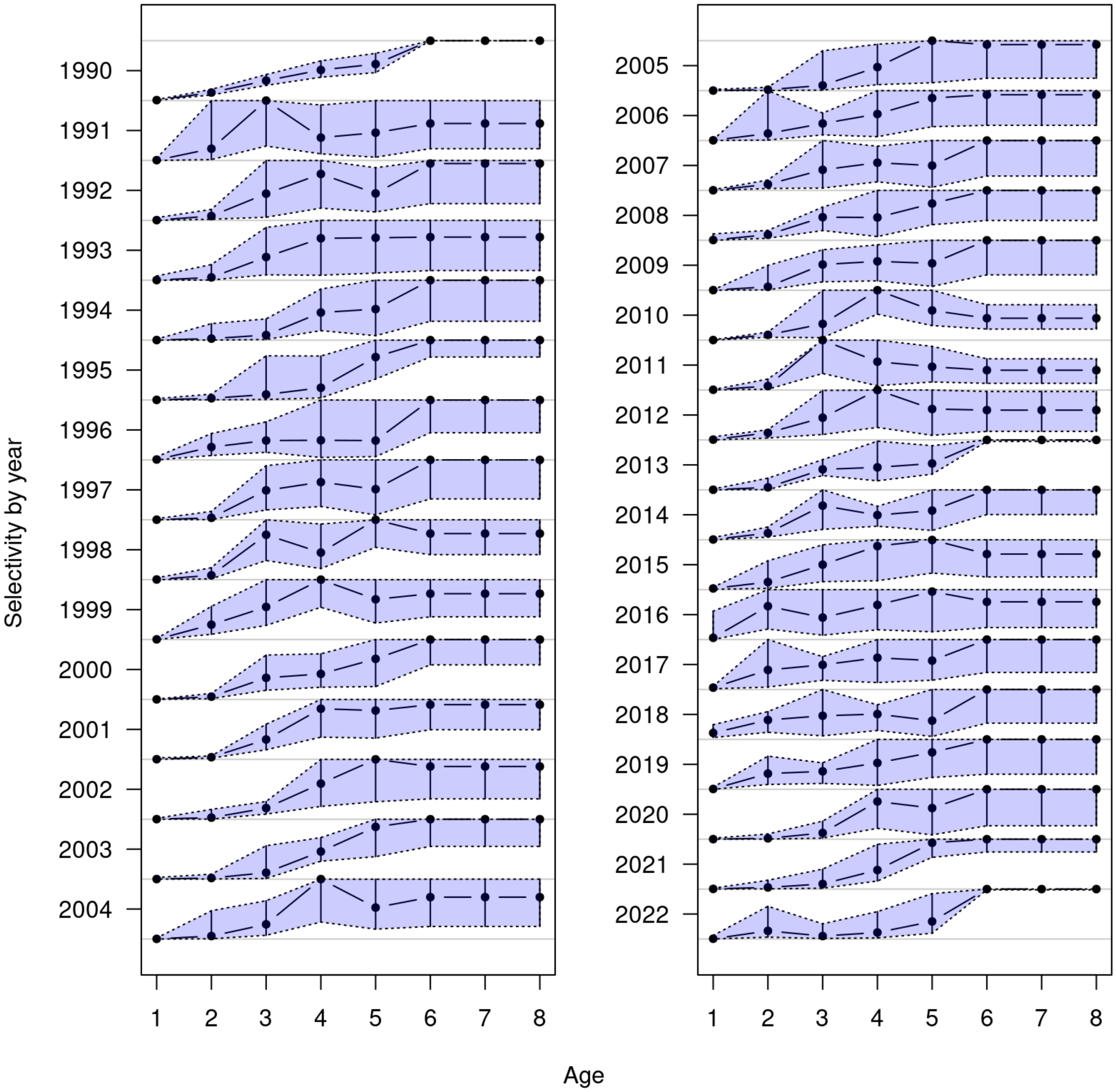


Figure 23. Fishery selectivity sampled from posterior probability distribution by year for the base model. Black dots and bars indicate the median and 95% credibility interval, respectively. The shaded polygon also shows the 95% credibility interval. Range is from 0 to 1 within each year. Selectivity for 1990 is shared for all years from 1966 to 1990.

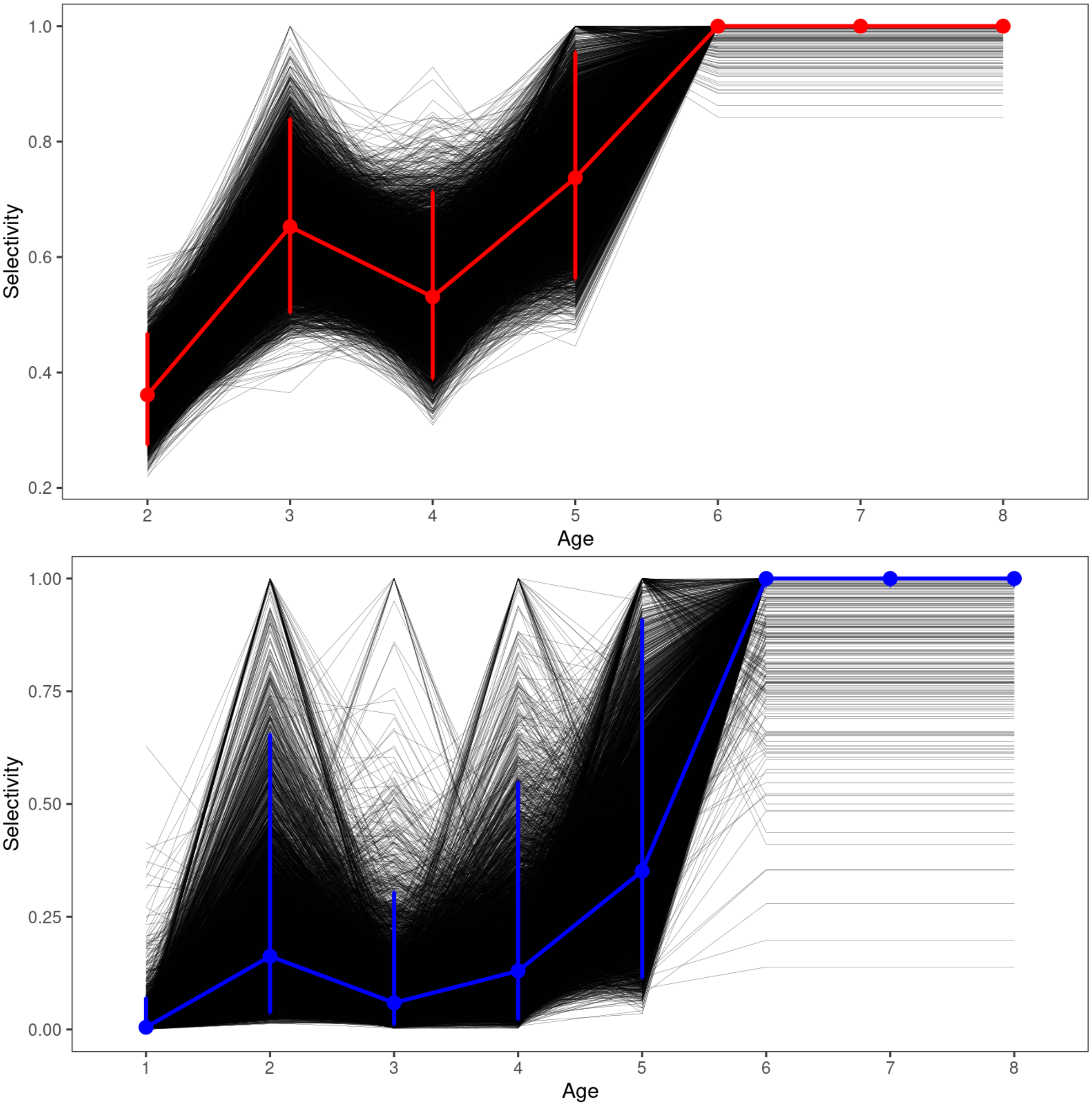


Figure 24. Estimated selectivities for the acoustic survey (top – for all years age-2 and older) and fishery (bottom – shown for 2022 only, age-1 and older) from the posterior distribution for the base model.

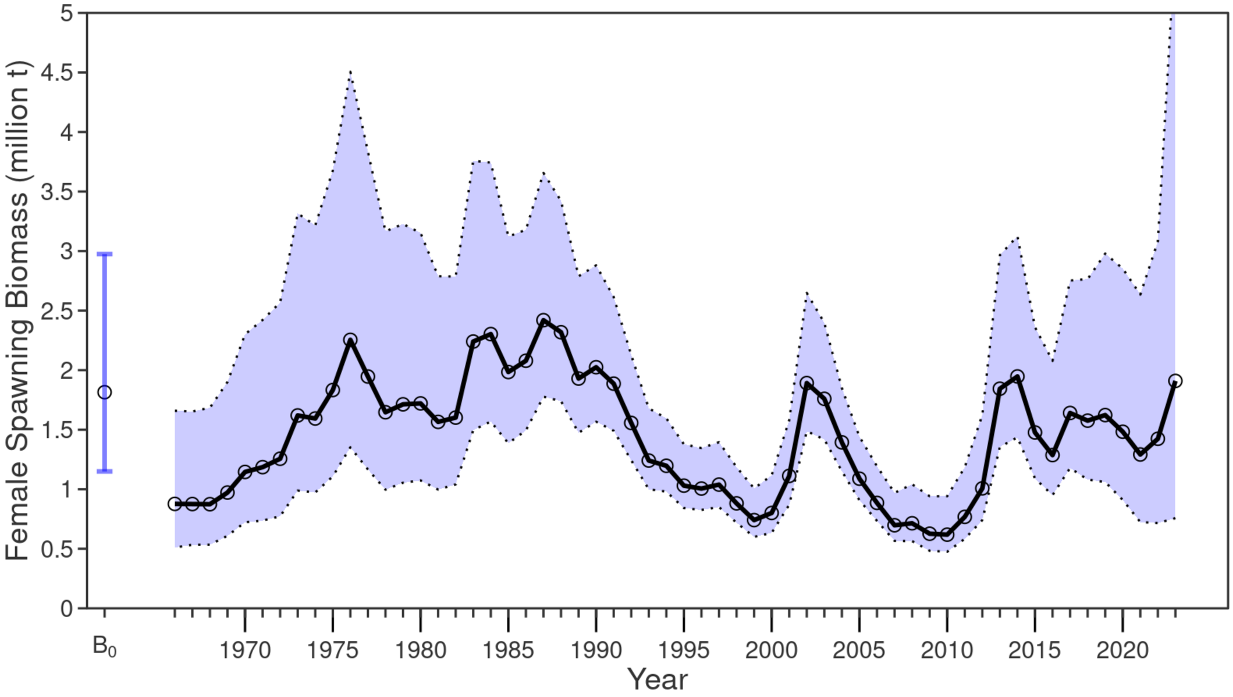


Figure 25. Median of the posterior distribution for female spawning biomass at the start of each year (B_t) for the base model up to 2023 (solid line) with 95% posterior credibility intervals (shaded area).

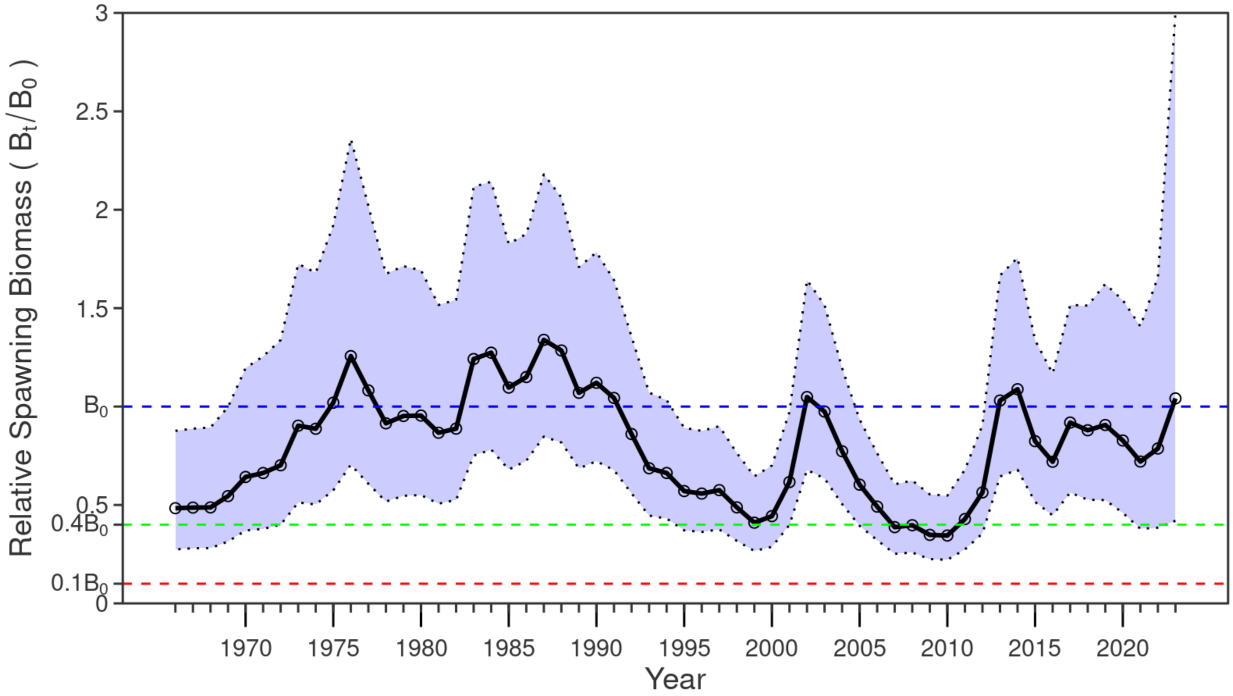


Figure 26. Median (solid line) of the posterior distribution for relative spawning biomass (B_t/B_0) for the base model through 2023 with 95% posterior credibility intervals (shaded area). Dashed horizontal lines show the values for 10%, 40% and 100% of B_0.

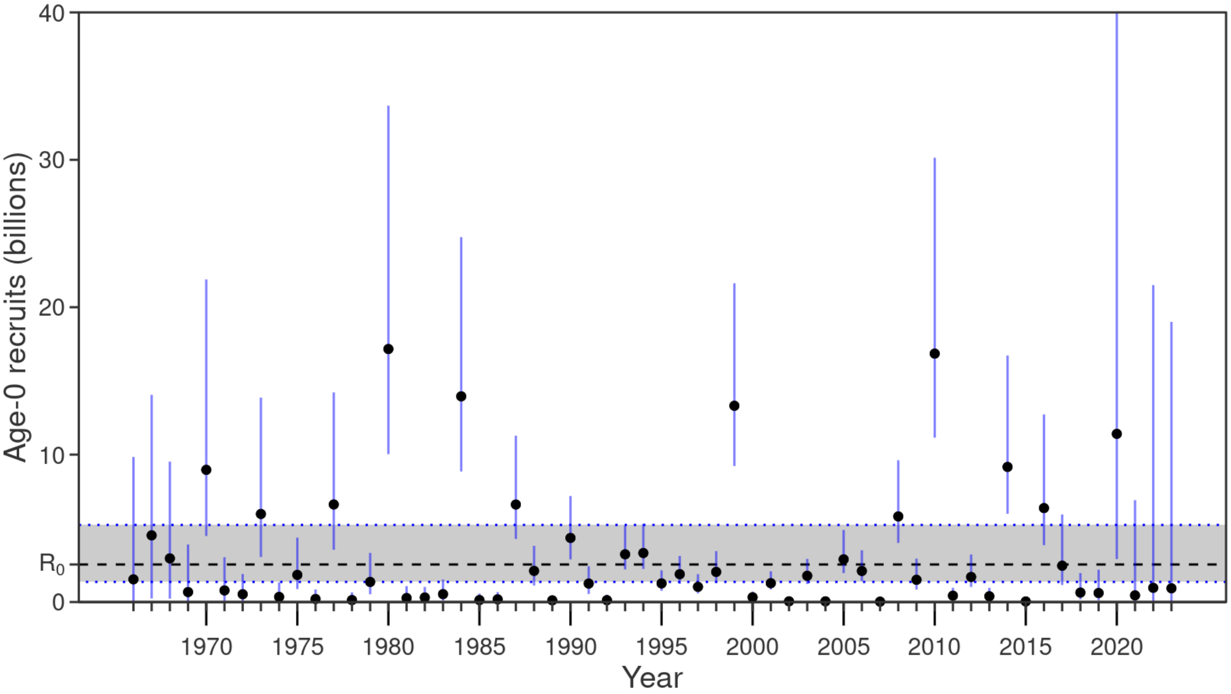


Figure 27. Medians (solid circles) of the posterior distribution for recruitment (billions of age-0 fish) with 95% posterior credibility intervals (blue lines). The median of the posterior distribution for mean unfished equilibrium recruitment (R_0) is shown as the horizontal dashed line with a 95% posterior credibility interval shaded between the dotted lines.

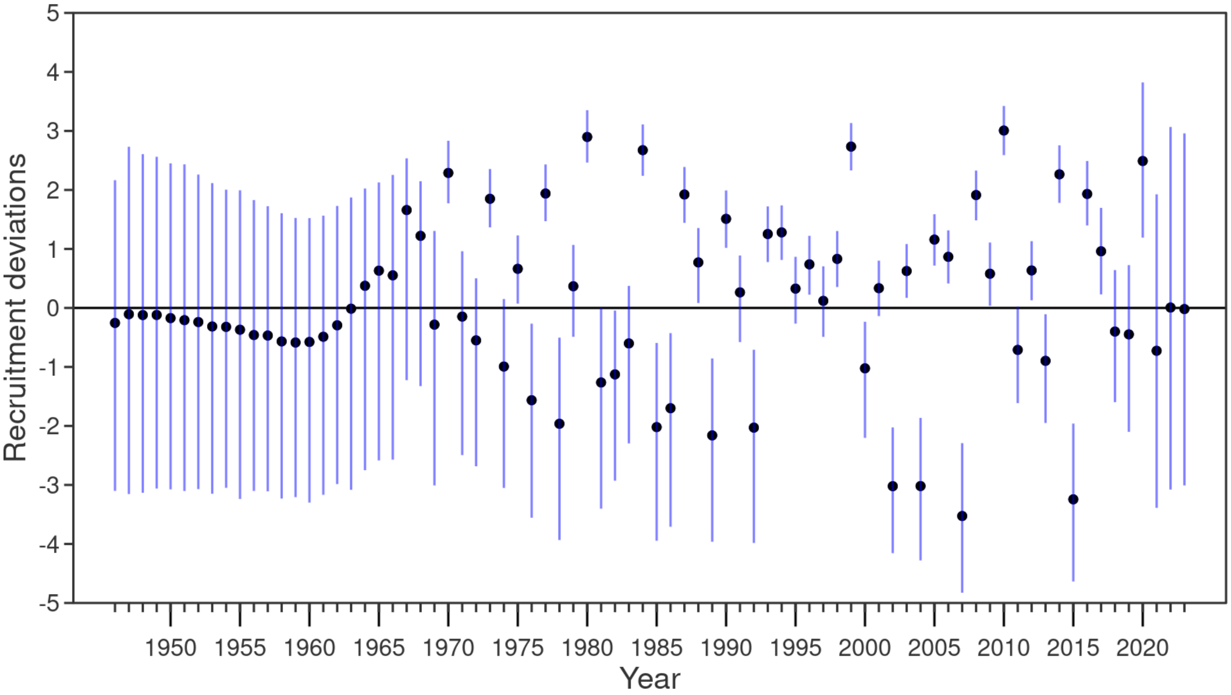


Figure 28. Medians (solid circles) of the posterior distribution for log-scale recruitment deviations with 95% posterior credibility intervals (blue lines). Recruitment deviations for the years 1946–1965 are used to calculate the numbers at age in 1966, the initial year of the model.

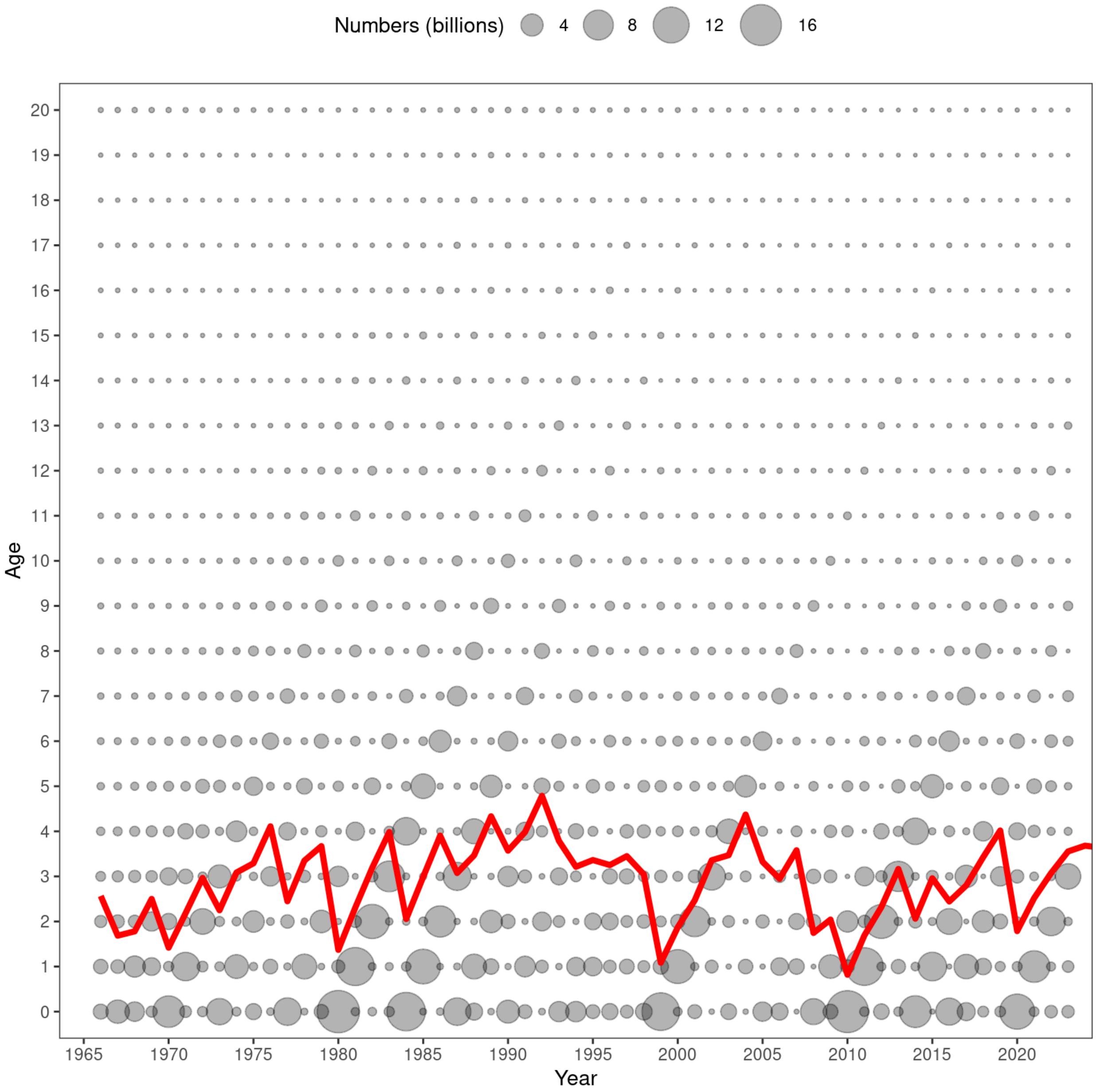


Figure 29. Bubble plot of the medians of the posterior distributions of population numbers at age at the beginning of each year, where diagonals follow each year-class through time. The red line represents the mean age. The scale of the bubbles is represented in the key where the units are billions of fish; the largest overall bubble represents the 17.2 billion age-0 recruits in 1980. See Table 18 for values.

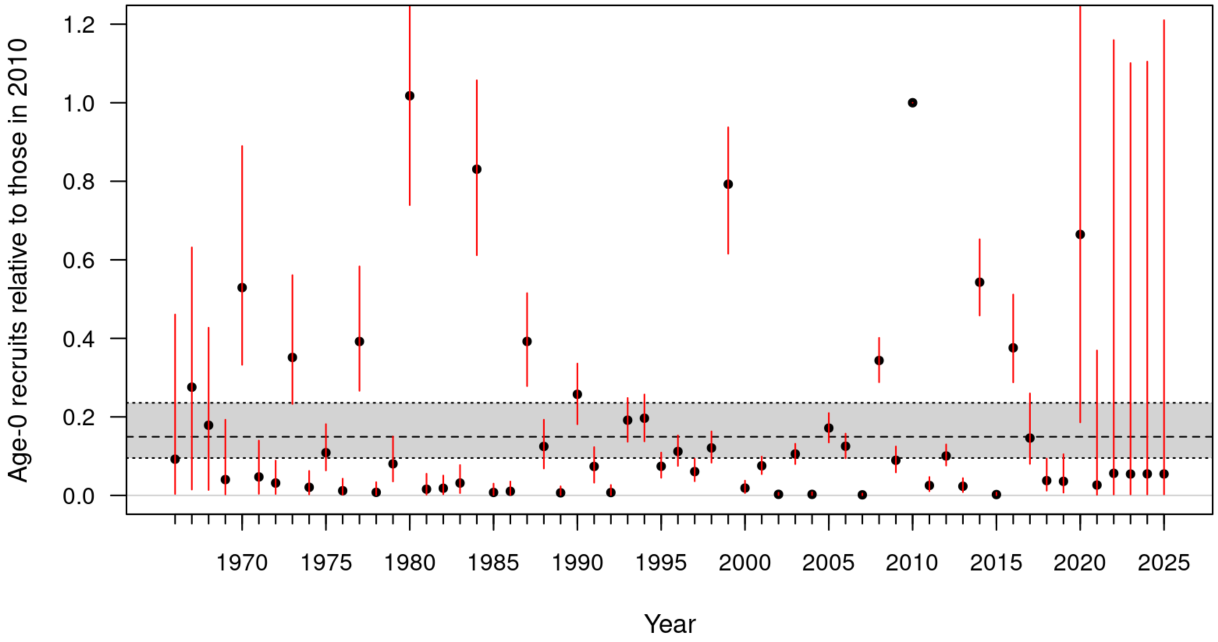


Figure 30. Medians (solid circles) of the posterior distribution of annual recruitment relative to recruitment in 2010 (recruitment divided by the 2010 recruitment for every MCMC sample), with 95% posterior credibility intervals (red lines). This procedure somewhat scales out the uncertainty due to uncertainty in mean unfished equilibrium recruitment (R_0), and better elicits comparisons of relative cohort sizes; for example, recruitment in 2014 is clearly smaller than in 2010. The year 2010 was chosen as the basis for comparison due to its well recognized size and the stability of cohort strength estimates over time. The median of R_0/R_{2010} is shown as the horizontal dashed line with the 95% posterior credibility interval shaded between the dotted lines.

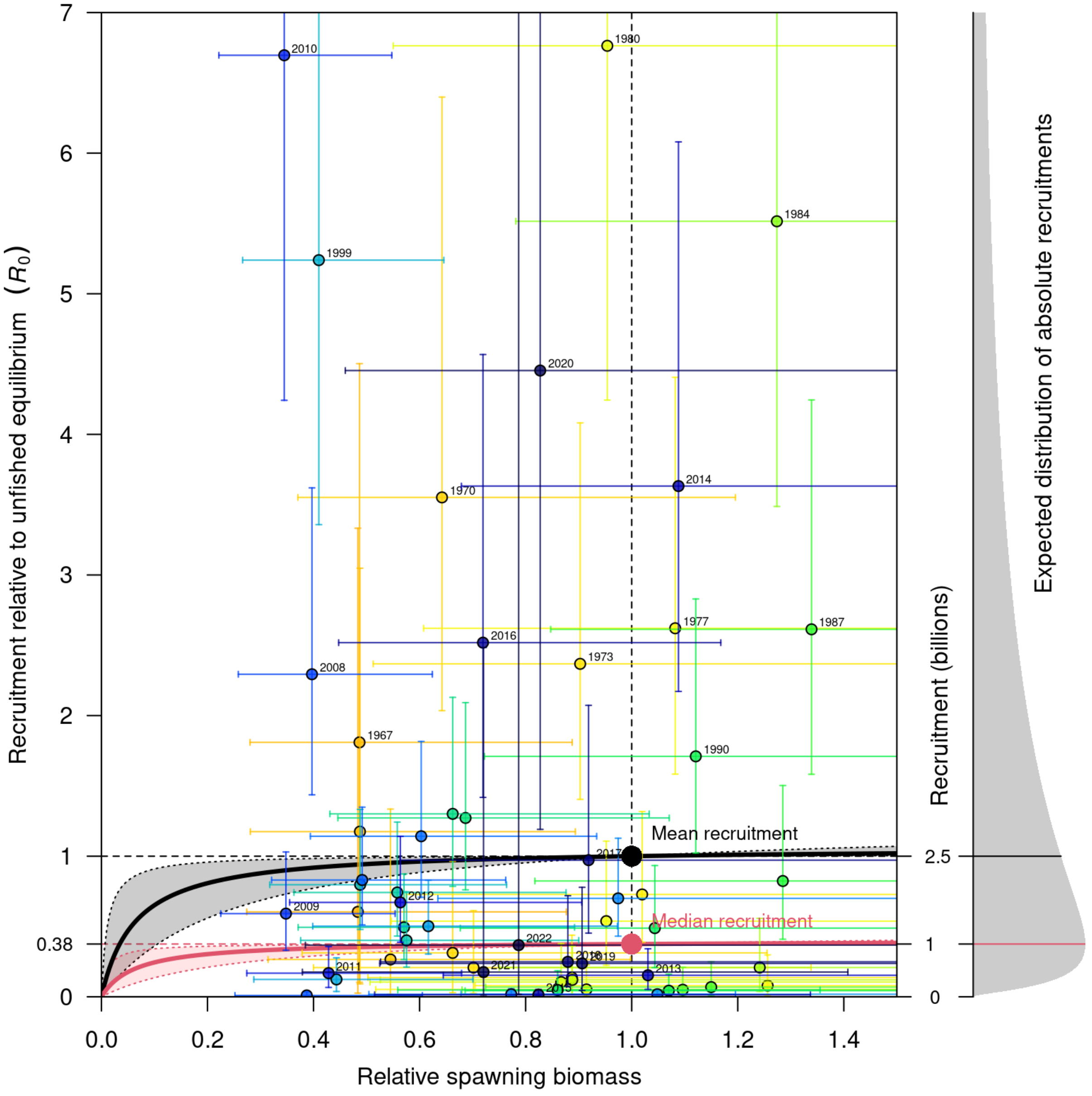


Figure 31. Estimated stock-recruit relationship for the base model with median predicted recruitments and 95% posterior credibility intervals. Colors indicate time-period, with yellow colors in the early years and blue colors in the recent years. The thick solid black line indicates the central tendency (mean) and the red line indicates the central tendency after bias correcting for the log-normal distribution (median). Shading around stock-recruit curves indicates uncertainty in shape associated with distribution of the steepness parameter (h). The gray polygon on the right indicates the expected distribution of absolute recruitments.

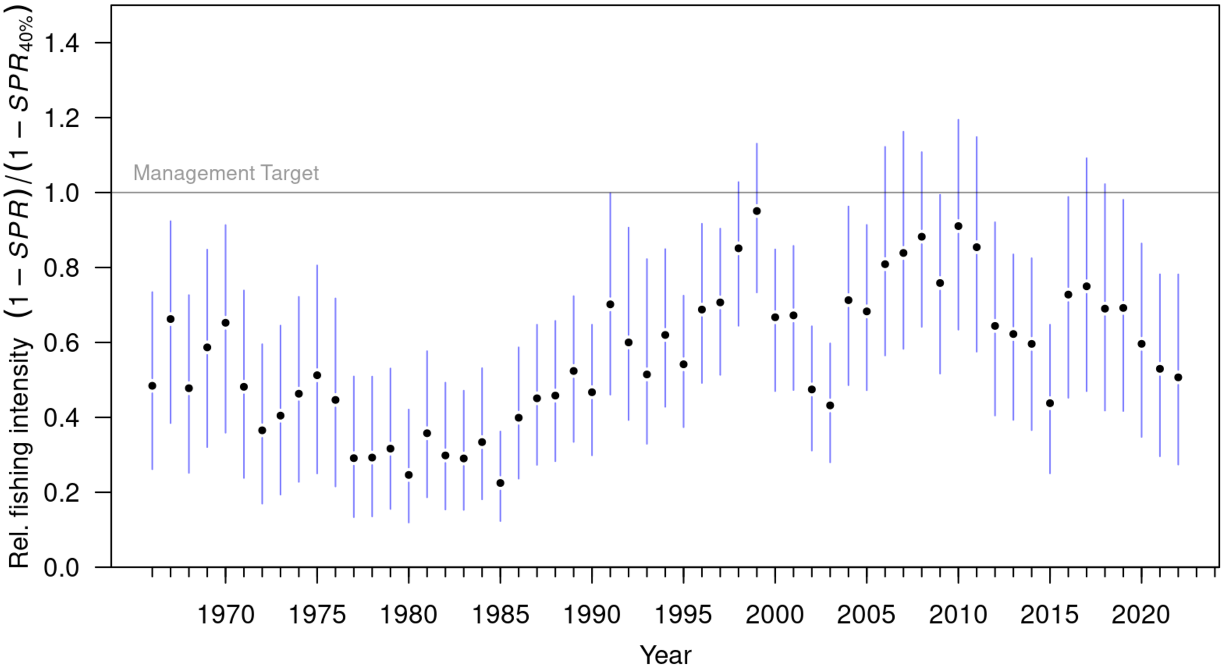


Figure 32. Trend in median fishing intensity (relative to the SPR management target) through 2022 with 95% posterior credibility intervals. The management target defined in the Agreement is shown as a horizontal line at 1.0.

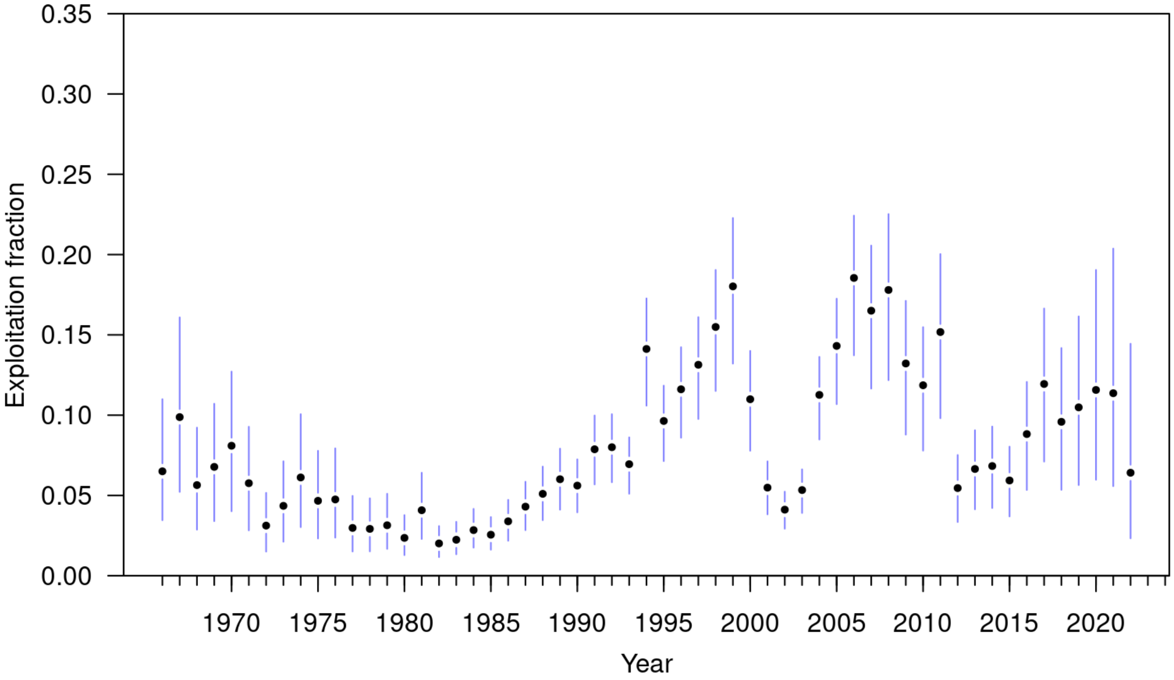


Figure 33. Trend in median exploitation fraction (catch divided by biomass of fish of age-2 and above) through 2022 with 95% posterior credibility intervals.

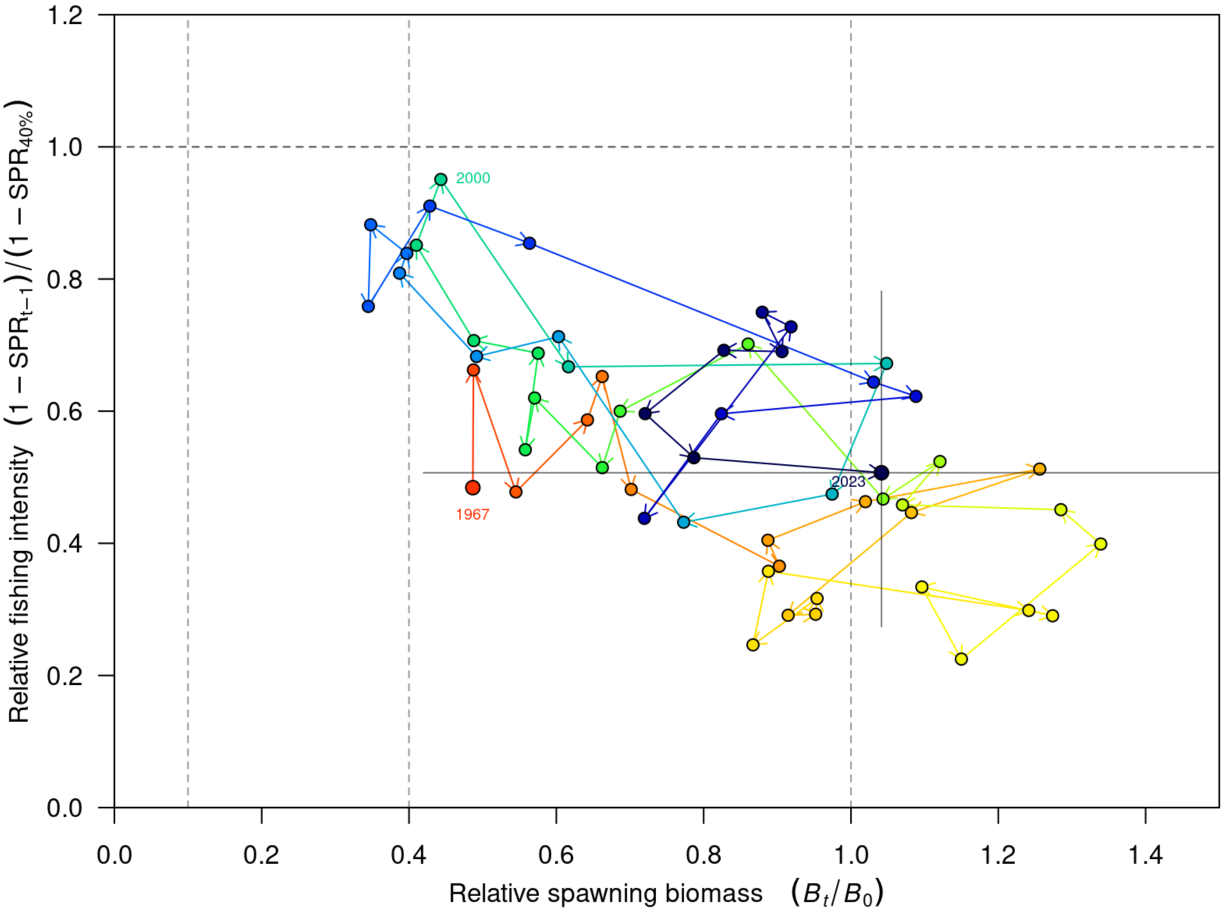


Figure 34. Estimated historical path of median relative spawning biomass in at the beginning of year *t* and corresponding median relative fishing intensity in the fishing year $(t-1)$ leading up to year *t*. Labels show the start year, end year and year of highest relative fishing intensity; labels correspond to year *t* (i.e., year of the relative spawning biomass). Gray bars span the 95% credibility intervals for 2023 relative spawning biomass (horizontal) and 2022 relative fishing intensity (vertical).

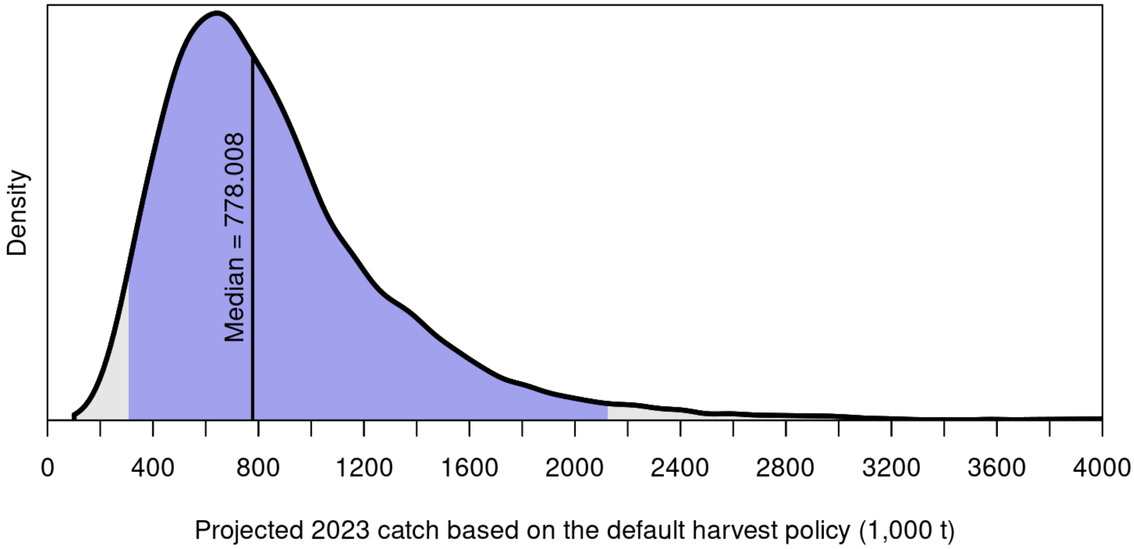


Figure 35. The posterior distribution of the default 2023 catch limit calculated using the default harvest policy ($F_{\mathrm{SPR}=40\%}$–40:10). The median is 778,008 t (vertical line), with the dark shaded area ranging from the 2.5% quantile to the 97.5% quantile, covering the range 301,205–2,136,434 t.

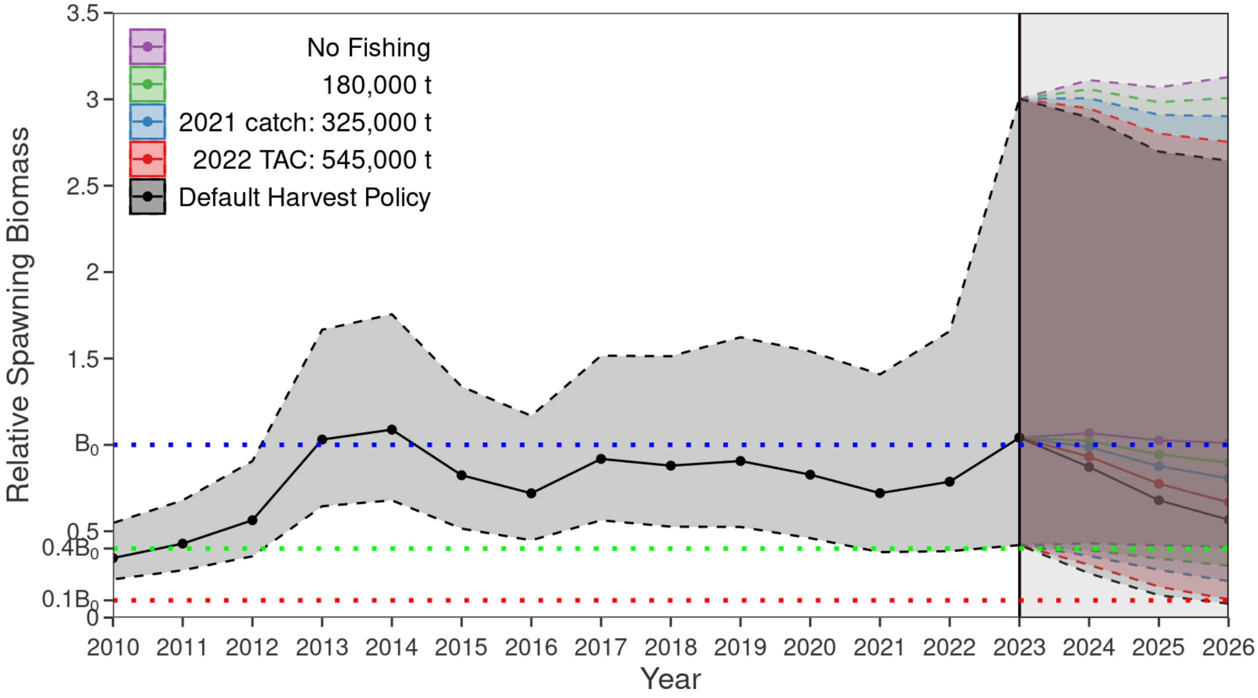


Figure 36. Time series of relative spawning biomass at the start of each year until 2023 as estimated from the base model, and forecast trajectories to the start of 2026 for several management options from the decision table (grey rectangle), with 95% posterior credibility intervals. The default harvest policy catches are 778,008 t in 2023, 740,322 t in 2024, and 621,315 t in 2025.

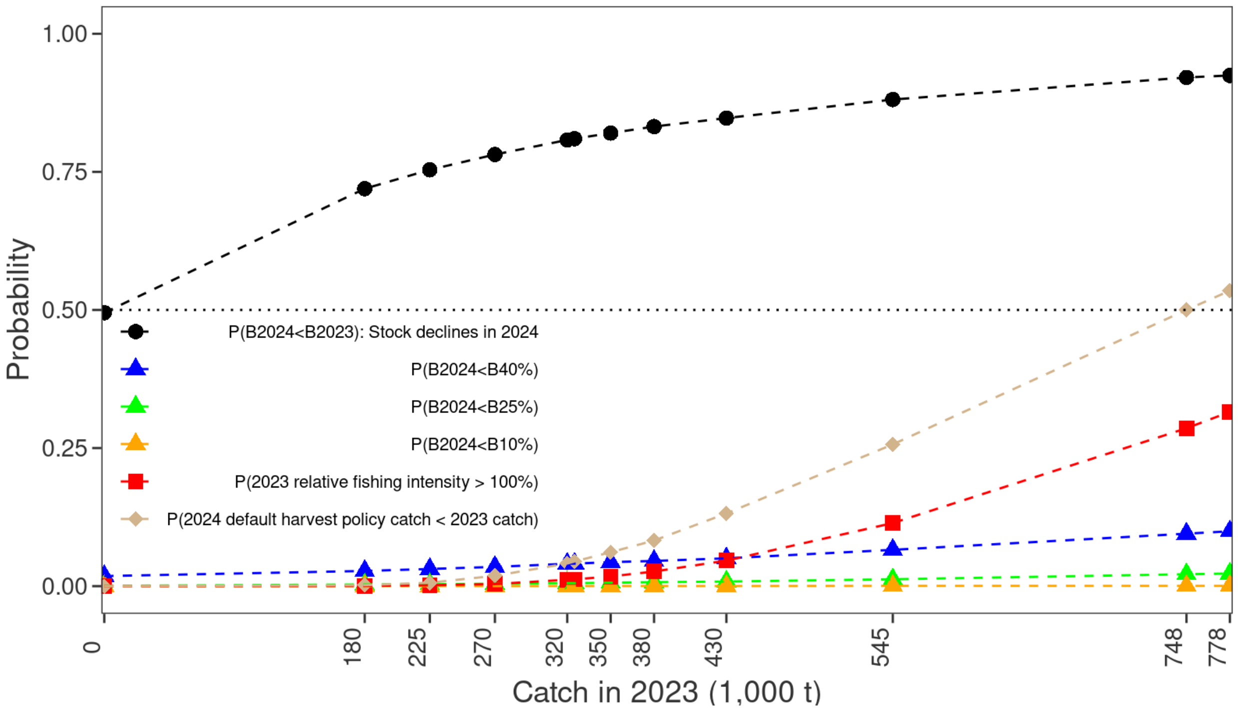


Figure 37. Graphical representation of the base model results presented in Table 30 for various catches in 2023. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

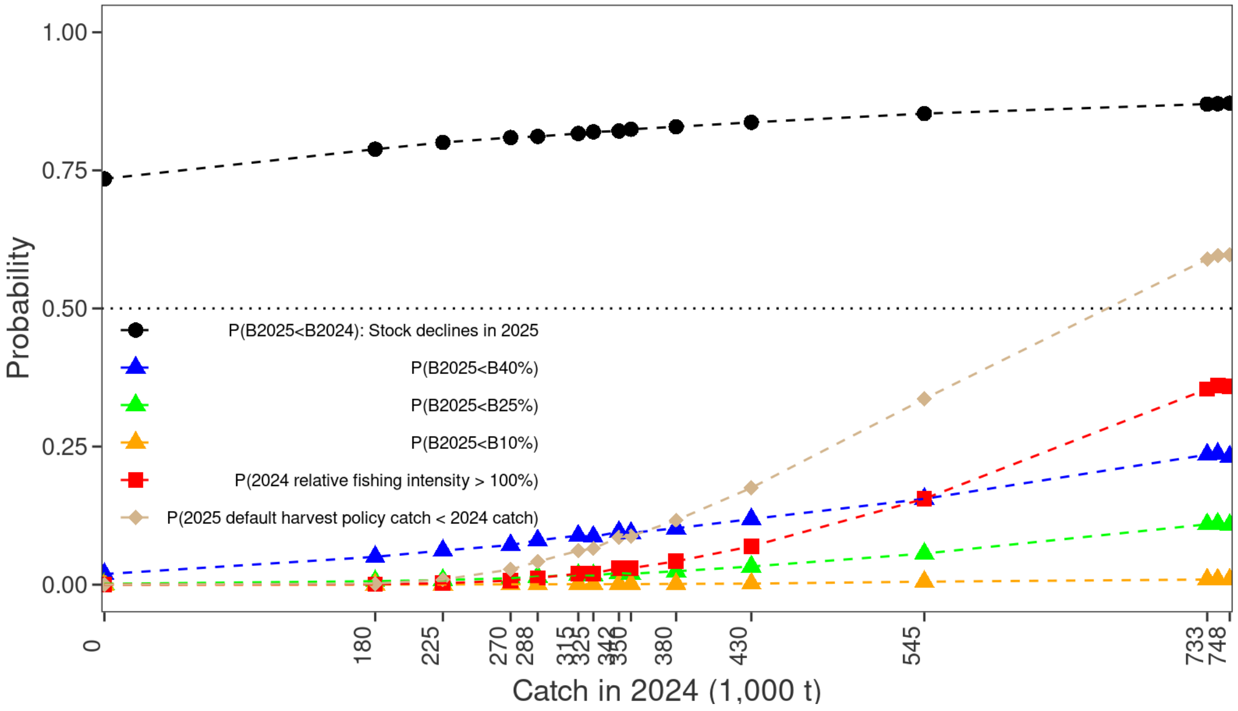


Figure 38. Graphical representation of the base model results presented in Table 31 for catch in 2024, given the 2023 catch level shown in Table 30. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

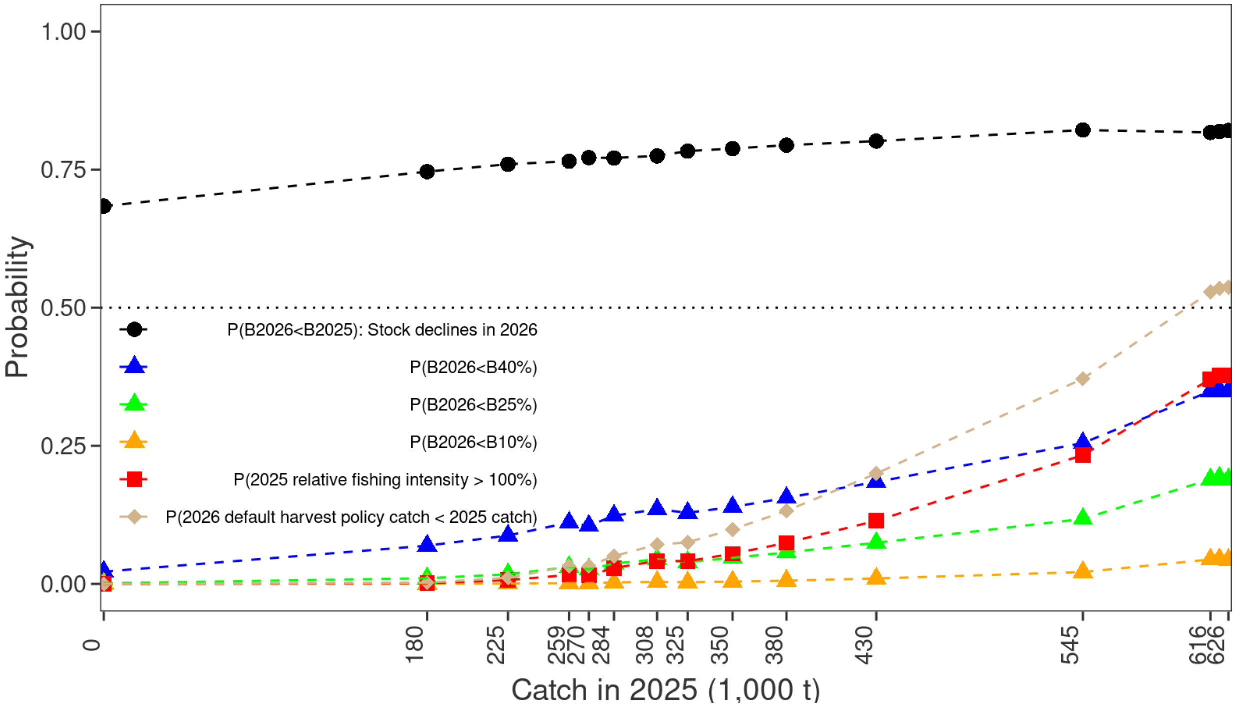


Figure 39. Graphical representation of the base model results presented in Table 32 for catch in 2025, given the 2023 and 2024 catch levels shown in Tables 30 and 31. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

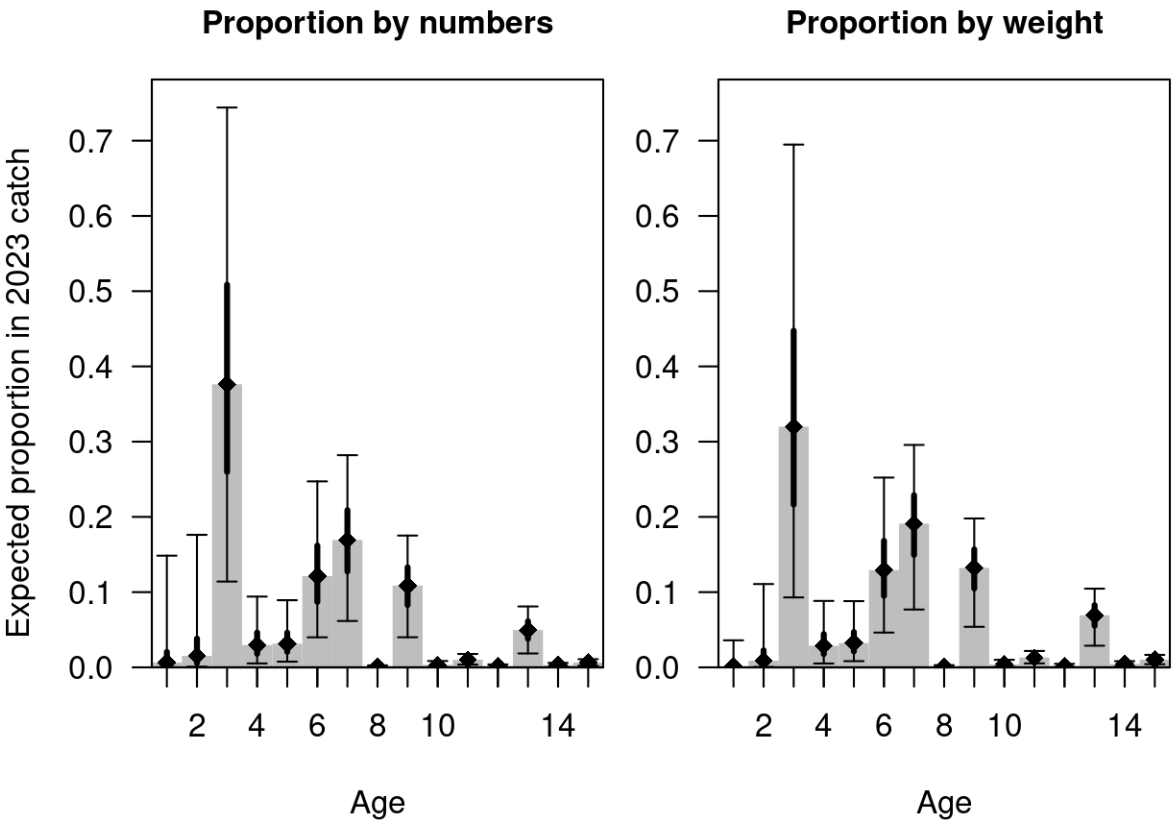


Figure 40. Forecast age compositions in numbers and in weight for the 2023 fishery catch (combined across all sectors in both countries). Gray bars show median estimates. Thick black lines show 50% credibility intervals and thin black lines show 95% credibility intervals. These estimates are based on the posterior distribution for selectivity averaged across the most recent five years, weight-at-age data averaged across the most recent five years, and the distribution for expected numbers at age at the start of 2023 (see Table 18 for the MCMC medians of numbers-at-age for all years). The panel on the right is scaled based on the weight at each age averaged across the last five years.

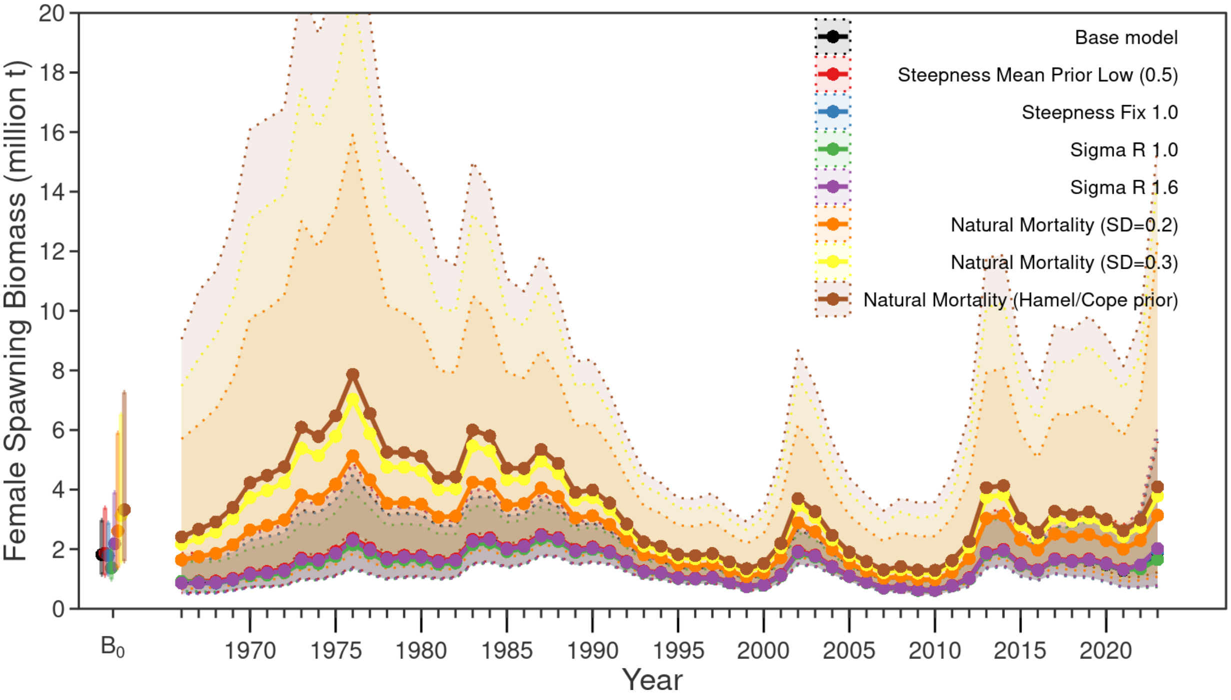


Figure 41. MCMC estimates of spawning biomass for the base model and alternative sensitivity runs representing changing the mean of the prior for steepness from 1.0 to 0.5, fixing steepness at 1.0, lower (1.0) and higher (1.6) levels of variation assumed about the stock-recruitment relationship (σ_r), changing the standard deviation of the prior for natural mortality, and using the Hamel prior distribution for natural mortality.

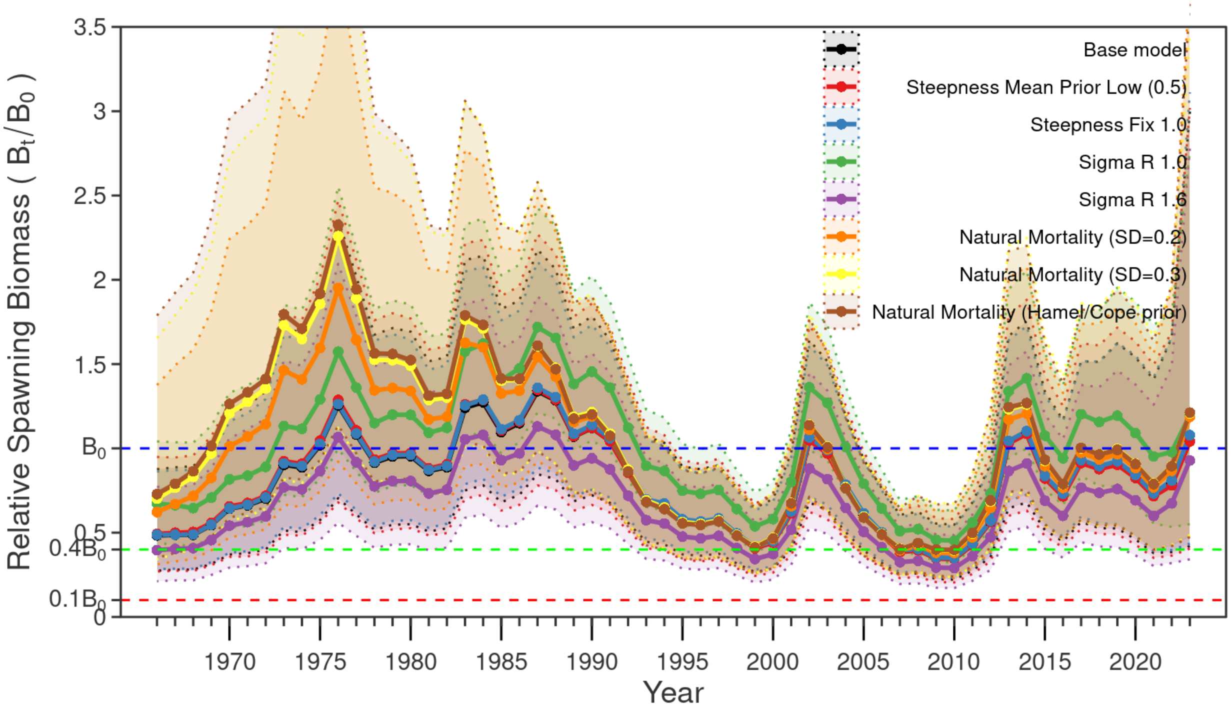


Figure 42. MCMC estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity runs representing changing key parameters. See Figure 41 for sensitivity descriptions.

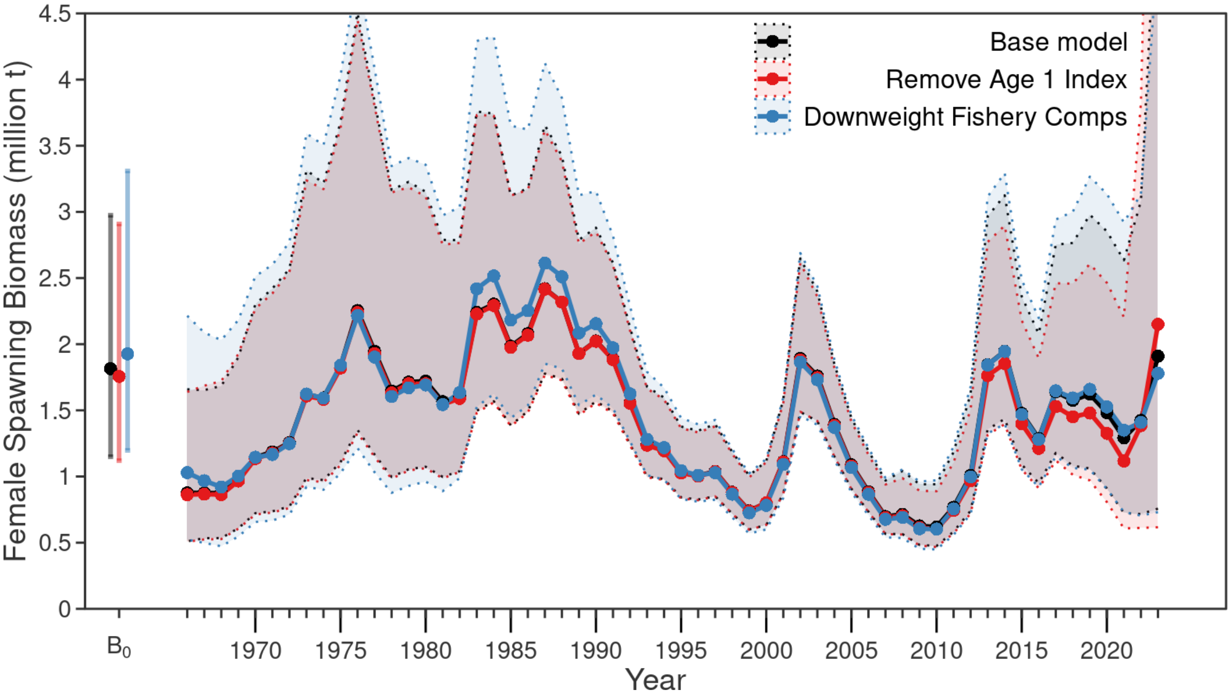


Figure 43. MCMC estimates of spawning biomass for the base model and alternative sensitivity models that represent the following changes in data: removing the index of age-1 fish and down-weighting fishery composition data using the McAllister-Ianelli method.

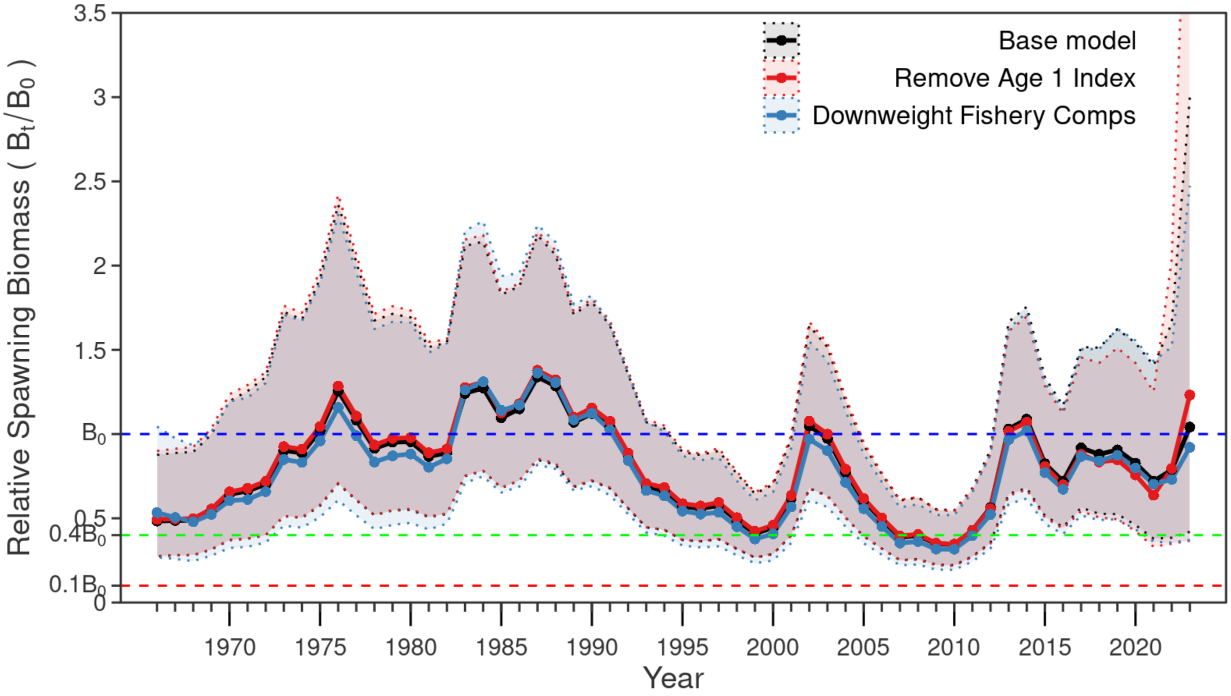


Figure 44. MCMC estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity models that represent changes in data. See Figure 43 for sensitivity descriptions.

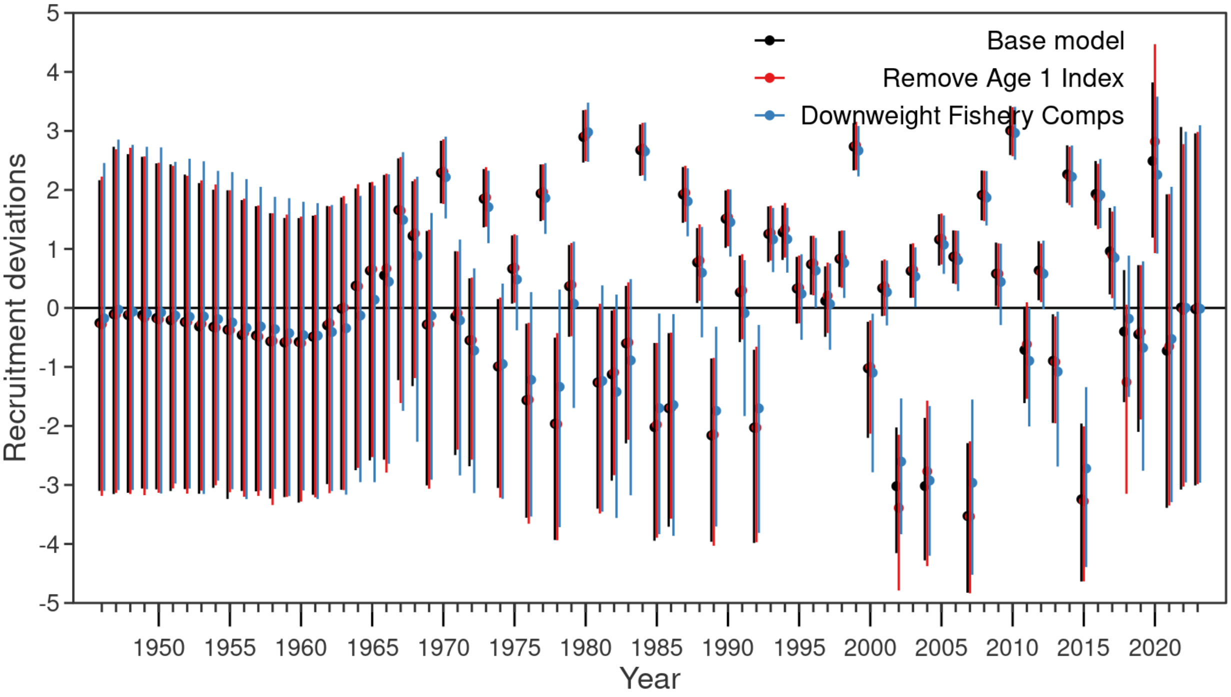


Figure 45. MCMC estimates of recruitment deviations for the base model and alternative sensitivity runs that represent changes in data. See Figure 43 for sensitivity descriptions.

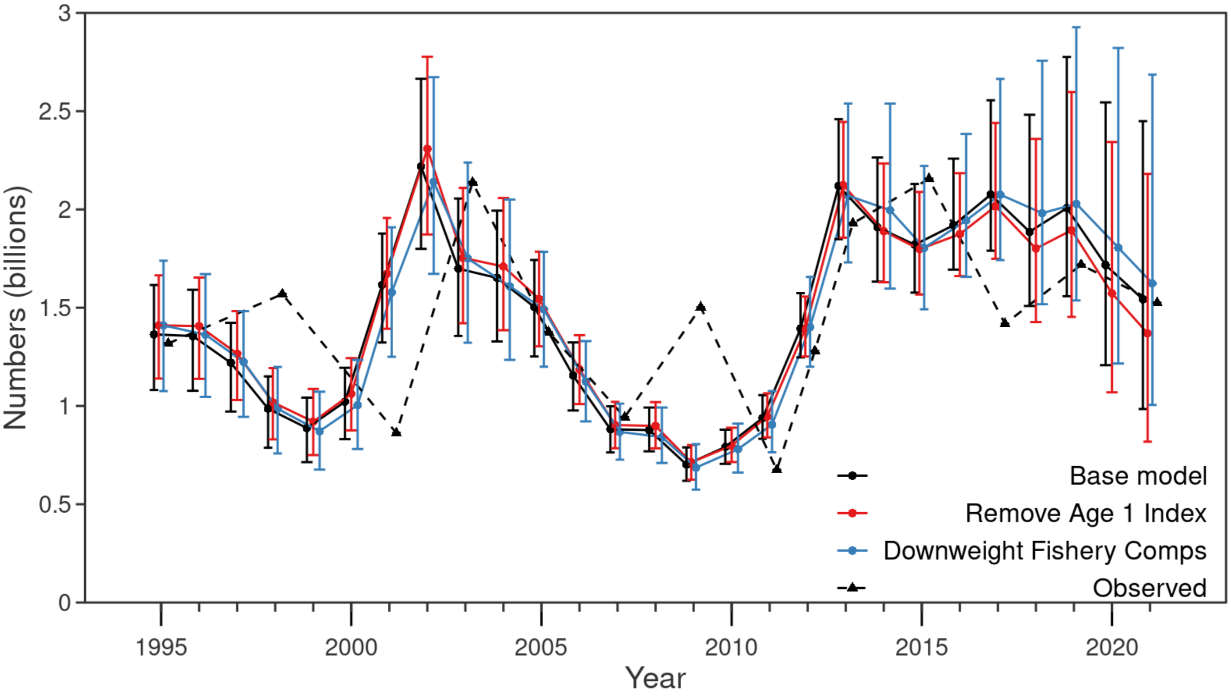


Figure 46. MCMC estimates of the fit to the acoustic survey biomass time series for the base model and alternative sensitivity runs that represent changes in data. See Figure 43 for sensitivity descriptions.

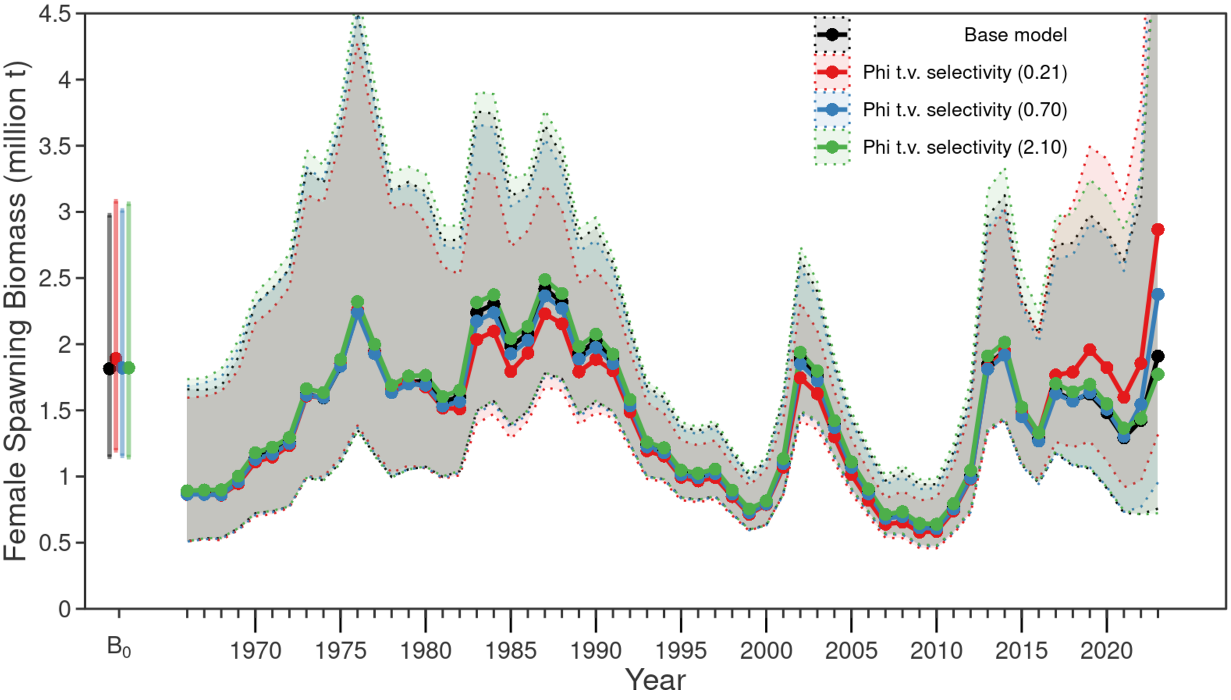


Figure 47. MCMC estimates of spawning biomass for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. Standard deviations examined are below (0.21 and 0.70) and above (2.10) the base model value of 1.4.

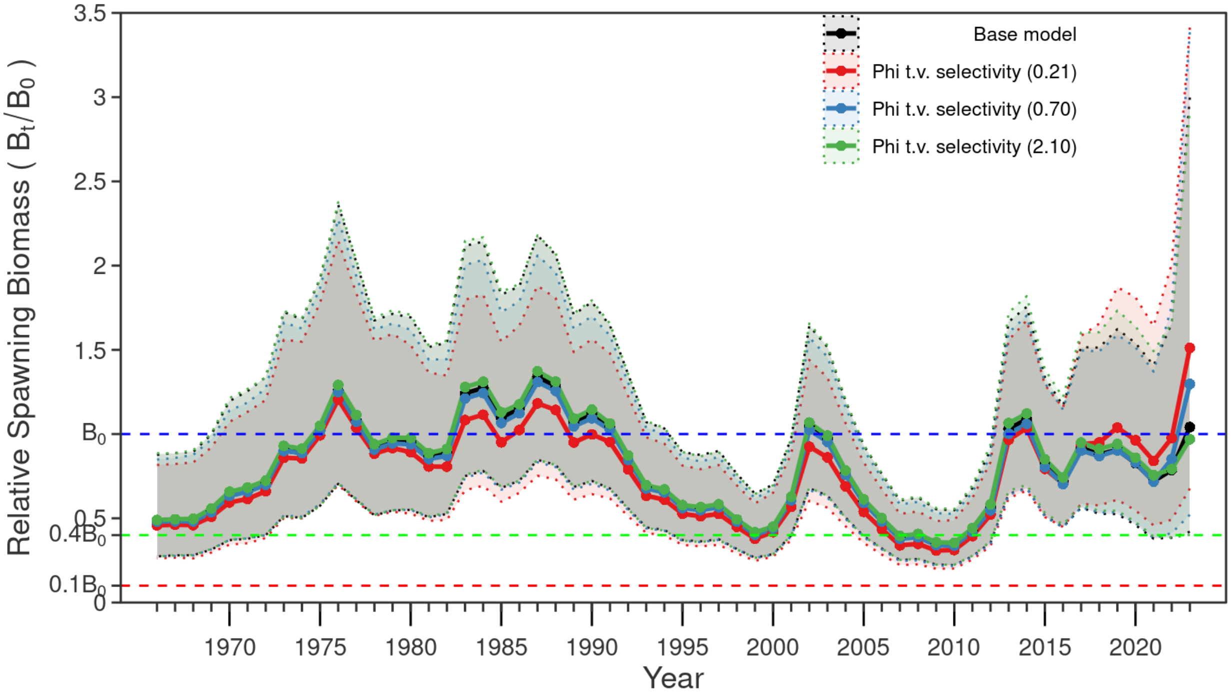


Figure 48. MCMC estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

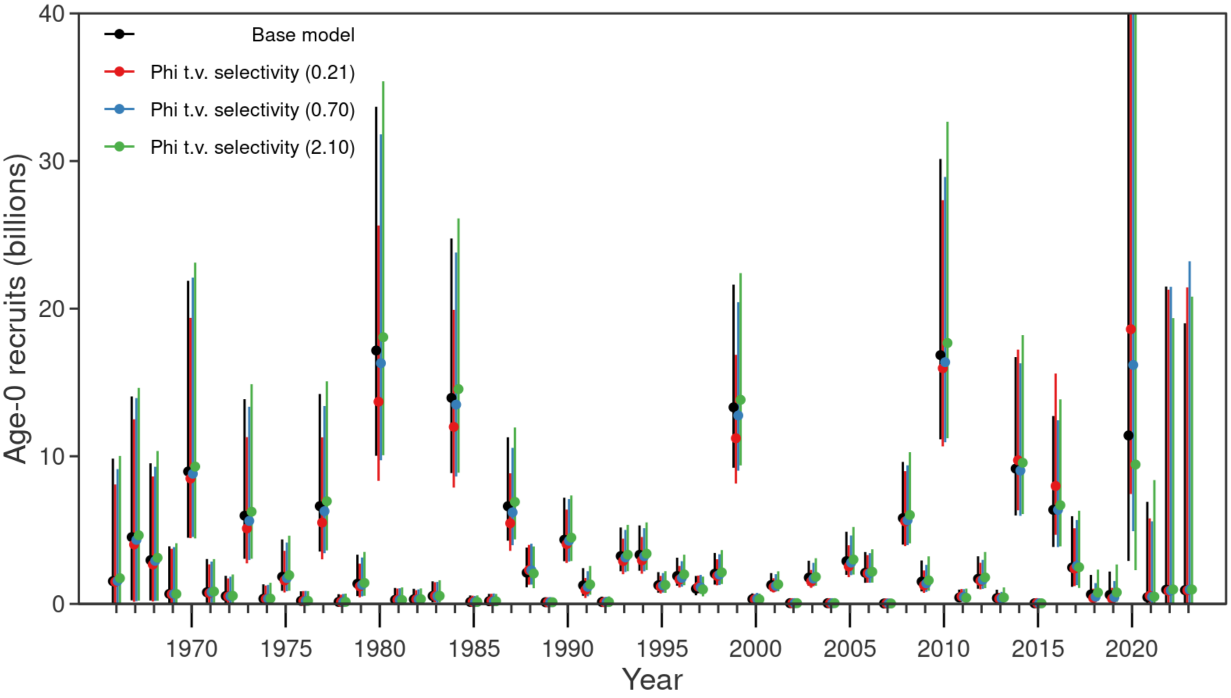


Figure 49. MCMC estimates of recruitment for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

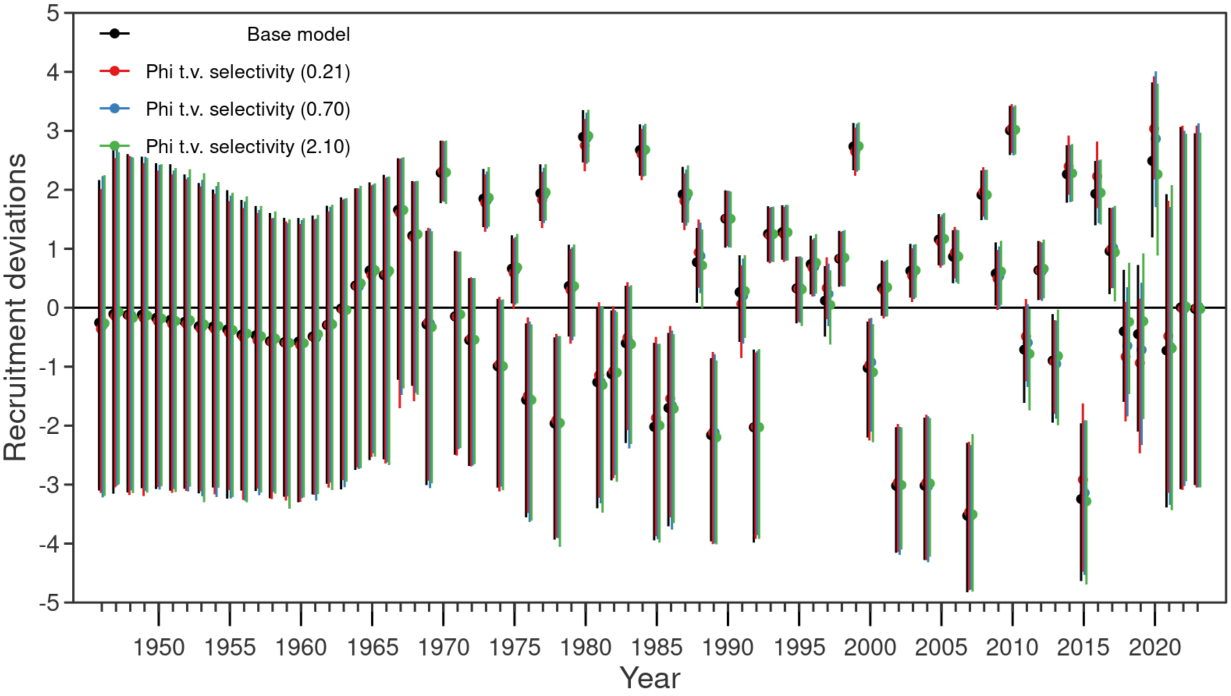


Figure 50. MCMC estimates of recruitment deviations for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

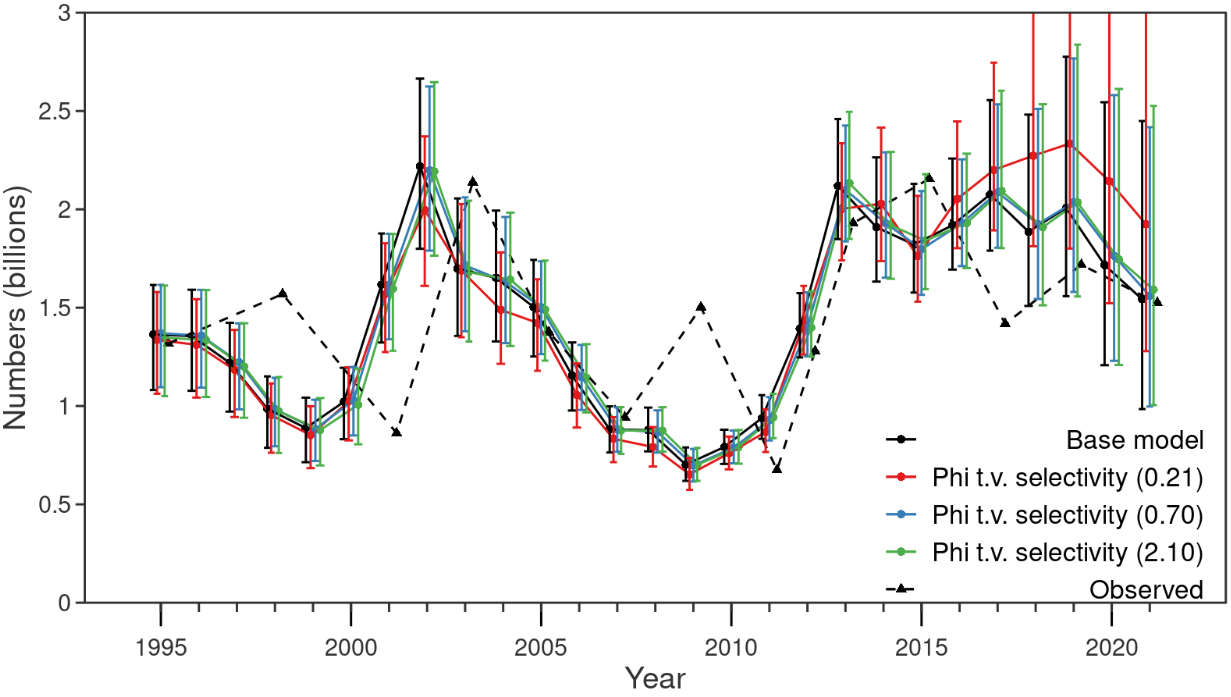


Figure 51. MCMC estimates of the fit to the survey index of age-2+ biomass for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

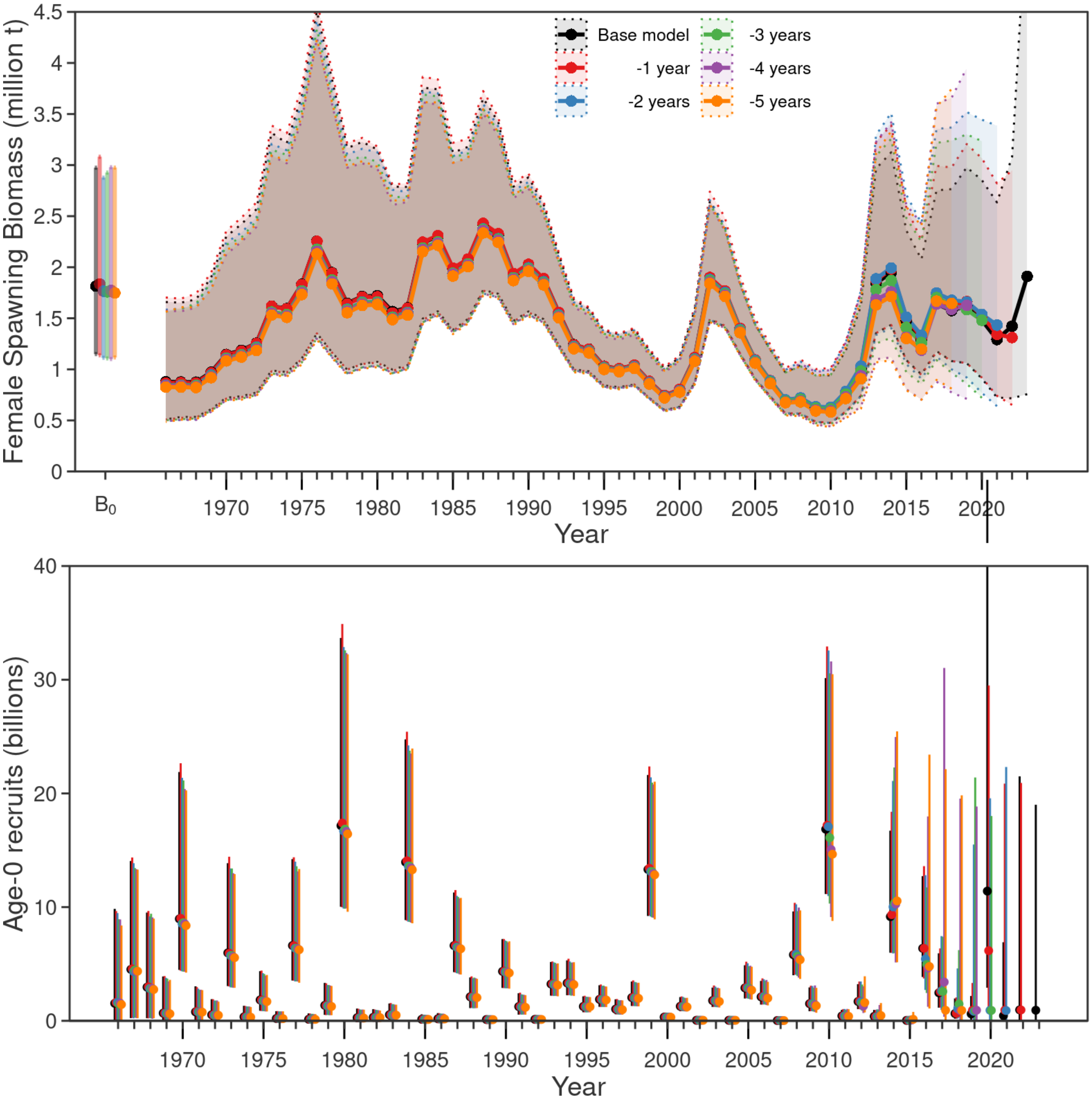


Figure 52. Estimates of spawning biomass at the start of each year (top) and recruitment (bottom) for the base model and 5-year retrospective runs (based on MCMC model runs).

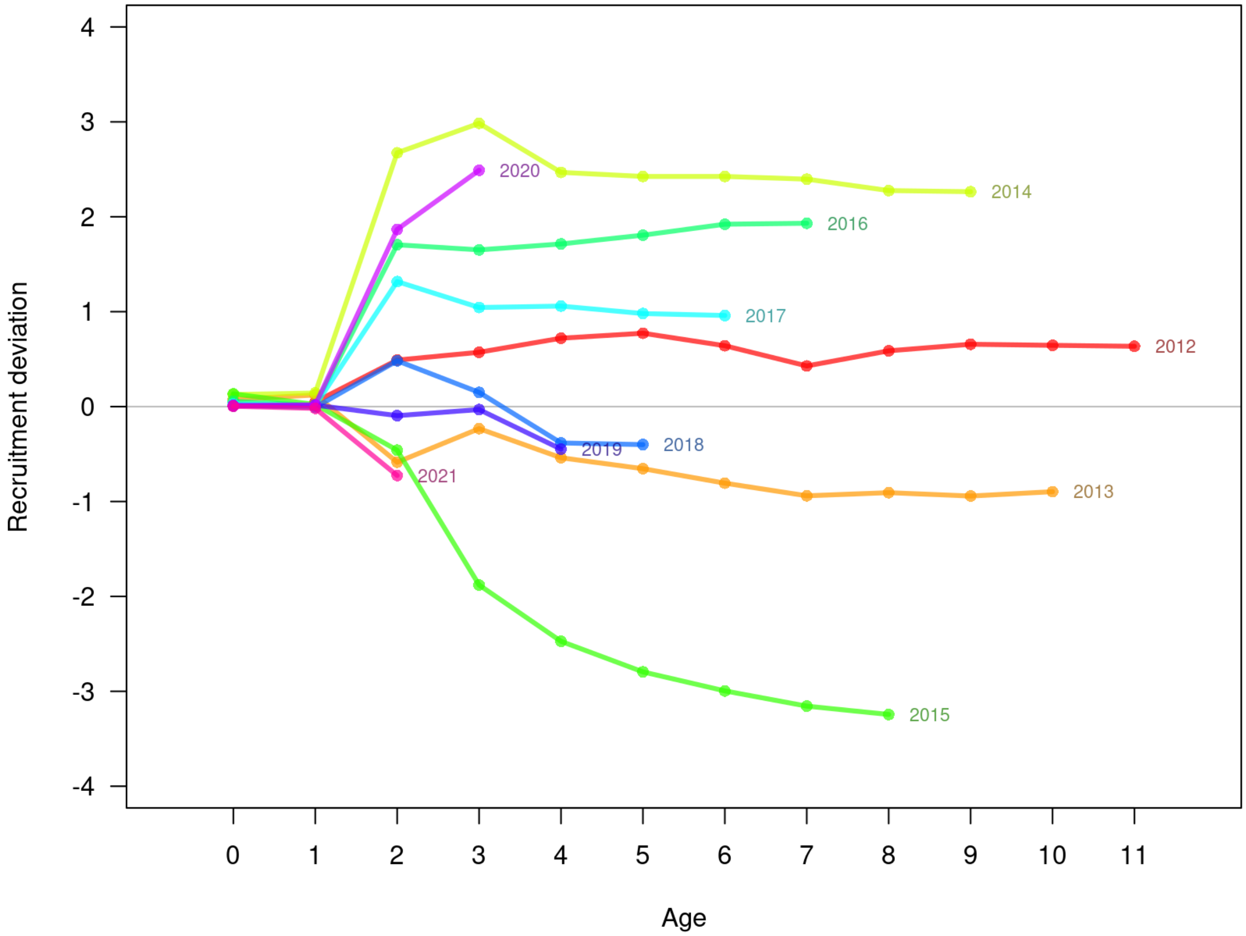


Figure 53. Retrospective analysis of recruitment deviations from MCMC models over the last 10 years. Recruitment deviations are the median log-scale differences between recruitment estimated by the model and expected recruitment from the spawner-recruit relationship. Age-0 recruitment deviations are non-zero because MCMC allows for sampling from the full log-normal distribution. Lines represent estimated recruitment deviations for cohorts born from 2012 to 2021, with cohort birth year marked at the right of each color-coded line. For example, the right-most point for the 2015 cohort shows the cohort at age-8 (i.e., at the start of 2023, which represents the base model and includes data through 2022). The next point to the left is the 2015 cohort at age-7, calculated by removing one year of data (so includes data up to 2021). Thus, models are fit to data available only up to the start of the year in which each cohort became a given age, such that the last year of data for a given point equals cohort birth year + cohort age −1.

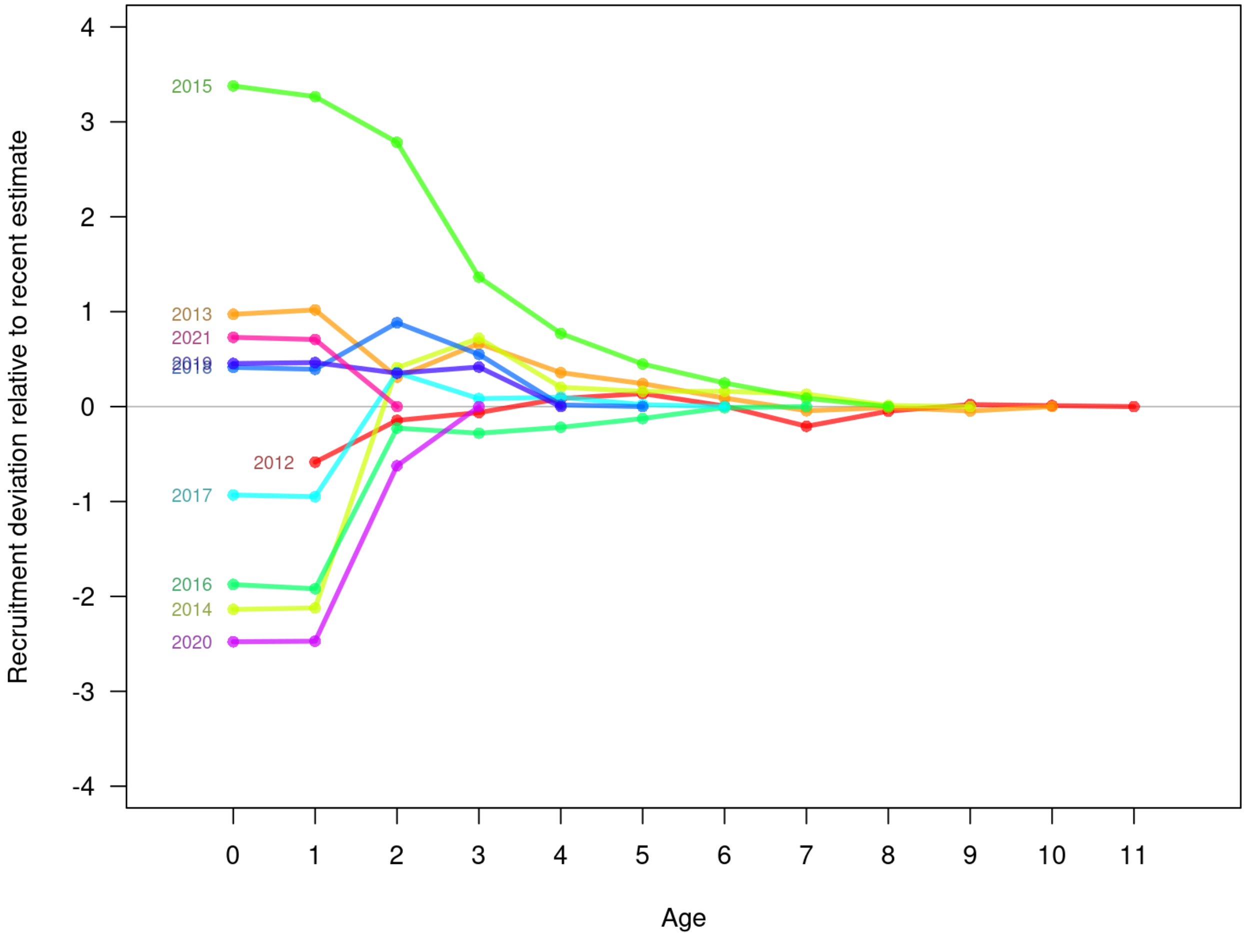


Figure 54. Retrospective recruitment estimates shown in Figure 53 scaled relative to the most recent estimate of the strength of each cohort.

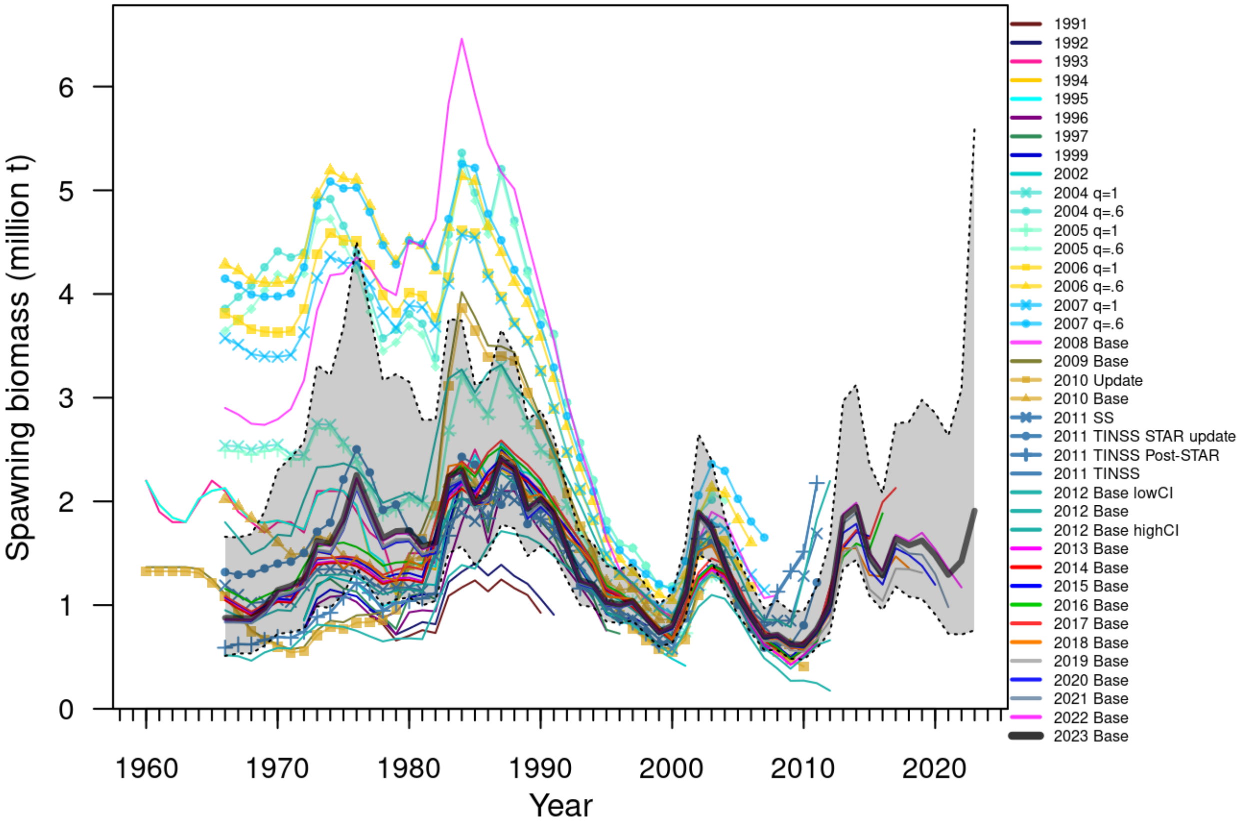


Figure 55. Summary of historical Pacific Hake assessment estimates of spawning biomass. Estimates are MLEs or MCMC medians depending on the model structure. Shading represents the 95% credible interval from the 2023 base model.

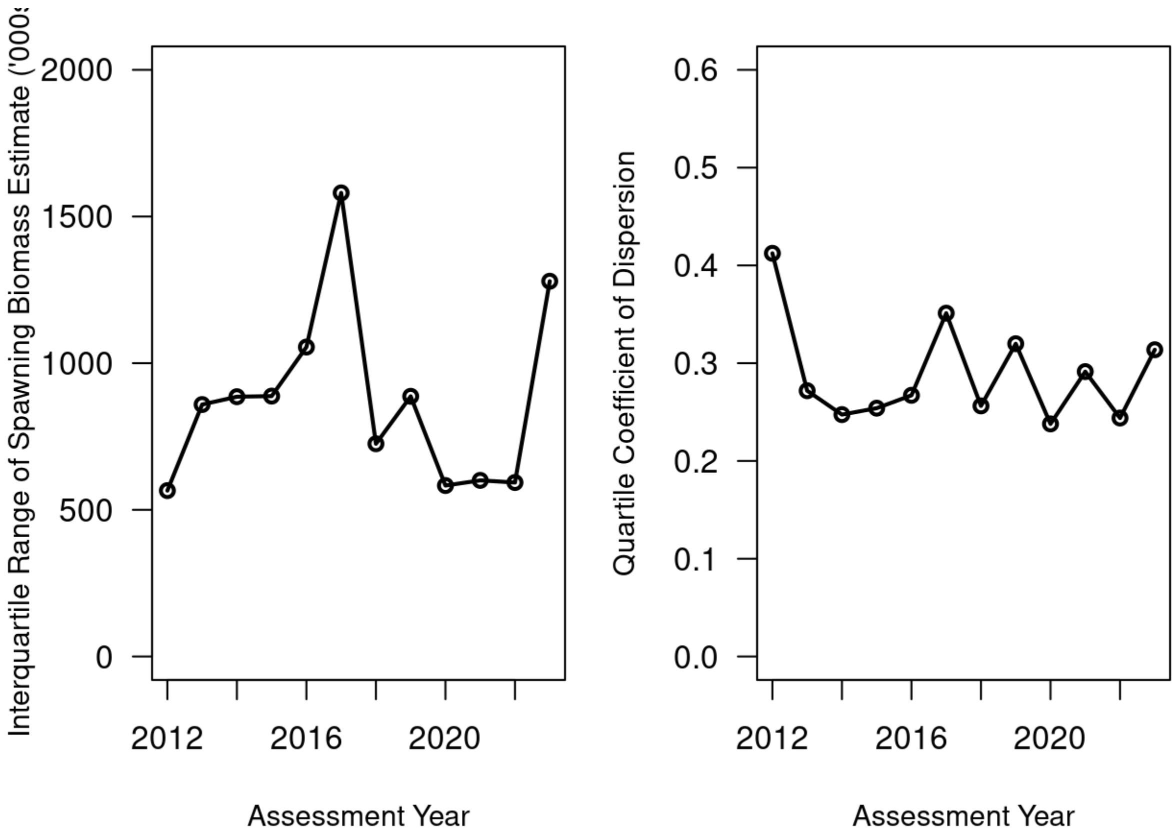


Figure 56. Comparison of absolute (left panel) and relative (right panel) variability associated with terminal year estimates of spawning biomass from Pacific Hake stock assessments dating back to 2012 (note: terminal year is the same as assessment year). The interquartile range specifies the width from quartile 1 (Q1: 25th percentile) to quartile 3 (Q3: 75th percentile) of terminal year spawning biomass from the posterior distribution and is a measure of absolute variability (similar to credible intervals). The quartile coefficient of dispersion is a relative measure of variability that can be compared across different data sets (similar to the coefficient of variation but less susceptible to outliers) and is calculated as $(Q3-Q1)/(Q1+Q3)$.

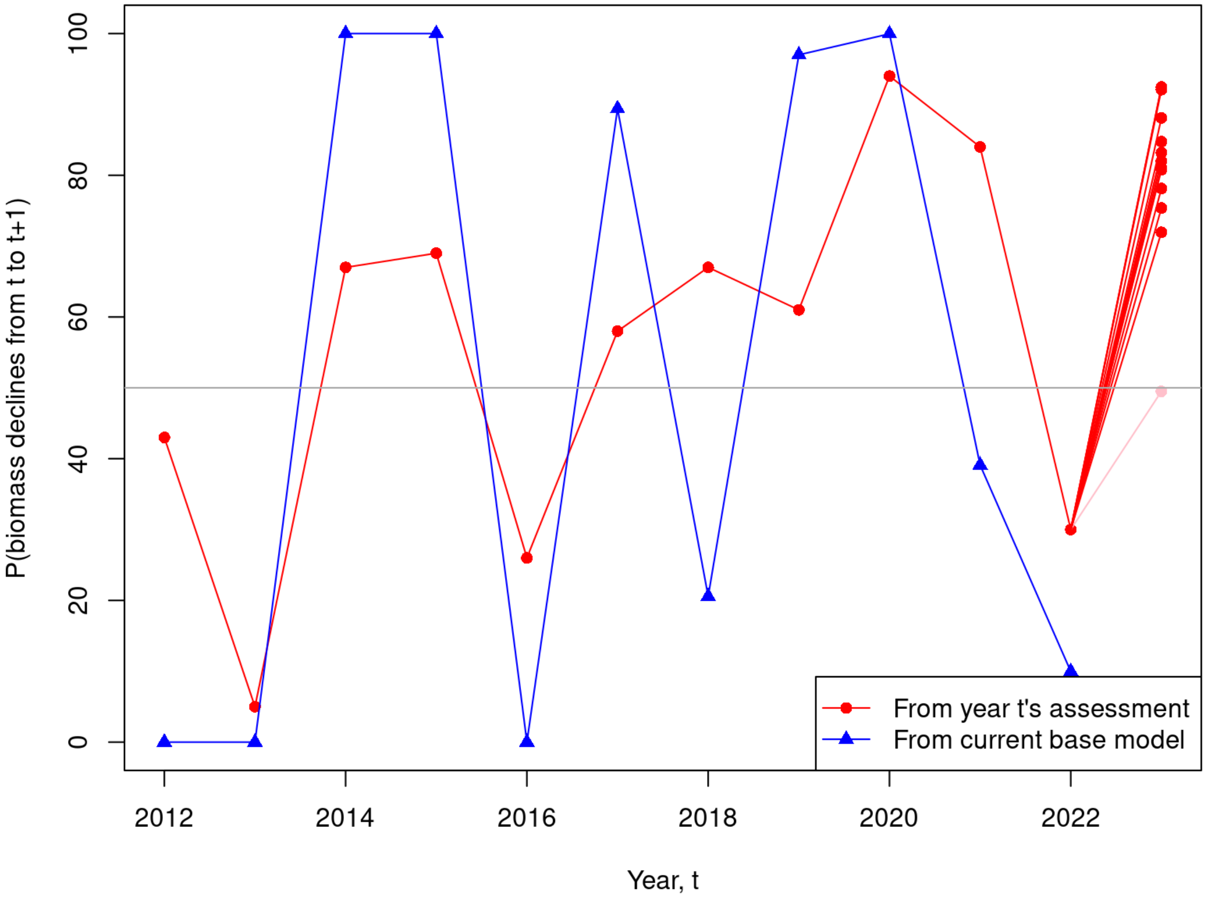


Figure 57. For each year t, $P(B_{t+1} < B_t)$ is the probability that the spawning biomass at the start of $t+1$ is below that at the start of t. It is calculated in two ways. Red circles: the probability is taken from year t's stock assessment document, from the row in the decision table corresponding to the consequent catch in year t (with interpolation if necessary). Blue squares: the probability is calculated using the current 2023 base model. The grey horizontal line is the 50% value. For each year except 2018 and 2021, both probabilities lie on the same side of the grey line, indicating that each year's assessment model has almost always 'correctly' estimated an increase or decrease the subsequent year's biomass. For the 2023 assessment the probabilities are shown for all catch alternatives for 2023, as described in Table 28, with 0 t shown in pink.

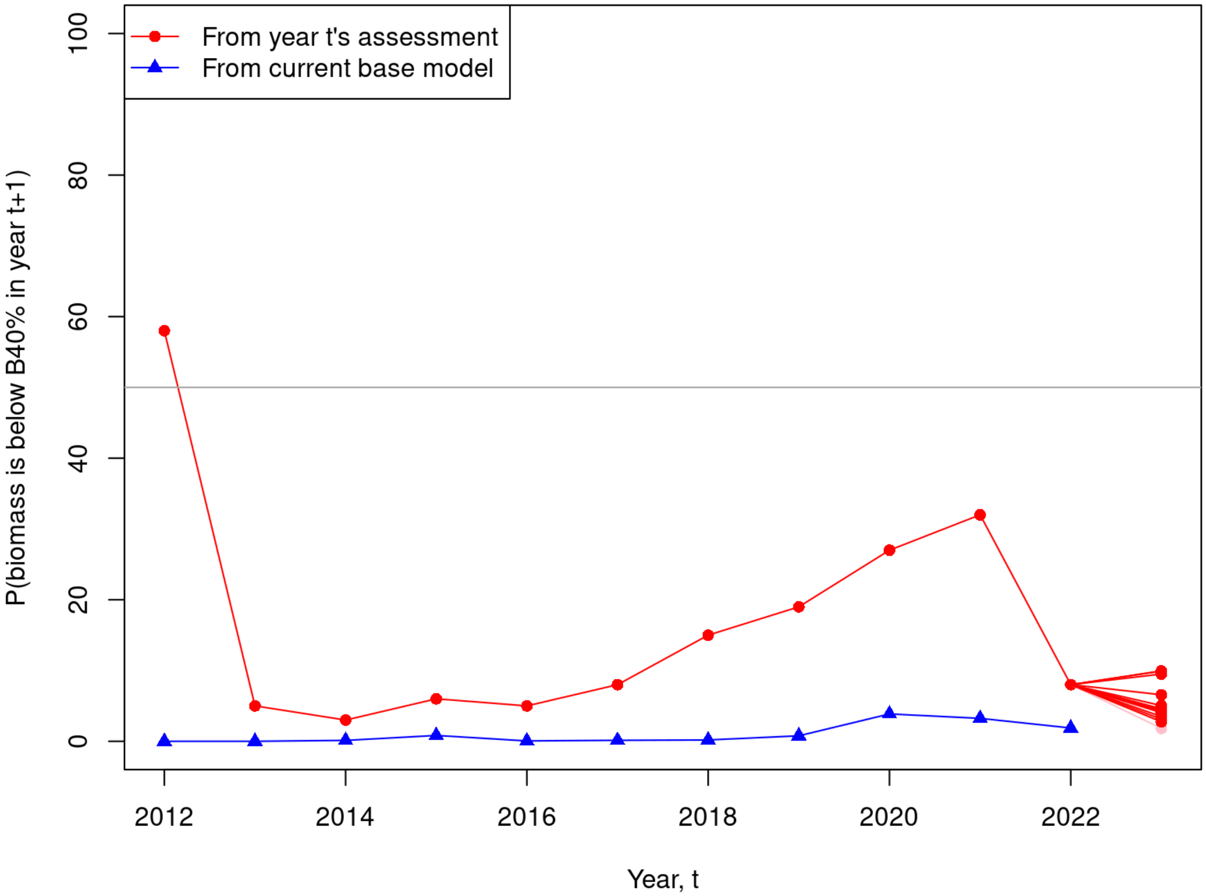


Figure 58. For each year t, $P(B_{t+1} < B_{40\%})$ is the probability that the spawning biomass at the start of $t+1$ is below $B_{40\%}$. The red circles and blue squares represent probabilities calculated analogously to Figure 57. The grey horizontal line is the 50% value. For each year except 2012, both probabilities lie on the same side of the grey line, indicating that each year's assessment model almost always 'correctly' estimated that the subsequent year's biomass will not fall below $B_{40\%}$. For the 2023 assessment the probabilities are shown for all catch alternatives for 2023, as described in Table 28, with 0 t shown in pink.

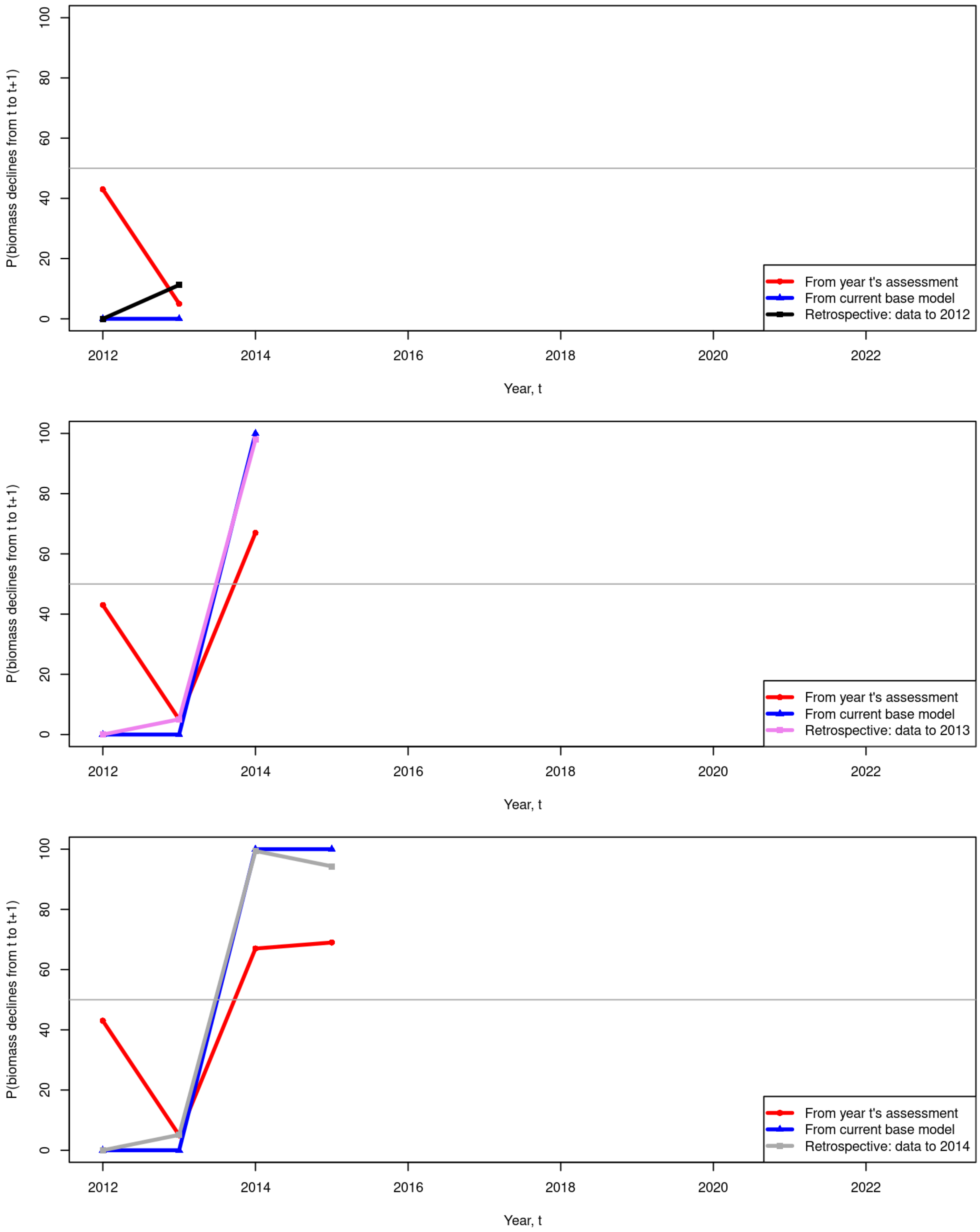


Figure 59. Retrospective versions of Figure 57. For each panel, the current base model is run using only data up to (and including) the year shown (i.e. a retrospective analysis) – data to 2012 would equate to doing an assessment at the start of 2013. Results are shown for further retrospective years in Figures 60, 61 and 62, and in a single panel in Figure 63.

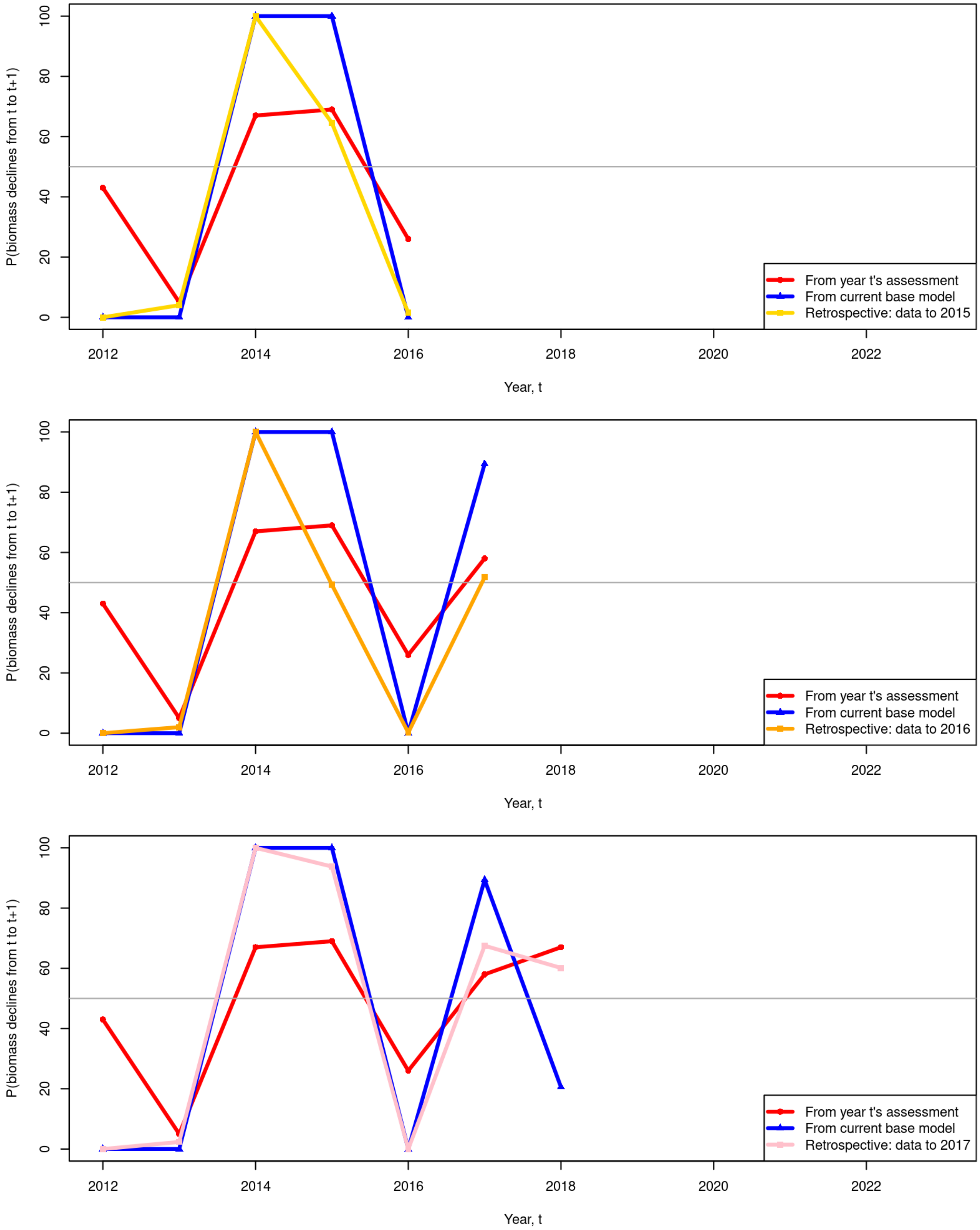


Figure 60. As for Figure 59 for further retrospective years.

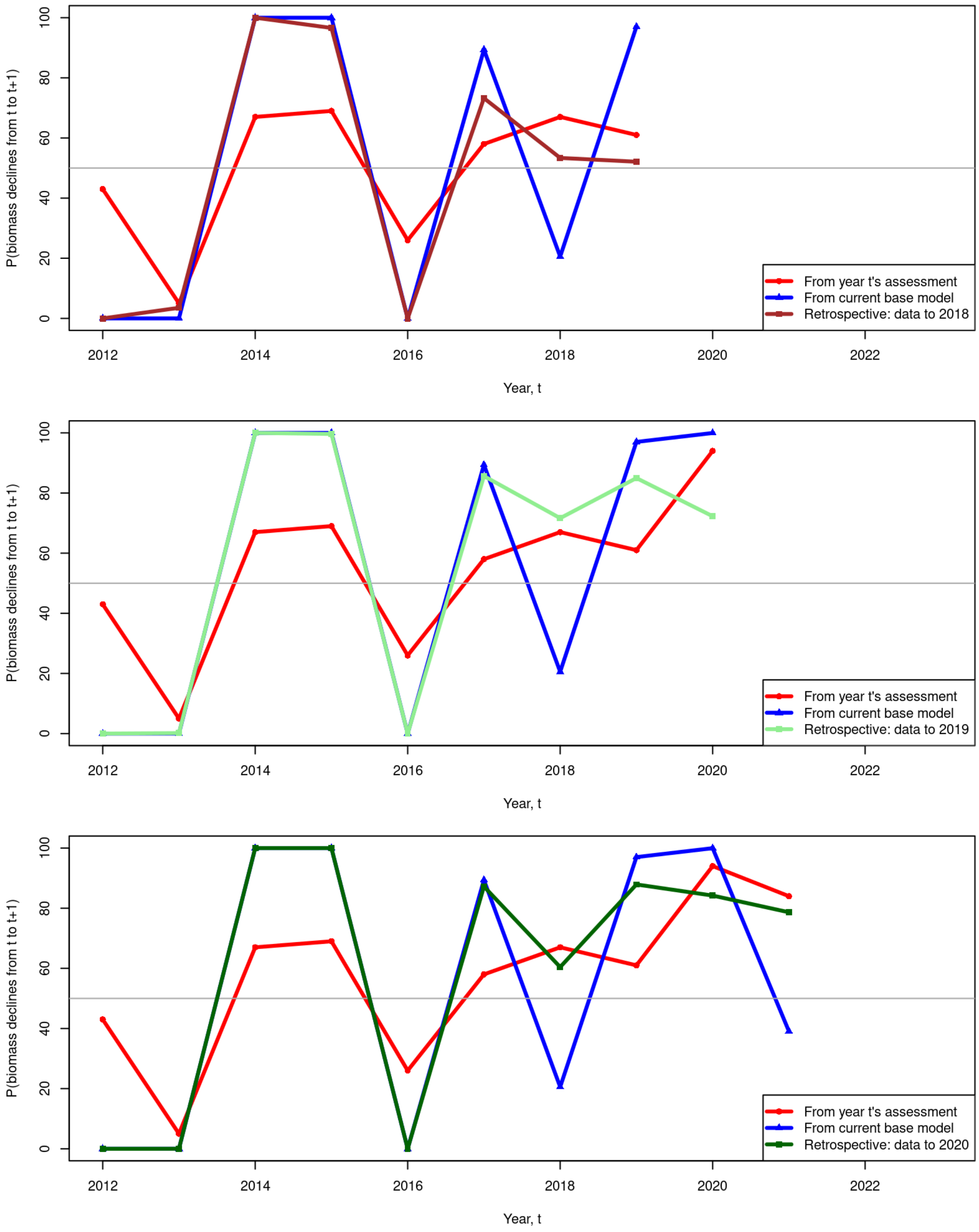


Figure 61. As for Figure 59 for further retrospective years.

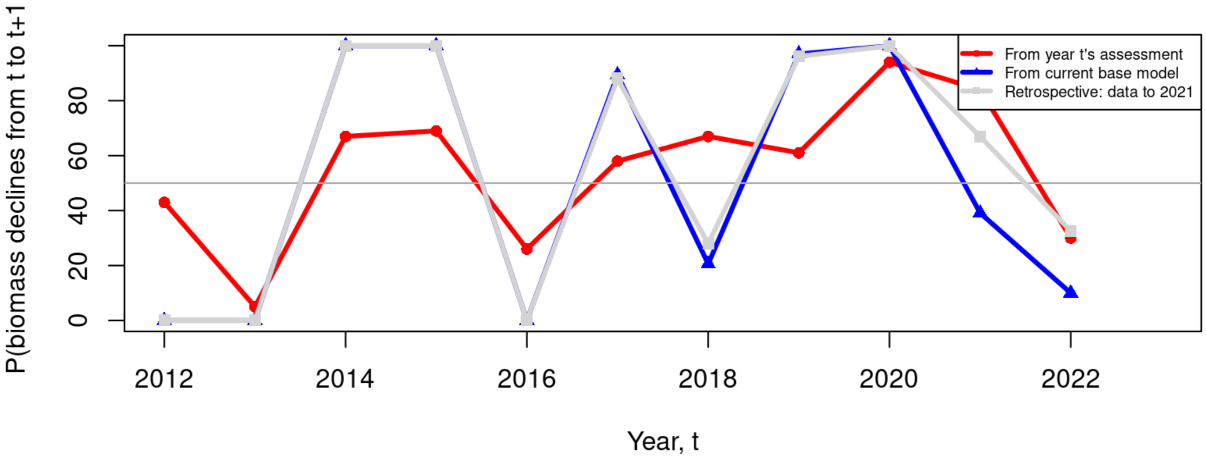


Figure 62. As for Figure 59 for the final retrospective year.

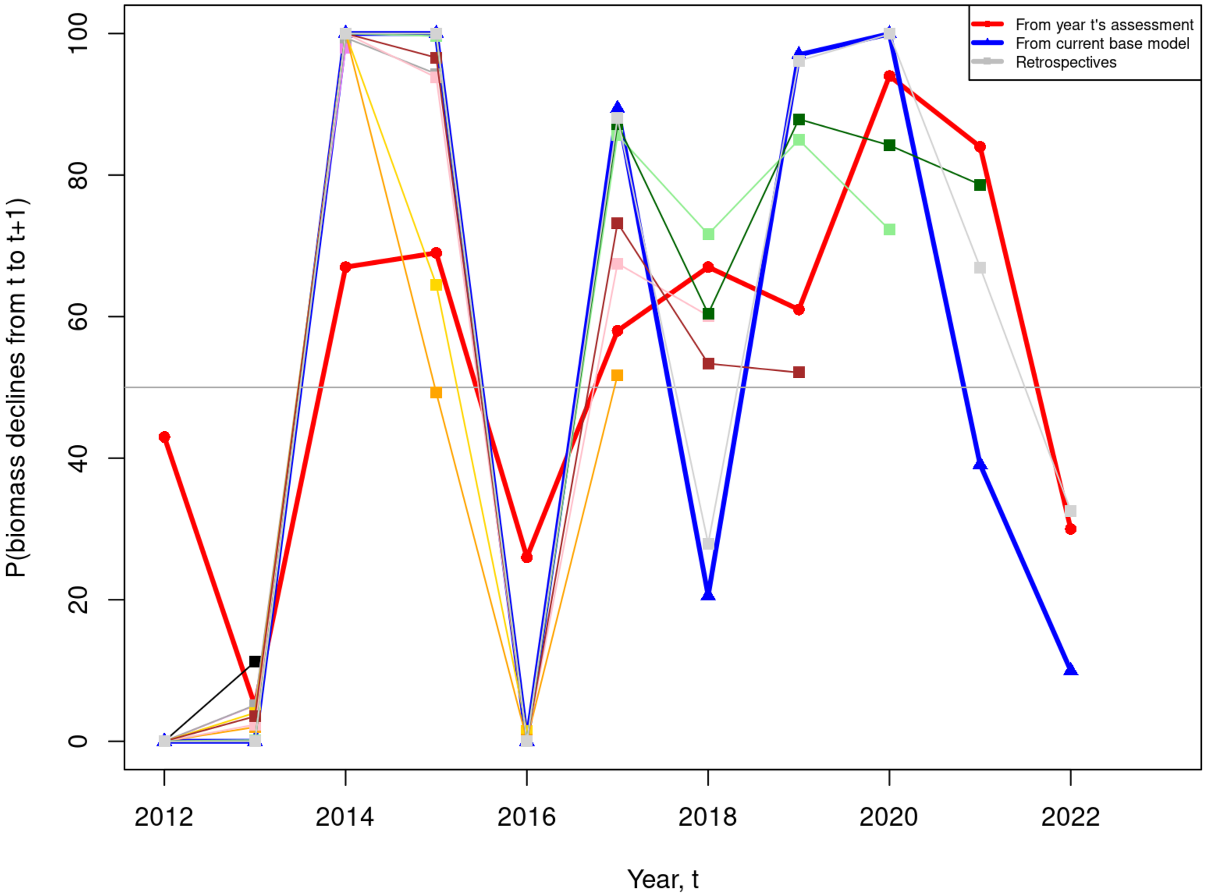


Figure 63. Retrospective results of Figures 59–62 shown in a single panel.

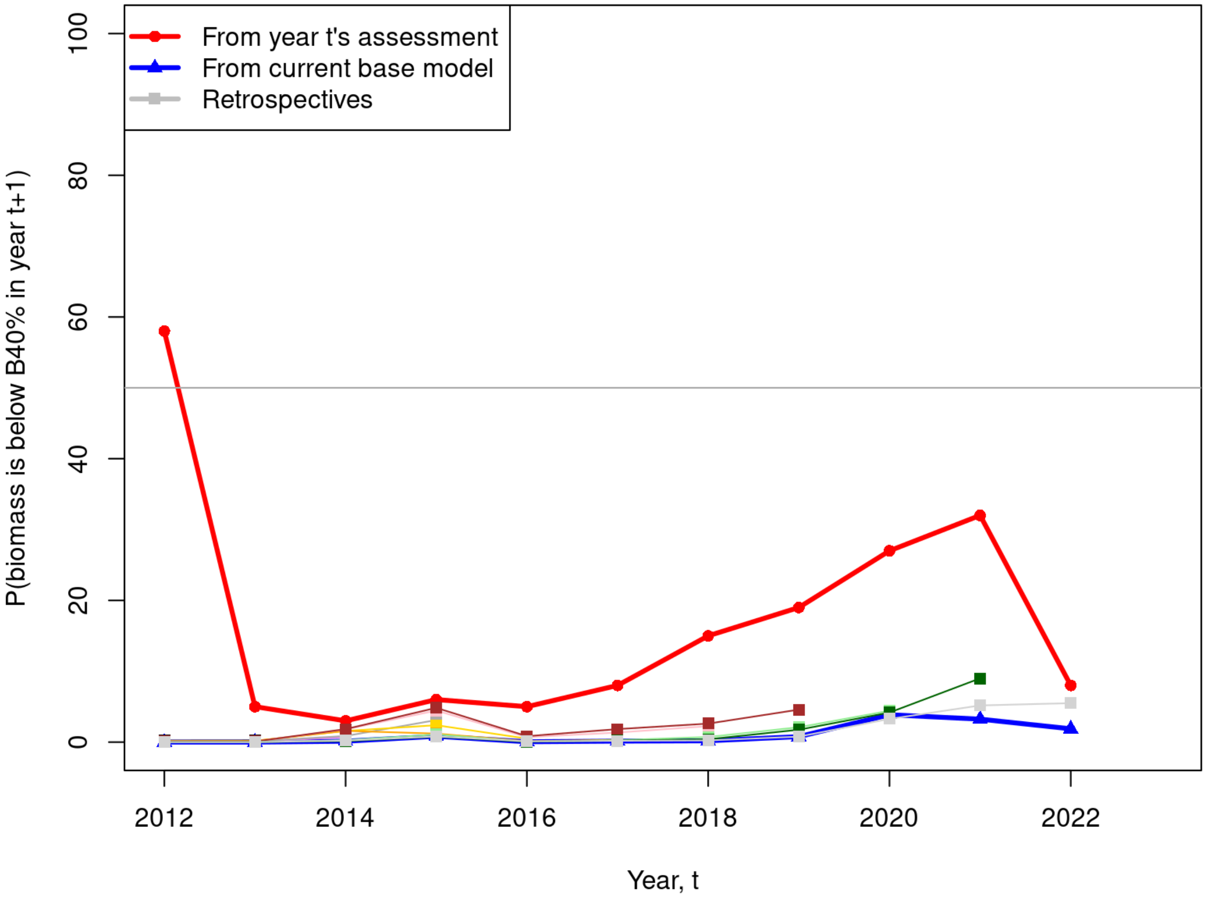


Figure 64. Retrospective results of Figure 58 for $P(B_{t+1} < B_{40\%})$ for each year t.

A BASE MODEL MCMC DIAGNOSTICS

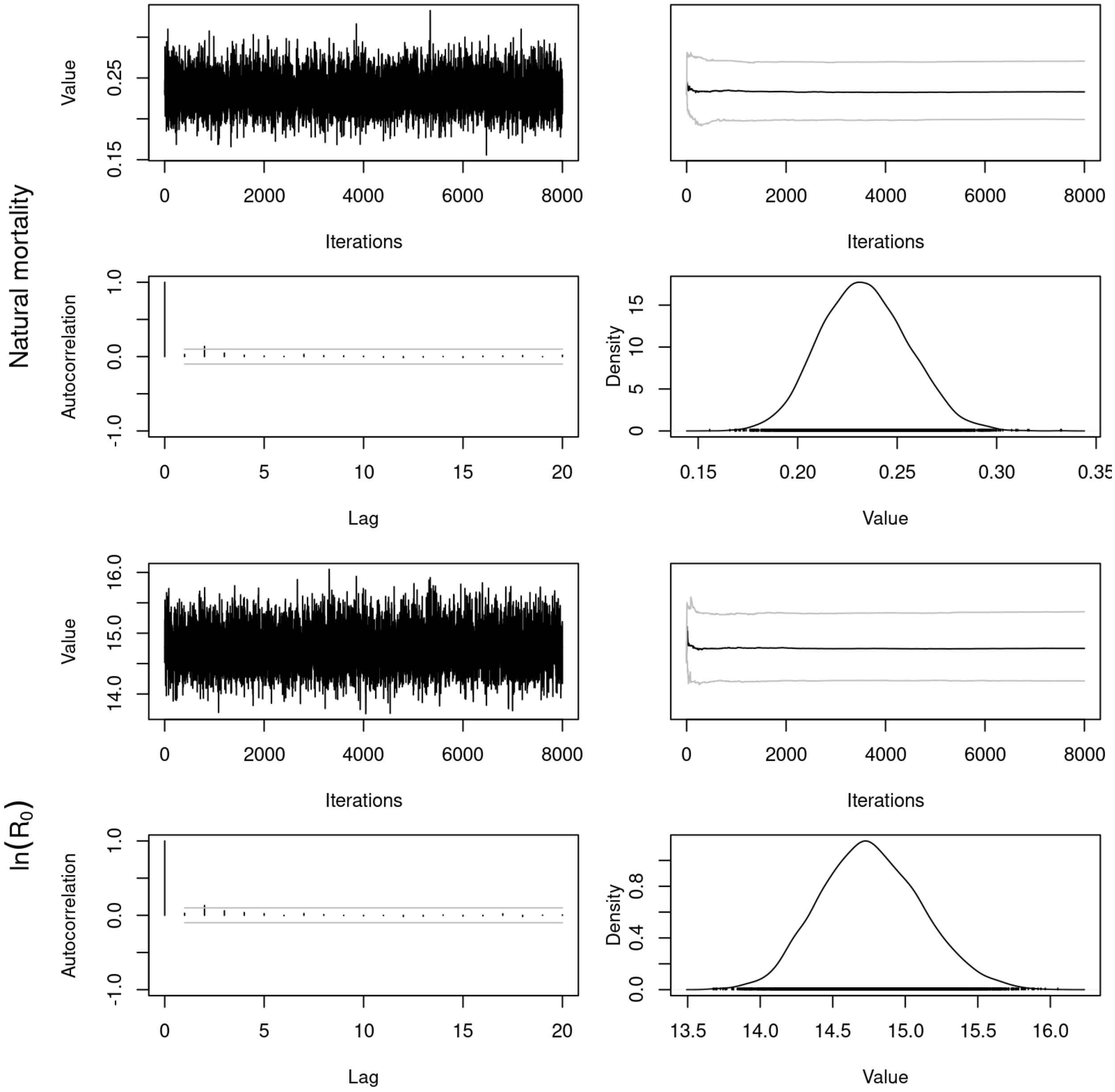


Figure A.1. Summary of Markov chain Monte Carlo diagnostics for natural mortality (upper panels) and the natural log of mean unfished equilibrium recruitment (ln(R_0); lower panels) in the base model. Top sub-panels show the trace of the sampled values across iterations (absolute values, top left; cumulative running mean with 5th and 95th percentiles, top right). The lower left sub-panel indicates the autocorrelation present in the chain at different lag times (i.e., distance between samples in the chain), and the lower right sub-panel shows the distribution of the values in the chain (i.e., the marginal density from a smoothed histogram of values in the trace plot).

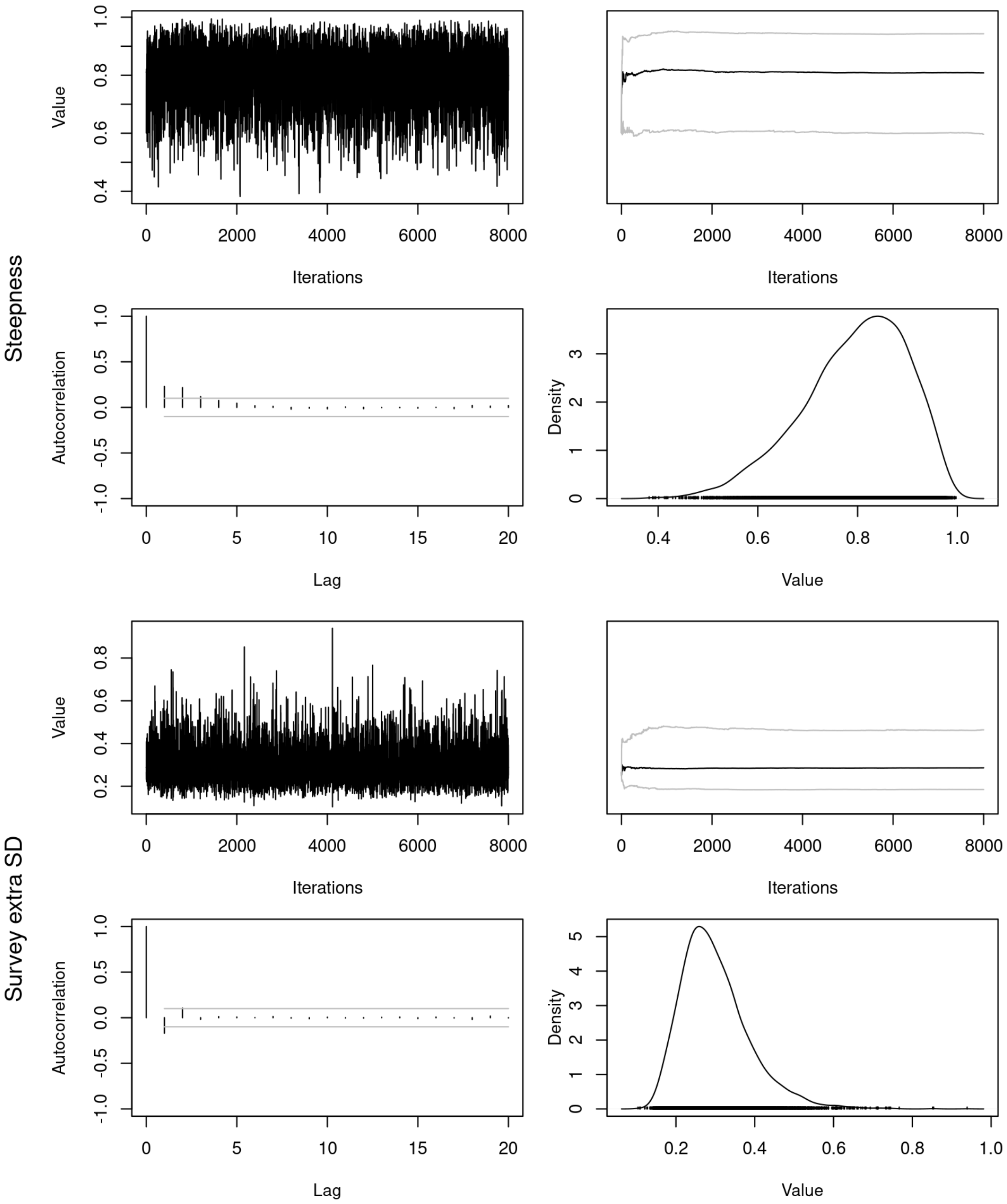


Figure A.2. Summary of Markov chain Monte Carlo diagnostics for steepness (upper panels) and the additional standard deviation (SD) in the biomass index (lower panels) in the base model. Sub-panel descriptions as in Figure A.1.

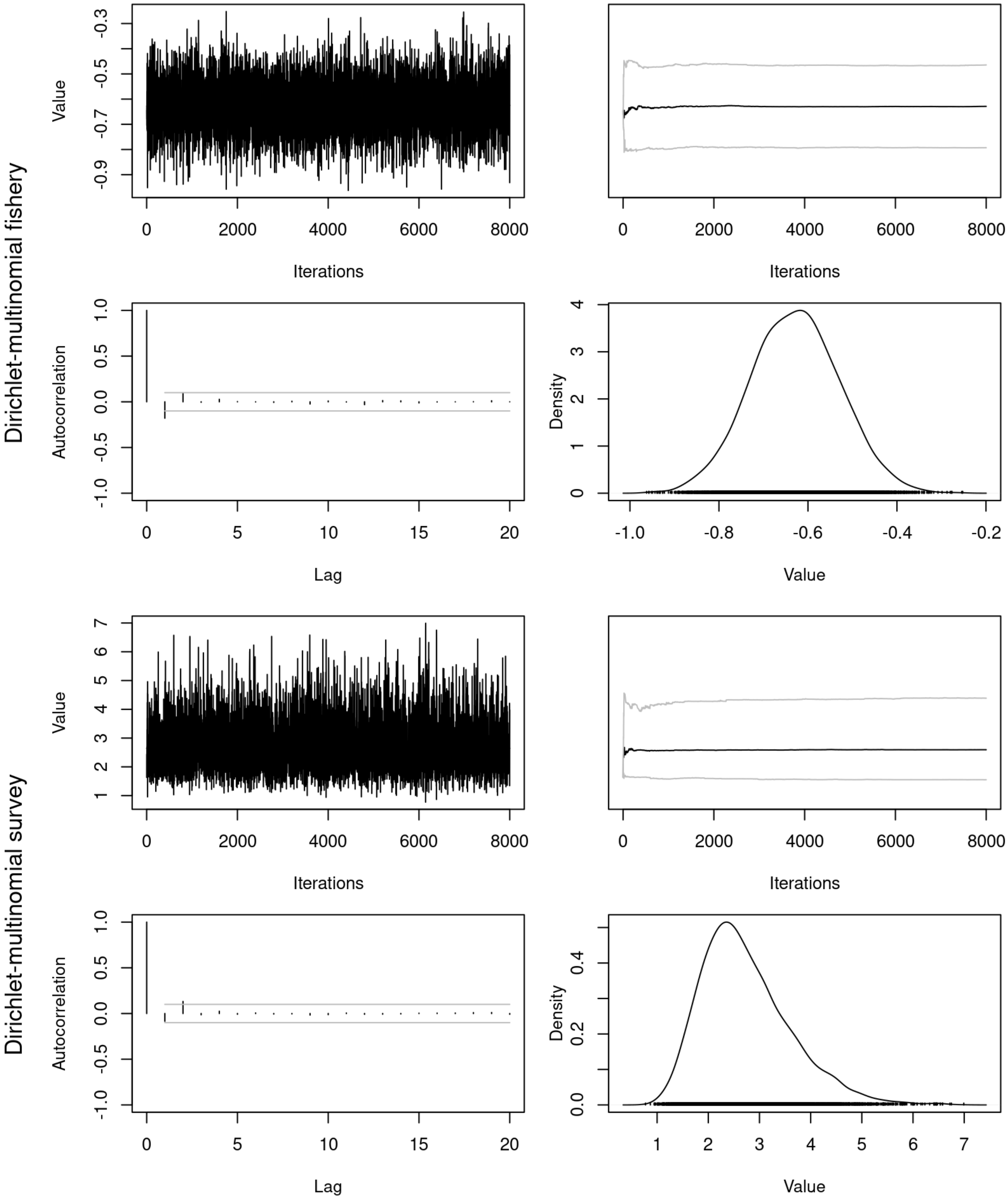


Figure A.3. Summary of Markov chain Monte Carlo diagnostics for the Dirichlet-multinomial age-composition parameters for the fishery (θ_{fish}, upper panels) and the survey (θ_{surv}, lower panels) in the base model. Sub-panel descriptions as in Figure A.1.

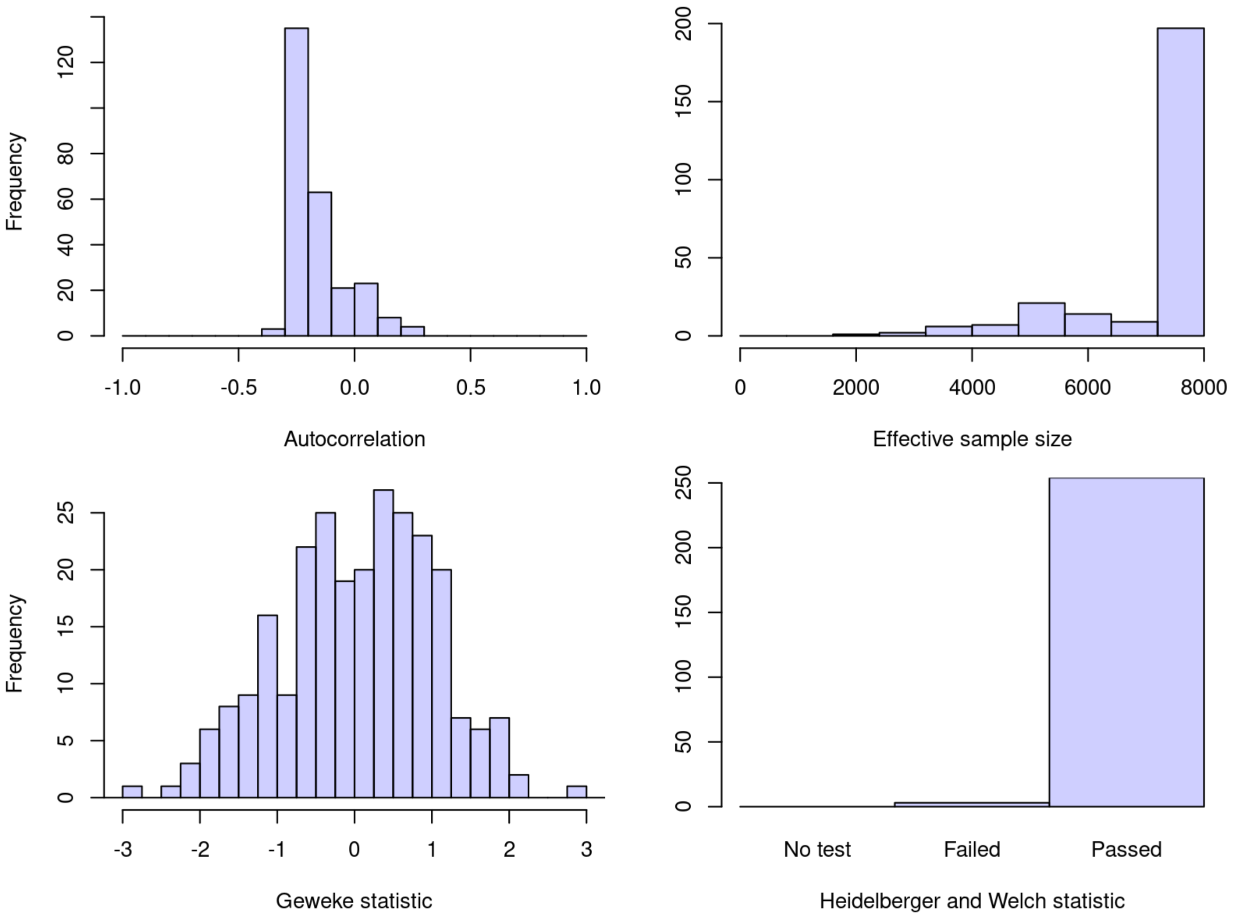


Figure A.4. Summary histograms of MCMC diagnostics for all base model parameters. The level of autocorrelation in the chain (distribution across lag times, i.e., distance between samples in the chain, shown in the top left panel) influences the effective sample size (top right panel) used to estimate posterior distributions. The Geweke statistic (lower left panel) tests for equality between means located in the first part of the chain against means in the last part of the chain. The Heidelberger and Welch statistic (lower right panel) tests if the sampled values come from a stationary distribution by comparing different sections of the chain.

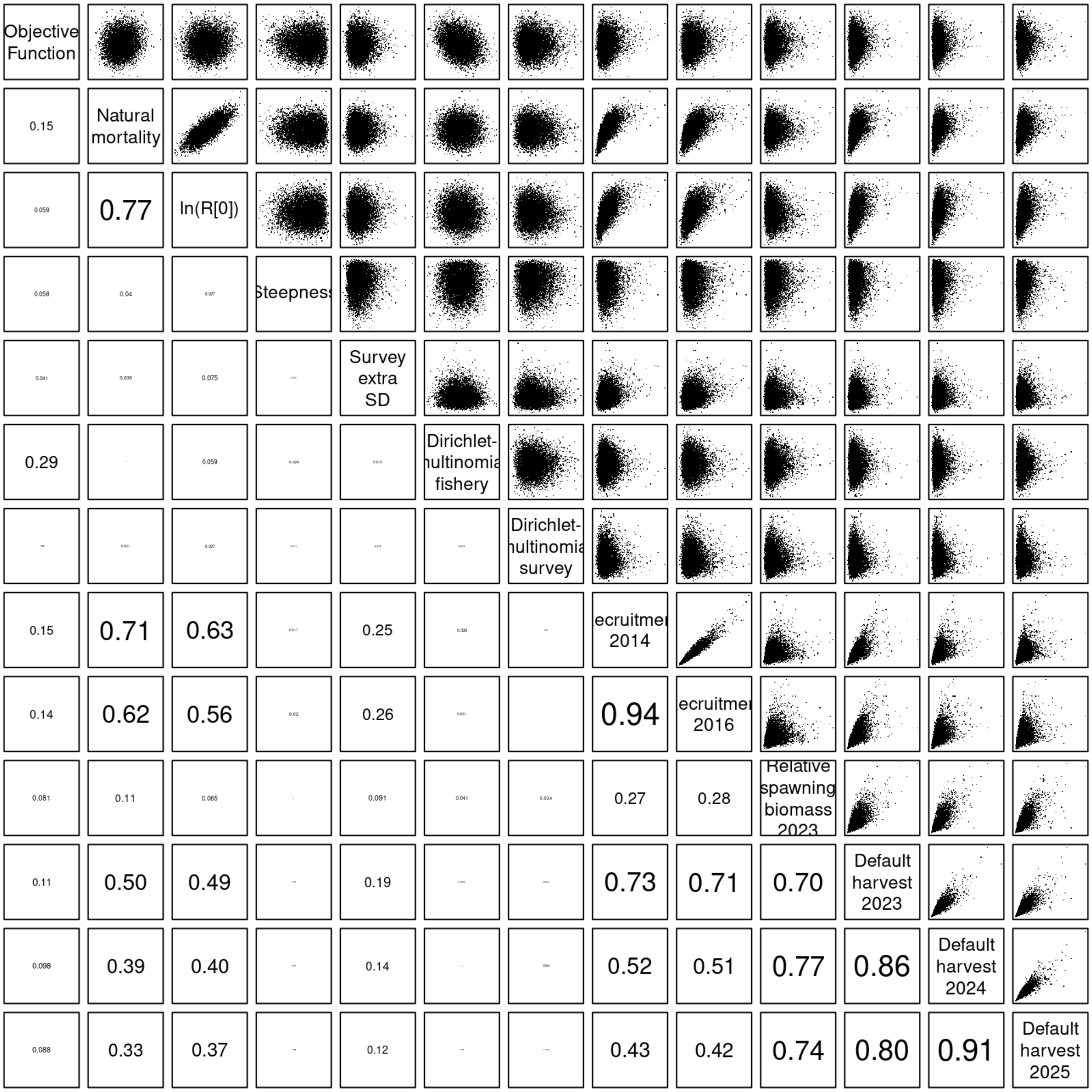


Figure A.5. Posterior correlations among the objective function which is minimized during model fitting, key base-model parameters, and derived quantities. Numbers refer to the absolute correlation coefficients, with font size proportional to the square root of the coefficient.

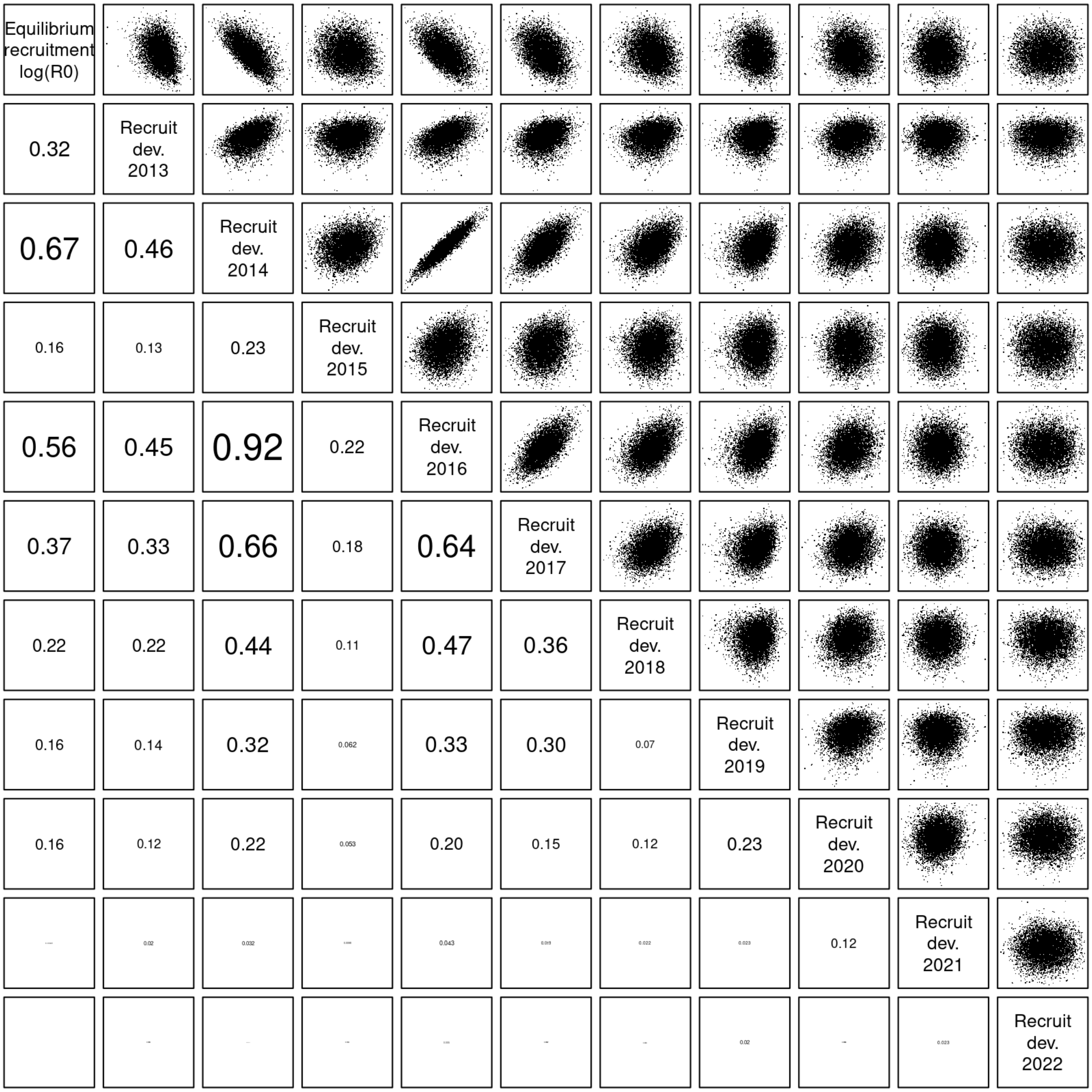


Figure A.6. Posterior correlations among recruitment deviations from recent years and mean unfished equilibrium recruitment. Numbers refer to the absolute correlation coefficients, with font size proportional to the square root of the coefficient.

B SCIENTIFIC REVIEW GROUP (SRG) REQUESTS FROM 2023 MEETING

This appendix will summarize results produced in response to any Scientific Review Group requests made during the meeting to be held from 7th to 10th February 2023.

C GLOSSARY OF TERMS AND ACRONYMS USED IN THIS DOCUMENT

40:10 adjustment: a reduction in the overall total allowable catch that is triggered when the female spawning biomass falls below 40% of its unfished equilibrium level. This adjustment reduces the total allowable catch on a straight-line basis from the 40% level such that the total allowable catch would equal zero when the biomass is at 10% of its unfished equilibrium level. This is one component of the default harvest policy (see below).

ABC: Acceptable biological catch. See below.

Acceptable biological catch (ABC): The acceptable biological catch is a scientific calculation of the sustainable harvest level of a fishery used historically to set the upper limit for fishery removals by the Pacific Fishery Management Council. It is calculated by applying the estimated (or proxy) harvest rate that produces maximum sustainable yield (MSY, see below) to the estimated exploitable biomass (the portion of the fish population that can be harvested). For Pacific Hake, the calculation of the acceptable biological catch and application of the 40:10 adjustment is now replaced with the default harvest rate and the Total Allowable Catch.

Adjusted: A term used to describe Total Allowable Catch or allocations that account for carryovers of uncaught catch from previous years (see Carryover below).

Advisory Panel (AP): The advisory panel on Pacific Hake established by the Agreement.

Agreement (“Treaty”): The Agreement between the government of the United States and the government of Canada on Pacific Hake, signed at Seattle, Washington, on November 21, 2003, and entered into force June 25, 2008.

AFSC: Alaska Fisheries Science Center (National Marine Fisheries Service).

B_0: The unfished equilibrium female spawning biomass.

$B_{10\%}$: The level of female spawning biomass corresponding to 10% of unfished equilibrium female spawning biomass, i.e., $B_{10\%} = 0.1B_0$. This is the level below which the calculated TAC is set to 0, based on the 40:10 adjustment (see above).

$B_{40\%}$: The level of female spawning biomass corresponding to 40% of unfished equilibrium female spawning biomass, i.e., $B_{40\%} = 0.4B_0$. This is the level below which the calculated TAC is decreased from the value associated with $F_{\text{SPR}=40\%}$, based on the 40:10 adjustment (see above).

B_{MSY}: The estimated female spawning biomass which theoretically would produce the maximum sustainable yield (MSY) under equilibrium fishing conditions (constant fishing and average recruitment in every year). Also see $B_{40\%}$ (above).

Backscatter: The scattering by a target back in the direction of an acoustic source. Specifically, the Nautical Area Scattering Coefficient (a measure of scattering per area) is frequently referred to as backscatter.

California Current Ecosystem: The waters of the continental shelf and slope off the west coast of North America, commonly referring to the area from central California to southern British Columbia.

Carryover: If at the end of the year, there are unharvested allocations, then there are provisions for an amount of these fish to be carried over into the next year's allocation process. The Agreement states that "[I]f, in any year, a Party's catch is less than its individual TAC, an amount equal to the shortfall shall be added to its individual TAC in the following year, unless otherwise recommended by the JMC. Adjustments under this sub-paragraph shall in no case exceed 15 percent of a Party's unadjusted individual TAC for the year in which the shortfall occurred."

Catchability (q): The parameter defining the proportionality between a relative index of stock abundance (often a fishery-independent survey) and the estimated stock abundance available to that survey (as modified by selectivity) in the assessment model.

Catch-per-unit-effort (CPUE): A raw or (frequently) standardized and model-based metric of fishing success based on the catch and relative effort expended to generate that catch. Catch-per-unit-effort is often used as an index of stock abundance in the absence of fishery-independent indices and/or where the two are believed to be proportional.

Catch target: A general term used to describe the catch value used for management. Depending on the context, this may be a limit rather than a target and may be equal to a TAC, an ABC, the median result of applying the default harvest policy, or some other number. The JTC welcomes input from the JMC on the best terminology to use for these quantities.

Closed-loop simulation: A subset of an MSE that iteratively simulates a population using an operating model, generates data from that population and passes it to an estimation model, uses the estimation model and a management strategy to provide management advice, which then feeds back into the operating model to simulate an additional fixed set of time before repeating this process.

Cohort: A group of fish born in the same year. Also see recruitment and year-class.

Constant catch: A catch scenario used for forecasting in which the same catch is used in successive years.

CPUE: Catch-per-unit-effort (see above).

CV: Coefficient of variation. A measure of uncertainty defined as the standard deviation (SD, see below) divided by the mean.

Default harvest policy (rate): The application of $F_{\text{SPR}=40\%}$ (see below) with the 40:10 adjustment (see above). Having considered any advice provided by the JTC, SRG or AP, the JMC may recommend a different harvest rate if the scientific evidence demonstrates that a different rate is necessary to sustain the offshore Pacific Hake resource.

Depletion: Term used for relative spawning biomass (see below) prior to the 2015 stock assessment. “Relative depletion” was also used.

DFO: Department of Fisheries and Oceans (Canada). See Fisheries and Oceans Canada.

El Niño: Abnormally warm ocean climate conditions in the California Current Ecosystem (see above) as a result of broad changes in the Eastern Pacific Ocean across the eastern coast of Latin America (centered on Peru) often around the end of the calendar year.

Exploitation fraction: A metric of fishing intensity that represents the total annual catch divided by the estimated population biomass over a range of ages assumed to be vulnerable to the fishery (set to ages 2+ in this assessments; note that in previous assessments is was 3+). This value is not equivalent to the instantaneous rate of fishing mortality (see below) or the spawning potential ratio (SPR, see below).

F: Instantaneous rate of fishing mortality (or fishing mortality rate); see below.

$F_{\text{SPR}=40\%}$: The rate of fishing mortality estimated to give a spawning potential ratio (SPR, see below) of 40%. Therefore, by definition this satisfies

$$0.4 = \frac{\text{spawning biomass per recruit with } F_{\text{SPR}=40\%}}{\text{spawning biomass per recruit with no fishing}}, \tag{C.1}$$

and $\text{SPR}(F_{\text{SPR}=40\%}) = 40\%$. The 40% value is specified in the Agreement.

$F_{\text{SPR}=40\%}$–40:10 harvest policy: The default harvest policy (see above).

Female spawning biomass: The biomass of mature female fish at the beginning of the year. Sometimes abbreviated to spawning biomass.

Fisheries and Oceans Canada: Federal organization which delivers programs and services that support sustainable use and development of Canada’s waterways and aquatic resources.

Fishing intensity: A measure of the magnitude of fishing, defined for a fishing rate F as:

$$\text{fishing intensity for } F = 1 - \text{SPR}(F), \tag{C.2}$$

where $\text{SPR}(F)$ is the spawning potential ratio for the value of F accumulated over the entire year. It is often given as a percentage. Relative fishing intensity is the fishing intensity relative to that at the SPR target fishing rate $F_{\text{SPR}=40\%}$, where $F_{\text{SPR}=40\%}$ is the F that gives an SPR of 40% such that, by definition, $\text{SPR}(F_{\text{SPR}=40\%}) = 40\%$ (the target spawning ratio). Therefore

$$\text{relative fishing intensity for } F = \frac{1-\mathrm{SPR}(F)}{1-\mathrm{SPR}(F_{\mathrm{SPR}=40\%})} \tag{C.3}$$

$$= \frac{1-\mathrm{SPR}(F)}{1-0.4} \tag{C.4}$$

$$= \frac{1-\mathrm{SPR}(F)}{0.6}, \tag{C.5}$$

as shown in Figure C.1. For brevity we use $\mathrm{SPR}_{40\%} = \mathrm{SPR}(F_{\mathrm{SPR}=40\%})$ in the text. Although this simply equals 40%, it can be helpful to explicitly write:

$$\text{relative fishing intensity for } F = \frac{1-\mathrm{SPR}(F)}{1-\mathrm{SPR}_{40\%}}. \tag{C.6}$$

The calculation of relative fishing intensity is shown graphically in Figure C.2.

Fishing mortality rate, or instantaneous rate of fishing mortality (F): A metric of fishing intensity that is usually reported in relation to the most highly selected ages(s) or length(s), or occasionally as an average over an age range that is vulnerable to the fishery. Because it is an instantaneous rate operating simultaneously with natural mortality, it is not equivalent to exploitation fraction (or percent annual removal; see above) or the spawning potential ratio (SPR, see below).

F_{MSY}: The rate of fishing mortality estimated to produce the maximum sustainable yield (MSY) from the stock.

Harvest strategy: A formal system for managing a fishery that includes the elements shown in Figure A.1 of Taylor et al. (2015).

Harvest control rule: A process for determining an ABC from a stock assessment. Also see default harvest policy (above).

Joint Management Committee (JMC): The joint management committee established by the Agreement.

Joint Technical Committee (JTC): The joint technical committee established by the Agreement. The full formal name is “Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States and Canada”.

Logistic transformation: A mathematical transformation used to translate between numbers bounded within some range to numbers on the real line ($-\infty$ to $+\infty$).

Magnuson-Stevens Fishery Conservation and Management Act: The MSFCMA, sometimes known as the “Magnuson-Stevens Act”, established the 200-mile fishery conservation zone, the regional fishery management council system, and other provisions of U.S. marine fishery law.

Management Strategy Evaluation (MSE): A formal process for evaluating Harvest Strategies (see above).

Markov chain Monte Carlo (MCMC): A numerical method used to sample from the posterior distribution (see below) of parameters and derived quantities in a Bayesian analysis. It is more computationally intensive than the maximum likelihood estimate (see below), but provides a more accurate depiction of parameter uncertainty. See Stewart et al. (2013) for a discussion of issues related to differences between MCMC and MLE.

Maximum likelihood estimate (MLE): A method used to estimate a single value for each of the parameters and derived quantities. It is less computationally intensive than MCMC methods (see below), but parameter uncertainty is less well determined.

Maximum sustainable yield (MSY): An estimate of the largest sustainable annual catch that can be continuously taken over a long period of time from a stock under equilibrium ecological and environmental conditions.

MCMC: Markov chain Monte Carlo (see above).

MLE: Maximum likelihood estimate (see above).

MSE: Management Strategy Evaluation (see above).

MSY: Maximum sustainable yield (see above).

t: Metric ton(s). A unit of mass (often referred to as weight) equal to 1,000 kilograms or 2,204.62 pounds. Previous stock assessments used the abbreviation “mt” (metric tons).

NA: Not available.

National Marine Fisheries Service: See NOAA Fisheries below.

NMFS: National Marine Fisheries Service. See NOAA Fisheries below.

NOAA Fisheries: The division of the United States National Oceanic and Atmospheric Administration (NOAA) responsible for conservation and management of offshore fisheries (and inland salmon). This is also known as the National Marine Fisheries Service (NMFS), and both names are commonly used at this time.

NORPAC: North Pacific Database Program. A database storing U.S. fishery observer data collected at sea.

NUTS: No-U-Turn Sampler is an advanced Hamiltonian Bayesian MCMC sampling algorithm used to efficiently create posterior distributions and used in Pacific Hake Bayesian stock assessments beginning in 2021.

NWFSC : Northwest Fisheries Science Center. A NOAA Fisheries Science Center located primarily in Seattle, Washington, but also in Newport, Oregon and other locations.

Operating Model (OM): A model used to simulate data for use in the MSE (see above). The operating model includes components for the stock and fishery dynamics, as well as the simulation of the data sampling process, potentially including observation error. Cases in the MSE represent alternative configurations of the operating model.

OM: Operating Model (see above).

PacFIN: Pacific Coast Fisheries Information Network. A database that provides a central repository for commercial fishery information from Washington, Oregon, and California.

PBS: Pacific Biological Station of Fisheries and Oceans Canada (DFO, see above), located in Nanaimo, British Columbia.

Pacific Fishery Management Council (PFMC): The U.S. organization under which historical stock assessments for Pacific Hake were conducted.

Pacific Hake: Common name for *Merluccius productus*, the species whose offshore stock in the waters of the United States and Canada is subject of this assessment.

Pacific whiting: an alternative name for Pacific Hake commonly used in the United States.

Posterior distribution: The probability distribution for parameters or derived quantities from a Bayesian model representing the result of the prior probability distributions (see below) being updated by the observed data via the likelihood equation. For stock assessments, posterior distributions are approximated via numerical methods; one frequently employed method is MCMC (see above).

Prior distribution: Probability distribution for a parameter in a Bayesian analysis that represents the information available before evaluating the observed data via the likelihood equation. For some parameters, noninformative priors can be constructed which allow the data to dominate the posterior distribution (see above). For other parameters, informative priors can be constructed based on auxiliary information and/or expert knowledge or opinions.

q: Catchability (see above).

R_0: Estimated annual recruitment at unfished equilibrium.

Recruits/recruitment: the estimated number of new members in a fish population born in the same age. In this assessment, recruitment is reported at age 0. See also cohort and year-class.

Recruitment deviation: The offset of the recruitment in a given year relative to the stock-recruit function; values occur on a logarithmic scale and are relative to the expected recruitment at a given spawning biomass (see below).

Relative fishing intensity: See definition of fishing intensity.

Relative spawning biomass: The ratio of the beginning-of-the-year female spawning biomass to the unfished equilibrium female spawning biomass (B_0, see above). Thus, lower values are associated with fewer mature female fish. This term was introduced in the 2015 stock assessment as a replacement for "depletion" (see above) which was a source of some confusion.

rwMH: Random walk Metropolis Hastings Bayesian MCMC sampling algorithm used to create posterior distributions used in Pacific Hake Bayesian stock assessment models prior to 2021.

Scientific Review Group (SRG): The scientific review group established by the Agreement.

Scientific and Statistical Committee (SSC): The scientific advisory committee to the PFMC. The Magnuson-Stevens Act requires that each council maintain an SSC to assist in gathering and analyzing statistical, biological, ecological, economic, social, and other scientific information that is relevant to the management of council fisheries.

SD: Standard deviation. A measure of variability within a sample.

Simulation: A model evaluation under a particular state of nature, including combinations of parameters controlling stock productivity, stock status, and the time series of recruitment deviations. In this assessment, there are 8,000 simulations used to characterize alternative states of nature, each of which are based on a sample from the posterior distribution of the parameters, as calculated using MCMC, for a particular model (e.g., the base model).

Spawning biomass: Abbreviated term for female spawning biomass (see above).

Spawning biomass per recruit: The expected lifetime contribution of an age-0 recruit, calculated as the sum across all ages of the product of spawning biomass at each age and the probability of surviving to that age. See Figure C.2 for a graphical demonstration of the calculation of this value, which is found in both numerator and denominator of the Spawning potential ratio (SPR, see below).

Spawning potential ratio (SPR): The ratio of the spawning biomass per recruit under a given level of fishing to the estimated spawning biomass per recruit in the absence of fishing; i.e. for fishing mortality rate F

$$\mathrm{SPR}(F) = \frac{\text{spawning biomass per recruit with } F}{\text{spawning biomass per recruit with no fishing}}. \tag{C.7}$$

Often expressed as a percentage, it achieves a value of 100% in the absence of fishing and declines toward zero as fishing intensity increases. See Figure C.2 for a graphical demonstration of the calculation of SPR.

SPR: Spawning potential ratio (see above).

$\mathrm{SPR}_{40\%}$: See target spawning potential ratio.

SS: Stock Synthesis (see below).

Steepness (h): A stock-recruit relationship parameter representing the proportion of R_0 expected (on average) when the female spawning biomass is reduced to 20% of B_0 (i.e., when relative spawning biomass is equal to 20%).

Stock Synthesis (SS): The age-structured stock assessment model applied in this stock assessment.

Target spawning potential ratio ($\mathrm{SPR}_{40\%}$): The spawning potential ratio of 40%, where the 40% relates to the default harvest rate of $F_{\mathrm{SPR}=40\%}$ specified in the Agreement. Even under equilibrium conditions, $F_{\mathrm{SPR}=40\%}$ would not necessarily result in a female spawning biomass of $B_{40\%}$ because $F_{\mathrm{SPR}=40\%}$ is defined in terms of the spawning potential ratio which depends on the female spawning biomass *per recruit*.

Target strength (TS): The amount of backscatter from an individual acoustic target.

TAC: Total allowable catch (see below).

Total allowable catch (TAC): The maximum fishery removal under the terms of the Agreement.

U.S./Canadian allocation: The division of the total allowable catch of 73.88% as the United States' share and 26.12% as Canada's share.

Vulnerable biomass: The demographic portion of the stock available for harvest by the fishery.

Year-class: A group of fish born in the same year. See also 'cohort' and 'recruitment'.

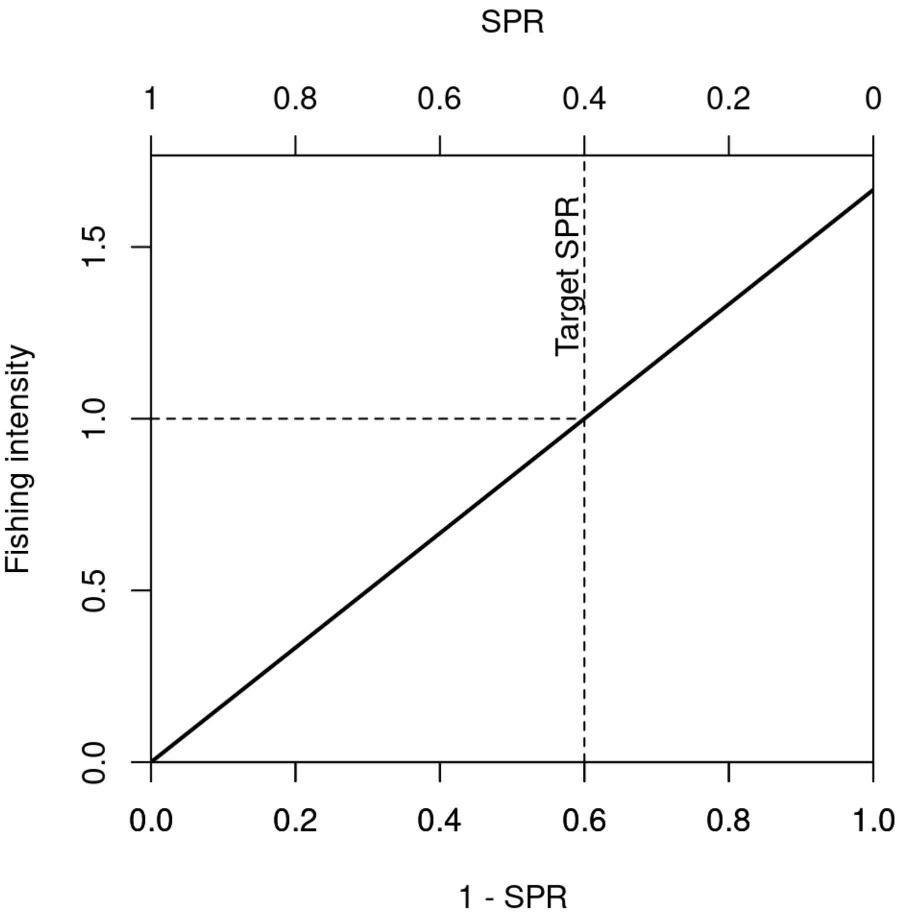


Figure C.1. Fishing intensity as a function of SPR (top axis) and 1-SPR (bottom axis); given the target SPR of 40%, the bold line is simply $1/0.6$, as shown in equation (C.5).

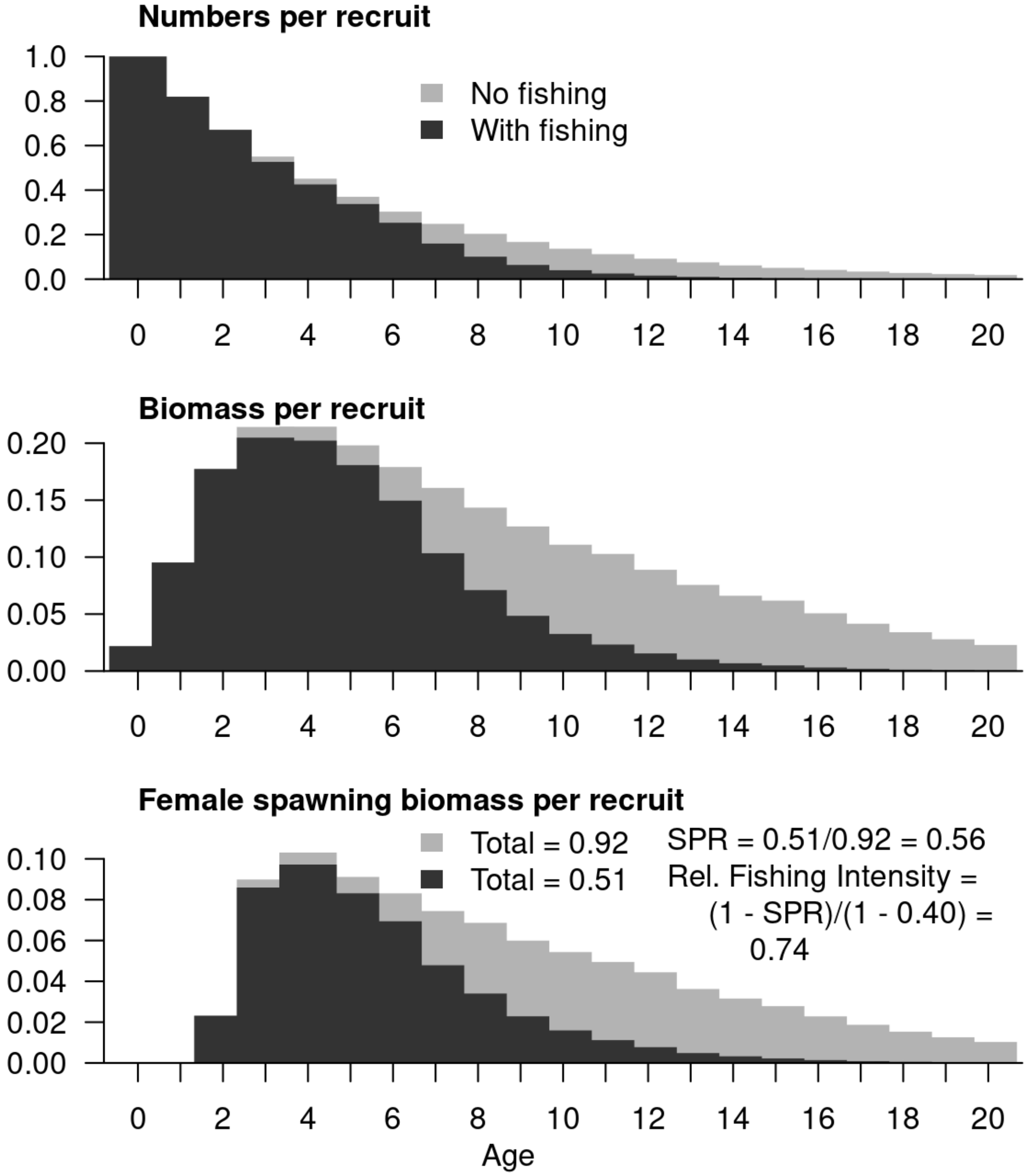


Figure C.2. Illustration of the spawning potential ratio (SPR) calculation based on the combination of maturity and fecundity used in the model, using the maximum likelihood estimates of natural mortality, selectivity, and fishing mortality in the final year of the base model from this year.

D REPORT OF THE 2023 PACIFIC HAKE FISHERY IN CANADA

Prepared by the Canadian Advisory Panel and submitted on 20th December 2022 for inclusion in this assessment document.

While there was some hake fishing in early April, significant effort and catch didn't start until early May and continued through to mid October. Fishing ceased in early December. A preliminary total of 27,160 tonnes of hake was caught in 2022 (less than half of 2021) which equates to 26% of the adjusted TAC of 105,000 tonnes. Minor differences in catch reported here compared to that used in the stock assessment can occur due to the timing of data extractions.

Very low hake abundance negatively impacted the Canadian offshore hake fishery in 2022. Cold ocean temperature in the spring may have contributed to poor northerly migration. As warmer sea currents started moving north decent bodies of hake showed. Hake exploratory fishing occurred from the southern Canada/US border all the way up to lower Queen Charlotte Sound both on the shelf and off the edge at depths between 40-180 fathoms.

The general view from the Canadian fleet is that the hake abundance was lower in 2022 than in 2021. This marks four consecutive years that the Canadian fleet saw declining abundance in the Canadian zone which results in much more time spent searching for fish and patchy fishing. While the entire Canadian fleet is negatively impacted, vessels delivering fresh fish for shoreside processing were affected the most.

The first significant body of fish encountered this season was in mid-May in areas between the Finger Bank, Dolly's, Swiftsure Bank, and Barkley Flats. This was encouraging as many square miles were sounded and the fleet enjoyed several days of good fishing. However, the fish soon disappeared as fast as it appeared, trend that continued throughout the season. Large bodies of fish would be sounded and then vanish within 24-48 hours regardless of the amount of fishing pressure applied. Another biomass of hake showed below the Submerged Buoy but didn't last. There were also a few good tows at Nitnat and some heavy spots were fished at Father Charles along the steep edge and up on the bank but only lasted a few days. Throughout the summer the traditional grounds continued to be the most consistent place to find fish, with deep water scuzz fishing outside the 100 fathom edge patchy and inconsistent for much of the season.

As with the previous two years pollock was pervasive in the region and presented a significant bycatch issue. Herring was also a notable bycatch in the lower south coast. In July a seemingly large biomass of fish was encountered in Queen Charlotte Sound on the "NE corner", however this fish disappeared after very light fishing pressure despite appearing to be spread over a large area. A biomass of hake was found in Juan de Fuca in early August, but fishing was curtailed because of high levels of pollock and salmon bycatch and the availability of limited pollock quota. During September the fleet mostly fished the deep water "scuzz" north of Cape Cook and out to Triangle Island where fishing was difficult with a couple days of good fishing followed by periods of poor fishing. Fishing continued late into fall with some good catches of fish in the deep water off Nootka Island and Estevan Pt as late as early December.

The fish on top of the continental shelf were generally large, 700-1000 grams round. This is typical as the older stronger fish travel to these zones seeking larger baitfish such as herring while the younger fish often stay in deeper water feeding on krill and viperfish. The fish encountered in deeper water was mostly medium sized fish between 500-800 grams round. No biomasses of juveniles were encountered in the Canadian zone.

E REPORT OF THE 2023 PACIFIC HAKE FISHERY IN THE UNITED STATES

Prepared by the United States Advisory Panel on 25 January 2023 for inclusion in this assessment document.

Total U.S. harvest in the 2022 whiting fishery was 290,900.38 t which is 78.3% of the U.S. allocation of 371,433 t. This is a higher utilization rate than recent years, however, the utilization rate is consistent with the industry's pre-season expectations for harvest in 2022.

At-Sea Fishery: The U.S. at-sea fishery, comprised of the Mothership (MS) and Catcher Processor (CP) sectors, generally followed their typical temporal pattern. However, the lower Bering Sea pollock TAC provided the opportunity for increased whiting effort throughout the season, with more participants and more days at sea. The fishery started May 15, with the CP sector ending the third week of June and the MS sector effort extending into July (a longer duration for this sector than most years). After B-season pollock, both at-sea sectors resumed whiting fishing in mid-August and ended in mid-October, finishing earlier than previous years. The timing of the at-sea fishery shifted in 2022 because the lower Bering Sea pollock TAC allowed whiting effort to last longer in the spring and to start earlier in the fall.

Shoreside (SS) and Mothership Catcher Vessels (CV): Fishing in the U.S. shoreside sector got off to a slow start in 2022. The season was characterized as spotty throughout most of the year, and overall, shoreside catch was the lowest it's been in several years, harvesting only 66.9% of its available allocation. While this is a considerably lower SS utilization rate than recent years, this lower catch is reflective of tradeoffs associated with increased effort in other sectors and the fishing conditions and locations of fish concentrations relative to markets, not coastwide fish abundance. There is significant overlap of catcher vessels between the MS and SS sectors and increased MS effort reduced SS effort resulting in a slower start to the SS season. In addition, the hake also seemed "slow to show up" near shoreside markets particularly to the north, possibly due to the environmental conditions reported earlier this year – cold (and often highly variable) surface temps, a poorly formed Pacific High, late wind patterns, and late upwelling. The scratchy fishing at the start of the season for the SS catcher vessels improved by July as the hake appeared to move north. However, the fishing conditions did not improve off Washington until later in the summer.

Fishing in the MS sector was generally good in the spring and more fish was caught in the spring fishery than in past years, in part due to good fishing and effort later into summer than in past years. In the fall fishery, catcher vessels delivering to MS had the potential to get more fish out of the water, but one MS platform broke down at the end of B season pollock and had to cancel their fall hake plans, while another MS breakdown down prevented completion of their remaining 1.5 trips.

Tribal Fishery: Tribal effort was sporadic through the summer and fall. Fish abundance in the Makah Tribal usual and accustomed fishing grounds was better than past years and exhibited more normal patterns of abundance and movement through the area following the deep water and moving northward, often quickly, across the US-Canada border. Total Tribal harvest continued to be limited by catcher vessel availability and availability of tenders to carry the catch to the market for processing.

Fish Size, Distribution and Abundance: The at-sea sectors reported good fish abundance generally on par with recent years. Hake, especially larger size classes, were deeper in the water column. For the at-sea sectors, the bulk of the catch was 450–550 grams, with smaller (less than 300 gram) and larger (more than 600 gram) also in the mix.

The SS sector reported a good size distribution of fish with most areas reporting average fish size of 550 grams or larger. Early in the spring, the fish were being found in larger concentrations further to the south. A few MS fleets made trips into federal waters off California in the early Spring (despite fuel costs), with their MS waiting at the OR/CA border – hake were reported to be abundant, catch per unit effort (CPUE) high, and fish size was on the smaller to moderate size. SS deliveries during this time were hampered by fuel costs and the vessels' ability to run up and down the coast often great distances from their SS market.

Throughout the season the SS sector reported over 90% of fish were over 400 grams. As reported by the MS sector in the spring, smaller fish (possibly 1-year olds) were seen south of Newport OR, particularly in the shallows, but they were avoided once the boats located better concentrations of larger fish further north. Strong market disincentives were again in place to discourage harvest of smaller fish.

Incidental Species: Catch of incidental species followed similar patterns as previous years, with the fleets focusing avoidance efforts on rockfish and Chinook salmon. Incidental catch of warmer water species, like Jack and Pacific mackerels, were lower than amounts observed in 2021, but encounters were still higher than normal, especially given the colder water temperatures. Shad bycatch was also notably higher than in recent years.

Large concentrations of small sablefish were again reported by all sectors and had to be actively avoided, especially early in the season. There are a couple of young, very abundant year classes of sablefish up in the water column. There were many reports of vessels moving from productive hake fishing grounds in order to avoid sablefish. In general, fishing at deeper depths allowed for cleaner fishing on larger fish for the vessels that were capable of doing so.

Table E.1. Final allocations (after reallocation of tribal quota) and catch totals (metric tons, mt). Note that 402,646 mt U.S. TAC is reduced by 750 mt for research and incidental catch set. Minor differences in catch in this table compared to that used in the stock assessment can occur due to the timing of data extractions.

	U.S. TAC	Shoreside (SS)	Catcher Processor (CP)	Mothership (MS)	Tribal
Allocation (mt)	401,896	156,002	126,287	89,144	30,463
Catch (mt)	290,901	104,323	126,247	59,157	1,174
% Utilization	72.4%	66.9%	100%	66.4%	3.9%

F ESTIMATED PARAMETERS IN THE BASE ASSESSMENT MODEL

Table F.1. Medians of estimated parameters for the base model.

Parameter	Posterior median
NatM_uniform_Fem_GP_1	0.2330
SR_LN(R0)	14.7505
SR_BH_steep	0.8079
Q_extraSD_Acoustic_Survey(2)	0.2863
ln(DM_theta)_Age_P1	-0.6288
ln(DM_theta)_Age_P2	2.5951
Early_InitAge_20	-0.2544
Early_InitAge_19	-0.1064
Early_InitAge_18	-0.1205
Early_InitAge_17	-0.1189
Early_InitAge_16	-0.1726
Early_InitAge_15	-0.2072
Early_InitAge_14	-0.2390
Early_InitAge_13	-0.3144
Early_InitAge_12	-0.3210
Early_InitAge_11	-0.3696
Early_InitAge_10	-0.4593
Early_InitAge_9	-0.4677
Early_InitAge_8	-0.5674
Early_InitAge_7	-0.5862
Early_InitAge_6	-0.5763
Early_InitAge_5	-0.4884
Early_InitAge_4	-0.2941
Early_InitAge_3	-0.0133
Early_InitAge_2	0.3753
Early_InitAge_1	0.6314
Early_RecrDev_1966	0.5527
Early_RecrDev_1967	1.6588
Early_RecrDev_1968	1.2217
Early_RecrDev_1969	-0.2831
Main_RecrDev_1970	2.2879
Main_RecrDev_1971	-0.1468
Main_RecrDev_1972	-0.5499
Main_RecrDev_1973	1.8495
Main_RecrDev_1974	-0.9931
Main_RecrDev_1975	0.6631
Main_RecrDev_1976	-1.5644
Main_RecrDev_1977	1.9391
Main_RecrDev_1978	-1.9631
Main_RecrDev_1979	0.3676
Main_RecrDev_1980	2.8978
Main_RecrDev_1981	-1.2636
Main_RecrDev_1982	-1.1265
Main_RecrDev_1983	-0.6016
Main_RecrDev_1984	2.6738
Main_RecrDev_1985	-2.0198
Main_RecrDev_1986	-1.6998
Main_RecrDev_1987	1.9224
Main_RecrDev_1988	0.7711

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Table F.1. Medians of estimated parameters for the base model.

Parameter	Posterior median
Main_RecrDev_1989	-2.1603
Main_RecrDev_1990	1.5100
Main_RecrDev_1991	0.2637
Main_RecrDev_1992	-2.0287
Main_RecrDev_1993	1.2526
Main_RecrDev_1994	1.2804
Main_RecrDev_1995	0.3273
Main_RecrDev_1996	0.7389
Main_RecrDev_1997	0.1200
Main_RecrDev_1998	0.8310
Main_RecrDev_1999	2.7343
Main_RecrDev_2000	-1.0238
Main_RecrDev_2001	0.3346
Main_RecrDev_2002	-3.0210
Main_RecrDev_2003	0.6254
Main_RecrDev_2004	-3.0190
Main_RecrDev_2005	1.1580
Main_RecrDev_2006	0.8660
Main_RecrDev_2007	-3.5268
Main_RecrDev_2008	1.9130
Main_RecrDev_2009	0.5797
Main_RecrDev_2010	3.0064
Main_RecrDev_2011	-0.7113
Main_RecrDev_2012	0.6355
Main_RecrDev_2013	-0.8966
Main_RecrDev_2014	2.2644
Main_RecrDev_2015	-3.2439
Main_RecrDev_2016	1.9317
Main_RecrDev_2017	0.9599
Main_RecrDev_2018	-0.4005
Main_RecrDev_2019	-0.4481
Main_RecrDev_2020	2.4901
Late_RecrDev_2021	-0.7263
Late_RecrDev_2022	0.0066
ForeRecr_2023	-0.0192
ForeRecr_2024	-0.0113
ForeRecr_2025	0.0142
ForeRecr_2026	-0.0218
AgeSel_P3_Fishery(1)	2.8599
AgeSel_P4_Fishery(1)	0.9061
AgeSel_P5_Fishery(1)	0.4273
AgeSel_P6_Fishery(1)	0.1753
AgeSel_P7_Fishery(1)	0.4953
AgeSel_P4_Acoustic_Survey(2)	0.5943
AgeSel_P5_Acoustic_Survey(2)	-0.2063
AgeSel_P6_Acoustic_Survey(2)	0.3275
AgeSel_P7_Acoustic_Survey(2)	0.3047
AgeSel_P3_Fishery(1)_DEVadd_1991	0.5569
AgeSel_P3_Fishery(1)_DEVadd_1992	-0.0030
AgeSel_P3_Fishery(1)_DEVadd_1993	-0.0191
AgeSel_P3_Fishery(1)_DEVadd_1994	0.1275

Continued on next page

Table F.1. Medians of estimated parameters for the base model.

Parameter	**Posterior median**
AgeSel_P3_Fishery(1)_DEVadd_1995	-0.1706
AgeSel_P3_Fishery(1)_DEVadd_1996	0.4348
AgeSel_P3_Fishery(1)_DEVadd_1997	0.0850
AgeSel_P3_Fishery(1)_DEVadd_1998	0.2042
AgeSel_P3_Fishery(1)_DEVadd_1999	1.0148
AgeSel_P3_Fishery(1)_DEVadd_2000	0.5020
AgeSel_P3_Fishery(1)_DEVadd_2001	0.0519
AgeSel_P3_Fishery(1)_DEVadd_2002	0.0896
AgeSel_P3_Fishery(1)_DEVadd_2003	-0.0232
AgeSel_P3_Fishery(1)_DEVadd_2004	0.2937
AgeSel_P3_Fishery(1)_DEVadd_2005	-0.0005
AgeSel_P3_Fishery(1)_DEVadd_2006	0.5830
AgeSel_P3_Fishery(1)_DEVadd_2007	0.5909
AgeSel_P3_Fishery(1)_DEVadd_2008	-0.0237
AgeSel_P3_Fishery(1)_DEVadd_2009	0.4341
AgeSel_P3_Fishery(1)_DEVadd_2010	0.9705
AgeSel_P3_Fishery(1)_DEVadd_2011	-0.0923
AgeSel_P3_Fishery(1)_DEVadd_2012	0.1025
AgeSel_P3_Fishery(1)_DEVadd_2013	0.2478
AgeSel_P3_Fishery(1)_DEVadd_2014	0.3074
AgeSel_P3_Fishery(1)_DEVadd_2015	-0.7282
AgeSel_P3_Fishery(1)_DEVadd_2016	-0.0381
AgeSel_P3_Fishery(1)_DEVadd_2017	-0.3967
AgeSel_P3_Fishery(1)_DEVadd_2018	-1.2847
AgeSel_P3_Fishery(1)_DEVadd_2019	0.7410
AgeSel_P3_Fishery(1)_DEVadd_2020	0.0101
AgeSel_P3_Fishery(1)_DEVadd_2021	-0.4508
AgeSel_P3_Fishery(1)_DEVadd_2022	0.4348
AgeSel_P4_Fishery(1)_DEVadd_1991	0.3801
AgeSel_P4_Fishery(1)_DEVadd_1992	0.5815
AgeSel_P4_Fishery(1)_DEVadd_1993	0.8130
AgeSel_P4_Fishery(1)_DEVadd_1994	0.2054
AgeSel_P4_Fishery(1)_DEVadd_1995	0.2199
AgeSel_P4_Fishery(1)_DEVadd_1996	-0.3576
AgeSel_P4_Fishery(1)_DEVadd_1997	1.2697
AgeSel_P4_Fishery(1)_DEVadd_1998	0.9818
AgeSel_P4_Fishery(1)_DEVadd_1999	-0.0965
AgeSel_P4_Fishery(1)_DEVadd_2000	0.8199
AgeSel_P4_Fishery(1)_DEVadd_2001	0.9400
AgeSel_P4_Fishery(1)_DEVadd_2002	0.7172
AgeSel_P4_Fishery(1)_DEVadd_2003	0.6638
AgeSel_P4_Fishery(1)_DEVadd_2004	0.4543
AgeSel_P4_Fishery(1)_DEVadd_2005	0.6456
AgeSel_P4_Fishery(1)_DEVadd_2006	-0.0590
AgeSel_P4_Fishery(1)_DEVadd_2007	0.2053
AgeSel_P4_Fishery(1)_DEVadd_2008	0.3572
AgeSel_P4_Fishery(1)_DEVadd_2009	0.7477
AgeSel_P4_Fishery(1)_DEVadd_2010	0.1348
AgeSel_P4_Fishery(1)_DEVadd_2011	1.0646
AgeSel_P4_Fishery(1)_DEVadd_2012	0.1937
AgeSel_P4_Fishery(1)_DEVadd_2013	0.8696

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Table F.1. Medians of estimated parameters for the base model.

Parameter	Posterior median
AgeSel_P4_Fishery(1)_DEVadd_2014	0.4869
AgeSel_P4_Fishery(1)_DEVadd_2015	0.1790
AgeSel_P4_Fishery(1)_DEVadd_2016	-0.9014
AgeSel_P4_Fishery(1)_DEVadd_2017	-0.4905
AgeSel_P4_Fishery(1)_DEVadd_2018	-0.5315
AgeSel_P4_Fishery(1)_DEVadd_2019	-0.5739
AgeSel_P4_Fishery(1)_DEVadd_2020	0.7642
AgeSel_P4_Fishery(1)_DEVadd_2021	0.1542
AgeSel_P4_Fishery(1)_DEVadd_2022	-1.3604
AgeSel_P5_Fishery(1)_DEVadd_1991	-0.8582
AgeSel_P5_Fishery(1)_DEVadd_1992	0.0944
AgeSel_P5_Fishery(1)_DEVadd_1993	-0.0067
AgeSel_P5_Fishery(1)_DEVadd_1994	0.8829
AgeSel_P5_Fishery(1)_DEVadd_1995	0.2481
AgeSel_P5_Fishery(1)_DEVadd_1996	-0.3181
AgeSel_P5_Fishery(1)_DEVadd_1997	-0.1305
AgeSel_P5_Fishery(1)_DEVadd_1998	-0.6369
AgeSel_P5_Fishery(1)_DEVadd_1999	0.0887
AgeSel_P5_Fishery(1)_DEVadd_2000	-0.1911
AgeSel_P5_Fishery(1)_DEVadd_2001	0.3112
AgeSel_P5_Fishery(1)_DEVadd_2002	0.5255
AgeSel_P5_Fishery(1)_DEVadd_2003	0.7317
AgeSel_P5_Fishery(1)_DEVadd_2004	0.6583
AgeSel_P5_Fishery(1)_DEVadd_2005	0.7158
AgeSel_P5_Fishery(1)_DEVadd_2006	-0.0356
AgeSel_P5_Fishery(1)_DEVadd_2007	-0.0896
AgeSel_P5_Fishery(1)_DEVadd_2008	-0.3405
AgeSel_P5_Fishery(1)_DEVadd_2009	-0.2204
AgeSel_P5_Fishery(1)_DEVadd_2010	0.4857
AgeSel_P5_Fishery(1)_DEVadd_2011	-0.7080
AgeSel_P5_Fishery(1)_DEVadd_2012	0.1820
AgeSel_P5_Fishery(1)_DEVadd_2013	-0.2460
AgeSel_P5_Fishery(1)_DEVadd_2014	-0.5078
AgeSel_P5_Fishery(1)_DEVadd_2015	-0.0042
AgeSel_P5_Fishery(1)_DEVadd_2016	-0.0290
AgeSel_P5_Fishery(1)_DEVadd_2017	-0.1291
AgeSel_P5_Fishery(1)_DEVadd_2018	-0.2363
AgeSel_P5_Fishery(1)_DEVadd_2019	-0.0732
AgeSel_P5_Fishery(1)_DEVadd_2020	0.9286
AgeSel_P5_Fishery(1)_DEVadd_2021	0.6408
AgeSel_P5_Fishery(1)_DEVadd_2022	0.2461
AgeSel_P6_Fishery(1)_DEVadd_1991	-0.0503
AgeSel_P6_Fishery(1)_DEVadd_1992	-0.4679
AgeSel_P6_Fishery(1)_DEVadd_1993	-0.0691
AgeSel_P6_Fishery(1)_DEVadd_1994	-0.0990
AgeSel_P6_Fishery(1)_DEVadd_1995	0.7531
AgeSel_P6_Fishery(1)_DEVadd_1996	-0.1357
AgeSel_P6_Fishery(1)_DEVadd_1997	-0.3195
AgeSel_P6_Fishery(1)_DEVadd_1998	0.3799
AgeSel_P6_Fishery(1)_DEVadd_1999	-0.3778
AgeSel_P6_Fishery(1)_DEVadd_2000	0.1741

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Table F.1. Medians of estimated parameters for the base model.

Parameter	Posterior median
AgeSel_P6_Fishery(1)_DEVadd_2001	-0.1409
AgeSel_P6_Fishery(1)_DEVadd_2002	0.1527
AgeSel_P6_Fishery(1)_DEVadd_2003	0.2678
AgeSel_P6_Fishery(1)_DEVadd_2004	-0.5733
AgeSel_P6_Fishery(1)_DEVadd_2005	0.2842
AgeSel_P6_Fishery(1)_DEVadd_2006	0.2164
AgeSel_P6_Fishery(1)_DEVadd_2007	-0.2269
AgeSel_P6_Fishery(1)_DEVadd_2008	0.2422
AgeSel_P6_Fishery(1)_DEVadd_2009	-0.2204
AgeSel_P6_Fishery(1)_DEVadd_2010	-0.4723
AgeSel_P6_Fishery(1)_DEVadd_2011	-0.2017
AgeSel_P6_Fishery(1)_DEVadd_2012	-0.4635
AgeSel_P6_Fishery(1)_DEVadd_2013	-0.0121
AgeSel_P6_Fishery(1)_DEVadd_2014	-0.0024
AgeSel_P6_Fishery(1)_DEVadd_2015	-0.0290
AgeSel_P6_Fishery(1)_DEVadd_2016	0.0042
AgeSel_P6_Fishery(1)_DEVadd_2017	-0.1657
AgeSel_P6_Fishery(1)_DEVadd_2018	-0.3123
AgeSel_P6_Fishery(1)_DEVadd_2019	0.1630
AgeSel_P6_Fishery(1)_DEVadd_2020	-0.3153
AgeSel_P6_Fishery(1)_DEVadd_2021	0.4731
AgeSel_P6_Fishery(1)_DEVadd_2022	0.5857
AgeSel_P7_Fishery(1)_DEVadd_1991	-0.1020
AgeSel_P7_Fishery(1)_DEVadd_1992	0.0770
AgeSel_P7_Fishery(1)_DEVadd_1993	-0.3560
AgeSel_P7_Fishery(1)_DEVadd_1994	0.1068
AgeSel_P7_Fishery(1)_DEVadd_1995	-0.1217
AgeSel_P7_Fishery(1)_DEVadd_1996	0.4087
AgeSel_P7_Fishery(1)_DEVadd_1997	0.1130
AgeSel_P7_Fishery(1)_DEVadd_1998	-0.4969
AgeSel_P7_Fishery(1)_DEVadd_1999	-0.2640
AgeSel_P7_Fishery(1)_DEVadd_2000	-0.0791
AgeSel_P7_Fishery(1)_DEVadd_2001	-0.2766
AgeSel_P7_Fishery(1)_DEVadd_2002	-0.4101
AgeSel_P7_Fishery(1)_DEVadd_2003	-0.2556
AgeSel_P7_Fishery(1)_DEVadd_2004	-0.1623
AgeSel_P7_Fishery(1)_DEVadd_2005	-0.3936
AgeSel_P7_Fishery(1)_DEVadd_2006	-0.3194
AgeSel_P7_Fishery(1)_DEVadd_2007	0.0706
AgeSel_P7_Fishery(1)_DEVadd_2008	-0.1711
AgeSel_P7_Fishery(1)_DEVadd_2009	0.0863
AgeSel_P7_Fishery(1)_DEVadd_2010	-0.5757
AgeSel_P7_Fishery(1)_DEVadd_2011	-0.4852
AgeSel_P7_Fishery(1)_DEVadd_2012	-0.3105
AgeSel_P7_Fishery(1)_DEVadd_2013	0.0972
AgeSel_P7_Fishery(1)_DEVadd_2014	-0.0202
AgeSel_P7_Fishery(1)_DEVadd_2015	-0.5083
AgeSel_P7_Fishery(1)_DEVadd_2016	-0.4255
AgeSel_P7_Fishery(1)_DEVadd_2017	-0.0416
AgeSel_P7_Fishery(1)_DEVadd_2018	0.2749
AgeSel_P7_Fishery(1)_DEVadd_2019	-0.1854

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Table F.1. Medians of estimated parameters for the base model.

Parameter	Posterior median
AgeSel_P7_Fishery(1)_DEVadd_2020	-0.0267
AgeSel_P7_Fishery(1)_DEVadd_2021	-0.3011
AgeSel_P7_Fishery(1)_DEVadd_2022	0.3907