Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2024

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

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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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Appendices

ONE-PAGE SUMMARY

- The stock assessment model for 2024 has the same population dynamics structure as the 2023 model. The model is fit to an acoustic survey index of biomass, a relative index of age-1 fish, annual commercial catch data, and age-composition data from the survey and commercial fisheries.
- Data for 2023 were included for each data set and minor changes to pre-2023 data were made as necessary. In addition, a new model-based approach was used to develop the input weight-at-age matrix, and time-varying temperature-dependent maturity was introduced to better inform fecundity.
- Coast-wide catch in 2023 was 263,981 t [t represents metric tons], 22% below the average over the most recent 10 years (338,606 t), out of a total allowable catch (TAC), adjusted for carryovers, of 625,000 t. The U.S. caught 240,424 t (52.1% of their quota) and Canada caught 23,557 t (14.4% of their quota).
- The median estimate of the 2024 relative spawning biomass (female spawning biomass at the start of 2024 divided by that at unfished equilibrium, B_0) is 99% but is highly uncertain (with 95% credible interval from 45% to 230%). After declining from 2018–2022, the median relative spawning biomass increased in 2023 and 2024, due to the estimated above average, but uncertain, size of the 2020 and 2021 cohorts entering maturity.
- The median estimate of female spawning biomass at the start of 2024 is 1,884,950 t (with 95% credible interval from 853,207 to 4,828,382 t). This is an upward shift from this assessment's estimate for the 2023 female spawning biomass of 1,335,485 t (with 95% credible interval from 652,495 to 3,224,819 t).
- The estimated probability that female spawning biomass at the start of 2024 is below the $B_{40\%}$ (40% of B_0) reference point is 1.3%, and the probability that the relative fishing intensity exceeded 1 in 2023 is 0.4%. The joint probability of both these occurring is 0.2%.
- Based on the default harvest rule, the estimated median catch limit for 2024 is 747,588 t (with 95% credible interval from 298,355 to 2,124,832 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 2024 and 2025 catches equal to the 2023 coast-wide TAC of 625,000 t show the estimated median relative spawning biomass decreasing from 99% in 2024 to 94% in 2025 and then to 83% in 2026, with a 11% chance of the female spawning biomass falling below $B_{40\%}$ in 2026. There is an estimated 76% chance of the female spawning biomass declining from 2024 to 2025, an 84% chance of it declining from 2025 to 2026, and an 83% chance of it declining from 2026 to 2027 with a constant catch of 625,000 t.
- Despite estimates of a healthy stock status, the recent lack of survey abundance and fishery catch in Canada suggests a population structure not conducive to achieving harvest quotas in northern fisheries over recent years.

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 2024. 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. The stock tends to move farther to the north during the summer in years with warmer water compared to years with colder waters. Older Pacific Hake tend to migrate farther north than younger Pacific Hake in all years, with catches in Canadian waters typically consisting of fish greater than four years old. Separate, and much smaller, populations of Pacific 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

Figure a. Total Pacific Hake catch used in the assessment by sector, 1966–2023. U.S. tribal catches are included in the sectors where they are represented.

Coast-wide fishery landings of Pacific Hake averaged 243,288 t from 1966 to 2023, with a low of 89,930 t in 1980 and a peak of 440,849 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 186,041 t (76.5% of the total catch), while catch from Canadian waters averaged 57,247 t. Over the last 10 years, 2014–2023 (Table a), the average coast-wide catch was 338,606 t with U.S. and Canadian catches averaging 275,957 t and 62,648 t, respectively. Since 2017, the coast-wide catch has been declining annually through 2023 to 263,981 t out of a total allowable catch (TAC, adjusted for carryovers) of 625,000 t. Attainment in the U.S. was 52.1% of its quota and in Canada it was 14.4%.

Table a. Total Pacific Hake catch used in the assessment by sector for the most recent ten years. U.S. tribal catches are included in the sectors where they are represented.

Year	U.S. Mother-ship	U.S. Catcher-processor	U.S. Shore-based	U.S. Research	U.S. Total	Canada Joint-venture	Canada Shore-side	Canada Freezer-trawler	Canada Total	Total
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	22,909	39,684	193,844
2016	65,036	108,786	87,760	745	262,327	0	35,012	34,731	69,743	332,070
2017	66,428	136,960	150,741	0	354,129	5,608	43,427	37,686	86,721	440,849
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	40,794	54,218	95,013	412,015
2020	37,978	111,147	138,688	95	287,908	0	30,085	62,404	92,489	380,397
2021	35,208	104,030	129,319	917	269,473	0	11,269	45,807	57,076	326,549
2022	59,516	126,247	105,939	0	291,702	0	3,868	27,803	31,671	323,372
2023	32,911	107,117	100,396	0	240,424	0	3,657	19,901	23,557	263,981

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 Pacific Hake, is estimated to be less than 1% of landings in recent years. During the last five years, catches were above the long-term average catch (243,288 t) but have been declining over that period (especially in Canada). Landings between 2001 and 2008 were predominantly comprised of fish from the very large 1999 year class, with a cumulative removal (through 2023) from that cohort of 2.13 Mt [1 Mt = 1 megatonne = 1 million metric tonnes]. Through 2023, the cumulative catches of the 2010, 2014, and 2016 year classes were 2.56 Mt, 1.76 Mt, and 1.13 Mt, respectively. In the 2023 catch, the 2021 cohort was the largest (35%), followed by the 2020 cohort (25%), and then the 2016 cohort (13%).

Data and assessment

This Joint Technical Committee (JTC) assessment depends on fishery landings (1966–2023), an acoustic survey biomass index of age-2+ fish (Figure b) and age compositions (1995–2023), a relative index of age-1 fish (Figure c; 1995–2023), fishery age compositions (1975–2023), and mean weight-at-age data (1975–2023). 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 survey shows a decline from 2019 (the fourth highest of the series) to 2023 (the third lowest of the series). 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 are no data to inform the size of the 2023 year class.

Figure b. Acoustic survey biomass index of age-2+ fish (Mt). Approximate 95% confidence intervals are based on sampling variability (intervals without the additional squid/Pacific Hake apportionment uncertainty included in 2009, black line).

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). 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 the distribution or Pacific Hake, 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.

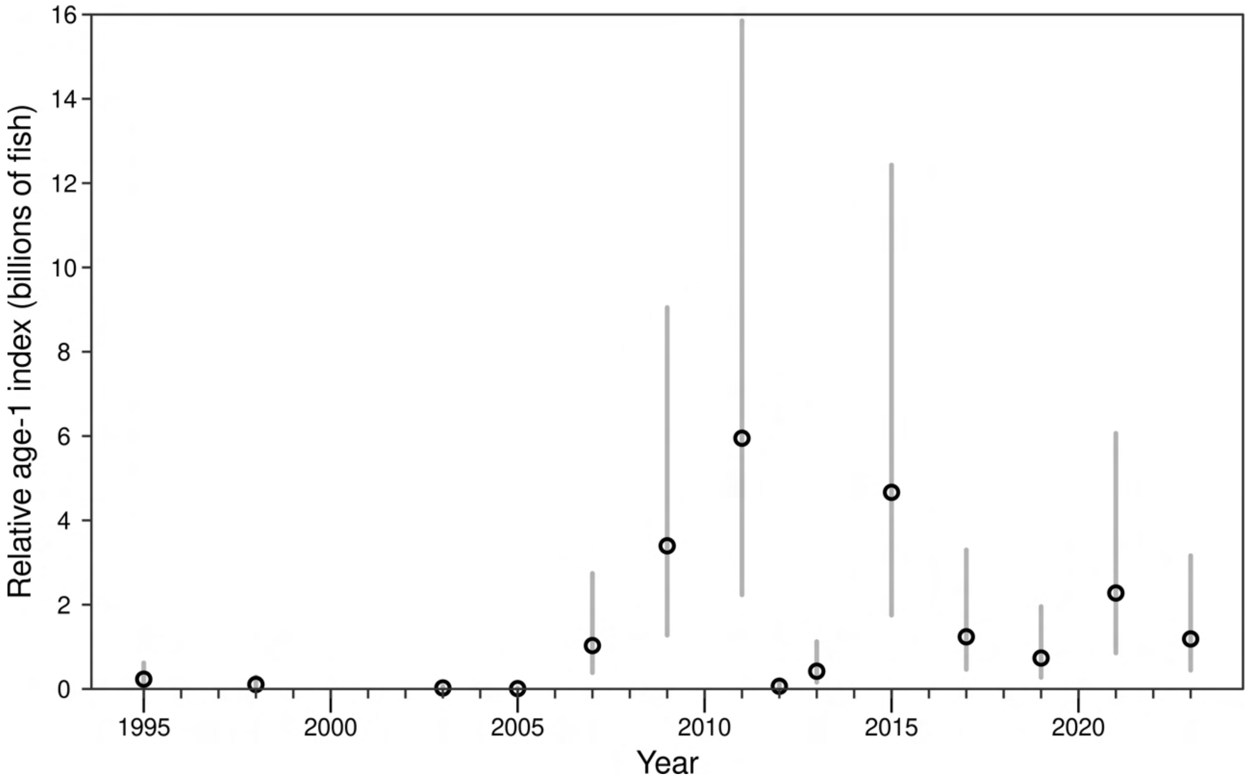

Figure c. Relative index of age-1 fish (numbers of fish) and approximate 95% confidence intervals based on sampling variability. The index is relative because the survey does not attempt to sample all available age-1 fish and the analysis does not include kriging as is done to estimate age-2+ biomass.

This 2024 assessment retained the same general population dynamics structure as the base assessment model from 2023 and again is configured using Stock Synthesis. Updates in this assessment include incorporating the new biomass estimate and age-composition data from the acoustic survey conducted in 2023, fishery catch and age-composition data from 2023, weight-at-age data for 2023, the 2023 age-1 index estimate, and minor changes to pre-2023 data. In addition, a new model-based approach was used to develop the input weight-at-age matrix, and time-varying temperature-dependent maturity was introduced to better inform fecundity.

This assessment continues to use (since 2014) time-varying (rather than constant) selectivity to maintain flexibility within the fishery 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 and improved upon with time-varying estimates of maturity. 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.

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.

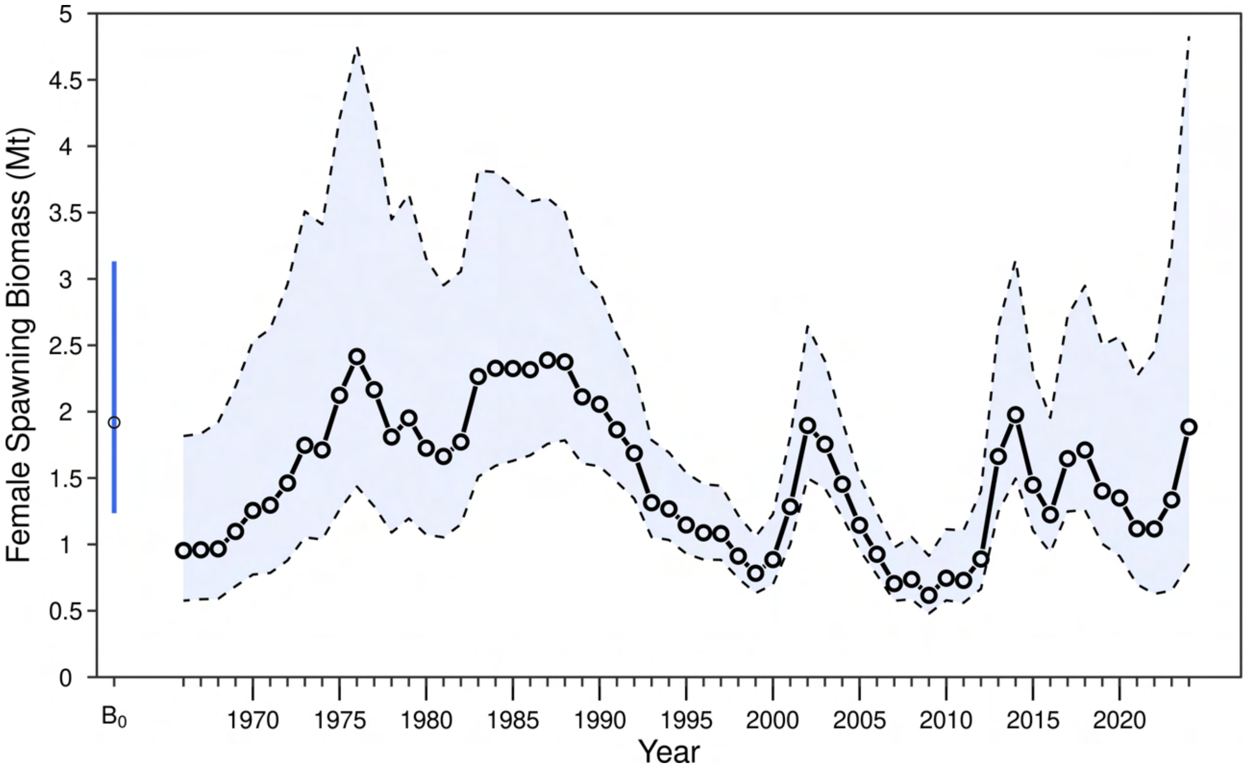

Figure d. Median (solid line) of the posterior distribution for beginning of the year female spawning biomass (B_t in year t; Mt) through 2024 with 95% posterior credibility intervals (shaded area). The left-most circle with a 95% posterior credibility interval is the estimated unfished equilibrium biomass, B_0.

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 2003 as the very large 1999 year class matured. The 1999 year class largely 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 0.616 Mt in 2009. Median female spawning biomass is estimated to have peaked again in 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 mostly declined from 2018 to 2022 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 in 2023 and 2024 is due to the expected above-average 2020 and potentially large 2021 cohorts entering maturity and the recent declining trend in catch.

The median estimate of the 2024 relative spawning biomass (spawning biomass at the start of 2024 divided by that at unfished equilibrium, B_0) is 99%. However, the uncertainty is large, with a 95% posterior credibility interval from 45% to 230% (Table b), partly due to remaining unknowns about the size of the potentially large 2021 cohort because the acoustic survey has only provided one year of information about it.

The median estimate of the 2024 female spawning biomass is 1.885 (with a 95% posterior credibility interval from 0.853 to 4.828) Mt. The current estimate of the 2023 female spawning biomass is 1.335 (0.652–3.225) Mt, giving less uncertainty than the estimate from the 2023 assessment of 1.910 (0.757–5.610) Mt. The current median is reduced from that in the 2023 assessment due to the tail of the distribution being greatly curtailed and a slight lowering of the lower end of the interval. The decrease appears to be due to the addition of the age-2+ biomass index pulling down the estimated biomass for recent years, plus the addition of the survey age compositions lowering the estimated 2020 recruitment.

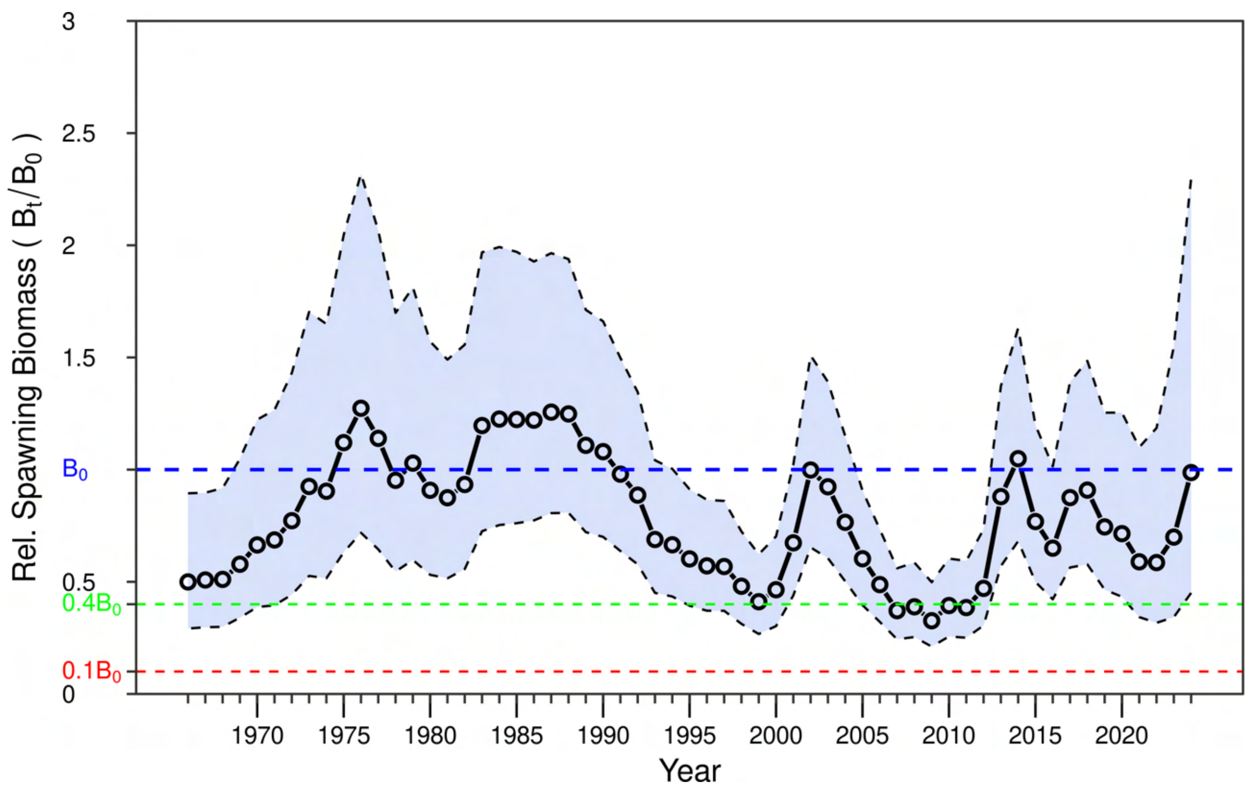

Figure e. Median (solid line) of the posterior distribution for relative spawning biomass (B_t/B_0) through 2024 with 95% posterior credibility intervals (shaded area). Dashed horizontal lines show 10%, 40%, and 100% of the unfished equilibrium (B_0).

Table b. Recent trends in estimated beginning of the year female spawning biomass (SB; kt) and SB relative to estimated SB at unfished equilibrium (Rel. SB; %).

Year	SB 2.5th percentile	SB Median	SB 97.5th percentile	Rel. SB 2.5th percentile	Rel. SB Median	Rel. SB 97.5th percentile
2015	1,105.1	1,447.8	2,310.3	50.0%	76.9%	119.8%
2016	940.3	1,223.3	1,954.2	42.2%	65.0%	101.5%
2017	1,248.0	1,646.4	2,720.8	56.4%	87.5%	139.1%
2018	1,259.3	1,711.2	2,948.4	57.8%	90.9%	148.5%
2019	1,004.3	1,402.1	2,500.9	46.5%	74.5%	125.4%
2020	911.0	1,349.6	2,566.1	43.3%	71.5%	125.4%
2021	699.4	1,118.3	2,268.8	34.3%	58.9%	110.0%
2022	627.0	1,116.3	2,453.2	31.7%	58.6%	118.5%
2023	652.5	1,335.5	3,224.8	34.2%	69.9%	154.7%
2024	853.2	1,884.9	4,828.4	45.0%	98.7%	229.8%

Recruitment

The addition of 2023 data changes the estimates of absolute recruitments for the most recent years, while the improved methods for modeling temporal weight-at-age and spatio-temporal maturity have slightly changed some historical estimated recruitments.

The estimate of 2020 recruitment in last year's assessment was based on only two years of data and thus was highly uncertain. It suggested the 2020 cohort could potentially be huge (95% credible interval: 2.9–47.6 billion fish), but now with information from the age-2+ biomass index and survey age-composition data the 2020 cohort looks to be less but still above average (95% interval: 2.1–12.7 billion fish). The median has consequently fallen from 11.4 to 4.7 billion fish between the two assessments.

The 2021 recruitment is estimated to be potentially large, whereas it was estimated to be below average in last year's assessment (with very limited data); the median has increased by 9.7 billion fish. The general notion remains that recent Pacific Hake recruitment is highly uncertain, and estimates for recent years (based on limited data) can change substantially.

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–recruitment relationship.

Year	Recruitment 2.5^{th} percentile	Recruitment Median	Recruitment 97.5^{th} percentile	Rec. Deviations 2.5^{th} percentile	Rec. Deviations Median	Rec. Deviations 97.5^{th} percentile
2014	5,667.0	8,255.9	14,926.2	1.701	2.150	2.591
2015	8.5	34.2	122.2	-4.674	-3.335	-2.134
2016	3,715.2	5,638.3	10,990.7	1.334	1.810	2.299
2017	848.7	1,565.0	3,553.1	-0.127	0.499	1.152
2018	112.1	397.2	1,287.3	-2.130	-0.887	0.130
2019	46.9	273.3	1,015.1	-2.959	-1.264	-0.063
2020	2,063.0	4,747.9	12,728.4	0.849	1.615	2.455
2021	4,085.1	10,187.3	29,499.4	1.556	2.394	3.281
2022	288.9	1,881.2	8,858.6	-1.148	0.699	2.142
2023	42.6	979.1	20,271.6	-3.038	0.014	3.018

Pacific Hake have low to moderate recruitment with occasional large year classes (Table c and Figure f). 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 and a very strong 2010 year class. Above average year classes occurred in 2014 and 2016, which have been sustaining the fishery in recent years, with small year classes for all other years from 2011–2019 (median recruitment well below the mean of all median recruitments).

The 2020 cohort is estimated to be above average, and the 2021 cohort is estimated to be potentially large from limited fishery data and the 2023 survey. The 2022 cohort was observed by the age-1 index in 2023, suggesting it is average to below average in size.

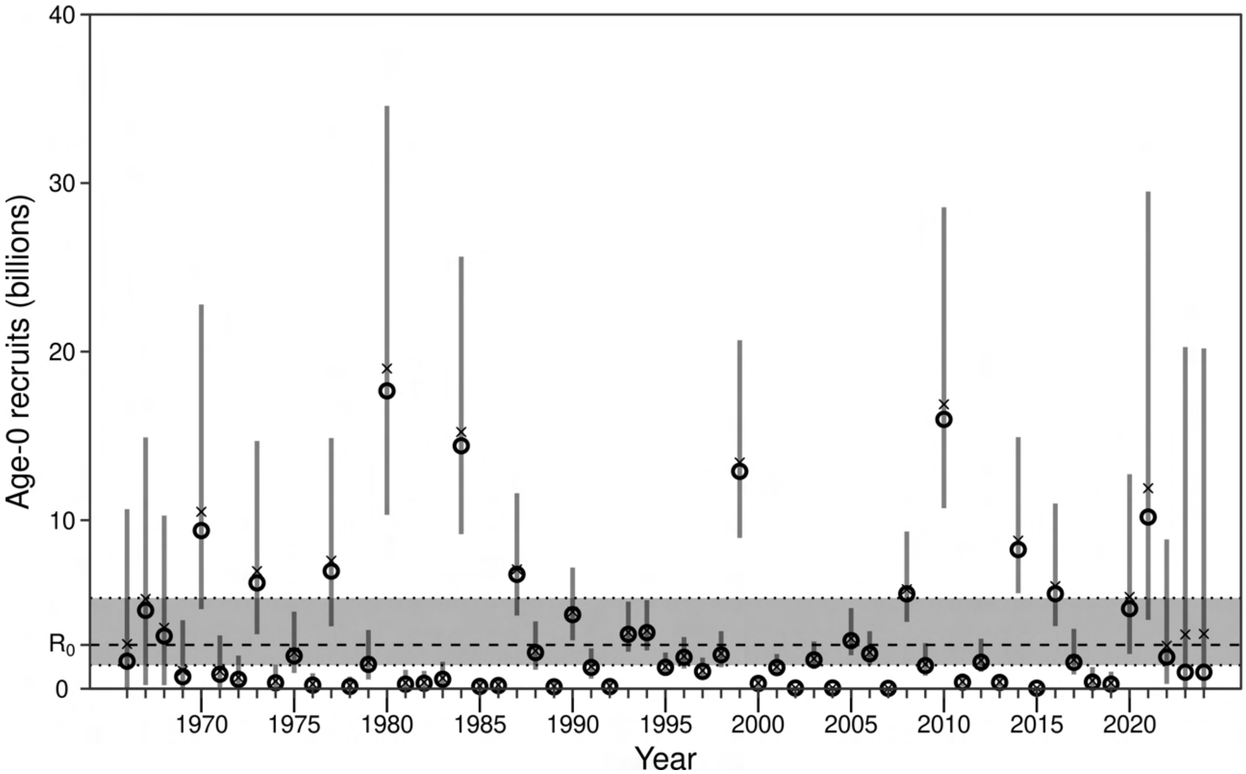

Figure f. Medians (solid circles) and means (X) of the posterior distribution for recruitment (billions of age-0 fish) with 95% posterior credibility intervals (vertical lines). The median of the posterior distribution for mean unfished equilibrium recruitment (R_0) is shown as the horizontal dashed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

There is no information in the data to estimate the sizes of the 2023 and 2024 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 modelled age of 3 (observed as age-2 fish the previous year) without a survey in the most recent year and a modelled age of two (observed as age-1 fish) with a survey.

Default harvest policy

The default $F_{40\%}$–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 - SPR(F))/(1 - $\text{SPR}_{40\%}$), where $\text{SPR}_{40\%}$ is an SPR of 40%; it is reported here interchangeably as a proportion or a percentage. A relative fishing intensity above 1.0 means fishing at a rate above $F_{\text{SPR}=40\%}$.

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

Year	Rel. Fishing Intensity 2.5^{th} percentile	Rel. Fishing Intensity Median	Rel. Fishing Intensity 97.5^{th} percentile	Exploit. Fraction 2.5^{th} percentile	Exploit. Fraction Median	Exploit. Fraction 97.5^{th} percentile
2014	0.393	0.623	0.858	0.045	0.071	0.094
2015	0.264	0.455	0.666	0.042	0.067	0.087
2016	0.477	0.736	0.983	0.057	0.093	0.122
2017	0.504	0.793	1.135	0.077	0.128	0.168
2018	0.441	0.722	1.030	0.060	0.104	0.142
2019	0.497	0.803	1.078	0.067	0.122	0.173
2020	0.363	0.625	0.873	0.072	0.136	0.203
2021	0.353	0.624	0.877	0.072	0.145	0.232
2022	0.330	0.618	0.914	0.052	0.116	0.213
2023	0.267	0.551	0.872	0.026	0.066	0.138

Exploitation status

The median estimated relative fishing intensity on the stock is below the management level of 1.0 for all years (see Table d for recent years and Figure g).

Over the last five years, it was the highest in 2019 at 80.3%, dropped in 2020 to 62.5%, then remained stable for 2021 and 2022 at 62.4% and 61.8% respectively. The 3-year stable trend from 2020–2022 was ended in 2023 when the relative fishing intensity dropped to 55.1% (Table d and Figure g).

The median exploitation fraction (catch divided by biomass of fish of age-2 and above) peaked in 1999 and 2008 (Figure h). The median exploitation fraction has decreased from a recent high in 2021 of 0.15 to 0.07 in 2023, which is a comparable level to 10 years ago (Table d and Figure h).

Although there is a considerable amount of imprecision around these estimates due to uncertainty in recruitment and spawning biomass, the 95% posterior credibility interval of relative fishing intensity was below 1.0 from 2012–2016 and again in 2020–2023 (Figure g).

Management performance

Over the last decade (2014–2023), the mean coast-wide utilization rate (proportion of catch target removed) has been 63.5% and catches have been below coast-wide targets (Table e). From 2019 to 2023, the mean utilization rates differed between the United States (67.4%) and Canada (48.1%), though Canada's was higher than the U.S.'s in 2020. From 2020 the Canadian rate steadily declined to a time-series low of 14.4% in 2023, and the U.S. rate fell to 52.1% in 2023. 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 implemented in 2022 and 2023. Total landings last exceeded the coast-wide quota in 2002 when utilization was 112%.

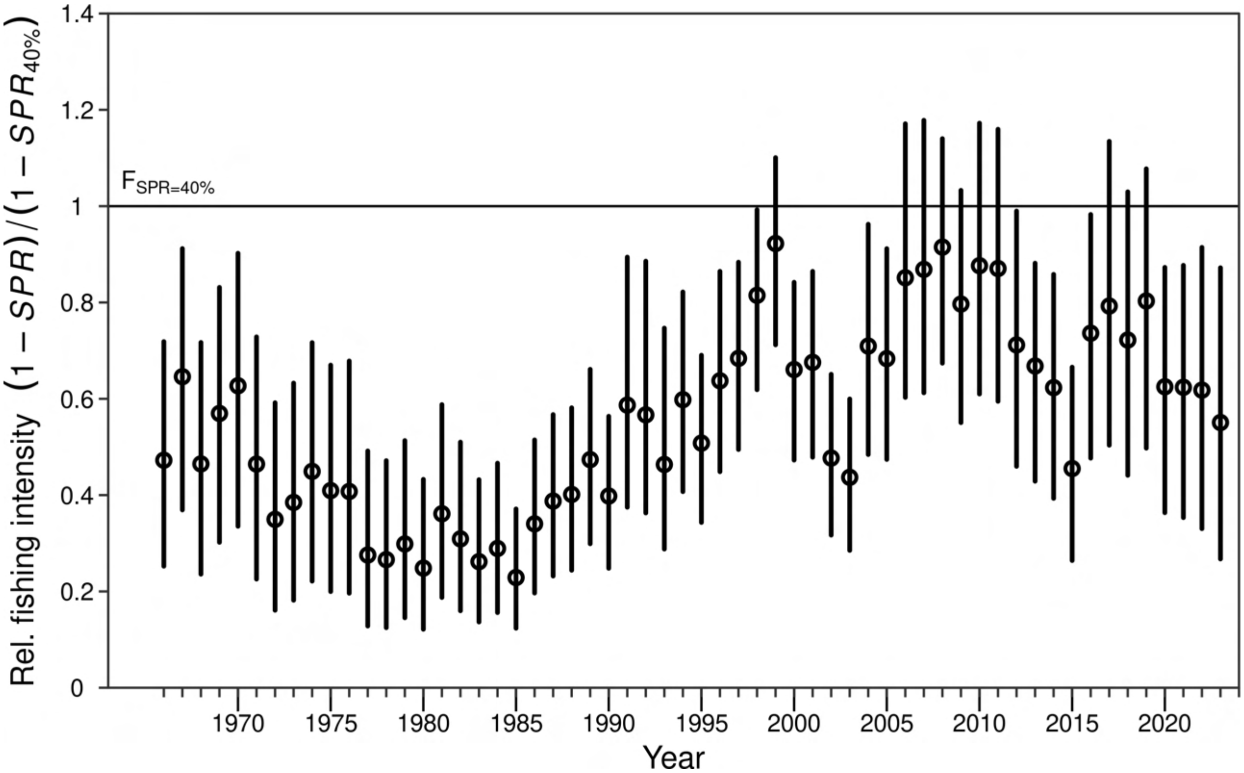

Figure g. Trend in median relative fishing intensity (relative to the $F_{\text{SPR}=40\%}$ management level) through 2023 with 95% posterior credibility intervals. The $F_{\text{SPR}=40\%}$ management level defined in the Joint U.S.-Canada Agreement for Pacific Hake is shown as a horizontal line at 1.0.

Figure h. Trend in median exploitation fraction (catch divided by age-2+ biomass) through 2023 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. All landings and catch targets are given in tonnes.

Year	U.S. landings	Canada landings	Total landings	U.S. prop. of total catch	Canada prop. of total catch	U.S. catch target	Canada catch target	Total catch target	U.S. prop. of catch target removed	Canada prop. of catch target removed	Total prop. of catch target removed
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	39,684	193,844	79.5%	20.5%	325,072	114,928	440,000	47.4%	34.5%	44.1%
2016	262,327	69,743	332,070	79.0%	21.0%	367,553	129,947	497,500	71.4%	53.7%	66.7%
2017	354,129	86,721	440,849	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	291,702	31,671	323,372	90.2%	9.8%	402,646	142,354	545,000	72.4%	22.2%	59.3%
2023	240,424	23,557	263,981	91.1%	8.9%	461,750	163,250	625,000	52.1%	14.4%	42.2%

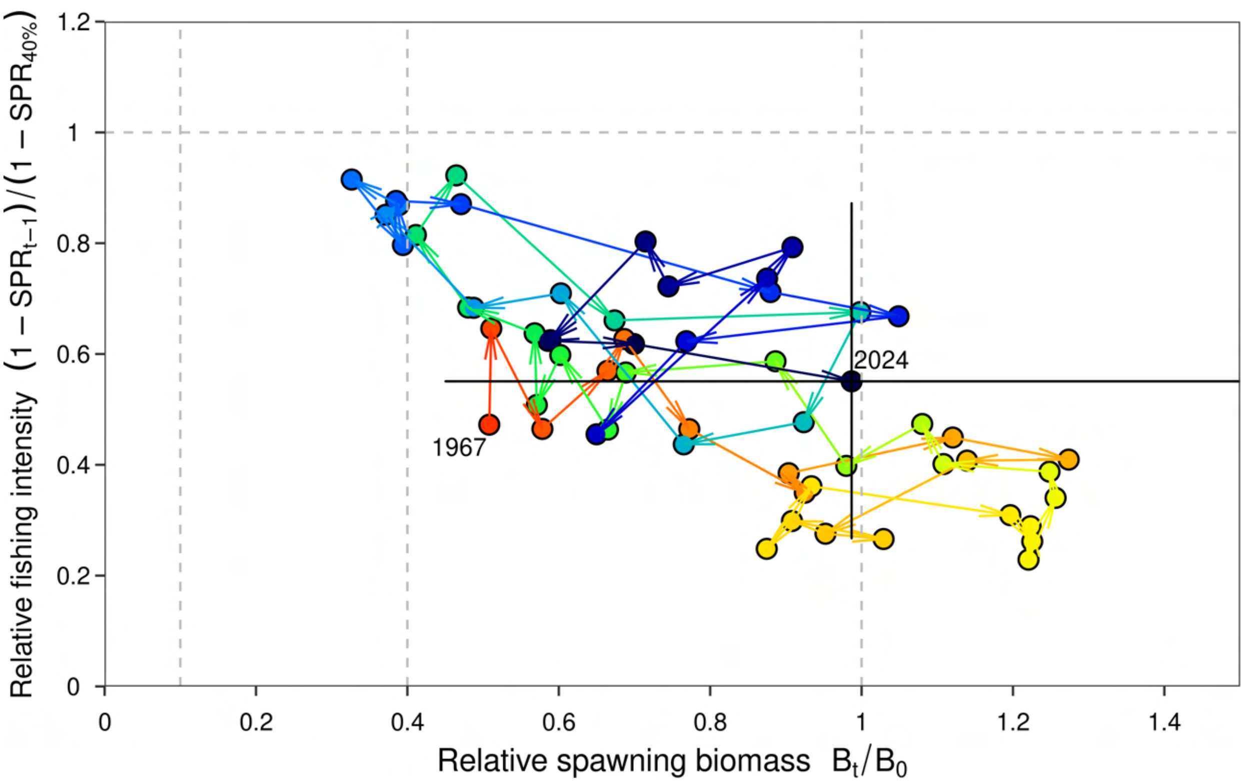

Figure i. Estimated historical path of median relative spawning biomass in year t and corresponding median relative fishing intensity in year $t-1$. Labels show the time series start and end years; labels correspond to year t (i.e., year of the relative spawning biomass). Gray bars span the 95% credibility intervals for 2024 relative spawning biomass (horizontal) and 2023 relative fishing intensity (vertical).

The median relative spawning biomass was above the $B_{40\%}$ reference level in all years except 2007–2011 (Figures e and i), and the median relative fishing intensity has always been below 1.0 (Figure i). Relative spawning biomass increased from the lows in 2007–2012 with above average recruitment in 2008, 2010, 2014, 2016, and 2020. Correspondingly, median relative fishing intensity has remained below 1, and total catch has been declining since the time series high in 2017. While there is large uncertainty in the 2023 estimates of relative fishing intensity and relative spawning biomass, the model estimates a 0.2% joint probability of being both above the target relative fishing intensity ($F_{\text{SPR}=40\%}$) in 2023 and below the relative spawning biomass level of $B_{40\%}$ at the start of 2024.

Reference points

The term 'reference points' is used throughout this document to describe common conceptual summary metrics (Table f). 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). The medians of sustainable yields and biomass reference points are similar to what was reported in the 2023 assessment. The probability that female spawning biomass at the beginning of 2024 is below $B_{40\%}$ is $\text{P}(B_{2024} < B_{40\%}) = 1.3\%$, and of being below $B_{25\%}$ is $\text{P}(B_{2024} < B_{25\%}) = 0.1\%$. The probability that the relative fishing intensity was above the $F_{\text{SPR}=40\%}$ level of 1.0 at the end of 2023 is 0.4%.

Table f. Summary of median and 95% credibility intervals of equilibrium conceptual reference points for the base assessment model. Equilibrium reference points were computed using 1975–2023 averages for mean weight-at-age and baseline selectivity-at-age (1966–1990; prior to time-varying deviations). Dashes (–) indicate values that are static at one value and do not have a credible interval associated with them.

Quantity	2.5%	Median	97.5%
Unfished female spawning biomass (B_0, kt)	1,235	1,919	3,132
Unfished recruitment (R_0, millions)	1,394	2,600	5,383
Reference points (equilibrium) based on $F_{SPR=40\%}$			
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, kt)	409	681	1,127
SPR at $F_{\text{SPR}=40\%}$	–	40%	–
Exploitation fraction corresponding to $F_{\text{SPR}=40\%}$	16.3%	19.1%	22.0%
Yield associated with $F_{\text{SPR}=40\%}$ (kt)	180	317	594
Reference points (equilibrium) based on $B_{40\%}$ (40% of B_0)			
Female spawning biomass ($B_{40\%}$, kt)	494	767	1,253
SPR at $B_{40\%}$	40.7%	43.5%	50.8%
Exploitation fraction resulting in $B_{40\%}$	12.9%	16.8%	20.2%
Yield at $B_{40\%}$ (kt)	177	309	580
Reference points (equilibrium) based on estimated MSY			
Female spawning biomass (B_{MSY}, kt)	297	490	867
SPR at MSY	22.8%	29.6%	45.1%
Exploitation fraction corresponding to SPR at MSY	15.8%	27.0%	36.5%
MSY (kt)	188	336	639

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 a 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 and 2021 cohorts as above average in size, their absolute size remains highly uncertain. This uncertainty propagates directly into current and forecasted estimates of female spawning biomass. The 2023 acoustic survey provided additional information on the size of the 2020 year-class (as well as informed the 2021 year class), and the 2023 age-1 index helped inform the size of the 2022 year class. Collectively, these lessened uncertainty around 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 2024 based on the default $F_{40\%}$–40:10 harvest policy has a median of 747,588 t with a wide range of uncertainty, the 95% credibility interval being 298,355–2,124,832 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 (2019–2023); and constant values for all other parameters.

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 2024 results in a median relative fishing intensity of 0.94 (Table h).

Table g. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year. Catch alternatives are defined by letters a-o and are a constant value across all forecasted years unless otherwise defined in the first column. Acronyms are defined in the glossary (Appendix C).

Catch alternative			**Biomass at**	**Relative spawning biomass**		
	Catch year	**Catch (t)**	**start of year**	**5%**	**50%**	**95%**
			Start of 2024	0.51	0.99	2.01
a:	2024	0	Start of 2025	0.57	1.11	2.23
	2025	0	Start of 2026	0.59	1.13	2.35
	2026	0	Start of 2027	0.57	1.12	2.45
b:	2024	180,000	Start of 2025	0.53	1.06	2.18
	2025	180,000	Start of 2026	0.50	1.04	2.26
	2026	180,000	Start of 2027	0.46	1.00	2.32
c:	2024	225,000	Start of 2025	0.52	1.05	2.16
	2025	225,000	Start of 2026	0.48	1.02	2.23
	2026	225,000	Start of 2027	0.43	0.97	2.29
d:	2024	320,000	Start of 2025	0.50	1.02	2.14
10% reduction	2025	288,000	Start of 2026	0.45	0.98	2.20
each year	2026	259,200	Start of 2027	0.39	0.93	2.24
e:	2024	264,000	Start of 2025	0.51	1.04	2.15
2023 catch	2025	264,000	Start of 2026	0.47	1.00	2.21
	2026	264,000	Start of 2027	0.41	0.94	2.26
f:	2024	350,000	Start of 2025	0.49	1.01	2.13
	2025	350,000	Start of 2026	0.42	0.96	2.17
	2026	350,000	Start of 2027	0.35	0.88	2.20
g:	2024	350,000	Start of 2025	0.49	1.01	2.13
10% reduction	2025	315,000	Start of 2026	0.43	0.97	2.18
each year	2026	283,500	Start of 2027	0.37	0.91	2.23
h:	2024	380,000	Start of 2025	0.49	1.01	2.12
	2025	380,000	Start of 2026	0.41	0.94	2.16
	2026	380,000	Start of 2027	0.33	0.86	2.17
i:	2024	380,000	Start of 2025	0.49	1.01	2.12
10% reduction	2025	342,000	Start of 2026	0.42	0.95	2.17
each year	2026	307,800	Start of 2027	0.36	0.89	2.21
j:	2024	430,000	Start of 2025	0.47	0.99	2.11
	2025	430,000	Start of 2026	0.39	0.92	2.14
	2026	430,000	Start of 2027	0.30	0.83	2.13
k:	2024	545,000	Start of 2025	0.45	0.96	2.08
2022 TAC	2025	545,000	Start of 2026	0.33	0.86	2.08
	2026	545,000	Start of 2027	0.22	0.75	2.05
l:	2024	625,000	Start of 2025	0.43	0.94	2.06
2023 TAC	2025	625,000	Start of 2026	0.30	0.83	2.03
	2026	625,000	Start of 2027	0.18	0.70	1.99
m:	2024	875,262	Start of 2025	0.37	0.88	1.99
Fishing intensity	2025	861,614	Start of 2026	0.22	0.71	1.91
at 100%	2026	782,426	Start of 2027	0.13	0.57	1.86
n:	2024	747,588	Start of 2025	0.40	0.91	2.02
Default HR	2025	772,111	Start of 2026	0.24	0.76	1.97
($F_{SPR=40\%}$–40:10)	2026	717,464	Start of 2027	0.14	0.62	1.91
o:	2024	767,382	Start of 2025	0.39	0.90	2.02
Equal catch	2025	767,382	Start of 2026	0.24	0.76	1.96
($C_{2024} \approxeq C_{2025}$)	2026	712,782	Start of 2027	0.14	0.62	1.91

Table h. Forecast quantiles of Pacific Hake relative fishing intensity (1 - SPR)/(1 - $SPR_{40\%}$), expressed as a proportion. Catch alternatives are defined by letters a-o and are a constant value across all forecasted years unless otherwise defined in the first column. Acronyms are defined in the glossary (Appendix C).

Catch alternative	Catch year	Catch (t)	Relative fishing intensity 5%	50%	95%
a:	2024	0	0.00	0.00	0.00
	2025	0	0.00	0.00	0.00
	2026	0	0.00	0.00	0.00
b:	2024	180,000	0.22	0.43	0.69
	2025	180,000	0.18	0.37	0.63
	2026	180,000	0.16	0.33	0.59
c:	2024	225,000	0.27	0.50	0.78
	2025	225,000	0.22	0.44	0.72
	2026	225,000	0.20	0.40	0.69
d:	2024	320,000	0.35	0.62	0.91
10% reduction	2025	288,000	0.27	0.53	0.83
each year	2026	259,200	0.23	0.46	0.78
e:	2024	264,000	0.30	0.55	0.84
2023 catch	2025	264,000	0.25	0.49	0.79
	2026	264,000	0.23	0.46	0.77
f:	2024	350,000	0.38	0.66	0.94
	2025	350,000	0.32	0.60	0.92
	2026	350,000	0.29	0.57	0.92
g:	2024	350,000	0.38	0.66	0.94
10% reduction	2025	315,000	0.30	0.56	0.88
each year	2026	283,500	0.25	0.49	0.83
h:	2024	380,000	0.40	0.69	0.97
	2025	380,000	0.34	0.63	0.96
	2026	380,000	0.31	0.60	0.97
i:	2024	380,000	0.40	0.69	0.97
10% reduction	2025	342,000	0.32	0.59	0.92
each year	2026	307,800	0.26	0.52	0.88
j:	2024	430,000	0.44	0.73	1.02
	2025	430,000	0.38	0.68	1.02
	2026	430,000	0.35	0.66	1.05
k:	2024	545,000	0.51	0.82	1.11
2022 TAC	2025	545,000	0.45	0.78	1.13
	2026	545,000	0.42	0.78	1.20
l:	2024	625,000	0.56	0.87	1.16
2023 TAC	2025	625,000	0.50	0.85	1.20
	2026	625,000	0.47	0.85	1.26
m:	2024	875,262	0.68	1.00	1.27
Fishing intensity	2025	861,614	0.62	1.00	1.30
at 100%	2026	782,426	0.57	1.00	1.31
n:	2024	747,588	0.62	0.94	1.22
Default HR	2025	772,111	0.58	0.94	1.28
($F_{SPR=40\%}$–40:10)	2026	717,464	0.53	0.94	1.30
o:	2024	767,382	0.63	0.95	1.23
Equal catch	2025	767,382	0.58	0.94	1.28
($C_{2024} \approxeq C_{2025}$)	2026	712,782	0.53	0.94	1.30

Management metrics that were identified as important to the Joint Management Committee and the Advisory Panel in 2012 are presented for 2025, 2026, and 2027 projections (Tables i, j, and k; Figures k, l, and m). 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 these results for intermediate catch values in 2024 (Table i and Figure k). However, interpolation is not appropriate for all catches in 2025 or 2026 because they are conditional on previous year(s) catch levels. This explains why probabilities can sometimes decline (rather than rise) with increased 2025 and 2026 catch levels (Tables j and k; Figures l and m).

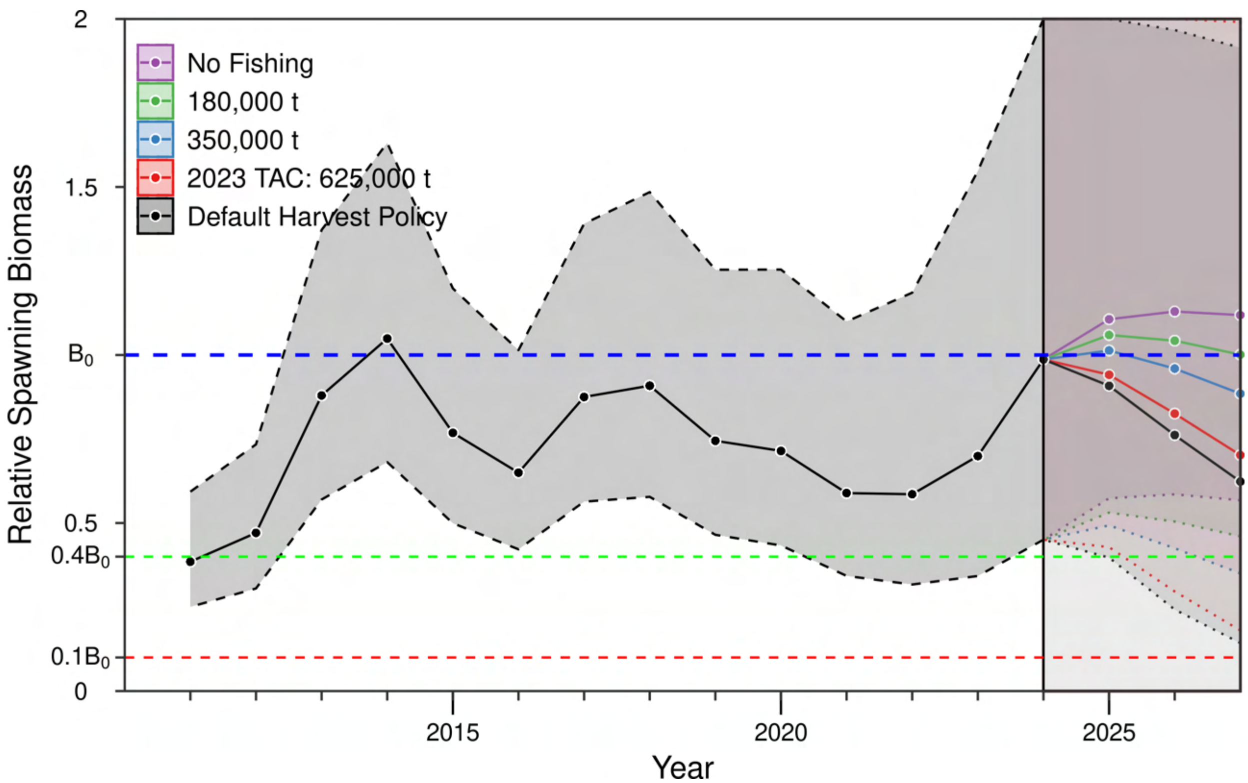

Figure j. Median and 95% posterior credibility intervals of estimated relative spawning biomass to the start of 2024 from the base model and projections to the start of 2027 for several management actions, which are defined in Table g.

With zero catch for the next three years, the biomass has a 3% probability of decreasing from 2024 to 2025 (Table i; Figure j), a 59% probability of decreasing from 2025 to 2026 (Table j), and a 66% probability of decreasing from 2026 to 2027 (Table k).

The probability of the female spawning biomass decreasing from 2024 to 2025 is 36% for a 2024 catch level similar to that for 2023 (scenario e: 2023 catch). For all explored catches, the maximum probability of female spawning biomass at the start of 2025 dropping below $B_{10\%}$ is 0.0% and of dropping below $B_{40\%}$ is 6.7% (Table i and Figure k). As the above average 2014 and 2016 cohorts continue to age, total biomass of these cohorts even without fishing mortality is expected to decrease as losses from mortality outweigh increases from growth. The estimated above-average (yet still highly uncertain) 2020 and 2021 cohorts will continue to play a large role in determining female spawning biomass during the forecast years presented here.

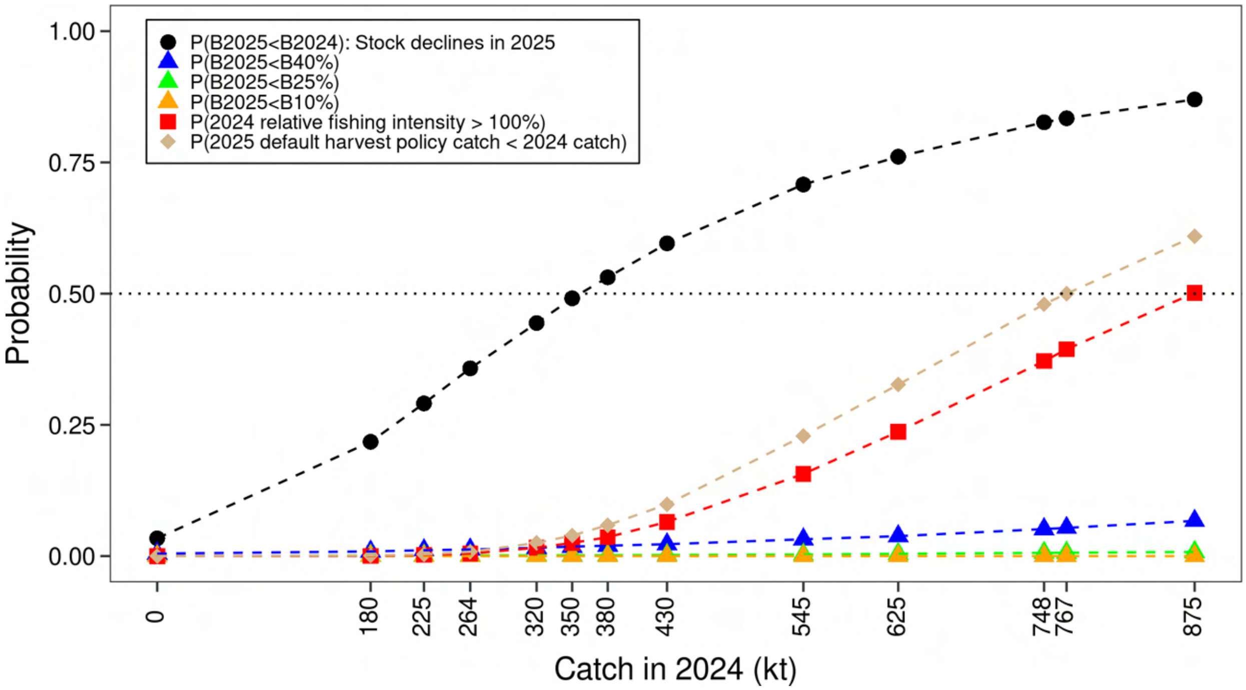

Figure k. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options (explained in Table g) as listed in Table i. The symbols indicate points that were computed directly from model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

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

	Catch (t) in 2024	$B_{2025} < B_{2024}$	$B_{2025} < B_{40\%}$	$B_{2025} < B_{25\%}$	$B_{2025} < B_{10\%}$	2024 Fishing intensity > 100%	2025 Default HR catch > 2024 catch
a:	0	0.03	0.00	0.00	0.00	0.00	0.00
b:	180,000	0.22	0.01	0.00	0.00	0.00	0.00
c:	225,000	0.29	0.01	0.00	0.00	0.00	0.00
d:	320,000	0.44	0.02	0.00	0.00	0.02	0.03
e:	264,000	0.36	0.01	0.00	0.00	0.00	0.01
f:	350,000	0.49	0.02	0.00	0.00	0.03	0.04
g:	350,000	0.49	0.02	0.00	0.00	0.03	0.04
h:	380,000	0.53	0.02	0.00	0.00	0.04	0.06
i:	380,000	0.53	0.02	0.00	0.00	0.04	0.06
j:	430,000	0.60	0.02	0.00	0.00	0.07	0.10
k:	545,000	0.71	0.03	0.00	0.00	0.16	0.23
l:	625,000	0.76	0.04	0.00	0.00	0.24	0.33
m:	875,262	0.87	0.07	0.01	0.00	0.50	0.61
n:	747,588	0.83	0.05	0.01	0.00	0.37	0.48

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	Catch (t) in 2024	**$B_{2025} < B_{2024}$**	**$B_{2025} < B_{40\%}$**	**$B_{2025} < B_{25\%}$**	**$B_{2025} < B_{10\%}$**	**2024 Fishing intensity > 100%**	**2025 Default HR catch > 2024 catch**
o:	767,382	0.83	0.05	0.01	0.00	0.39	0.50

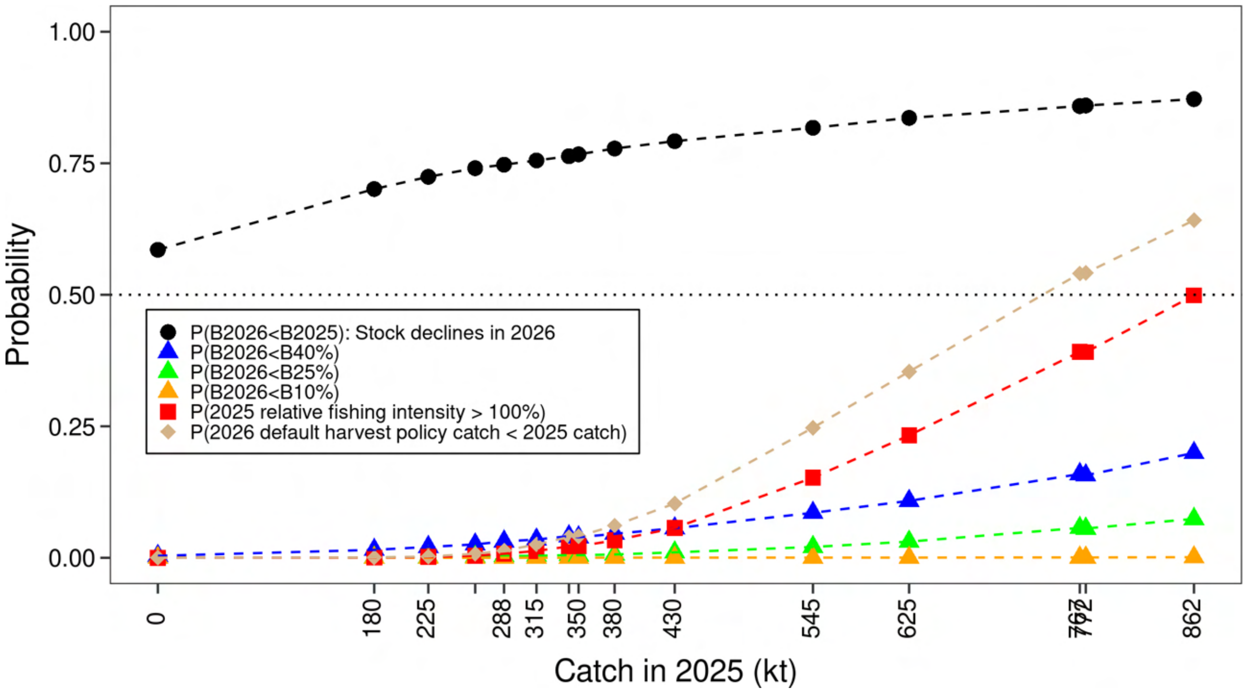

Figure l. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2026 default harvest policy catch for alternative 2025 catch options (including associated 2024 catch; catch options explained in Table g) as listed in Table j. The symbols indicate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

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

	Catch (t) in 2025	$B_{2026} < B_{2025}$	$B_{2026} < B_{40\%}$	$B_{2026} < B_{25\%}$	$B_{2026} < B_{10\%}$	2025 Fishing intensity > 100%	2026 Default HR catch > 2025 catch
a:	0	0.59	0.00	0.00	0.00	0.00	0.00
b:	180,000	0.70	0.02	0.00	0.00	0.00	0.00
c:	225,000	0.72	0.02	0.00	0.00	0.00	0.00
d:	288,000	0.75	0.03	0.00	0.00	0.01	0.01
e:	264,000	0.74	0.03	0.00	0.00	0.00	0.01
f:	350,000	0.77	0.04	0.00	0.00	0.02	0.04
g:	315,000	0.76	0.03	0.00	0.00	0.01	0.03
h:	380,000	0.78	0.05	0.01	0.00	0.03	0.06
i:	342,000	0.76	0.04	0.01	0.00	0.02	0.04
j:	430,000	0.79	0.06	0.01	0.00	0.06	0.10
k:	545,000	0.82	0.09	0.02	0.00	0.15	0.25
l:	625,000	0.84	0.11	0.03	0.00	0.23	0.35
m:	861,614	0.87	0.20	0.07	0.00	0.50	0.64
n:	772,111	0.86	0.16	0.06	0.00	0.39	0.54
o:	767,382	0.86	0.16	0.06	0.00	0.39	0.54

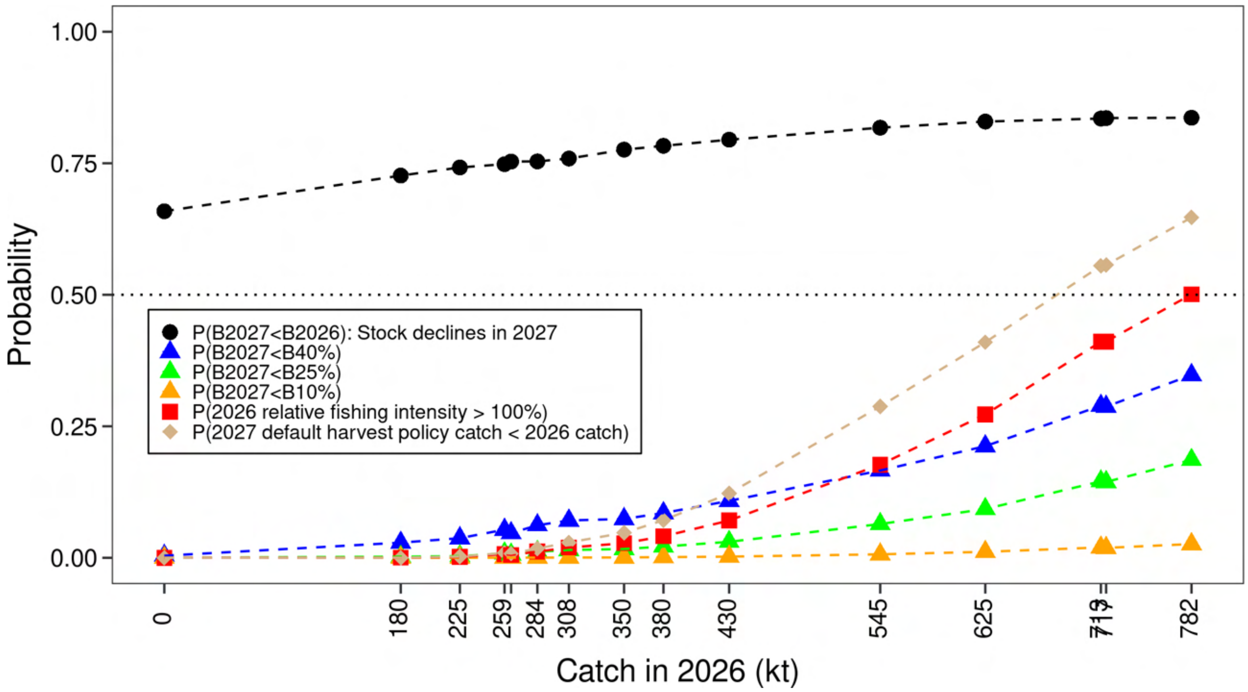

Figure m. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2027 default harvest policy catch for alternative 2026 catch options (including associated 2024 and 2025 catches; catch options explained in Table g) as listed in Table k. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table k. Probabilities related to spawning biomass, relative fishing intensity, and the 2027 default harvest policy catch for alternative 2026 catch options, given the 2024 and 2025 catch levels shown in Tables i and j (catch options are explained in Table g).

	Catch (t) in 2026	$B_{2027} < B_{2026}$	$B_{2027} < B_{40\%}$	$B_{2027} < B_{25\%}$	$B_{2027} < B_{10\%}$	**2026 Fishing intensity > 100%**	**2027 Default HR catch > 2026 catch**
a:	0	0.66	0.00	0.00	0.00	0.00	0.00
b:	180,000	0.73	0.03	0.00	0.00	0.00	0.00
c:	225,000	0.74	0.04	0.00	0.00	0.00	0.00
d:	259,200	0.75	0.05	0.01	0.00	0.01	0.01
e:	264,000	0.75	0.05	0.01	0.00	0.01	0.01
f:	350,000	0.78	0.07	0.02	0.00	0.03	0.05
g:	283,500	0.75	0.06	0.01	0.00	0.01	0.02
h:	380,000	0.78	0.09	0.02	0.00	0.04	0.07
i:	307,800	0.76	0.07	0.01	0.00	0.02	0.03
j:	430,000	0.79	0.11	0.03	0.00	0.07	0.12
k:	545,000	0.82	0.17	0.06	0.01	0.18	0.29
l:	625,000	0.83	0.21	0.09	0.01	0.27	0.41
m:	782,426	0.84	0.35	0.19	0.03	0.50	0.65
n:	717,464	0.84	0.29	0.14	0.02	0.41	0.56
o:	712,782	0.84	0.29	0.15	0.02	0.41	0.56

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 most important are as follows:

1. Continue to conduct research to evaluate ways to improve recent, current, and future estimates of recruitment 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. 2023). Explorations should also consider options for incorporating information on recruitment into the assessment model and the management framework for Pacific Hake. For example, time series could be included in the stock assessment as a standalone data source (similar to the acoustic indices) or improvements could be made to the modeling framework such that these environmental time series could impact the stock–recruitment relationship directly. 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 they are available across international boundaries and updated on a recurring basis, thereby allowing for their use 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 6–9 month forecasts of subsurface (i.e., 100 m depth) temperature from J-SCOPE. Furthermore, the existing management strategy evaluation framework should be used, or further developed, to examine how information on recruitment can inform robust management decisions.

2. Conduct research on estimates of uncertainty for the relative age-1 index and the age-2+ index and investigate alternative ways to utilize survey age-composition information in the assessment model. Bootstrapping of the acoustic survey time series, or related methods, could help incorporate uncertainty related to the target-strength relationship, subjective scoring of echograms, thresholding methods, and methods used to estimate the species mixes for interpreting the acoustic backscatter into the variance calculations. Research should be communicated with those involved in developing the U.S. West Coast Integrated Survey Initiative. The 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 coast-wide population of Pacific Hake. In particular, include indicators 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. This is the thirteenth 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, maturity-at-age data, as well as survey and fishery age-composition data. The assessment depends primarily upon an index of biomass from the acoustic survey for information on the scale of the current population. Age-composition data 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–recruitment 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 2024 base model, implemented using version 3.30.22 of the Stock Synthesis software (Methot, Jr. and Wetzel 2013), differ from the 2023 base model in that the distribution assumed for the relative age-1 index is now a student-t distribution rather than a log-normal distribution (Berger et al. 2023), and maturity-at-age is now year-specific (Section 2.4.2 and Appendix G). All model runs reported in this document are performed in a Bayesian context. Responses to 2023 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 (Figure 1). It is among 18 species of hake from four genera (being the majority of the family *Merluccidae*), 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; Longo et al. In press). 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. 2020a, 2020b). 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 being 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. 2020a) 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 the distribution of Pacific Hake, with a much smaller proportion of the population found in Canadian waters compared to during El Niño years, a trend evident from the acoustic surveys (Figure 2). In general, warmer than average thermal habitat conditions for mature Pacific Hake lead to relatively higher biomass further north and relatively lower biomass around the U.S.–Canadian border, while cooler than average conditions lead to relatively higher biomass of immature Pacific Hake generally spread evenly across their distribution (Malick et al. 2020a). 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 (i.e., 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 recruitment indicated recruitment is associated with eddy kinetic energy, the location of the North Pacific Current bifurcation, and upwelling during maternal preconditioning, as well as with northward long-shore transport and the number of days between storm events during larval stages (Vestfals et al. 2023). Phillips et al. (2022) suggest 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. Temperature was also found to impact the co-occurrence of Pacific Hake and shortbelly rockfish (*Sebastes jordani*, Sebastidae) during the 2014–2016 marine heatwave (Free et al. 2023). An index of abundance for Humboldt Squid (*Dosidicus gigas*) suggests that the abundance of Pacific Hake decreases 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. 2020a, 2020b) and provide a foundation for further research on these topics.

Recent oceanographic trends and large-scale ecosystem conditions, as summarized in NOAA's annual California Current Ecosystem Status Reports, provide insight into potential drivers of Pacific Hake population dynamics and fleet operations. Periods of high productivity are often 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). During 2023 (Leising et al. 2024), basin-scale climate patterns suggest average conditions for ecosystem productivity as El Niño conditions continue to strengthen. Despite being highly variable in strength, upwelling was generally less than in previous years. Weaker upwelling conditions have been associated with higher Pacific Hake recruitment (Vestfals et al. 2023). In the southern California Current Ecosystem, the abundance of Pacific Hake larvae in the CalCOFI survey area has been above average for two consecutive years, with 2023 being the highest since 2011. At the same time, hake predation by bluefin and swordfish were also well above average in recent years (2021 and 2022). Abundance of krill, a common prey of Pacific Hake, was below average in 2023. Lipid-rich copepod biomass was average and relatively stable throughout the summer ('northern' copepod index) of 2023 relative to previous years, but was below average in the winter ('southern' copepod index).

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 2.4.1). Furthermore, the new year-specific maturity-at-age specifically includes a temperature effect from a spatiotemporal model (Section 2.4.2 and Appendix G). Related ongoing research should provide more insights into the specific mechanisms affecting changes in growth and fecundity, which will enable further condition-specific prediction capabilities (e.g., assumptions of growth, or weight at age, and fecundity during forecast years). It is hypothesized that temporal changes in weight-at-age data may be due to ecosystem effects such as prey availability, predator abundance, and ocean temperature (Chittaro et al. 2022).

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. A bilateral agreement on the coast-wide TAC could not be reached in 2020 and 2021; so, catch targets were set unilaterally during these years for the first time since the inception of the Agreement. Catch allocations as specified in the Agreement have since been applied.

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 have also restricted the area and season of fishing to reduce the bycatch of Chinook Salmon (*Oncorhynchus tshawytscha*), depleted rockfish populations, 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 shore-based vessels (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 2023, Canadian hake fishermen were allocated a TAC of 163,250 t, which did not include any carryover quota. Canadian priority lies with the domestic fishery. However, 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 there was Joint-Venture quota allocation was in 2018.

In 2023, 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 is no in-person observer program for the Canadian Pacific Hake fisheries.

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. 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.

In 2021, the Pacific Hake fishery was Canada's largest commercial wild fishery (species with the largest catch), representing 10% of Canada's total landings of all species (www.dfo-mpo.gc.ca). Over CA$19 million in wages was estimated to have been paid to employees of the processing industry in British Columbia in 2021, with an exported value of >CA$60 million in product to Ukraine (>CA$25 million), China, South Africa, Lithuania, and other countries (Fisheries and Oceans Canada 2023).

In the U.S.A., over U.S.$75.1 million in wages is estimated to have been paid to employees in 2021 (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 U.S.$163 million in 2021, including to Ukraine, Nigeria, and Netherlands, which make up about 73% of the total (www.noaa.gov). The total economic impact of the Pacific Hake fishery on the U.S. West Coast in 2021 was U.S.$335 million in income and 4,450 jobs.

The Joint Management Committee (JMC) determined an adjusted (for carryovers) coast-wide TAC of 625,000 t for 2023. The U.S. catch target was set at 461,750 t and the Canadian catch target at 163,250 t. A brief review of the 2023 fishery is presented here by country (Tables 1–3 and Figure 4). Additional information is available in annual U.S. and Canada Advisory Panel reports (Appendices E and D).

1.4.1 Fisheries for Pacific Hake in the United States

The U.S. specified catch target (i.e., adjusted for carryovers) of 461,750 t was further divided among the research, tribal, catcher-processor, mothership, and shore-based sectors. After the tribal allocation of 17.5% (80,806 t) and a 750 t allocation for research catch and bycatch in non-groundfish fisheries, the 2023 non-tribal U.S. catch limit of 380,194 t was allocated to the catcher-processor (34%), mothership (24%), and shore-based (42%) commercial sectors. Reallocation of 45,000 t of tribal quota to non-tribal sectors on September 27 resulted in final quotas for the catcher-processor, mothership, and shore-based sectors of 144,566 t, 102,047 t, and 178,581 t, respectively.

The U.S. fishery for Pacific Hake began on May 1. Prior to 2015, the shore-based sector was allowed to fish starting June 15 north of 42° N latitude (the Oregon–California border) and April 1 between 40° 30'N and 42° N latitudes, whereas the at-sea sectors were allowed to fish starting May 15. Between 2015–2022, the shore-based sector was allowed to fish north of 40° 30'N latitude starting May 15 and south of 40° 30'N latitude starting April 15, although only 5% of the shore-based allocation was released for this early period. Since 2023, all sectors have been allowed to fish starting May 1. Regulations do not allow at-sea processing or night fishing (midnight to one hour after official sunrise) south of 42° N latitude at any time during the year.

The total catch of Pacific Hake in U.S. waters was the 13th highest value ever recorded (Table 1) and the U.S. utilization rate (52.1%) was the lowest it has been since 2015 (see Appendix E for more details). The catcher-processor, mothership, and shore-based sectors caught 74.1%, 32.3%, and 56.2% of their final reallocated quotas, respectively. Tribal landings, which are included in the shoreside sector totals were 0 t. The median fishing depth for the at-sea sectors was the same as last year (Figure 5). The shore-based sector had the largest monthly catches during July, August, and September. While, the at-sea sectors had the largest monthly catches during May, September, and October.

In both U.S. at-sea sectors, age-2, age-3, and age-7 fish, associated with the 2021, 2020, and 2016 year classes, were the most common ages. Both the age-3 and age-7 fish were seen last year in appreciable numbers as age-2 and age-6 fish. The reported proportions at age summarize sampling efforts on 391 catcher-processor hauls and 127 mothership hauls (Table 4). For the catcher-processor sector, the four most abundant age classes (by numbers) seen in 2023 were age-2 (51.3%), age-3 (24.0%), age-7 (8.9%), and age-9 (5.0%); Table 5. For the mothership sector, the four most abundant age classes for 2023 were age-2 (39.6%), age-3 (33.2%), age-7 (7.5%), and age-6 (5.5%) (Table 6).

Age-samples from 66 shoreside trips showed similar age compositions in the catch compared to the at-sea sectors, though not nearly as many age-2 fish. The four most abundant age classes for highest occurrences being for 2023 were age-3 (27.0%), age-7 (19.3%), age-2 (16.4%), and age-9 (11.6%) (Table 7). Age-compositions from the at-sea and shoreside sectors during this last year were more similar than they were the previous year.

1.4.2 Fisheries for Pacific Hake in Canada

The 2023 Canadian Pacific Hake domestic fishery removed 23,557 t from Canadian waters (Table 2), which was 14.4% of the Canadian TAC of 163,250 t. For the second year in a row, 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 and last year's assessment, Berger et al. (2023), for more details).

The shoreside vessels, which land fresh round product onshore, landed 3,657 t in 2023, the lowest on record since 1990, and a little less than the 2022 landings of 3,868 t. The Freezer trawlers, which freeze headed and gutted product while at sea, landed 19,901 t. This was the lowest amount the Freezer trawlers have landed since 2013, despite doubling the number of vessels since then.

Fishing started in early April and ended in November. The general view of the Canadian fleet is that abundance in Canadian waters remained below normal levels in 2023, including the normally-abundant areas outside of Southwest Vancouver Island. Reports of difficulties finding fish in 2023 led to some vessels not leaving the dock, therefore amplifying the effect of low catches. The fish caught in Canada appeared to be mostly from four age classes (see below), with very few smaller fish (less than 500 grams) caught.

The most abundant year classes in the Canadian shoreside catch (by numbers; Table 8) were age-7 (31.5%), age-6 (17.3%), age-9 (13.2%), and age-13 (9.4%). The most abundant year classes in the Canadian freezer-trawler catch (by numbers; Table 9) were age-7 (21.6%), age-9 (19.6%), age-6 (16.0%), and age-13 (13.9%).

2 DATA

Fishery-dependent and fishery-independent data used in this assessment (Figure 7) include the following sources:

- Total catch from all U.S. and Canadian fisheries that targeted Pacific Hake from 1966 to 2023 (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 (1975–2023) and the Canadian fishery (1988–2023), are used to fit the model (Table 10 and Figure 8).
- An age-2+ 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, 2023; Tables 11, 12, and 13; Figures 8 and 9).
- 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, 2023; Table 12; Figure 9).

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.
- Annual proportions of female Pacific Hake at each age that are mature, as developed from a new analysis (Section 2.4.2 and Appendix G) of histological analyses of ovary samples (Table 14; Figure 11).
- Mean observed weight-at-age data from fishery and survey catches (1975–2023; Figures 12–15) and, thus, derived fecundity-at-age as well (Figures 11 and 14).

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 1966–2023 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. 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 1991–2023 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 shoreside 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.

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.

Historically, the fishery for Pacific Hake has been well covered by observers with slight differences in coverage by sector. Currently, U.S. shore-based vessels carry observers and are required to retain all catch and bycatch for sampling by plant observers. Vessels participating in the U.S. at-sea sectors are also required to have observers on board and have since 1990. U.S. foreign and Joint-Venture vessels had varying levels of coverage from 1975–1990 ranging from 21–100% coverage. Canadian Joint-Venture and Canadian freezer-trawler vessels 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 and in 2022 the decision was made to stop providing observers on board all Canadian vessels. Early in 2022 a sampling plan designed by Canadian managers, scientists, and the sampling contractor, Archipelago Marine Research Ltd. (AMR), was put into place to ensure the ongoing sampling of Pacific Hake on Canadian vessels (see Section 2.1.2). 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.

2.1.2 Fishery biological data

Biological information from the U.S. at-sea sectors 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 collected 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.

Since 1991, biological samples from the U.S. shore-based sector have been sampled by port samplers located where there are substantial landings of Pacific Hake, primarily Eureka, Newport, Astoria, and Westport. Port samplers took one sample per offload (or trip) consisting of 100 randomly selected fish for individual length and weight. From those 100 fish, typically 20 fish were randomly subsampled for otolith extraction.

When there were observers (1996–2019) aboard Canadian freezer trawlers, they collected 50 otoliths and 300 lengths per sample, sampling once per day during trips that on average last approximately seven days. Since 2022, freezer-trawler employees have collected fish for sampling from two tows per trip and delivered them to the dock as frozen specimens where they are eventually sampled for length, weight, sex, and otoliths. Each delivery consists of approximately 100 fish in two separate bags. The bags each hold approximately 50 fish which were removed from a single tow. Due to unforeseen circumstances while at sea, some trips did not deliver any bags and some only delivered single bags upon arrival from a trip.

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

In years when there was a Canadian Joint-Venture fishery, length samples were collected every second day of fishing operations and otoliths were collected once per week. Length and age samples were taken randomly from a given codend. The sample weight from which biological information was collected was inferred from length-weight relationships.

The sampling unit for shore-based samples is the trip, while the haul is the primary unit for the at-sea samples (Table 4). There is no least common denominator for aggregating at-sea and shore-based samples because detailed haul-level information is not recorded for shore-based trips and hauls sampled in the at-sea sectors 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 (1975–2023) confirm the well-known pattern of large cohorts born in 1973, 1977, 1980, 1984, 1987, 1999, 2008, 2010, 2014, and 2016, and suggests large cohorts for 2020 and 2021 (Table 10 and Figure 8). Recent age-composition data still easily track the 2010 cohort, as well as the large cohorts born since then (Table 10 and Figure 8). Currently, the 2021 cohort is the largest observed cohort in the U.S. at-sea sectors (Tables 5–6), the 2020 cohort is the largest observed cohort in the U.S. shore-based sector (Table 7), and the 2016 cohort is 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. For the combined data in 2023, the 2021 cohort was the largest (35%), followed by the 2020 cohort (25%), and then the 2016 cohort (13%). For the combined data in 2022, the 2020 cohort was the largest (32%), followed by the 2016 cohort (24%), and then the 2014 cohort (15%).

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 but 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 2.4.1) 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 are not fit explicitly in the base model presented here, the presence of the 2008 and 2010 year classes have been clearly observed in length data from the U.S. fishery sectors and the 2014 year class has been apparent since 2016.

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, 2021, and 2023 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 2023 survey covered U.S. and Canadian waters from Point Conception to north of Haida Gwaii using 116 transects (Figure 2). In the U.S.A., transects were mostly separated by 10 nmi; six transects were dropped 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 NOAA Ship Bell M. Shimada and the Canadian Coast Guard Ship Sir John Franklin worked collaboratively to complete the full extent of the survey in 2023.

Distributions of the backscatter of Pacific Hake plotted for each acoustic survey since 1995 illustrate the variable spatial patterns across time of age-2+ fish (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 partially due to environmental and/or climatic factors. The 1998 acoustic survey is notable because it shows an extreme northward distribution that is thought to be related to the strong 1997–1998 El Niño. In contrast, the distribution of Pacific Hake during the 2001 acoustic survey was compressed into the lower latitudes off the coast of Oregon and Northern California following the 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 because 2013 had 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, which is likely a result of having large proportions of both the 2010 and 2014 cohorts (Figure 2). Weak 2019 El Niño conditions decreased in their prevalence starting in March of that year, leading to neutral conditions by July. Consequently, during the 2019 survey Pacific Hake were found 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. During the 2021 survey, the majority of Pacific Hake were found in U.S. waters, congruent with the continuation of La Niña conditions in the California Current from 2020 to 2021. Despite the switch to El Niño conditions in April of 2023, very few fish were seen in Canadian waters during the 2023 survey. 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. 2020b; Phillips et al. 2023).

During the acoustic surveys, mid-water trawls are made opportunistically to determine the species composition of the 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 ($k_{min} = 10$) 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).

Starting in 2021, the EK 60 echosounders were replaced with EK 80 echosounders, and thus, survey estimates from years using the new echosounders are scaled by factor of 1.06 to convert the EK 80 to EK 60 acoustic data. 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 9) and age compositions (Table 11 and Figure 8) 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.

Estimated age-2+ biomass in the survey increased steadily over the four surveys conducted in 2011–2013 and 2015 (Table 12 and Figure 9). It decreased in 2017 to 1.42 Mt, then increased to 1.72 Mt in 2019, and has since decreased to 0.91 Mt in 2023. The 2023 survey age composition was made up of 50.58%, 24.66%, 8.09%, 5.38%, and 2.92% from the 2021, 2020, 2016, 2014, and 2017 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). Estimates of country-specific age-2+ biomass are also provided (Table 13).

A separate relative age-1 index (numbers of fish) is used to fit the assessment model and inform recruitment. For the 2013–2021 assessments (Hicks et al. 2013; Johnson et al. 2021), the relative age-1 index was only explored as a sensitivity and not included in the base model. The relative index of age-1 fish fit to in this assessment was estimated similarly to previous years. like the age-2+ index, data collected using EK 80 echosounders are scaled by a factor of 1.06 to account for differences between the EK 60 and EK 80 echosounders. Note that, in error, this scaling factor was not applied to the 2021 estimate in the 2022 (Edwards et al. 2022) and 2023 (Berger et al. 2023) assessments. The index indicates relative changes between years, not absolute values, and confirms the large year classes in 2008, 2010, 2014, and 2016, and suggests large cohorts for 2020 and 2022 (Table 12 and Figure 3).

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 (e.g., 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 informs recruitment such that the direction of cohort strength (i.e., weak, strong, or neutral) remains unchanged in subsequent assessments even after being informed by more data. The utility of an informed recruitment signal is far greater than an uninformed recruitment assumption. Finally, the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey team supports its use in the stock assessment and is committed to continually evaluating and refining approaches to improve the 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, were 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). These primarily include those listed below.

- Fishery and survey length compositions.
- Fishery and survey age-at-length compositions.
- Calculation of a reliable fishery catch-per-unit-effort (CPUE) metric is particularly problematic for Pacific Hake, and it has never been used as an index for the assessment of this stock (see Hicks et al. 2013 for more details).
- 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 1977–2023).
- Northwest Fisheries Science Center/Southwest Fisheries Science Center/PWCC coast-wide juvenile Pacific Hake and rockfish surveys (2001–2023). However, the JTC is analysing the age-0 Pacific Hake data from these surveys in collaboration with researchers from the Southwest Fisheries Science Center and Australia, to investigate potential for developing an early indication of potential cohort strength.
- 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 (related to previous bullet).
- 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. prior to 1975 but currently not available in electronic form or too incomplete to allow for their analysis with methods consistent with more current sampling programs.
- Northwest Fisheries Science Center winter 2016 and 2017 acoustic research surveys of spawning Pacific Hake.

2.4 Externally analyzed data

2.4.1 Weight-at-age

A matrix of empirically derived population weight-at-age data by year (Figures 12–15) is used in the current assessment model to translate numbers at age to biomass at age. Annual weight-at-age data was modelled from biological samples pooled from all fisheries and summer surveys for the years 1975 to 2023 (Figures 12–15). Samples from winter and research surveys were not included, nor were samples from near-shore areas. Past investigations into calculating weight-at-age data for the fishery and survey independently showed little impact on model results, and thus, a single matrix is used for all fleets and beginning and middle-of-the-year population weight-at-age.

New for this assessment, a generalized linear mixed model (GLMM) with a lognormal distribution was used to model weight-at-age data external to the assessment. Weight was thought to relate to a smoothed effect of age between ages zero and fifteen; random effects for cohort and year; and fixed effects for sex. The model is similar to models investigated for Walleye pollock off of Alaska, where models with correlations between age, cohort, and year were found to best fit the data (Cheng et al. 2023). Here, all unsexed fish were removed from the analysis given the small sample sizes. Weights from fish ages 15 and above for each year were pooled, and thus, ages 15–20 are assumed to have the same weight-at-age. Estimated parameters from this model were used to predict weight for ages zero to fifteen from 1975 to 2023 for each sex. The means of annual, age-specific estimates across both sexes were used for input into the assessment model. The number of samples (Figure 13) is generally proportional to the amount of catch.

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 modelled using the empirical weight-at-age data from 2021 (Figure 12). Prior to 1975, weight-at-age input to Stock Synthesis is assumed to be equal to the mean of all available years for each respective age (1975-2023) (Figure 12). Forecast weight-at-age data are based on age-specific means from the most recent five years (2019–2023), consistent with forecast selectivity (Figure 12).

The use of empirical weight-at-age data 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 growth relationships. Previous attempts to explicitly model year- and cohort-specific growth were not successful for Pacific Hake and have not been revisited since Stewart et al. (2011). The empirical weight-at-age 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).

2.4.2 Maturity and fecundity

Maturity-at-age has always been modelled external to the assessment but up through the the 2023 assessment (Berger et al. 2023) the maturity ogive was time-invariant. Starting with the 2024 assessment, annual age-based maturity ogives (Figure 11) were developed using the same data, i.e., histological estimates of functional maturity, but fit with a spatiotemporal GLMM. The current data set is comprised of 2,836 ovaries with information on histological estimates of functional maturity. The samples were collected from the acoustic survey, winter and summer acoustic research trips, U.S. catcher-processor vessels by observers in the U.S. At-Sea Hake Observer Program, and the U.S. West Coast Groundfish Bottom Trawl Survey (Table 14) since 2009. Samples from south of Point Conception (34.44° N) have been excluded from maturity analyses since 2018 (Edwards et al. 2018) because they were thought to mature at earlier ages and smaller sizes. Samples from Canada were excluded from this analysis because the spatiotemporal resolution was insufficient and led to model-convergence issues. Additional samples are available to update the maturity relationship (including samples collected from Canadian waters since 2018) but have yet to be analyzed.

The spatiotemporal GLMM used to estimate the probability of being functionally mature included an estimated spatial field, spatially varying coefficients for the quadratic function of age, and year effects as a quadratic function of subsurface (130.67 m) temperature indices in the domain of the West Coast Groundfish Bottom Trawl Survey. The stochastic partial differential equation approximation to Gaussian Random Fields (Lindgren et al. 2011) was used to approximate the spatial surface with a series of estimated random effects. The temperature covariate has the potential to add mechanistic relationships to the modeling and reduce uncertainty in years where no or few samples are collected. Annual maturity-at-age was then predicted for each year since 2009 using estimated coefficients for non-ASHOP samples and day 278 (i.e., October 5th). Projections were also made forward in time to 2023 using available temperature indices. This forward projection was needed because maturity information was not sampled in 2022 and data from 2023 have yet to be analyzed. More detailed information on the modeling and projection methods is available in Appendix G.

Time-varying fecundity at age (Figure 14) was previously modeled using year-specific weight-at-age values multiplied by maturity-at-age (Berger et al. 2019). For this assessment, the maturity-at-age is also year specific. The same methods were used to estimate early (before 2009) and projection period maturity as was done for the weight-at-age data. Additionally, 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 in the population dynamics model (Figure 11).

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.

Tissue samples have been collected from many of the same fish from which ovaries were sampled. In the future, these tissue samples may help determine whether the fish south of 34.44° N are from the same population as the rest of the coastal population via genetic analyses.

2.4.3 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 assessments have utilized the cross- and double-read 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 was consistent with 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.

2.5 Estimated parameters and prior probability distributions

Several prior distributions (Table 15) 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 (Hoenig 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 an alternative prior distribution altogether based on a life history meta-analysis Hamel and Cope (2022). The Hamel-Cope prior used a lognormal prior distribution with a median of 0.22 (based on a maximum age of 25) 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 relationship is based on the median (0.79) and the 20th (0.67) and 80th (0.87) percentiles from the meta-analysis of the family Gadidae (Myers et al. 1999) 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 degrees 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

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

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 (n_{eff}) associated with this likelihood is given by

$$n_{\text{eff}} = \frac{1}{1+\theta} + \frac{n\theta}{1+\theta}. \tag{2}$$

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 (M-I) data-weighting method (McAllister and Ianelli 1997) that was used for assessments prior to 2018 (Table 16) and as a sensitivity here (see Section 3.8). In short, the M-I 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 $\log\theta_{\text{fish}}$ and $\log\theta_{\text{surv}}$ tends to lead to inefficient sampling of $\log\theta_{\text{surv}}$ because many samples occur in a part of the parameter space where the effective sample size multiplier, $\theta_{\text{surv}}/(1+\theta_{\text{surv}})$, 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 $\log\theta_{\text{surv}}$. The current prior on $\log\theta_{\text{surv}}$ can be associated with an approximately uniform prior of the weight $\theta_{\text{surv}}/(1+\theta_{\text{surv}})$, 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 $\log\theta_{\text{fish}}$ and $\log\theta_{\text{surv}}$ 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 M-I 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 16). 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; Helser et al. 2005; Stewart and Hamel 2010), except for the fishery-independent acoustic-based relative age-1 index that has been included in the base model since the 2022 assessment. The process for generating fecundity-at-age from the combination of weight-at-age and maturity data changed in 2019 from using time-invariant to year-specific weight-at-age values. In 2024, time-varying maturity ogives were also added to the calculation of fecundity-at-age (see Section 2.4.2 for details). 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; Helser et al. 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: $F_{\text{SPR}=35\%}$, $F_{\text{SPR}=40\%}$, $F_{40\%}$–40:10, $F_{\text{SPR}=45\%}$, $F_{45\%}$–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 $F_{40\%}$–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 2024 base model has the same general population dynamics structure as the 2023 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, Jr. and Wetzel 2013) version 3.30.22 was the modeling platform used. The largest changes between the 2023 and 2024 stock assessments are the addition of another year of fishery and survey data, an age-1 index data point, a model-based method for empirical weight-at-age data, and time-varying maturity information integrated into the base model.

The 2024 base model includes a time series (1995 to 2023) of acoustic age-2+ biomass estimates and acoustic estimates of relative numbers of age-1 fish (see Section 2.2.1 for more details on the age-1 index). Maturity is assumed to be time-invariant prior to 2009, and time-varying, with the integration of annual maturity ogives informed by sea temperature at depth, since 2009 (see Section 2.4.2). Fecundity is time-varying as defined by annual weight-at-age multiplied by annual maturity ogives (1975–2023; additionally see Section 2.4.1). The D-M likelihood approach (Thorson et al. 2017) is 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 2024 base model with the magnitude of the allowable deviations unchanged from the 2023 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 two for the index of age-2+ biomass and age one for the fishery until a maximum age of 6, after which all ages are assumed to have the same selectivity. Selectivity for the relative age-1 index was set to one for age one 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 time-invariant 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 relationship 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–recruitment 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 1966–2022. 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 2023 (Table 16). Catchabilities associated with the biomass index (q_{b}) and with the relative 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 lognormal likelihood function, using the observed (and extra 2009) sampling variability, estimated via kriging, as year-specific weightings. The relative age-1 index was specified as having a Student's t-distribution for its error structure with the number of degrees of freedom equal to one less than the number of available data points. An additional constant and additive standard deviation on the log-scale component is included for both the biomass index and the relative 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)] compiled across 8 chains, each with a 250 sample burn in period, 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 2023 Scientific Review Group (SRG) review

The Scientific Review Group (SRG) meeting was held from February 7–10th, 2023, at the Graduate Hotel, Seattle, WA, U.S.A.

The following are the 'SRG Recommendations and Conclusions for the Stock Assessment' from the 2023 SRG report and the associated responses from the JTC:

1. **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 estimating dynamic reference points within the assessment and MSE, and encourage those groups to jointly develop alternative reference points, including dynamic reference points, for future SRG consideration.**

   Response – An evaluation of alternative reference points and how they may best be used in Pacific Hake management continues to be an important area for ongoing research. Future reference point discussions stemming from simulation work, preferably through *the MSE, would be beneficial. The JTC, nor the MSE Working Group, have had the capacity to initiate simulations that explore alternative reference points, including dynamic reference points, to date. Several alternative simulation-based study designs have been fleshed out but the resources to complete such research is currently the limiting factor.*

2. **The SRG also recommends continuing sensitivities for steepness, natural mortality, σ_R, excluding the age-1 index, alternative standard deviations for time-varying selectivity, and using the McAllister-Ianelli method to weight fishery age- composition data.**

   Response – The JTC has conducted all of the requested sensitivities and provides summaries in written (Section 3.8), tabular (beginning with Table 32), and graphical (beginning with Figure 48) formats in this document. Many other model explorations were conducted during the development and exploration of the base model to understand model performance and sensitivity to data and structural decisions.

3. **The SRG recommends that the JTC include dynamic unfished spawning biomass in the 2024 assessment as a comparator with the equilibrium unfished spawning biomass used to provide management advice. The SRG also encourages the continued outreach regarding the use of dynamic reference points to stakeholders and managers, including identifying pros and cons of using dynamic unfished spawning biomass.**

   Response – Two figures have been added to the assessment document. The first shows the unfished spawning stock biomass time series relative to the standard 'fished' spawning stock biomass time series (see Figure 41). The second shows a comparison of relative spawning biomass when spawning biomass in year t is related to unfished equilibrium biomass, B_0 (static B_0; as in Figure 31) and when spawning biomass in year t is related to the unfished biomass time series in year t (dynamic B_0; see Figure 42). These can be used to visually compare equilibrium versus non-equilibrium assumptions and estimated changes in population dynamics in the absence of fishing.

   The JTC once again delivered a presentation on dynamic reference points at the October 2023 JMC and AP meeting as a way to provide education and outreach opportunities related to dynamic reference point methods and approaches.

4. **The SRG recommends that the JTC explore alternative ways of estimating natural mortality to update the current approach in the model, which is based on methods from more than a decade ago, since newer methods are available. Information presented during the SRG meeting implies that natural mortality on age-2 Pacific Hake is higher than currently assumed in the assessment model and should be explored more fully.**

   Response – The JTC investigated estimating a vector of natural mortality parameters instead of a single age-invariant parameter. Several configurations, i.e., breakpoints at different ages, were explored but no combination of breakpoints led to natural mortality decreasing with age as hypothesized given the diet data of predators of Pacific Hake. Instead parameters were estimated near the median of the prior. When the prior was *removed, natural mortality at younger ages was estimated to be lower than natural mortality at older ages largely due to the lack of information in the data. If age-specific natural mortality is desired in the future, tagging studies could be used to help inform the parameters. Or, diet data could be used to externally estimate natural mortality at age. Other modeling frameworks, such as the Woods Hole Assessment Model have more flexibility in modeling natural mortality and might also be an option for future explorations.*

5. **The SRG encourages an analysis of catch and CPUE distribution for Canada and US that examines latitudinal shifts in fishing over time.**

   Response – The JTC has not officially investigated CPUE data since prior to the 2013 assessment because of the many difficulties in accurately characterizing catch rates given the difficulties inherent in calculating effort within the Pacific Hake fishery (Hicks et al. 2013). Furthermore, vessel locations for the U.S. shore-based sector must be extracted from log-book information, which is known to be problematic, and current data confidentiality agreements do not allow the sharing of vessel-specific information amongst the JTC members making it difficult to do a comprehensive analysis. Maps of CPUE for the U.S. at-sea sectors and Canadian vessels were presented in the data presentation at the SRG meeting as a first take at fulfilling this request.

6. **The SRG recommends continued work to collect ovary samples and data to develop a picture of the Pacific Hake reproductive cycle both seasonally, inter-annually and at the life-time scale based on histological and physiological measurements. Given the inter-annual variability in age-at-maturity, the SRG recommends that the JTC explore ways to incorporate time-varying maturity in the stock assessment model.**

   Response – Melissa Head has been working hard to continuously collect maturity information for Pacific Hake since 2009. Up until this assessment, maturity was included in the fecundity relationship as a single ogive. Maturity-at-age ogives are now estimated for each year since 2009 and used to calculate fecundity (i.e., maturity ∗ weight at age). Moreover, the relationship between age and maturity includes a coefficient for temperature (see Appendix G). This relationship could be enhanced in the future by including samples from Canada, samples that have previously been analyzed, collected samples that have yet to be analyzed, and samples collected during future endeavors. During the JTC meeting, it was also brought to our attention that there is the potential for samples to be collected from the U.S. shoreside sector as well. The JTC, Melissa Head, and the Sarah Nayani are investigating the feasibility of this in attempts to increase the seasonal coverage of sampling, though winter months will still remain sparsely sampled without a dedicated winter survey.

7. **The SRG noted that the age-1 index did not include a value for 2001 because it was zero. Although this decision had negligible influence on the results because the estimate for 2000 recruitment was close to zero, the SRG noted that Stock Synthesis uses a lognormal likelihood which does not handle zero values. Given that future zero values are expected to have a bigger influence on the results in the short-term, the SRG recommends that the JTC explore likelihood forms that**

can fit to very low index values from the age-1 survey (e.g., robust likelihood). The SRG acknowledges that implementing new likelihoods will require changes to the Stock Synthesis platform.

Response – A Student's t-distribution was implemented for the relative age-1 index of abundance. The Student's t-distribution cannot accommodate values of zero but it does allow for fatter tails than the lognormal distribution. Secondly, the Student's t-distribution is known to provide more accurate estimates of the variability of the sample mean for small sample sizes than the lognormal distribution when the standard deviation is unknown or imprecise. In the future, additional distributions should be investigated that can accommodate values of zero but this change was seen as a positive step forward until the survey team can estimate the variability of the survey.

8. **Given the importance of the age-1 index in estimating the size of the age-classes entering the fishery, the SRG recommends that the JTC implement updated age-1 index CVs, when they are provided by the Survey Team, in the stock assessment model.**

   Response – The joint survey team continues to be short staffed. During 2023, priority was given to completing the 2023 survey, including providing the 2023 survey biomass estimate, associated age compositions, and the 2023 relative age-1 index in a timely manner for the stock assessment. Age-1 index CVs were not available for inclusion in the 2024 assessment; so, the fixed values of 0.5 were retained but a Student's t-distribution was used to fit the survey instead of a lognormal distribution (see the above response).

9. **A new at-sea sampling program in the Canadian freezer-trawler fleet was implemented in 2022 involving vessel crews sampling 50 fish per tow from two tows per trip. The SRG recommends that Canada consider sampling fewer fish from more tows to spread the sampling out and provide a more representative sample of fishery catches.**

   Response – This was discussed briefly in a meeting involving industry representatives and one member of the Canadian JTC and determined to be too much to ask of crew at the time. They would have to deal with more than two bags on a trip which would lead to space limitations in the freezer that they are currently using for the purpose and organizational difficulties. The space limitations could be overcome by storing bags of fish in the galley but after a short discussion on the idea, it was determined not to be feasible for food safety and storage-space reasons. The idea will be introduced again for the 2024 fishing season.

10. **The SRG encourages the JTC to consider methods to determine the maximum input sample size for the age compositions (e.g., Stewart and Hamel 2014).**

    Response – Determining input sample sizes is important for how annual fishery and survey age compositions are initially weighted, which then provides the basis from which wholesale re-weighting of data sources (fishery or survey) is done with the Dirichlet-multinomial data weighting model parameters. The JTC has considered alternative methods, including that of Stewart and Hamel (2014), and has determined *that the first step is to explore the handling of survey age-composition data (given that initial effective sample sizes and data source weighting is relative to other data sources in the model). Currently, survey age compositions represent age structure associated with the acoustic survey as viewed through an estimated selectivity curve for the acoustic-trawl sampling net. Yet, selectivity for ages two and older with acoustics is theoretically at or near one. The JTC plans to investigate whether there is a more informative way to utilize survey age-composition information in the stock assessment model in the coming year.*

11. **The SRG notes that there have been multiple strong cohorts in the stock recently compared to earlier periods where there was only one strong cohort supporting the stock, including during the period of sample collection for the ageing error matrix that supports the assessment model. Therefore, the SRG encourages the resumption of the ageing error study by the Committee of Age Reading Experts (CARE) using samples collected during the past decade.**

    Response – An ageing error study in conjunction with CARE has been planned for several years but a full exchange remains on hold due to continuing difficulties with permits to send biological specimens across the U.S.–Canada border. The JTC plans to move forward with updating the ageing error analysis in the coming year with the data that are available regardless of the status of the in progress CARE study.

12. **The SRG supports the investigation of alternative selectivity functions, which may include a two-dimensional autoregressive (AR) approach, which may use information from the previous year and from adjacent year classes to predict selectivity.**

    Response – The JTC agrees that investigations into alternative selectivity functions is a priority research area for Pacific Hake. The JTC would like to make incremental progress on this in the coming year as time allows, including also looking into alternative methods (e.g., random effects models) to best capture age, year, and cohort effects.

3.4 Modeling results

3.4.1 Changes from 2023

A set of 'bridging' models was constructed to evaluate the component-specific effects of the steps to change from the 2023 base model to the 2024 base model. The steps are as follows:

- Update to the latest version of Stock Synthesis, version 3.30.22, to follow current best practices;
- Incrementally update catch, weight-at-age, age-1 index, and fishery age-composition data from years previous to 2023 (in that order);
- Incrementally add 2023 catch, weight-at-age, biomass survey, survey age-composition, age-1 index, and fishery age-composition data (in that order);
- Change the error distribution associated with the age-1 index from lognormal to Student's t-distribution;

- Use a model-based matrix of input weight-at-age data; and
- Incorporate model-based estimates of time-varying maturity ogives into the calculation of time-varying fecundity.

Stock Synthesis version 3.30.22 includes a number of changes since the version used by Berger et al. (2023). However, none of the changes were specifically relevant to this assessment, and thus, the software update had no effect on assessment results (Figure 16).

The update of pre-2023 data occurs because databases are continually updated; this yielded minor adjustments to the data. For example, samples that were recently aged but not available for the 2023 assessment were included. Updates to pre-2023 data were small enough that they had little impact on the model results.

The addition of the 2023 catch and weight-at-age data extends the model to the start of 2024. Recruitment estimates and historical stock trajectory were relatively unchanged, and the new data suggest a slight decrease in female spawning biomass from 2023 to 2024 (Figure 16).

Including the 2023 fishery-independent biomass estimate led to a downward shift in the stock trajectory going back to 2017 and a similar shift in the fit to the survey (Figure 16). The addition of the 2023 survey biomass age compositions led to an estimated increase in stock biomass from 2023 to 2024 as a result of small shifts in expected recruitment, particularly for the 2020 and 2021 year classes. While the addition of the 2023 relative age-1 index had a negligible effect on the stock trajectory, it did slightly adjust estimates of recent recruitment strength, in particular raising the 2022 recruitment somewhat.

The final step of adding 2023 data involved incorporating fishery age-composition information, which shifted the ending year of the deviations in the selectivity parameters from 2022 to 2023. These data had relatively little impact on the historical biomass estimates but did shift recent estimates of spawning biomass upwards (Figure 16). Recruitment increased in 2021 and 2022, while the 2020 cohort was reduced. The increase in 2021 and 2022 recruitment contributes to the increase in female spawning biomass by the start of 2024, as these fish are considered mostly mature at the start of 2024. Despite both fishery age compositions and the relative age-1 index pointing towards above average cohorts in 2020, 2021 and, to a lesser extent, 2022, estimates of 2024 female spawning biomass remain highly uncertain (Figure 16).

Structurally changing the error distribution for the relative age-1 index from a lognormal to a Student's t-distribution (with 13 degrees of freedom) had negligible effect on assessment results (Figure 17). Nonetheless, the t-distribution is better suited for these data given the low sample size (14) and broader distribution tails compared to a lognormal when sample sizes are less than 30.

Input weight-at-age data were constructed using a model-based approach (see Section 2.4.1 for details) to better inform changes in weight-at-age for years and ages when there is little or no data. Model predictions were based on a smoothed fixed effect for age and random effects for year and cohort. During periods of more consistent sampling protocols (since the mid-1990s), there was little effect on overall stock size or status (Figure 17). However, there were refinements to stock size and status during the 1970s and 1980s, a period when sampling protocols were not as well documented (e.g., from foreign vessels).

Lastly, model-based estimates of time-varying maturity ogives were incorporated into the calculation of time-varying fecundity (Section 2.4.2 and Appendix G). This is in addition to using time-varying weight-at-age inputs, which improves the assessment model inputs that translate total biomass to spawning biomass. The addition of time-varying maturity resulted in annual differences in the age at which Pacific Hake mature, such that there were minor shifts in the translation of total biomass to spawning biomass by one year in some cases within the time series (Figure 17), but the general trend in spawning biomass and population status remained largely the same.

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; Appendix A). 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.4). 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.5). 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.6). Estimates of recruitment in 2014 and 2016 were correlated with the derived quantity of catch from the default harvest rule in 2024, as to be expected given the dependencies among these quantities (Figure A.6). An examination of deviations in recruitment (log-scale differences between estimated and expected recruitment values) from recent years (Figure A.7) indicates the highest correlation (0.92) was between the 2014 and 2016 recruitment deviations. This is the same as in 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 $\log \theta_{\text{fish}}$ was -0.663 (-0.853–-0.470), giving an effective sample size multiplier $\theta_{\text{fish}}/(1+\theta_{\text{fish}})$ of 0.340 (0.299–0.385). The related log of the survey age-composition parameter θ_{surv}, i.e., $\log \theta_{\text{surv}}$, was 2.770 (1.541–4.986), and the resulting effective sample size multiplier $\theta_{\text{surv}}/(1+\theta_{\text{surv}})$ of 0.941 (0.824–0.993).

The base model fit to the acoustic survey biomass index (Figure 18) remains similar to the 2023 base model, up to 2017. The low 2023 survey biomass pulls down the last few years of estimated biomass, such that the fit to the 2019 data point is very good (for the 2023 assessment it was overestimated), the 2021 fit is underestimated (for the 2023 assessment it was very good). The median of the posterior distribution for the analytically-derived catchability associated with the acoustic survey biomass index (q_b) was 0.838 (Figure 20).

The 2023 biomass index is the third lowest in the series (Table 12), and is well below the model estimate, similar to the 2001 index that has always been below model estimates (Berger et al. 2023). While no direct cause for the 2001 index anomaly 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 age structure. For 2023, the survey timing is not anomalous. The estimated biomass increase from 2023 to 2024 is driven by the addition of 2023 survey age-composition data (Figure 16). The addition of the 2023 relative age-1 index suggested an above-average 2022 cohort (and also increased the 2021 relative age-1 index compared to the previous assessment due to a previous omission; Section 2.2.1).

The relatively stable estimated biomass from 2013–2019 is unchanged from the previous assessment. The underestimation of the 2009 and 2023 biomass estimates are larger than the underestimation of any other year. The uncertainty of the 2009 value (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, which also likely influenced the population dynamics of Pacific Hake through predation in that year. Future data will reduce the large uncertainty in the 2023 biomass estimate, which may reduce the underestimation.

Differences between the median posterior density estimates from the fit to the survey index are 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 relative index of age-1 fish highlights an overall general confirmation of relative cohort strength (Figure 19). In particular, the 2008, 2014, and 2018 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 2011 value (the large 2010 cohort) was closely fit. Age-1 fish in 2021 (2020 cohort) were estimated slightly below the index value (in last year's assessment they were estimated slightly above) and, being so young, include a large amount of uncertainty. The median of the posterior distribution for the analytically-derived catchability associated with the age-1 index (q_1) was 0.490 (Figure 21).

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 (Figures 22 and 23). 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 2023 fishery, the 2021 cohort was the largest (35%), followed by the 2020 cohort (25%), and then the 2016 cohort (13%). Age compositions from the 2023 acoustic survey suggest a similar age structure for older fish.

The 2020 cohort has now been observed by, and is well fit by, the acoustic survey (Figure 23), with the survey's inclusion decreasing its estimated size (Figure 16). Combined, the 2015–2023 fishery age-composition data and the 2017–2023 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 23). The 2016 cohort, which has been observed three times by the survey, still appears to be smaller than the 2014 cohort.

The 2023 survey was the first to sample the 2021 cohort, suggesting that it was a large contingent of the population (50.6% of the 2023 survey catch). The 2020 cohort, which has now been observed by the acoustic survey, is 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 24).

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 17–21. For the major cohorts, the resulting estimated age-specific catch, natural mortality, and surviving biomasses are given in Table 22. For example, at age-5 the catch weight of the 2014 cohort was slightly more than that of the 2010 cohort, 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 (Figures 25–26). 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 likewise very uncertain (Figures 28 and 29), 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 30 and 31 and Tables 23 and 24). 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 2003 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 0.616 million t in 2009. The assessment model estimates that median female spawning biomass then peaked again in 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 mostly declined from 2018 to 2022 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 in 2023 and 2024 is due to the expected above-average 2020 and potentially large 2021 cohorts entering maturity, and the recent declining trend in catch.

The median estimate of the 2024 relative spawning biomass (spawning biomass at the start of 2024 divided by that at unfished equilibrium, B_0) is 99%. However, the uncertainty is large, with a 95% posterior credibility interval from 45% to 230% (Tables 23 and 24), partly due to remaining unknowns about the size of the potentially large 2021 cohort because the acoustic survey has only provided one year of information about it.

The median estimate of the 2024 female spawning biomass is 1.885 million t (with a 95% posterior credibility interval from 0.853 to 4.828 million t). The current estimate of the 2023 female spawning biomass is 1.335 (0.652–3.225) million t, giving less uncertainty than the estimate from the 2023 assessment of 1.910 (0.757–5.610) million t. The current median is reduced from last year, partly due to the tail of the distribution being greatly curtailed (upper end of the interval is much lower than it was in the 2023 assessment), and a slight lowering of the lower end of the interval. The decrease appears to be due to the addition of the age-2+ biomass index pulling down the estimated biomass for recent years, plus the addition of the survey age compositions lowering the estimated 2020 recruitment (Figure 16).

Recruitment

The new data for this assessment do not significantly change the general pattern of recruitment estimated in recent assessments. However, estimates of absolute recruitment for the most recent years can change with new data, and the improved methods for modeling temporal weight-at-age and spatio-temporal maturity can slightly change some historical estimated recruitments.

The estimate of 2020 recruitment in last year's assessment was based on only two years of data and thus was highly uncertain; it suggested the cohort could potentially be huge (95% credible interval: 2.9–47.6 billion fish). But with the extra data in this year's assessment the 2020 cohort looks to be above average but not huge (95% interval: 2.1–12.7 billion fish). The median has consequently fallen from 11.4 to 4.7 billion fish between the two assessments.

Similarly, median estimates of 2019 recruitment have changed by -55% (which is only 0.3 billion fish because 2019 was already estimated to be a small year class).

The 2021 recruitment is now estimated to be potentially large, whereas it was estimated to be below average in last year's assessment (for which the only information was the proportions of age-1 fish caught in the 2022 commercial fishery). The 95% credible interval in the 2023 assessment was 0.03–6.91 billion fish), expanding in the current assessment to 4.1–29.5 billion fish). Consequently, the median has increased by 2,162% (9.7 billion fish). The general notion remains that recent recruitment is highly uncertain, and estimates for recent years (based on limited data) can change substantially.

Pacific Hake have low average recruitment with occasional large year classes (Figures 32 and 33, Tables 23 and 24). 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 and a very strong 2010 year class. Above average year classes occurred in 2014 and 2016, which have been sustaining the fishery in recent years (Figure 22).

The current assessment estimates a strong 2014 year class (Figure 34) comprising 50% of the 2016 catch, 38% of the 2017 catch, 28% of the 2018 catch, 33% of the 2019 catch, 31% of the 2020 catch, 25% of the 2021 catch, 15% of the 2022 catch, and 8% of the 2023 catch.

The 2016 cohort also appears to be strong, comprising 26% of the 2018 catch, 21% of the 2019 catch, 36% of the 2020 catch, 34% of the 2021 catch, 24% of the 2022 catch, and 13% of the 2023 catch.

The large size of the 2014 and 2016 cohorts is informed by observations from several years of fishery data and the acoustic survey. For all other years from 2011 to 2019, the model currently estimates small year classes (median recruitment below the mean of all median recruitments). As noted above, the 2020 cohort is estimated to be somewhat smaller than in last year's assessment (though last year's estimate was highly uncertain), due to the introduction of new information from the 2023 age-2+ biomass index and survey age-composition data (Figure 16). The 2021 cohort strength is only informed by fishery data and the 2023 biomass survey, and is estimated to be potentially large with a median and 95% credible interval of 10.187 (4.085–29.499) billion fish.

The 2022 cohort was observed by the age-1 index in 2023, suggesting it is average to below average (Figures 10 and 32), and it will not be observed as part of the age-2+ survey index until 2025. There is no information in the data to estimate the sizes of the 2023 and 2024 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 the previous year) without a survey in the most recent year and age-2 (observed at age-1) with a survey.

From Figure 32 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 32 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 35 provides an intuitive way to compare recruitment across years (see Edwards et al. 2022 for motivation and methods). It shows that only the 1980 recruitment is probably larger than 2010 (median relative values > 1), and the 1984 recruitment has a small chance of being as large as 2010. Whereas Figure 32 suggests that 1967, 1973, 1977, 1999, 2014, and 2020 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 2021 cohort is still very uncertain but has a small chance of exceeding the 2010 cohort (Figure 35). Participants in the Pacific Hake process have an intuition that the 2010 is a very large recruitment event – Figure 35 shows how it is the largest in the last 30 years, and that such large cohorts are rarer than is inferred from Figure 32.

The estimated recruitments with uncertainty for each year and the overall stock–recruitment relationship are provided in Figure 36. Extremely large variability about the expectation and about the joint uncertainty of individual recruitment and female spawning biomass pairs are evident. High and low recruitments have been produced throughout the range of observed female spawning biomass (Figure 36). The standard deviation of the time series of median recruitment deviation estimates for the years 1970–2022, which are informed by the age compositions and the age-1 index, is 1.73.

Exploitation status

The median estimated relative fishing intensity on the stock is below 1.0 for all years (Figure 37 and Tables 23 and 24). It was closest to 1.0 in 1999 and 2008, but catch in 2008 did not exceed the catch limit that was specified, based on the best available science and harvest control rules in place at the time; however, catch did exceed the catch limit in 1999 (Table 3). Exploitation fraction (catch divided by biomass of fish of age-2 and above) has shown relatively similar patterns (Figure 38 and Tables 23 and 24). 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 87.6% in 2010 to 45.5% in 2015, and then leveled off around 73–80% from 2016 to 2019 before declining to 55.1% in 2023. The median exploitation fraction has increased from a recent low of 0.06 in 2012 to 0.15 in 2021 then declined to 0.07 in 2023. 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 100% from 2012–2016 and again from 2020–2023 (Figure 37).

Management performance

Over the last decade (2014–2023), the mean coast-wide utilization rate (i.e., proportion of catch target removed) has been 63.5% and catches have been below coast-wide targets (Table 3). From 2019 to 2023, the mean utilization rates differed between the United States (67.4%) and Canada (48.1%), though Canada's rate was higher than the U.S.'s in 2020. 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 under-utilization 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, it decreased to 59.3% in 2022 and to 42.2% in 2023. This is due to the utilization rate in Canada steadily declining since 2020 to a time-series low of 16.5% in 2023, and also a fall in the U.S. utilization rate to 59.7% in 2023. 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 and 2023. Total landings last exceeded the coast-wide quota in 2002 when utilization was 112%.

As noted above, the median relative fishing intensity was below 100% (i.e. median fishing intensity below $F_{\text{SPR}=40\%}$) in all years. The median relative spawning biomass was above 40% (the $B_{40\%}$ reference point) in all years except 2007–2011 (Table 23 and Figure 31). These are also shown on a phase plot of the joint history of relative spawning biomass and relative fishing intensity (Figure 39). Relative spawning biomass increased from the lows in 2007–2012 with above average recruitment in 2008, 2010, 2014, 2016, and 2020. Correspondingly, median relative fishing intensity has remained below 100%, and total catch has been declining since the time series high in 2017. While there is large uncertainty in the 2023 estimates of relative fishing intensity and relative spawning biomass, the model estimates a 0.2% joint probability of being both above the $F_{\text{SPR}=40\%}$ fishing intensity in 2023 and below the $B_{40\%}$ spawning biomass level at the start of 2024.

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 generally similar to those in last year's base model (Table 25). The largest change was a reduction of the 2020 recruitment by more than half, as discussed above, leading to a fall in the estimated median relative spawning biomass at the start of 2023. Medians of the 2014 and 2016 recruitment also both decreased, by about 10% from those estimated in the 2023 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 female spawning biomass estimates in 2024 and throughout the current forecast period, because there is considerable uncertainty associated with the absolute size of the, now mostly mature, 2020 and 2021 year classes that propagates into forecasts. Although the 2023 acoustic survey helped to refine these estimates and reduce uncertainty, further observations of these year classes will improve estimates. The inclusion of the age-1 index in this assessment will, in some cases, also help to reduce this uncertainty (as it currently does in this case; see Figure 52 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 3.12), 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 26. 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 2023 assessment (Table 25).

As part of the DFO Sustainable Fisheries Framework, Fisheries and Oceans Canada (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 2024 being above each of these points are $\text{P}(B_{2024} > B_{10\%}) = 100\%$ and $\text{P}(B_{2024} > B_{40\%}) = 98.7\%$ such that the stock is estimated to be in the 'healthy zone' (above the upper stock reference point of $B_{40\%}$). This probability is slightly higher than in last year's assessment, where the equivalent calculation was $\text{P}(B_{2023} > B_{40\%}) = 98.1\%$. 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 $\text{P}(B_{2024} > 0.4B_{\text{MSY}}) = 100\%$ and $\text{P}(B_{2024} > 0.8B_{\text{MSY}}) = 100\%$ such that the stock is estimated to be in the provisional 'healthy zone'. For completeness, we note that $\text{P}(B_{2024} > B_{\text{MSY}}) = 99.9\%$.

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 2024, the estimated posterior median relative spawning biomass is 99%, such that the female spawning biomass is well above $B_{40\%}$ and $B_{25\%}$. The probability that female spawning biomass at the beginning of 2024 is above $B_{40\%}$ is $\text{P}(B_{2024} > B_{40\%}) = 98.7\%$ (as noted above), and of being above $B_{25\%}$ is $\text{P}(B_{2024} > B_{25\%}) = 99.9\%$.

3.7 Model projections

The catch limit for 2024 based on the default $F_{40\%}$–40:10 harvest policy has a median of 747,588 t and a wide range of uncertainty (Figure 40), with the 95% credibility interval being 298,355–2,124,832 t.

Decision tables give projected population status (relative spawning biomass and relative fishing intensity) under different catch alternatives for the base model (Tables 27 and 28). 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. Table 27 shows projected relative spawning biomass outcomes, and Table 28 shows projected fishing intensity outcomes relative to $F_{\text{SPR}=40\%}$.

Population dynamics and governing parameters assumed during the forecast period include random recruitment; selectivity, weight-at-age and maturity (and thus fecundity) averaged over the five most recent years (2019–2023); 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. A slight exceedance can happen for the median relative fishing intensity in 2024, 2025 and 2026 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 slight over- or under-fishing relative to the desired $F_{\text{SPR}=40\%}$ rate.

Key management metrics are presented for 2025, 2026 and 2027 projections (Tables 29–31 and Figures 44–46). 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 2024 (Table 29 and Figure 44). However, interpolation may not be applicable for all catches in 2025 and 2026 because they are conditional on catch levels from the previous year or years. This explains why a few probabilities decline (rather than rise) with increased 2025 and 2026 catch levels in Tables 30 and 31 and Figures 45 and 46.

Figure 43 shows the projected relative spawning biomass trajectory through 2027 for several of these management actions. With zero catch for the next three years, the biomass has a 3% probability of decreasing from 2024 to 2025 (Table 29 and Figure 44), a 59% probability of decreasing from 2025 to 2026 (Table 30 and Figure 45), and a 66% probability of decreasing from 2026 to 2027 (Table 31 and Figure 46).

The probability of the female spawning biomass decreasing from 2024 to 2025 is greater or equal to 22% for all catch levels examined other than zero (Table 29 and Figure 44). The probability is 36% for the 2024 catch level similar to that for 2023 (catch alternative e). For all explored catches, the maximum probability of the female spawning biomass dropping below $B_{10\%}$ at the start of 2025 is 0.0%, at the start of 2026 is 0.1%, and at the start of 2027 is 2.6% (Tables 29–31 and Figures 44–46). The similar maximum probability of dropping below $B_{40\%}$ at the start of 2025 is 6.7%, at the start of 2026 is 19.9%, and at the start of 2027 is 34.8%.

It should be noted that forecasted biomass is not only influenced by catch levels. As the above average 2014 and 2016 cohorts continue to age, total biomass of these cohorts even without fishing mortality will continue to decrease (Tables 18 and 22) as losses from mortality outweigh increases from growth. The above-average 2020 cohort entered this growth-mortality transition period around 2023 (Tables 18 and 22). During 2024, the age-3 2021 cohort will likely begin the growth-mortality transition where a net increase in total biomass is less likely (note that fecundity will increase which will influence the exact change in female spawning biomass, Figure 11). The estimated above-average (yet still highly uncertain) 2020 and 2021 cohorts will continue to play a large role in determining female spawning biomass during the forecast years presented here. The below-average 2015, 2018, and 2019 cohorts will contribute much less to forecasted spawning biomass than the larger cohorts.

The age composition (in numbers) of the catch in 2024 is projected to be (using MCMC medians) 38% age-3 fish from the 2021 cohort, 23% age-4 fish from the 2020 cohort, 9% age-8 fish from the 2016 cohort, 7% age-2 fish from the 2022 cohort, and 6% age-10 fish from the large 2014 cohort (Figure 47). However, those estimates are highly uncertain with the 95% credibility interval for the age-3 fraction spanning 21%–57%.

Due to the higher average weight of older fish compared to younger fish, the median expected proportion of the 2024 catch by weight is 32% for the age-3 2021 cohort (compared to 38% by numbers) and 23% for the age-4 2020 cohort (compared to 23% by numbers; Figure 47).

With respect to the DFO reference points, with the largest 2024 catch of 875,262 t given in Table 29, at the start of 2025 the stock is expected to be above the critical zone with a probability of $\mathrm{P}(B_{2025} > B_{10\%}) = 100\%$ and in the healthy zone with a probability of $\mathrm{P}(B_{2025} > B_{40\%}) = 93\%$. 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 $\mathrm{P}(B_{2025} > 0.4B_{\mathrm{MSY}}) = 100\%$, in the healthy zone with a probability of $\mathrm{P}(B_{2025} > 0.8B_{\mathrm{MSY}}) = 100\%$, and above B_{MSY} with a probability of $\mathrm{P}(B_{2025} > B_{\mathrm{MSY}}) = 99\%$ for this catch.

With respect to PFMC stock size reference points, a level of 2024 catch consistent with the Agreement default harvest control rule (747,588 t) has a 5% estimated probability of resulting in the biomass going below $B_{40\%}$ at the start of 2025 (and 1% probability of going below $B_{25\%}$; Table 29). If catches in 2024 and 2025 are the same as in 2023 (264,000 t, catch scenario e) then the probability of the biomass going below $B_{40\%}$ is 1% for the start of 2025 and 3% for the start of 2026.

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 with the same 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 while developing and testing the 2024 base model. Here we focus on the main sensitivities, relative to the base model, which are as follows:

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. Consideration of higher and lower variation about the stock–recruitment relationship (σ_r);

5. Removal of the age-1 index as a data source;

6. Downweighting the fishery age-composition data; and

7. Consideration of alternative standard deviations for time-varying selectivity.

None of the sensitivities resulted in a substantial departure from the main population dynamics of the base model (Tables 32–34 and Figures 48–58). All sensitivity models showed large estimated increases in female spawning biomass in the early- to mid-2010s that continues to be driven by the 2010, 2014, and 2016 cohorts, followed by a period of general decline (2018–2023) before increasing again due to the above average 2020 and 2021 cohorts. All sensitivity models indicate that 2024 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 that 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, 0.3, and 0.31. Note that the median of the prior was also changed for the latter sensitivity. Each of these sensitivities led to an increase in estimates of natural mortality relative to the base model. The medians of the MCMC posteriors for natural mortality increased from 0.235 to 0.290, 0.312, and 0.315, respectively. The 95% credibility intervals also increased, with the largest differences in the upper rather than the lower credible interval. Credible intervals were 0.194–0.280 for the base model, 0.227–0.343 for the sensitivity run with the prior standard deviation set to 0.2, 0.242–0.360 for the sensitivity run with the prior standard deviation set to 0.3, and 0.248–0.361 for the sensitivity run with the Hamel and Cope (2022) prior (Table 32). In addition to increased estimates of natural mortality, results from these sensitivity models also showed an increase in the overall scale of the population, the estimated stock status relative to B_0 prior to 1990, the uncertainty in female spawning biomass on both absolute and relative scales, roughly halved estimated relative fishing intensity in 2023, and more than doubled equilibrium yield at $B_{\text{SPR}=40\%}$ (Table 32 and Figures 48 and 49).

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 0.812 with a 95% credible interval of 0.582–0.958 to a median of 0.541 with a 95% credible interval of 0.345–0.756 (Table 32). However, neither steepness sensitivity analysis had a large impact on the overall model results (Figures 48 and 49), because Pacific Hake female spawning biomass has remained above levels where changes in steepness would appreciably influence the stock–recruitment relationship (Figure 36).

Input values of σ_r were changed from 1.40 (base) to alternative high (1.60) and low (1.00) states. Both sensitivities were similar to the base model in that the calculated standard deviation of recruitment deviations (from the main period) was higher than the input σ_r, i.e., 1.58 and 1.89 when σ_r was 1.00 and 1.60, respectively. The calculated standard deviation of recruitment deviations from the base model was intermediate at 1.70. These calculated standard deviations should match the input if the vectors of deviations were from the 'population' of values rather than just a sample. However, this systematic bias to be larger than the input value indicates that the standard deviation of recruitment deviations is accounting for more variability than just variability in recruitment. The high σ_r model led to 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 48). 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 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 method is not used here to tune the fixed input value.

The sensitivity of the base model to the removal of the relative age-1 index provides a method to evaluate how the information about juvenile fish is propagated through the model. Estimates of female spawning biomass throughout most of the time series are similar between models with and without the relative age-1 index but diverge near the end of the time series (Table 32, Figures 50 and 51). The 2024 estimates of relative spawning biomass are 98.7% for the base model (95% credible interval of 45.0–229.8%) and 78.4% for the model where the relative age-1 index is removed (95% credible interval of 34.2–184.1%). This difference is due to the relative age-1 index providing additional information on recruitment for cohorts associated with recent age-1 indices (i.e., 2020 and 2022 cohorts detected in the 2021 and 2023 age-1 indices). In particular, the base model with the relative age-1 index indicates slightly larger 2020 and 2021 year classes than the model removing the age-1 index (Figure 52). Similarly, recruitment in 2022 is estimated to be slightly above average when the model is fit to the relative age-1 index compared to slightly below average without the index. Removing the relative age-1 index led to minor changes in fit to the age-2+ survey biomass index, with 2021 showing a slight improvement and 2023 a deterioration compared to the base model (Figure 53).

The base model includes a Dirichlet-multinomial likelihood component that includes two estimated parameters to automatically weight each of the fishery and survey age compositions. The base model was compared to a model that downweighted the fishery age compositions relative to the survey age compositions. This downweighting was based on the McAllister–Ianelli method, which 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 16), attempts to make the arithmetic mean of the input sample size approximately equal to the harmonic mean of the effective sample size. Here, this was accomplished with weighting factors of 0.14 and 0.46 (ratio of 0.30) for fishery and survey age compositions, respectively. These weighting factors are not specific to this year's base model, rather they are values calculated from previous maximum likelihood estimates. The median estimate from the Dirichlet-multinomial method used in the base model was 0.340 and 0.941 (ratio of 0.36). Downweighting fishery composition data led to minor changes in relative spawning biomass, recruitment estimates, and increased uncertainty in estimates of early recruitments compared to the base model (Figures 51 and 52). The largest changes in the time series occurred prior to the availability of survey data.

The degree of flexibility of annual variation in the fishery selectivity was tested using three alternative values of standard deviations (Φ) (Figures 54–58). The consideration of alternative Φ values is discussed earlier in Section 2.5.3. Changing Φ, which controls the flexibility in time-varying selectivity, from the base model value of $\Phi = 1.40$ to 0.21, 0.70, and 2.10 did not appreciably influence the estimates, or precision, associated with recruitment in 2014 or 2016 but it did impact more recent recruitments (Figure 56). In particular, recruitment estimates for 2020 and 2021 are linked to the choice of Φ, where the smallest investigated value of Φ (0.21) led to the highest estimates of the 2020 and 2021 recruitment deviations of the investigated models (Figure 57). The high estimates of recruitment led to a large increase in female spawning biomass in recent years compared to the base model (Figure 54). When $\Phi = 0.21$, the fit to the most recent age-2+ survey biomass index was the worst of the three investigated models (Figure 58).

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 59 and Edwards et al. 2022) for the older cohorts. Uncertainties are shown for select cohorts in Figures 59 and 60. In previous years, thes figures showed only the median lines. The uncertainty is represented as credible intervals from 2.5% to 97.5% as shaded areas surrounding the median lines. For cohorts that have positive recruitment deviations, the uncertainty is a narrower band around the median due to a higher sampling rate over the years than the cohorts with negative recruitments.

The 2020 cohort has been estimated lower this year than in last year's assessment, which is also evident in Figure 60 when excluding the 2023 data – the uncertainty at age-3 gets reduced when including the 2023 data, shown by the age-4 intervals being tighter and also lower. The latest data no longer suggest that 2020 is a huge cohort. The 2021 cohort at age-3 has a similar median to the 2020 cohort at age-3, but with less uncertainty (narrower credibility interval in Figure 60) because it has been seen in the age-2+ biomass survey (whereas the 2020 cohort was not seen in that survey until it was another year older). Although the 2021 displays unusual behaviour in that the median is below 0 at age-2 and then above 0 at age-3, its uncertainty at age-2 was very large (Figure 60).

Some cohort recruitments are over or under-estimated at age-2. Over-estimation can be seen most clearly with the 2014, 2015, 2017, 2018, and 2020 cohorts (Figures 59 and 61). The

2014 cohort reached 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 by a small amount since the estimate at age-3. The under-estimation of the 2021 cohort stands out as it was estimated as being slightly smaller than average at age-2 in last year's assessment and then estimated to be a very large cohort at age-3 this year, though this is based on medians and the age-2 estimate was highly uncertain, as mentioned above.

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 absolute estimates of uncertainty for each cohort. Uncertainty of the 2016–2021 cohorts has been substantially reduced compared to removing five years of data (Figure 62, bottom figure). The uncertainty of the 2020 cohort was substantially increased with the removal of only 1 year of data. This increase was exacerbated by the removal of the 2023 survey index as well as the fishery catch, as all data sources are removed for each year of the retrospectives. Medians of various quantities of interest are given in Table 35.

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 5 years of the retrospective model (upper panel of Figure 62). In this assessment, there is very little retrospective bias, with only slight year-specific positive and negative bias in female 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.

3.10 Comparison with past assessments

A comparison of the base models, approved for management, used in each year since 1991 indicates that the variability between model results, especially early on in the estimated time series, is larger than the estimated uncertainty reported from the current base model (Figure 63). There have been substantial differences in the structural assumptions of the models and, thus, results submitted each year. Prior to 2004, catchability was fixed at 1.0. This assumption was investigated between 2004 and 2007, leading to variability in model results because of the use of several different, but fixed, values of catchability. Since 2008, catchability has been freely estimated by the model ($q_b = 0.84$). 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 female spawning biomass for 2016 and 2017 have remained similar to the previous assessment, being somewhat lower than in the 2016 and 2017 assessments. 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 16). The uncertainty interval associated with the 2024 assessment brackets the majority of the historical estimates.

The level of uncertainty associated with each assessment's estimate of that year's current female 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. Uncertainty around the absolute amount of 2024 female spawning biomass is similar to the final-year estimates from previous assessments, with both absolute interquartile range and the relative amount of dispersion (or variability relative to the stock size; similar to a coefficient of variation) consistent with previous assessments (Figure 64).

3.11 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 29 and 30) 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., $\mathrm{P}(B_{2020} < B_{2019})$, 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 $\mathrm{P}(B_{2020}<B_{2019}) =$ 61%; Figure 65. We can also calculate this probability from the current assessment model, which implicitly includes the 412,015 t catch from 2019, giving $\mathrm{P}(B_{2020} < B_{2019}) = 83\%$; Figure 65. We extracted similar probabilities from past assessment documents going back to 2012 and calculate analogous probabilities, $\mathrm{P}(B_{\mathrm{t+1}} < B_{\mathrm{t}})$, from the current base model [Figure 65; see Edwards et al. (2022) for full methods].

Each assessment correctly predicted whether the stock would most likely increase or decrease the following year, except for 2017 and 2023; Figure 65. Estimates from previous assessments are almost always closer to 50% than those from the current base model (Figure 65), 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 2017 and 2023 assessments 'incorrectly' projected that the stock would likely decline the following year (given the catch that subsequently occurred), because the current assessment model estimates a likely increase (Figure 65). For the 2017 (Berger et al. 2017) assessment the biomass trend was projected to be relatively flat the following year, so even slight changes in biomass could influence the binomial outcome of an 'increase' or 'decrease' in biomass, despite the overall change in biomass not being very substantial. The 2023 assessment (Berger et al. 2023) had minimal information on the 2021 cohort and predicted the biomass would probably decline in 2024 with any non-zero 2023 catch. However, the current assessment estimates that the 2021 cohort was potentially large, which further 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 65). A range of catch alternatives are shown for the current assessment because realized 2024 catches are not yet known (Figure 65), and give a mostly greater that 50% chance that the stock will decline from 2024 to 2025.

A similar approach was used to calculate the probability of the biomass falling below $B_{40\%}$ in the subsequent year, i.e., $\mathrm{P}(B_{\mathrm{t+1}} < B_{40\%})$; Figure 66. 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 substantial and so in hindsight the probability of going below $B_{40\%}$ was 0% (based on the current assessment). From the 2018 assessment onwards, the estimated $\mathrm{P}(B_{\mathrm{t+1}} < B_{40\%})$ probabilities rose, until falling due to the incoming above-average 2020 cohort and lower catches (Figure 66). The same probabilities calculated from the current base model similarly rose, but all remained lower than the previous assessments' calculations, similar to the analogous figure in the 2023 assessment (Berger et al. 2023).

3.12 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 most important are as follows:

1. Continue to conduct research to evaluate ways to improve recent, current, and future estimates of recruitment 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. 2023). Explorations should also consider options for incorporating information on recruitment into the assessment model and the management framework for Pacific Hake. For example, time series could be included in the stock assessment as a standalone data source (similar to the acoustic indices) or improvements could be made to the modeling framework such that these environmental time series could impact the stock–recruitment relationship directly. 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 they are available across international boundaries and updated on a recurring basis, thereby allowing for their use 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 6–9 month forecasts of subsurface (i.e., 100 m depth) temperature from J-SCOPE. Furthermore, the existing management strategy evaluation framework should be used, or further developed, to examine how information on recruitment can inform robust management decisions.

2. Conduct research on estimates of uncertainty for the relative age-1 index and the age-2+ index and investigate alternative ways to utilize survey age-composition information in the assessment model. Bootstrapping of the acoustic survey time series, or related methods, could help incorporate uncertainty related to the target-strength relationship, subjective scoring of echograms, thresholding methods, and methods used to estimate the species mixes for interpreting the acoustic backscatter into the variance calculations. Research should be communicated with those involved in developing the U.S. West Coast Integrated Survey Initiative. The 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 coast-wide population of Pacific Hake. In particular, include indicators 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 MSE 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, the effects of large cohorts, and comparisons between ageing methods such as break and burn, surface reads, and Fourier-Transform Near Infrared Spectroscopy. 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. Improve stock assessment forecasts through research that identifies linkages between Pacific Hake biology and ecosystem, oceanographic, or climate variables across the population domain. In particular, explore possible relationships with recruitment, growth, fecundity (including weight-at-age and maturity), and population density to improve biomass forecasting capabilities for Pacific Hake.

7. Explore the operational use of environmental DNA data for characterizing aspects of Pacific Hake population dynamics, such as changes in species distribution or density and the incorporation of these data into the assessment. 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, 2021,and 2023 (three years total). Continuing to extend the time series would allow for its incorporation in future stock assessments as a relative 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. 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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5 REFERENCES

Agostini, V.N., Francis, R.C., Hollowed, A.B., Pierce, S.D., Wilson, C., and Hendrix, A.N. 2006. The relationship between Pacific hake (*Merluccius productus*) distribution and poleward subsurface flow in the California Current System. Canadian Journal of Fisheries and Aquatic Sciences 63: 2648–2659.

Alheit, J., and Pitcher, T.J. (*Editors*). 1995. Hake: Biology, fisheries and markets. Springer, Netherlands.

Bailey, K.M., Francis, R.C., and Stevens, P.R. 1982. The life history and fishery of Pacific whiting, *Merluccius productus*. CalCOFI Reports XXIII: 81–98.

Berger, A.M., Edwards, A.M., Grandin, C.J., and Johnson, K.F. 2019. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2019. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Berger, A.M., Grandin, C.J., Johnson, K.F., and Edwards, A.M. 2023. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2023. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Berger, A.M., Grandin, C.J., Taylor, I.G., Edwards, A.M., and Cox, S. 2017. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2017. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Buckley, T.W., and Livingston, P.A. 1997. Geographic variation in the diet of Pacific hake, with a note on cannibalism. CalCOFI Reports XXXVIII: 53–62.

Cheng, M.L.H., Thorson, J.T., Ianelli, J.N., and Cunningham, C.J. 2023. Unlocking the triad of age, year, and cohort effects for stock assessment: Demonstration of a computationally efficient and reproducible framework using weight-at-age. Fisheries Research 266: 106755.

Chittaro, P., Grandin, C., Pacunski, R., and Zabel, R. 2022. Five decades of change in somatic growth of Pacific hake from Puget Sound and Strait of Georgia. PeerJ 10: e13577.

Dorn, M.W. 1994. Status of the coastal Pacific whiting resource in 1994. U.S. Dep. Commer., NOAA Tech. Memo.

Dorn, M.W. 1995. The effects of age composition and oceanographic conditions on the annual migration of Pacific whiting, *Merluccius productus*. CalCOFI Reports XXXVI: 97–105.

Dorn, M.W. 1996. Status of the coastal Pacific whiting resource in 1996. *In* Appendix Volume I: Status of the Pacific Coast Groundfish Fishery through 1996 and recommended acceptable biological catches in 1997: Stock assessment and fishery evaluation. Pacific Fisheries Management Council, Portland, OR. pp. A1–A77.

Dorn, M.W. 1997. Mesoscale fishing patterns of factory trawlers in the Pacific hake (*Merluccius productus*) fishery. CalCOFI Reports XXXVIII: 77–89.

Dorn, M.W., and Methot, R.D. 1991. Status of the coastal Pacific whiting resource in 1991. *In* Appendix: Status of the Pacific Coast Groundfish Fishery through 1991 and recommended biological catches for 1992: Stock assessment and fishery evaluation. Pacific Fishery Management Council, Portland, OR.

Dorn, M.W., and Methot, R.D. 1992. Status of the coastal Pacific whiting resource in 1992.

Dorn, M.W., and Saunders, M.W. 1997. Status of the coastal Pacific whiting stock in U.S. And Canada in 1997. *In* Appendix: Status of the Pacific Coast Groundfish Fishery through 1997 and recommended biological catches for 1998: Stock assessment and fishery evaluation. Pacific Fishery Management Council, Portland, OR. pp. 1–84.

Dorn, M.W., Saunders, M.W., Wilson, C.D., Guttormsen, M.A., Cooke, K., Kieser, R., and Wilkins, M.E. 1999. Status of the coastal Pacific hake/whiting stock in U.S. And Canada in 1998.

Edwards, A.M., Berger, A.M., Grandin, C.J., and Johnson, K.F. 2022. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2022. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Edwards, A.M., Taylor, I.G., Grandin, C.J., and Berger, A.M. 2018. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2018. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Fisch, N., Ahrens, R., Shertzer, K., and Camp, E. 2022. An empirical comparison of alternative likelihood formulations for composition data, with application to cobia and Pacific hake. Canadian Journal of Fisheries and Aquatic Sciences 79: 1745–1764.

Fisheries and Oceans Canada. 2009. A fishery decision-making framework incorporating the precautionary approach.

Fisheries and Oceans Canada. 2023. DFO Groundfish Pacific Region 2023/2024 Integrated Fisheries Management Plan, version 3.1. 23-2236.337: 367 p.

Francis, R.C., Swartzman, G.L., Getz, W.M., Haar, R., and Rose, K. 1982. A management analysis of the Pacific whiting fishery. U.S. Dep. Commer., NOAA Tech. Memo. NWAFC Processed Report 82-06.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences 68: 1124–1138.

Free, C.M., Anderson, S.C., Hellmers, E.A., Muhling, B.A., Navarro, M.O., Richerson, K., Rogers, L.A., Satterthwaite, W.H., Thompson, A.R., Burt, J.M., Gaines, S.D., Marshall, K.N., White, J.W., and Bellquist, L.F. 2023. Impact of the 2014–2016 marine heatwave on US and Canada West Coast fisheries: Surprises and lessons from key case studies. Fish and Fisheries 24: 652–674.

García-De León, F.J., Galván-Tirado, C., Sánchez Velasco, L., Silva-Segundo, C.A., Hernández-Guzmán, R., de los Angeles Barriga-Sosa, I., Díaz Jaimes, P., Canino, M., and Cruz-Hernández, P. 2018. Role of oceanography in shaping the genetic structure in the North Pacific hake *Merluccius productus*. PLOS ONE 13(3): e0194646.

Grandin, C.J., Hicks, A.C., Berger, A.M., Edwards, A.M., Taylor, N., Taylor, I.G., and Cox, S. 2016. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2016. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Grandin, C.J., Johnson, K.F., Edwards, A.M., and Berger, A.M. 2020. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2020. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Hamel, O.S. 2015. A method for calculating a meta-analytical prior for the natural mortality rate using multiple life history correlates. ICES Journal of Marine Science 72(1): 62–69.

Hamel, O.S., and Cope, J.M. 2022. Development and considerations for application of a longevity-based prior for the natural mortality rate. Fisheries Research 256: 106477.

Hamel, O.S., Ressler, P.H., Thomas, R.E., Waldeck, D.A., Hicks, A.C., Holmes, J.A., and Fleischer, G.W. 2015. Biology, fisheries, assessment and management of Pacific hake (*Merluccius productus*). *In* Hakes: Biology and exploitation. *Edited by* H. Arancibia. John Wiley & Sons, Ltd. pp. 234–262.

Hamel, O.S., and Stewart, I.J. 2009. Stock assessment of Pacific Hake, *merluccius productus*, (a.k.a. Whiting) in U.S. And Canadian waters in 2009. Pacific Fishery Management Council, Portland, OR.

Harvey, C.J., Garfield, N., Williams, G.D., and Tolimieri, N. 2021. Ecosystem status report of the California Current for 2020–21: A summary of ecosystem indicators compiled by the California Current Integrated Ecosystem Assessment Team (CCIEA). U.S. Dept. Comm., NOAA Tech. Memo. NMFS-NWFSC-170.

Helser, T.E., Dorn, M.W., Saunders, M.W., Wilson, C.D., Guttormsen, M.A., Cooke, K., and Wilkins, M.E. 2002. Stock assessment of Pacific whiting in U.S. And Canadian waters in 2001.

Helser, T.E., Fleischer, G.W., Martell, S., and Taylor, N. 2005. Stock assessment of Pacific hake (whiting) in U.S. And Canadian waters in 2004.

Helser, T.E., and Martell, S. 2007. Stock assessment of Pacific hake (whiting) in U.S. And Canadian waters in 2007. U.S.-Canada Pacific Hake Joint Technical Committee (JTC).

Helser, T.E., Stewart, I.J., Fleischer, G.W., and Martell, S. 2006. Stock assessment of Pacific hake (whiting) in U.S. And Canadian waters in 2006.

Hicks, A.C., Taylor, N., Grandin, C., Taylor, I.G., and Cox, S. 2013. Status of the Pacific hake (whiting) stock in U.S. and Canadian waters in 2013. International Joint Technical Committee for Pacific Hake.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin 82(4): 898–903.

Hoffman, M.D., and Gelman, A. 2014. The No-U-Turn Sampler: Adaptively setting path lengths in Hamiltonian Monte Carlo. Journal of Machine Learning Research 15: 1593–1623.

Hollowed, A.B., Adlerstein, S., Francis, R.C., and Saunders, M. 1988. Status of the Pacific whiting resource in 1987 and recommendations for management in 1988.

Iwamoto, E., Ford, M.J., and Gustafson, R.G. 2004. Genetic population structure of Pacific hake, *Merluccius productus*, in the Pacific Northwest. Environmental Biology of Fishes 69: 187–199.

Jacobsen, N.S., Marshall, K.N., Berger, A.M., Grandin, C.J., and Taylor, I.G. 2021. Management strategy evaluation of Pacific Hake: Exploring the robustness of the current harvest policy to spatial stock structure, shift in fishery selectivity, and climate-driven distribution shifts. U.S. Dept. Comm., NOAA Tech. Memo. NMFS-NWFSC-168.

Johnson, K.F., Edwards, A.M., Berger, A.M., and Grandin, C.J. 2021. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2021. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

King, J.R., McFarlane, G.A., Jones, S.R.M., Gilmore, S.R., and Abbott, C.L. 2012. Stock delineation of migratory and resident Pacific hake in Canadian waters. Fisheries Research 114: 19–30.

Kuriyama, P.T., Ono, K., Hurtado-Ferro, F., Hicks, A.C., Taylor, I.G., Licandeo, R.R., Johnson, K.F., Anderson, S.C., Monnahan, C.C., Rudd, M.B., Stawitz, C.C., and Valero, J.L. 2016. An empirical weight-at-age approach reduces estimation bias compared to modeling parametric growth in integrated, statistical stock assessment models when growth is time varying. Fisheries Research 180: 119–127.

Leising, A., Husicker, M., Tolimieri, N., and Williams, G. 2024. 2023-2024 california current ecosystem status report: A report of the NOAA california current integrated ecosystem assessment team (CCIEA) to the pacific fishery management council. U.S. Dept. Comm., NOAA Tech. Memo. NMFS-NWFSC-XXX.

Lindgren, F., Rue, H., and Lindström, J. 2011. An explicit link between Gaussian fields and Gaussian Markov random fields: The stochastic partial differential equation approach. Journal of the Royal Statistical Society Series B: Statistical Methodology 73(4): 423–498.

Lloris, D., Matallanas, J., and Oliver, P. 2005. Hakes of the world (family Merlucciidae). An annotated and illustrated catalogue of hake species known to date. FAO Species Catalogue for Fishery Purposes, Rome.

Longo, G.C., Head, M.A., Parker-Stetter, S.L., Taylor, I.G., Tuttle, V.J., Billings, A.A., Gauthier, S., McClure, M.M., and Nichols, K.M. (In press). Population genomics of coastal Pacific Hake. North American Journal of Fisheries Management 00: 10969.

Ludwig, D., and Walters, C.J. 1981. Measurement errors and uncertainty in parameter estimates for stock and recruitment. Canadian Journal of Fisheries and Aquatic Sciences 38(6): 711–720.

Malick, M.J., Hunsicker, M.E., Haltuch, M.A., Parker-Stetter, S.L., Berger, A.M., and Marshall, K.N. 2020a. Relationships between temperature and Pacific hake distribution vary across latitude and life-history stage. Marine Ecology Progress Series 639: 185–197.

Malick, M.J., Siedlecki, S.A., Norton, E.L. and, Kaplan, I.C., Haltuch, M.A., Hunsicker, M.E., Parker-Stetter, S.L., Marshall, K.N., Berger, A.M., Hermann, A.J., Bond, N.A., and Gauthier, S. 2020b. Environmentally driven seasonal forecasts of Pacific hake distribution. Frontiers in Marine Science 7: 578490.

Martell, S. 2010. Assessment and management advice for Pacific hake in U.S. And Canadian waters in 2010.

McAllister, M.K., and Ianelli, J.N. 1997. Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. Canadian Journal of Fisheries and Aquatic Sciences 54(2): 284–300.

Mello, L.G.S., and Rose, G.A. 2005. Using geostatistics to quantify seasonal distribution and aggregation patterns of fishes: An example of Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Sciences 62(3): 659–670.

Methot, Jr., R.D., and Wetzel, C.R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research 142: 86–99.

Methot, R.D., and Taylor, I.G. 2011. Adjusting for bias due to variability of estimated recruitments in fishery assessment models. Canadian Journal of Fisheries and Aquatic Sciences 68(10): 1744–1760.

Monnahan, C.C., Branch, T.A., Thorson, J.T., Stewart, I.J., and Szuwalski, C.S. 2019. Overcoming long Bayesian run times in integrated fisheries stock assessments. ICES Journal of Marine Science 76: 1477–1488.

Monnahan, C.C., and Kristensen, K. 2018. No-U-turn sampling for fast Bayesian inference in ADMB and TMB: Introducing the adnuts and tmbstan R packages. PLOS ONE 13(5): e0197954.

Myers, R.A., Bowen, K.G., and Barrowman, N.J. 1999. Maximum reproductive rate of fish at low population sizes. Canadian Journal of Fisheries and Aquatic Sciences 56(12): 2404–2419.

Petitgas, P. 1993. Geostatistics for fish stock assessments: A review and an acoustic application. ICES Journal of Marine Science 50: 285–298.

Phillips, E.M., Chu, D., Gauthier, S., Parker-Stetter, S.L., Shelton, A.O., and Thomas, R.E. 2022. Spatiotemporal variability of euphausiids in the California Current Ecosystem: Insights from a recently developed time series. ICES Journal of Marine Science 79: 1312–1326.

Phillips, E.M., Malick, M.J., Gauthier, S., Haltuch, M.A., Hunsicker, M.E., Parker-Stetter, S.L., and Thomas, R.E. 2023. The influence of temperature on Pacific hake co-occurrence with euphausiids in the California Current Ecosystem. Fisheries Oceanography 32(3): 267–279.

R Core Team. 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ressler, P.H., Holmes, J.A., Fleischer, G.W., Thomas, R.E., and Cooke, K.C. 2007. Pacific hake, *Merluccius productus*, autecology: A timely review. Marine Fisheries Review 69(1-4): 1–24.

Rivoirard, J., Simmonds, J., Foote, K.G., Fernandes, P., and Bez, N. 2000. Geostatistics for estimating fish abundance. Blackwell Science, Osney Mead, Oxford.

Shelton, A.O., Ramón-Laca, A., Wells, A., Clemons, J., Chu, D., Feist, B.E., Kelly, R.P., Parker-Stetter, S.L., Thomas, R., Nichols, K.M., and Park, L. 2022. Environmental DNA provides quantitative estimates of Pacific hake abundance and distribution in the open ocean. Proceedings of the Royal Society B 289: 20212613.

Simmonds, J., and MacLennan, D.N. 2006. Fisheries acoustics: Theory and practice, 2nd edition. Wiley-Blackwell, Oxford, UK.

Stewart, I.J., Forrest, R.E., Grandin, C., Hamel, O.S., Hicks, A.C., Martell, S.J.D., and Taylor, I.G. 2011. Status of the Pacific Hake (Whiting) stock in U.S. and Canadian waters in 2011. Joint U.S.; Canada Hake Technical Working Group.

Stewart, I.J., Forrest, R.E., Taylor, N., Grandin, C., and Hicks, A.C. 2012. Status of the Pacific hake (whiting) stock in U.S. and Canadian Waters in 2012. International Joint Technical Committee for Pacific hake.

Stewart, I.J., and Hamel, O.S. 2010. Stock Assessment of Pacific Hake, *Merluccius productus*, (a.k.a. Whiting) in U.S. and Canadian Waters in 2010. Pacific Fisheries Management Council, Portland, OR.

Stewart, I.J., and Hamel, O.S. 2014. Bootstrapping of sample sizes for length- or age-composition data used in stock assessments. Canadian Journal of Fisheries and Aquatic Sciences 71(4): 581–588.

Stewart, I.J., Hicks, A.C., Taylor, I.G., Thorson, J.T., Wetzel, C., and Kupschus, S. 2013. A comparison of stock assessment uncertainty estimates using maximum likelihood and Bayesian methods implemented with the same model framework. Fisheries Research 142: 37–46.

Stewart, J.S., Hazen, E., Bograd, S.J., Byrnes, J.E.K., Foley, D.G., Gilly, W.F., Robison, B.H., and Field, J.C. 2014. Combined climate- and prey-mediated range expansion of Humboldt squid (*Dosidicus gigas*), a large marine predator in the California Current System. Global Change Biology 20(6): 1832–1843.

Stienessen, S.C., Honkalehto, T., Lauffenburger, N.E., Ressler, P.H., and Lauth, R.R. 2019. Acoustic Vessel-of-Opportunity (AVO) index for midwater Bering Sea walleye pollock, 2016–2017. U.S. Dept. Comm., NOAA Tech. Memo. AFSC Processed Rep. 2019-01, Seattle, WA.

Taylor, I.G., Grandin, C., Hicks, A.C., Taylor, N., and Cox, S. 2015. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2015. Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States; Canada.

Taylor, N., Hicks, A.C., Taylor, I.G., Grandin, C., and Cox, S. 2014. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2014 with a management strategy evaluation. International Joint Technical Committee for Pacific Hake.

Thorson, J.T., Johnson, K.F., Methot, R.D., and Taylor, I.G. 2017. Model-based estimates of effective sample size in stock assessment models using the Dirichlet-multinomial distribution. Fisheries Research 192: 84–93.

Turley, B.D., and Rykaczewski, R.R. 2019. Influence of wind events on larval fish mortality rates in the southern California Current Ecosystem. Canadian Journal of Fisheries and Aquatic Sciences 76(12): 2418–2432.

Vestfals, C.D., Marshall, K.N., Tolimieri, N., Hunsicker, M.E., Berger, A.M., Taylor, I.G., Jacox, M.G., and Turley, B.D. 2023. Stage-specific drivers of Pacific hake (*Merluccius productus*) recruitment in the California Current Ecosystem. Fisheries Oceanography 32(4): 352–389.

Vrooman, A.M., and Paloma, P.A. 1977. Dwarf hake off the coast of Baja California, Mexico. CalCOFI Reports XXIV: 67–72.

Xu, H., Thorson, J.T., Methot, R.D., and Taylor, I.G. 2019. A new semi-parametric method for autocorrelated age- and time-varying selectivity in age-structured assessment models. Canadian Journal of Fisheries and Aquatic Sciences 76(2): 268–285.

Zamora-García, O.G., Márquez-Farías, J.F., Stavrinaky-Suárez, A., Díaz-Avalos, C., Zamora-García, N., and Lara-Mendoza, R.E. 2020. Catch rate, length, and sex ratio of Pacific hake (*Merluccius productus*) in the northern Gulf of California. Fishery Bulletin 118(4): 365–379.

6 TABLES

Table 1. Annual catches of Pacific Hake (t) in U.S. waters by fleet, 1966–2023. 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	Joint-venture	Mother-ship	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	67,760	0	248,395
2009	0	0	37,550	34,552	49,222	0	121,324
2010	0	0	52,022	54,284	64,653	0	170,960
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
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	150,741	0	354,129
2018	0	0	67,121	116,073	135,112	0	318,306
2019	0	0	52,646	116,146	148,210	0	317,002

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Year	Foreign	Joint-venture	Mother-ship	Catcher-processor	Shore-based	Research	Total
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	59,516	126,247	105,939	0	291,702
2023	0	0	32,911	107,117	100,396	0	240,424

Table 2. Annual catches of Pacific Hake (t) in Canadian waters by fleet, 1966–2023.

Year	Foreign	Joint-venture	Shore-side	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

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Year	Foreign	Joint-venture	Shore-side	Freezer-trawler	Total
2007	0	6,780	52,649	14,121	73,550
2008	0	3,592	57,795	13,214	74,602
2009	0	0	44,130	13,223	57,353
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
2015	0	0	16,775	22,909	39,684
2016	0	0	35,012	34,731	69,743
2017	0	5,608	43,427	37,686	86,721
2018	0	2,724	50,747	41,942	95,413
2019	0	0	40,794	54,218	95,013
2020	0	0	30,085	62,404	92,489
2021	0	0	11,269	45,807	57,076
2022	0	0	3,868	27,803	31,671
2023	0	0	3,657	19,901	23,557

Table 3. Pacific Hake landings and management decisions, 1966–2023. 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	Canada landings	Total landings	U.S. prop. of total catch	Canada prop. of total catch	U.S. catch target	Canada catch target	Total catch target	U.S. prop. of catch target removed	Canada prop. of catch target removed	Total prop. 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%

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Year	U.S. landings	Canada landings	Total landings	U.S. prop. of total catch	Canada prop. of total catch	U.S. catch target	Canada catch target	Total catch target	U.S. prop. of catch target removed	Canada prop. of catch target removed	Total prop. of catch target removed
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%
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	73,550	291,231	74.7%	25.3%	242,591	85,767	328,358	89.7%	85.8%	88.7%
2008	248,395	74,602	322,997	76.9%	23.1%	269,545	95,297	364,842	92.2%	78.3%	88.5%
2009	121,324	57,353	178,677	67.9%	32.1%	135,939	48,061	184,000	89.2%	119.3%	97.1%
2010	170,960	57,016	227,975	75.0%	25.0%	193,935	68,565	262,500	88.2%	83.2%	86.8%
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	39,684	193,844	79.5%	20.5%	325,072	114,928	440,000	47.4%	34.5%	44.1%
2016	262,327	69,743	332,070	79.0%	21.0%	367,553	129,947	497,500	71.4%	53.7%	66.7%
2017	354,129	86,721	440,849	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	291,702	31,671	323,372	90.2%	9.8%	402,646	142,354	545,000	72.4%	22.2%	59.3%
2023	240,424	23,557	263,981	91.1%	8.9%	461,750	163,250	625,000	52.1%	14.4%	42.2%

Table 4. Annual summary of U.S. and Canadian fishery sampling included in this stock assessment by fleet, 1975–2023. The 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.

Year	U.S. Foreign (hauls)	U.S. Joint-venture (hauls)	U.S. Mother-ship (hauls)	U.S. Combined Mother-ship Catcher-processor (hauls)	U.S. Catcher-processor (hauls)	U.S. Shore-based (trips)	Canada Foreign (hauls)	Canada Joint-venture (hauls)	Canada Shore-side (trips)	Canada 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	–

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Year	U.S. Foreign (hauls)	U.S. Joint-venture (hauls)	U.S. Mother-ship (hauls)	U.S. Combined Mother-ship Catcher-processor (hauls)	U.S. Catcher-processor (hauls)	U.S. Shore-based (trips)	Canada Foreign (hauls)	Canada Joint-venture (hauls)	Canada Shore-side (trips)	Canada Freezer trawlers (hauls)
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+
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	1,670	569	4.58	35.63	1.05	27.44	1.90	2.57	2.83	19.47	2.22	1.05	0.30	0.54	0.15	0.19	0.09
2019	1,685	566	0.00	6.45	26.06	1.43	38.29	1.60	4.00	1.54	17.34	1.20	1.10	0.28	0.14	0.25	0.32
2020	1,281	433	0.00	0.14	9.33	41.91	1.55	29.82	1.72	1.63	1.59	10.41	0.65	1.01	0.07	0.05	0.11
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	1,269	472	0.89	47.51	1.65	1.90	8.54	19.54	0.74	12.20	1.58	0.74	0.44	2.86	1.08	0.28	0.04
2023	1,277	391	0.69	51.27	24.03	0.78	0.93	3.56	8.87	1.21	4.97	0.59	0.35	0.50	1.91	0.27	0.06

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+
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	1,230	414	16.95	25.30	1.18	28.83	1.14	2.28	1.70	16.82	2.47	1.24	0.74	0.32	0.48	0.49	0.05
2019	903	307	0.00	14.98	20.59	0.97	36.30	1.33	4.12	1.53	16.62	1.47	1.04	0.42	0.48	0.14	0.01
2020	568	192	0.00	0.00	8.62	40.11	2.40	28.62	1.49	2.06	2.51	11.89	1.12	0.80	0.39	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	840	299	1.45	42.64	1.97	2.83	6.91	19.41	1.07	14.51	1.82	0.47	0.52	3.82	1.53	0.43	0.62
2023	448	127	2.28	39.60	33.17	1.15	1.21	5.46	7.49	0.67	5.19	0.70	0.25	0.49	2.06	0.29	0.00

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+
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	25.93	1.92	2.80	2.08	11.12	2.27	0.85	0.22	0.50
2022	1,800	90	0.41	10.55	1.19	1.86	11.71	34.34	1.74	20.59	2.37	1.49	1.30	9.22	1.83	0.85	0.55
2023	1,328	66	0.14	16.44	27.02	2.21	3.54	7.54	19.29	1.98	11.59	2.02	0.88	1.14	4.34	0.87	1.00

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+
2014	279	28	0.00	0.00	0.18	15.00	12.67	23.68	9.31	14.61	8.57	1.75	4.76	0.58	0.43	0.86	7.61
2015	296	6	2.71	0.00	1.15	2.68	63.57	8.08	11.53	1.32	5.61	1.82	0.00	0.52	0.00	0.34	0.69
2016	188	19	0.00	4.67	0.81	7.51	3.92	62.23	5.83	7.35	1.54	2.10	0.00	1.22	0.91	0.27	1.65
2017	680	68	6.94	0.33	7.83	1.72	3.00	7.29	48.07	13.25	6.94	1.32	1.25	1.19	0.14	0.15	0.55
2018	466	43	0.50	5.15	1.91	22.50	1.23	4.48	5.93	35.33	12.44	4.43	2.61	1.05	0.96	1.23	0.24
2019	296	33	0.00	13.24	11.41	2.87	30.27	1.90	4.36	2.70	26.37	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	2.11	0.22	0.48	0.54
2022	596	22	0.00	0.00	0.13	1.42	13.76	22.91	6.59	17.47	4.75	4.29	4.52	13.98	5.88	2.41	1.88
2023	413	12	0.00	0.31	5.16	1.37	2.64	17.33	31.55	6.31	13.18	1.35	2.87	3.12	9.43	3.12	2.26

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+
2014	381	28	0.00	0.00	1.16	18.83	12.41	27.83	7.19	10.72	7.84	2.46	1.80	0.54	2.00	1.05	6.18
2015	215	21	0.00	0.00	4.46	1.85	55.54	12.22	15.64	2.84	2.82	3.24	1.13	0.28	0.00	0.00	0.00
2016	352	40	0.51	4.54	0.77	2.23	9.15	64.20	6.89	6.91	1.98	0.76	0.16	0.70	0.42	0.00	0.78
2017	760	76	0.00	0.52	7.41	2.45	5.46	5.04	50.03	12.19	9.69	2.40	2.51	1.38	0.22	0.19	0.50
2018	1,225	91	0.10	4.67	0.72	17.63	2.46	3.96	5.15	45.58	9.47	5.25	2.38	1.15	0.65	0.56	0.26
2019	901	103	0.04	18.04	15.07	3.66	19.21	2.75	3.93	4.56	23.12	5.38	2.37	1.15	0.37	0.36	0.00
2021	100	2	0.00	0.00	0.00	17.26	24.00	6.74	27.37	2.88	2.88	9.51	5.37	1.12	0.00	2.88	0.00
2022	421	16	0.00	0.00	0.00	0.24	6.20	22.15	8.02	17.76	7.55	4.38	6.08	16.52	7.45	2.87	0.76
2023	369	14	0.00	0.00	0.27	0.40	3.26	15.99	21.59	5.06	19.62	6.11	3.20	7.55	13.89	1.95	1.10

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.

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	0.44
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	14.68	3.77	3.19	10.19	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	7.64	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	0.70
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	5.61	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	0.06	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	1.26	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	0.01	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	15.69	8.56	12.10	5.99	1.78	2.23	1.81	0.70	1.42	0.69	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	0.48	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	8.12	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

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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+
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
2008	763	0.77	8.85	30.57	2.24	14.21	1.09	3.75	3.47	28.85	2.69	1.47	0.68	0.50	0.22	0.65
2009	664	0.79	0.62	37.45	30.09	2.76	9.07	0.70	2.00	1.30	12.41	1.48	0.36	0.60	0.17	0.19
2010	860	0.03	25.01	3.32	35.14	23.84	2.35	2.57	0.35	0.46	0.96	4.33	1.08	0.28	0.15	0.15
2011	1,075	2.67	8.69	71.58	2.60	6.05	4.26	0.99	0.81	0.28	0.33	0.07	1.33	0.14	0.08	0.12
2012	796	0.18	40.41	11.58	33.19	2.45	5.37	2.58	1.11	0.66	0.23	0.35	0.33	0.92	0.26	0.40
2013	1,044	0.03	0.54	69.85	5.92	10.51	1.19	3.54	2.08	0.98	1.44	0.28	0.32	0.56	2.28	0.48
2014	1,104	0.00	3.29	3.82	64.81	7.05	12.20	1.69	2.90	1.82	0.68	0.39	0.07	0.19	0.22	0.87
2015	745	3.62	1.10	7.06	3.85	69.58	4.95	5.56	0.93	1.45	1.20	0.24	0.17	0.04	0.03	0.21
2016	1,308	0.32	50.49	1.65	4.68	2.74	32.54	2.31	3.00	0.81	0.44	0.27	0.33	0.14	0.06	0.21
2017	1,293	3.77	0.72	38.47	2.38	4.12	3.10	36.81	4.38	3.08	1.33	0.61	0.72	0.21	0.09	0.20
2018	1,209	7.15	25.58	1.37	27.78	1.51	2.76	3.04	22.52	4.00	1.85	0.97	0.58	0.41	0.36	0.10
2019	1,138	0.01	13.13	21.21	1.61	32.56	1.84	3.78	2.12	18.63	1.91	1.65	0.69	0.40	0.25	0.22
2020	756	0.00	0.06	8.84	36.46	1.55	30.68	1.57	2.14	1.78	14.21	1.08	1.03	0.28	0.09	0.23
2021	721	1.39	0.36	1.96	13.45	33.99	2.87	24.69	1.98	2.44	3.06	10.54	1.81	0.57	0.57	0.30
2022	899	0.80	32.37	1.46	1.96	9.01	23.93	1.63	15.48	2.28	1.18	1.12	5.89	1.86	0.67	0.37
2023	610	0.69	35.25	24.90	1.28	1.95	5.88	12.93	1.63	7.97	1.36	0.67	1.09	3.40	0.58	0.43

Table 11. Acoustic age 2+ 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)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
1995	69	0.00	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	0.00	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	0.00	50.62	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	0.00	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	0.00	19.07	1.23	5.10	4.78	50.67	6.99	2.50	3.99	2.45	1.71	0.74	0.48	0.14	0.16
2007	69	0.00	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	0.00	0.55	29.33	40.21	2.29	8.22	1.25	1.79	1.93	8.32	3.63	1.44	0.28	0.48	0.26
2011	46	0.00	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	0.00	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	0.00	2.17	74.97	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	0.00	7.45	9.19	4.38	58.98	4.88	7.53	1.69	1.68	1.64	0.95	0.16	0.29	0.24	0.92
2017	58	0.00	0.49	52.73	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	0.00	10.72	27.23	1.51	31.31	2.50	3.18	2.68	16.12	2.28	0.96	0.36	0.38	0.47	0.28
2021	65	0.00	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
2023	64	0.00	50.58	24.66	1.03	1.17	2.92	8.09	0.88	5.38	0.77	0.58	0.67	2.30	0.41	0.56

Table 12. Summary of the acoustic age 2+ surveys from 1995 to 2023.

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	2.276	0.500
2023	23-Jun	6-Sep	Bell Shimada John Franklin	0.907	0.086	64	1.187	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. prop. of biomass	Canada Age-2+ biomass (million t)	Canada sampling CV age-2+	Canada prop. of biomass
1995	1.061	0.084	0.805	0.257	0.271	0.195
1998	0.606	0.093	0.386	0.963	0.047	0.614
2001	0.793	0.088	0.920	0.069	0.777	0.080
2003	1.678	0.063	0.785	0.459	0.174	0.215
2005	0.707	0.096	0.514	0.669	0.076	0.486
2007	0.683	0.085	0.724	0.260	0.149	0.276
2009	1.104	0.106	0.735	0.398	0.210	0.265
2011	0.602	0.104	0.893	0.072	0.607	0.107
2012	1.141	0.059	0.892	0.139	0.342	0.108
2013	1.805	0.054	0.936	0.124	0.568	0.064
2015	1.698	0.085	0.788	0.458	0.214	0.212
2017	1.028	0.073	0.725	0.390	0.126	0.275
2019	1.527	0.054	0.889	0.191	0.334	0.111
2021	1.459	0.103	0.957	0.066	1.641	0.043
2023	0.885	0.071	0.976	0.022	2.113	0.024

Table 14. Number of Pacific Hake ovaries collected for histological analysis and included in the estimates of time-varying maturity. Note that data from 2023 have yet to be analyzed.

Year	NWFSC Trawl Survey	U.S. Acoustic Survey/ Research	U.S. At-Sea Hake Observer Program	Total
2009	244	0	0	**244**
2012	64	181	0	**245**
2013	63	186	135	**384**
2014	197	0	196	**393**
2015	216	160	131	**507**
2016	66	131	194	**391**
2017	102	57	177	**336**
2018	109	54	0	**163**
2019	46	59	0	**105**
2020	0	0	0	**0**
2021	0	68	0	**68**
2022	0	0	0	**0**
2023	0	76	0	**76**
Total	**1,107**	**972**	**833**	**2,912**

Table 15. Summary of estimated model parameters and priors in the base model. The beta prior is parameterized with a mean and standard deviation (SD). The lognormal prior is parameterized with the median and SD 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: 1946–2023	78	(-6, 6)	Lognormal (0.00, 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 Survey			
Non-parametric age-based selectivity: ages 2–6	5	(-5, 9)	Uniform
Selectivity deviations (1991–2023, ages 2–6)	165	(-10, 10)	Normal (0.00, 1.40)
Data Weighting			
Dirichlet-multinomial fishery likelihood, $\log(\theta_{fishery})$	2	(-5, 20)	Normal (0.00, 1.81)
Dirichlet-multinomial survey likelihood, $\log(\theta_{survey})$	2	(-5, 20)	Normal (0.00, 1.81)

Table 16. 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 (M-I) and Dirichlet-multinomial (D-M) approaches, are explained in the main text. The Markov chain Monte Carlo column gives the number of Markov chain Monte Carlo samples used to describe model results and produce statistical inference.

Year	Framework	Survey	Comp Method	Num. MCMC samples	Change
2011	SS3 3-20, TINSS	yes	M-I (0.100, 0.890)	999	Increased compatibility of SS and TINSS, except for age-composition likelihood
2012	SS3 3-23b	yes	M-I (0.120, 0.940)	999	One framework for base model; TINSS changed to CCAM
2013	SS3 3-24j	no	M-I (0.120, 0.940)	999	Developed MSE
2014	SS3 3-24s	yes	M-I (0.120, 0.940)	999	Time-varying fishery selectivity
2015	SS3 3-24u	no	M-I (0.120, 0.940)	999	No major changes
2016	SS3 3-24u	yes	M-I (0.110, 0.510)	999	Re-analyzed 1998-2015 acoustic-survey data; Removed 1995 survey data
2017	SS3 3-24u	no	M-I (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
2024	SS3 3-30-22-00	yes	D-M (0.348, 0.930)	8,000	Time-varying maturity

Table 17. Estimated numbers-at-age at the beginning of the year from the base model (posterior medians; millions).

Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	1,633	1,466	907	496	293	187	142	106	91	75	61	53	43	36	29	24	20	16	13	11	32
1967	4,651	1,294	1,161	707	378	218	138	100	75	64	53	43	38	30	26	20	17	14	11	9	41
1968	3,128	3,692	1,020	897	525	272	154	90	66	49	42	35	28	25	20	17	13	11	9	7	41
1969	717	2,485	2,926	801	682	393	201	110	64	47	35	30	25	20	17	14	12	9	8	7	42
1970	9,385	568	1,976	2,280	602	501	283	137	74	44	32	24	20	17	14	12	10	8	6	5	39
1971	860	7,412	448	1,529	1,706	436	356	187	90	49	29	21	16	13	11	9	8	6	5	4	33
1972	554	684	5,854	350	1,167	1,279	324	253	133	64	35	21	15	11	10	8	6	6	5	4	30
1973	6,282	440	542	4,584	270	892	970	238	186	97	47	26	15	11	8	7	6	5	4	3	28
1974	353	4,974	349	425	3,525	204	671	705	173	135	71	34	19	11	8	6	5	4	3	3	25
1975	1,948	281	3,932	272	325	2,651	152	478	501	123	96	50	25	13	8	6	4	4	3	2	22
1976	215	1,542	222	3,079	210	247	1,990	110	346	363	89	70	36	18	10	6	4	3	3	2	20
1977	6,980	170	1,218	175	2,376	160	187	1,468	81	254	267	65	51	27	13	7	4	3	2	2	18
1978	138	5,521	135	956	137	1,840	124	142	1,112	61	192	202	49	39	20	10	5	3	2	2	16
1979	1,446	109	4,364	106	746	106	1,419	94	108	844	46	145	154	37	29	15	8	4	2	2	15
1980	17,672	1,143	87	3,425	83	577	82	1,069	70	81	636	35	109	116	28	22	12	6	3	2	13
1981	274	13,984	906	68	2,671	64	446	62	813	54	62	484	27	83	89	22	17	9	4	2	12
1982	325	218	11,049	710	53	2,047	49	331	46	604	40	46	359	20	62	66	16	12	7	3	12
1983	564	259	173	8,686	552	41	1,570	37	248	35	454	30	34	270	15	46	49	12	9	5	13
1984	14,415	447	205	136	6,771	427	31	1,190	28	188	26	344	23	26	204	11	35	37	9	7	15
1985	139	11,394	354	161	105	5,224	328	24	895	21	142	20	259	17	20	154	8	26	28	7	18
1986	191	110	9,019	280	126	82	4,043	250	18	682	16	108	15	197	13	15	117	6	20	21	21
1987	6,785	151	87	7,074	216	97	62	3,008	186	13	508	12	80	11	147	10	11	87	5	15	32
1988	2,144	5,369	120	68	5,447	165	73	45	2,202	136	10	371	9	59	8	107	7	8	64	3	35
1989	114	1,699	4,246	94	53	4,139	124	53	33	1,606	99	7	271	6	43	6	78	5	6	46	29
1990	4,395	90	1,344	3,304	71	39	3,058	88	38	23	1,136	70	5	191	4	30	4	55	4	4	54
1991	1,261	3,475	71	1,053	2,534	54	30	2,213	63	27	17	823	51	4	138	3	22	3	40	3	42
1992	127	999	2,745	53	720	1,872	38	21	1,578	45	19	12	586	36	3	99	2	16	2	28	32
1993	3,230	100	789	2,141	37	507	1,378	26	15	1,095	31	13	8	407	25	2	68	2	11	2	42
1994	3,331	2,556	79	619	1,603	26	362	992	19	11	787	22	10	6	292	18	1	49	1	8	32
1995	1,271	2,637	2,023	62	477	1,133	17	229	629	12	7	500	14	6	4	185	11	1	31	1	25
1996	1,864	1,006	2,084	1,592	48	362	789	11	152	418	8	4	332	9	4	3	123	8	1	21	17
1997	1,027	1,476	793	1,564	1,162	34	264	498	7	96	263	5	3	210	6	3	2	78	5	0	24
1998	2,013	812	1,168	621	1,094	786	23	166	313	4	60	165	3	2	132	4	2	1	49	3	15
1999	12,898	1,594	642	901	391	747	465	14	103	195	3	38	103	2	1	82	2	1	1	30	11
2000	315	10,204	1,259	465	590	224	473	285	9	63	119	2	23	63	1	1	50	1	1	0	26
2001	1,256	250	8,060	985	338	422	152	299	180	5	40	75	1	14	40	1	0	32	1	0	17
2002	44	994	198	6,319	724	226	283	99	196	118	4	26	49	1	9	26	0	0	21	1	11
2003	1,715	35	785	155	4,876	530	160	201	70	140	84	3	19	35	1	7	19	0	0	15	8

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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+
2004	43	1,356	27	620	121	3,650	381	113	142	50	99	60	2	13	25	0	5	13	0	0	16
2005	2,857	34	1,071	21	460	73	2,528	253	75	94	33	66	40	1	9	17	0	3	9	0	11
2006	2,076	2,260	27	841	16	320	44	1,614	162	48	60	21	42	25	1	6	11	0	2	6	7
2007	25	1,642	1,784	19	596	10	196	27	972	97	29	36	13	25	15	0	3	6	0	1	8
2008	5,629	20	1,297	1,353	12	388	6	113	15	562	56	17	21	7	15	9	0	2	4	0	5
2009	1,371	4,449	15	990	908	8	235	3	62	8	306	31	9	11	4	8	5	0	1	2	3
2010	15,979	1,085	3,515	12	670	619	5	154	2	41	6	202	20	6	8	3	5	3	0	1	3
2011	384	12,618	857	2,674	8	369	379	4	106	2	28	4	138	14	4	5	2	4	2	0	3
2012	1,575	303	9,952	659	1,581	5	253	265	2	74	1	19	3	96	10	3	4	1	2	2	2
2013	371	1,247	240	7,665	478	1,063	3	178	187	2	52	1	14	2	68	7	2	3	1	2	2
2014	8,256	294	986	188	5,658	350	769	2	118	124	1	34	1	9	1	45	4	1	2	1	3
2015	34	6,522	232	765	134	4,149	251	530	2	81	85	1	24	0	6	1	31	3	1	1	2
2016	5,638	27	5,140	180	575	98	3,015	184	390	1	60	63	1	17	0	5	1	23	2	1	3
2017	1,565	4,458	21	3,660	133	411	68	2,122	130	274	1	42	44	0	12	0	3	0	16	2	2
2018	397	1,236	3,494	14	2,594	91	286	44	1,373	84	178	1	27	29	0	8	0	2	0	10	3
2019	273	315	943	2,555	10	1,849	66	189	29	907	55	117	0	18	19	0	5	0	1	0	9
2020	4,748	216	249	671	1,851	7	1,233	42	120	18	577	35	75	0	11	12	0	3	0	1	6
2021	10,187	3,749	171	195	506	1,232	4	797	27	77	12	374	23	48	0	7	8	0	2	0	4
2022	1,881	8,073	2,964	132	149	353	804	3	512	17	50	8	240	14	31	0	5	5	0	1	3
2023	979	1,486	6,371	2,189	101	111	246	510	2	324	11	31	5	152	9	20	0	3	3	0	3
2024	980	772	1,174	4,877	1,616	77	83	162	338	1	215	7	21	3	101	6	13	0	2	2	2

Table 18. Estimated total biomass-at-age at the beginning of the year from the base model (posterior medians; kilotonnes).

Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	33	138	234	197	142	103	84	67	63	56	48	45	39	34	29	26	21	17	14	11	34
1967	93	122	299	281	182	120	82	63	52	48	42	37	35	29	25	22	18	15	12	10	45
1968	63	347	263	357	253	150	92	57	46	37	33	29	26	23	20	18	14	12	10	8	44
1969	14	234	755	319	329	217	119	69	45	35	28	25	23	19	17	15	13	10	9	7	45
1970	188	53	509	907	291	276	168	86	52	33	25	20	19	16	13	13	10	9	7	6	42
1971	17	697	116	608	824	240	211	118	63	37	23	18	15	13	11	10	8	7	6	5	36
1972	11	64	1,510	139	564	705	192	160	93	48	28	17	14	11	10	9	7	6	5	4	33
1973	126	41	140	1,824	130	491	576	150	130	73	37	22	14	10	8	8	6	5	4	4	30
1974	7	468	90	169	1,702	113	399	445	121	102	56	29	17	10	8	6	6	5	4	3	27
1975	40	26	1,132	114	185	1,808	115	418	498	131	112	68	38	21	15	6	5	4	3	3	24
1976	4	170	63	1,557	122	182	1,651	101	378	441	112	98	60	32	18	13	10	7	6	5	45
1977	179	14	361	76	1,441	104	146	1,274	81	294	333	86	76	44	24	14	8	6	5	4	35
1978	2	603	28	398	65	1,156	78	106	963	60	210	243	63	53	31	18	10	6	4	3	29
1979	30	9	1,431	37	415	63	1,048	69	97	864	51	186	217	53	45	28	14	8	4	3	27
1980	341	92	17	1,453	30	306	44	702	48	66	567	34	125	140	35	31	16	8	4	3	18
1981	4	1,253	197	20	1,364	26	251	35	580	39	52	453	28	95	108	28	22	12	6	3	16
1982	4	13	2,453	217	17	1,080	19	179	26	420	27	37	325	19	66	79	19	15	8	4	14
1983	7	16	29	2,983	205	15	887	15	148	21	328	22	30	249	15	54	57	14	11	6	15
1984	270	29	35	36	2,951	189	13	744	13	126	17	276	18	24	201	13	39	42	10	8	17
1985	2	1,115	69	48	38	2,884	172	12	683	12	109	15	246	16	21	183	10	32	33	8	22
1986	4	9	2,348	82	44	33	2,326	136	10	546	9	86	12	186	12	17	130	7	22	24	23
1987	128	12	17	2,601	70	35	24	1,678	102	7	386	7	62	8	129	9	10	79	4	14	29
1988	43	498	27	22	2,554	64	30	20	1,414	84	6	314	5	49	7	108	7	8	64	3	36
1989	2	154	1,035	32	19	2,128	49	22	15	1,067	61	4	234	4	35	5	66	4	5	39	24
1990	88	8	335	1,256	30	17	1,697	37	17	12	791	46	3	170	3	27	4	50	3	4	48
1991	28	327	17	406	1,170	26	13	1,301	30	13	9	608	36	2	126	2	15	2	27	2	29
1992	3	103	708	20	338	989	19	10	1,023	23	10	7	462	26	2	98	2	16	2	28	32
1993	59	8	188	724	14	230	660	12	7	647	14	6	4	277	16	1	41	1	6	1	25
1994	71	239	19	248	717	12	191	548	10	6	526	12	5	3	222	13	1	36	1	6	23
1995	26	283	550	24	248	616	9	137	407	8	4	378	8	4	2	164	10	1	28	1	22
1996	36	93	584	639	22	205	438	6	95	278	5	3	255	5	2	2	78	5	0	13	11
1997	22	134	203	684	573	18	161	296	4	65	184	3	2	166	3	2	1	49	3	0	15
1998	37	77	270	228	540	410	12	100	190	3	40	114	2	1	99	2	1	1	29	2	9
1999	230	137	163	316	172	413	255	8	67	125	2	26	74	1	1	66	2	1	1	24	9
2000	8	1,104	382	236	326	145	362	214	7	57	103	1	22	60	1	1	43	1	1	0	22
2001	33	29	2,465	477	216	275	109	251	154	5	39	71	1	14	40	1	0	31	1	0	16
2002	1	124	65	3,044	435	168	201	77	185	111	3	27	51	1	10	29	1	0	23	1	12
2003	43	4	239	70	2,547	324	113	135	53	126	73	2	18	33	0	7	19	0	0	15	8

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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+**
2004	1	146	8	268	61	1,997	229	78	96	37	85	51	2	12	22	0	4	12	0	0	15
2005	53	3	308	9	237	41	1,450	158	56	67	25	59	35	1	8	16	0	3	8	0	10
2006	35	200	7	378	8	191	27	996	112	39	45	17	41	23	1	6	11	0	2	6	7
2007	0	120	406	8	306	6	117	16	618	68	23	27	10	23	13	0	3	6	0	1	7
2008	94	2	294	539	7	257	4	82	12	436	47	16	19	7	16	10	0	2	4	0	6
2009	24	342	3	341	432	5	163	2	48	7	242	26	9	10	4	9	5	0	1	2	3
2010	286	94	784	4	297	356	4	121	2	36	5	179	20	6	7	3	6	3	0	1	4
2011	7	1,038	199	902	3	183	228	3	89	1	25	3	128	13	4	5	2	4	2	0	3
2012	33	28	2,266	240	657	2	136	172	2	68	1	19	3	92	10	3	4	1	3	2	2
2013	8	131	65	2,889	227	539	2	109	142	2	53	1	15	2	72	8	2	3	1	2	3
2014	192	32	306	86	2,816	205	453	1	86	110	1	40	1	11	1	56	6	2	2	1	3
2015	1	578	56	298	60	1,907	127	269	1	51	64	1	24	0	6	1	33	3	1	1	2
2016	124	3	1,244	67	272	50	1,484	99	217	1	39	50	1	18	0	5	1	25	2	1	3
2017	41	504	6	1,501	66	243	41	1,214	84	180	1	32	41	0	14	0	4	1	20	2	3
2018	8	160	1,143	7	1,371	55	192	30	914	62	128	0	23	29	0	11	0	3	0	14	3
2019	6	28	298	1,151	5	992	38	119	19	578	38	80	0	14	17	0	6	0	2	0	10
2020	119	23	62	333	1,029	4	718	26	85	13	389	26	55	0	9	12	0	3	0	1	6
2021	212	461	52	78	318	815	3	514	19	61	9	278	19	38	0	7	7	0	2	0	4
2022	37	825	1,044	66	76	265	596	2	380	14	43	7	200	13	26	0	4	5	0	1	3
2023	19	130	1,693	1,134	58	62	188	382	1	246	8	27	4	122	8	17	0	3	3	0	2
2024	22	79	349	2,302	907	48	56	111	245	1	163	5	17	2	86	6	13	0	2	2	2

Table 19. 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	0.62	5.03	7.88	9.67	10.07	15.23	14.33	12.97	12.00	11.43	10.63	9.86	9.55	9.12	8.36	8.36	8.36	8.36	8.36	8.36
1967	0.00	1.04	8.37	13.03	15.84	16.53	24.68	23.22	21.01	19.43	18.52	17.23	15.97	15.46	14.78	13.54	13.54	13.54	13.54	13.54	13.54
1968	0.00	0.61	4.89	7.67	9.39	9.86	14.90	14.02	12.69	11.73	11.18	10.40	9.64	9.34	8.92	8.17	8.17	8.17	8.17	8.17	8.17
1969	0.00	0.83	6.72	10.60	12.96	13.52	20.17	18.98	17.18	15.89	15.14	14.08	13.05	12.64	12.08	11.07	11.07	11.07	11.07	11.07	11.07
1970	0.00	0.99	7.94	12.45	15.17	15.88	23.61	22.21	20.10	18.59	17.72	16.48	15.28	14.80	14.14	12.95	12.95	12.95	12.95	12.95	12.95
1971	0.00	0.60	4.86	7.70	9.46	9.92	14.94	14.05	12.72	11.76	11.21	10.43	9.67	9.36	8.95	8.20	8.20	8.20	8.20	8.20	8.20
1972	0.00	0.41	3.30	5.22	6.43	6.75	10.22	9.62	8.70	8.05	7.67	7.14	6.61	6.40	6.12	5.61	5.61	5.61	5.61	5.61	5.61
1973	0.00	0.46	3.74	5.94	7.31	7.64	11.57	10.88	9.85	9.11	8.68	8.07	7.48	7.25	6.93	6.34	6.34	6.34	6.34	6.34	6.34
1974	0.00	0.58	4.66	7.40	9.07	9.50	14.28	13.44	12.16	11.25	10.72	9.97	9.24	8.95	8.55	7.84	7.84	7.84	7.84	7.84	7.84
1975	0.00	0.49	3.45	5.80	6.35	6.34	9.26	8.03	7.08	6.61	6.04	5.17	4.50	4.46	3.78	6.50	6.50	6.50	6.50	6.50	6.50
1976	0.00	0.34	2.97	4.07	5.30	4.97	7.23	6.54	5.49	4.93	4.77	4.27	3.64	3.32	3.26	2.60	2.60	2.60	2.60	2.60	2.60
1977	0.00	0.28	1.77	2.97	3.17	3.53	4.85	4.35	3.80	3.26	3.03	2.87	2.56	2.28	2.06	1.91	1.91	1.91	1.91	1.91	1.91
1978	0.00	0.20	2.39	2.91	3.79	3.44	5.61	4.73	4.10	3.66	3.25	2.96	2.79	2.60	2.31	1.96	1.96	1.96	1.96	1.96	1.96
1979	0.00	0.30	1.75	4.01	3.79	4.20	5.59	5.59	4.56	4.04	3.73	3.24	2.94	2.90	2.69	2.24	2.24	2.24	2.24	2.24	2.24
1980	0.00	0.26	2.42	2.74	4.85	3.91	6.37	5.20	5.03	4.19	3.83	3.47	3.00	2.85	2.79	2.44	2.44	2.44	2.44	2.44	2.44
1981	0.00	0.38	3.49	6.21	5.44	8.22	9.64	9.63	7.60	7.50	6.46	5.79	5.22	4.72	4.46	4.11	4.11	4.11	4.11	4.11	4.11
1982	0.00	0.46	2.82	4.97	6.95	5.16	11.44	8.27	7.98	6.43	6.57	5.54	4.95	4.67	4.19	3.73	3.73	3.73	3.73	3.73	3.73
1983	0.00	0.39	3.10	3.69	5.12	6.03	6.59	8.97	6.26	6.17	5.15	5.14	4.33	4.04	3.79	3.20	3.20	3.20	3.20	3.20	3.20
1984	0.00	0.42	3.47	5.39	5.00	5.88	10.17	6.82	8.97	6.39	6.52	5.32	5.30	4.66	4.33	3.82	3.82	3.82	3.82	3.82	3.82
1985	0.00	0.21	2.30	3.69	4.49	3.56	6.12	6.50	4.21	5.65	4.17	4.17	3.39	3.53	3.09	2.70	2.70	2.70	2.70	2.70	2.70
1986	0.00	0.43	2.84	6.18	7.71	8.01	9.21	9.76	10.01	6.62	9.20	6.65	6.62	5.63	5.83	4.79	4.79	4.79	4.79	4.79	4.79
1987	0.00	0.53	4.76	6.18	10.46	11.10	16.79	11.87	12.15	12.74	8.71	11.86	8.54	8.89	7.51	7.32	7.32	7.32	7.32	7.32	7.32
1988	0.00	0.48	4.31	7.58	7.66	11.08	17.14	15.95	10.90	11.39	12.35	8.28	11.22	8.45	8.74	6.96	6.96	6.96	6.96	6.96	6.96
1989	0.00	0.68	5.54	9.66	13.20	11.37	23.68	22.65	20.37	14.21	15.37	16.32	10.90	15.45	11.56	11.26	11.26	11.26	11.26	11.26	11.26
1990	0.00	0.55	4.29	6.87	9.33	10.90	13.69	17.80	16.45	15.10	10.90	11.55	12.22	8.53	12.02	8.47	8.47	8.47	8.47	8.47	8.47
1991	0.00	0.80	13.10	30.80	12.34	13.08	19.44	15.03	18.89	17.82	16.93	11.97	12.63	13.98	9.70	12.87	12.87	12.87	12.87	12.87	12.87
1992	0.00	0.47	4.14	15.04	20.50	11.51	21.38	22.52	16.83	21.58	21.08	19.61	13.81	15.25	16.76	10.95	10.95	10.95	10.95	10.95	10.95
1993	0.00	0.35	2.74	14.16	17.61	17.84	16.89	17.63	17.95	13.69	18.17	17.37	16.11	11.87	13.02	13.47	13.47	13.47	13.47	13.47	13.47
1994	0.00	0.30	2.67	4.87	21.10	20.21	33.44	31.95	32.25	33.50	26.44	34.37	32.75	31.77	23.24	24.00	24.00	24.00	24.00	24.00	24.00
1995	0.00	0.25	1.72	3.78	6.30	19.26	25.89	23.87	22.04	22.70	24.41	18.87	24.44	24.36	23.46	16.17	16.17	16.17	16.17	16.17	16.17
1996	0.00	1.27	16.05	16.46	13.65	11.86	32.55	32.39	28.85	27.20	28.99	30.52	23.51	31.86	31.54	28.61	28.61	28.61	28.61	28.61	28.61
1997	0.00	0.34	2.93	23.33	25.82	18.39	29.85	30.61	29.44	26.77	26.11	27.26	28.60	23.04	31.01	28.91	28.91	28.91	28.91	28.91	28.91
1998	0.00	0.75	9.08	48.76	24.08	42.55	35.94	31.05	30.77	30.20	28.42	27.15	28.24	30.99	24.80	31.43	31.43	31.43	31.43	31.43	31.43
1999	0.00	1.14	29.01	43.20	55.49	32.23	36.84	37.32	31.15	31.51	32.01	29.49	28.08	30.56	33.30	25.10	25.09	25.10	25.10	25.10	25.10
2000	0.00	0.24	3.27	13.97	15.41	19.19	23.34	23.72	23.22	19.79	20.71	20.60	18.92	18.84	20.36	20.90	20.90	20.90	20.90	20.90	20.90
2001	0.00	0.25	2.29	12.91	21.78	21.07	20.97	17.88	17.56	17.55	15.47	15.86	15.72	15.10	14.94	15.20	15.20	15.20	15.20	15.20	15.20
2002	0.00	0.11	1.04	4.55	11.23	12.97	12.62	11.57	9.53	9.56	9.88	8.53	8.72	9.04	8.62	8.03	8.03	8.03	8.03	8.03	8.03
2003	0.00	0.07	0.62	2.52	9.08	13.18	12.79	13.49	11.95	10.05	10.43	10.56	9.09	9.71	10.00	8.98	8.98	8.98	8.98	8.98	8.98
2004	0.00	0.38	4.29	12.65	38.25	20.29	23.38	20.31	20.71	18.72	16.29	16.56	16.71	15.04	15.96	15.48	15.48	15.48	15.48	15.48	15.48
2005	0.00	0.19	1.62	6.04	20.22	31.16	30.08	27.65	23.22	24.17	22.61	19.27	19.51	20.60	18.41	18.40	18.40	18.40	18.40	18.40	18.40
2006	0.00	1.23	16.39	20.18	24.29	33.42	35.01	34.63	30.76	26.36	28.39	26.01	22.09	23.40	24.53	20.65	20.65	20.65	20.65	20.65	20.65

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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	0.00	1.13	16.11	29.93	30.68	24.45	40.16	39.53	37.77	34.25	30.38	32.04	29.25	25.99	27.34	26.99	26.99	26.99	26.99	26.99	26.99
2008	0.00	1.75	13.60	33.60	23.66	31.38	41.08	38.97	37.07	36.16	33.93	29.47	30.98	29.58	26.10	25.86	25.86	25.86	25.86	25.86	25.86
2009	0.00	0.78	9.36	37.28	26.16	15.37	21.24	20.84	19.10	18.55	18.72	17.20	14.89	16.37	15.53	12.90	12.90	12.90	12.90	12.90	12.90
2010	0.00	0.55	15.18	27.74	61.00	34.65	17.23	15.31	14.52	13.58	13.65	13.49	12.35	11.19	12.21	10.91	10.91	10.91	10.91	10.91	10.91
2011	0.00	1.78	10.26	67.18	31.70	24.07	16.90	14.06	12.07	11.68	11.31	11.13	10.97	10.50	9.44	9.71	9.71	9.71	9.71	9.71	9.71
2012	0.00	0.99	9.68	20.19	32.18	17.57	17.83	14.78	11.88	10.41	10.43	9.89	9.70	9.99	9.51	8.05	8.05	8.05	8.05	8.05	8.05
2013	0.00	0.26	2.90	15.48	13.89	14.64	25.63	23.29	18.66	15.32	13.89	13.62	12.87	13.20	13.51	12.11	12.11	12.11	12.11	12.11	12.11
2014	0.00	0.51	5.75	18.25	12.78	13.72	19.38	17.89	15.71	12.85	10.91	9.69	9.47	9.36	9.54	9.19	9.19	9.19	9.19	9.19	9.19
2015	0.00	2.35	5.77	10.95	13.65	15.69	12.21	12.24	10.92	9.79	8.28	6.89	6.10	6.23	6.12	5.87	5.87	5.87	5.87	5.87	5.87
2016	0.00	4.19	36.01	15.50	17.95	19.13	19.78	18.04	17.48	15.91	14.76	12.24	10.14	9.39	9.53	8.81	8.81	8.81	8.81	8.81	8.81
2017	0.00	6.52	27.54	22.42	21.67	17.70	26.86	28.16	24.82	24.56	23.13	21.01	17.36	15.05	13.84	13.23	13.23	13.23	13.23	13.23	13.23
2018	0.00	22.85	20.38	15.28	16.51	10.45	21.85	21.72	22.00	19.79	20.27	18.70	16.93	14.62	12.59	10.90	10.90	10.90	10.90	10.90	10.90
2019	0.00	1.78	28.20	16.20	17.65	26.08	30.01	27.17	26.10	26.99	25.13	25.20	23.17	21.94	18.82	15.26	15.26	15.26	15.26	15.26	15.26
2020	0.00	0.20	1.98	7.71	25.42	16.97	27.87	26.27	22.99	22.54	24.12	22.00	21.98	21.14	19.88	16.06	16.06	16.06	16.06	16.06	16.06
2021	0.00	1.06	3.92	7.24	16.12	23.48	24.16	25.96	23.65	21.12	21.43	22.46	20.41	21.33	20.37	18.04	18.04	18.04	18.04	18.04	18.04
2022	0.00	0.23	16.57	4.42	7.87	13.60	23.81	22.91	23.78	22.12	20.45	20.32	21.22	20.17	20.93	18.83	18.83	18.83	18.83	18.83	18.83
2023	0.00	0.58	10.58	11.07	4.69	7.30	18.54	18.94	17.61	18.66	17.96	16.26	16.10	17.59	16.60	16.23	16.23	16.23	16.23	16.23	16.23

Table 20. 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	804	11,444	15,264	13,766	10,440	12,805	9,606	8,410	6,772	5,523	4,871	3,975	3,291	2,607	2,181	1,771	1,458	1,178	939	2,878
1967	0	1,208	24,741	36,876	28,807	19,925	20,452	14,547	10,796	9,520	7,701	6,228	5,488	4,502	3,725	2,958	2,481	2,014	1,653	1,332	5,911
1968	0	2,016	12,766	27,862	23,867	14,612	13,782	8,049	5,744	4,258	3,739	3,015	2,441	2,142	1,755	1,471	1,149	972	788	651	3,536
1969	0	1,891	52,058	33,851	43,462	29,203	24,230	13,123	7,656	5,520	4,054	3,601	2,869	2,361	2,051	1,683	1,402	1,103	927	753	4,911
1970	0	507	40,530	115,976	44,282	45,222	40,249	18,922	10,328	6,027	4,402	3,227	2,827	2,293	1,854	1,615	1,350	1,105	874	743	5,276
1971	0	4,328	5,524	47,485	79,753	24,011	32,547	16,759	8,001	4,335	2,541	1,837	1,354	1,190	955	777	674	561	466	366	2,887
1972	0	254	50,302	7,175	36,920	49,421	19,862	15,631	8,110	3,858	2,102	1,229	895	658	577	465	377	328	273	228	1,812
1973	0	188	5,291	109,024	9,534	38,116	69,149	16,307	12,984	6,761	3,229	1,752	1,022	738	551	480	387	314	276	228	1,885
1974	0	2,776	4,235	12,680	155,594	10,577	57,894	62,185	14,853	11,725	6,087	2,928	1,569	915	666	492	430	347	283	247	2,132
1975	0	124	39,268	6,655	11,892	115,648	10,587	34,659	36,746	8,747	6,926	3,601	1,731	935	545	393	293	254	207	168	1,552
1976	0	591	1,899	63,565	6,534	9,181	120,263	6,547	21,256	22,733	5,417	4,295	2,225	1,071	576	335	244	180	159	128	1,160
1977	0	40	6,436	2,277	45,892	3,714	7,161	55,854	3,038	9,865	10,573	2,520	1,997	1,032	499	267	155	113	84	74	653
1978	0	1,262	662	11,586	2,510	40,036	4,456	5,091	39,729	2,176	7,032	7,510	1,793	1,421	735	355	191	111	81	60	558
1979	0	28	25,248	1,485	15,824	2,704	58,745	3,927	4,502	35,001	1,901	6,180	6,628	1,581	1,253	645	312	168	97	71	587
1980	0	244	415	39,978	1,427	12,039	2,819	36,544	2,437	2,803	21,798	1,185	3,838	4,118	982	782	403	194	104	61	445
1981	0	4,952	6,914	1,282	74,649	2,107	24,174	3,395	44,136	2,940	3,395	26,296	1,427	4,632	4,981	1,189	942	484	235	126	664
1982	0	60	69,759	10,877	1,211	56,252	2,165	14,801	2,076	27,003	1,795	2,067	16,023	874	2,838	3,029	723	570	300	143	533
1983	0	59	887	110,788	10,486	929	58,559	1,352	9,236	1,301	16,825	1,116	1,292	10,011	542	1,759	1,881	450	354	185	467
1984	0	116	1,208	1,939	148,338	11,069	1,350	50,644	1,175	7,988	1,124	14,582	962	1,114	8,655	469	1,522	1,630	392	310	627
1985	0	2,353	1,569	1,742	1,700	102,956	10,582	765	28,807	663	4,537	640	8,277	548	631	4,910	267	862	915	223	578
1986	0	36	67,447	5,006	3,376	2,586	214,204	13,211	955	36,027	831	5,687	801	10,354	682	790	6,153	335	1,070	1,147	1,104
1987	0	62	806	162,134	7,302	3,879	4,049	199,463	12,259	887	33,541	775	5,291	747	9,642	634	738	5,725	310	996	2,114
1988	0	2,436	1,169	1,636	197,086	7,050	5,038	3,117	154,354	9,496	685	25,900	600	4,087	574	7,458	492	571	4,421	239	2,440
1989	0	1,048	57,588	3,025	2,550	242,708	11,555	4,974	3,092	151,932	9,349	676	25,576	590	4,026	566	7,342	485	560	4,361	2,726
1990	0	43	14,419	86,481	2,773	1,803	232,179	6,589	2,827	1,743	86,090	5,273	381	14,444	334	2,281	321	4,169	275	317	4,046
1991	0	2,660	2,156	124,968	145,239	3,176	2,602	197,197	5,540	2,376	1,467	72,812	4,447	324	12,240	280	1,921	270	3,525	232	3,710
1992	0	476	29,979	2,851	69,769	115,068	4,121	2,297	173,148	4,897	2,092	1,297	64,055	3,907	285	10,762	248	1,691	237	3,102	3,482
1993	0	26	5,108	103,304	2,491	41,554	111,538	2,105	1,176	89,140	2,497	1,075	668	32,977	2,010	144	5,512	127	871	122	3,394
1994	0	716	477	11,990	151,229	2,458	63,787	175,125	3,306	1,838	139,554	3,951	1,692	1,044	51,754	3,152	229	8,677	201	1,366	5,541
1995	0	726	9,608	881	15,662	119,535	2,401	32,450	89,864	1,693	939	71,605	2,005	865	536	26,474	1,620	117	4,447	102	3,549
1996	0	1,188	94,583	105,816	2,912	23,979	142,294	2,020	27,377	75,336	1,417	792	60,098	1,697	730	451	22,280	1,356	98	3,724	3,087
1997	0	467	6,003	160,752	149,473	3,101	47,324	90,430	1,286	17,301	47,799	903	500	38,058	1,065	462	283	14,121	857	62	4,344
1998	0	582	24,646	112,252	130,732	175,544	4,179	30,575	58,223	827	11,041	30,889	581	320	24,640	686	299	183	9,121	555	2,855
1999	0	1,570	47,983	135,926	95,361	134,181	94,112	2,800	20,686	39,293	555	7,514	20,746	389	217	16,522	466	199	124	6,119	2,301
2000	0	2,694	12,736	33,225	50,606	27,998	84,167	50,742	1,532	11,191	21,173	303	4,044	11,244	213	118	8,938	254	108	67	4,555
2001	0	71	57,433	61,987	47,037	58,459	22,421	44,719	26,981	810	5,914	11,270	160	2,161	5,956	112	63	4,751	134	58	2,465
2002	0	143	650	139,826	49,136	21,660	25,252	8,884	17,626	10,609	316	2,327	4,436	63	845	2,350	44	24	1,878	52	1,001
2003	0	3	1,488	1,720	232,838	42,777	14,273	18,075	6,307	12,580	7,610	228	1,663	3,170	45	605	1,686	32	18	1,345	759
2004	0	571	327	34,584	23,499	407,662	53,254	15,606	19,794	6,953	13,845	8,349	249	1,830	3,473	50	665	1,848	35	19	2,315
2005	0	6	5,099	539	48,164	12,872	436,374	43,463	12,779	16,153	5,662	11,284	6,803	204	1,498	2,839	41	542	1,505	28	1,901
2006	0	2,540	1,196	77,098	1,994	64,002	9,368	345,386	34,377	10,143	12,760	4,490	8,917	5,391	161	1,187	2,248	32	429	1,191	1,528
2007	0	1,382	66,146	2,234	94,667	1,354	46,919	6,322	232,992	23,175	6,851	8,606	3,027	6,013	3,634	109	800	1,517	22	290	1,839
2008	0	27	40,540	181,756	1,599	81,013	1,768	31,806	4,267	157,874	15,683	4,620	5,826	2,044	4,067	2,460	74	541	1,023	15	1,446
2009	0	2,768	318	127,186	113,952	742	34,624	504	9,113	1,224	45,320	4,507	1,319	1,673	587	1,169	705	21	154	294	420
2010	0	524	119,722	1,182	181,730	123,709	618	18,510	266	4,871	652	24,349	2,407	703	891	315	623	378	11	83	384
2011	0	18,875	21,228	607,908	1,053	44,239	38,602	355	10,708	154	2,803	379	14,027	1,387	405	514	179	360	217	7	270
2012	0	277	220,913	49,163	211,980	421	23,931	25,324	231	7,008	102	1,845	249	9,204	912	266	338	119	237	143	183
2013	0	345	1,912	448,996	31,879	79,391	460	25,211	26,571	244	7,368	107	1,931	261	9,704	962	279	355	125	249	344
2014	0	165	18,117	16,001	361,417	28,506	87,913	249	13,370	14,119	129	3,912	57	1,025	138	5,127	508	149	188	66	315
2015	0	14,026	3,274	33,191	8,463	299,742	15,473	32,943	93	4,999	5,272	48	1,463	21	383	51	1,914	190	56	70	143
2016	0	113	448,494	10,600	49,434	9,916	294,038	17,804	37,667	106	5,729	6,037	56	1,673	24	438	59	2,201	218	64	246
2017	0	33,785	1,797	338,054	14,715	43,665	10,637	342,040	20,740	43,850	123	6,665	7,027	65	1,947	28	510	69	2,561	253	363
2018	0	37,766	233,090	1,083	227,091	5,840	41,772	6,306	201,691	12,232	25,869	73	3,932	4,143	38	1,148	17	301	41	1,508	366

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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+
2019	0	516	85,169	187,606	927	259,774	11,345	32,439	4,914	157,002	9,495	20,146	57	3,057	3,234	30	896	13	233	32	1,458
2020	0	44	1,264	26,736	263,752	686	200,508	6,772	19,325	2,926	93,776	5,665	12,043	34	1,827	1,927	18	534	8	140	893
2021	0	5,177	2,058	5,830	52,219	192,222	710	133,708	4,505	12,923	1,945	62,541	3,790	8,030	23	1,218	1,283	12	356	5	690
2022	0	1,919	172,880	2,896	6,164	36,855	142,112	476	90,492	3,042	8,722	1,317	42,275	2,555	5,411	15	822	871	8	240	470
2023	0	763	179,428	125,930	2,721	4,673	34,996	72,774	244	46,311	1,554	4,463	676	21,653	1,302	2,781	8	420	445	4	365

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

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	73	3,294	6,400	7,839	7,120	9,727	8,406	8,355	7,204	6,426	6,618	6,207	5,185	4,850	2,361	1,917	1,577	1,275	1,017	3,115
1967	0	110	7,120	15,462	16,405	13,588	15,536	12,731	10,725	10,128	8,960	8,463	8,571	7,094	6,932	3,201	2,685	2,179	1,789	1,442	6,397
1968	0	184	3,674	11,683	13,592	9,965	10,469	7,044	5,706	4,530	4,351	4,097	3,813	3,375	3,266	1,592	1,244	1,052	852	704	3,827
1969	0	173	14,982	14,194	24,751	19,915	18,406	11,484	7,606	5,872	4,718	4,893	4,481	3,720	3,817	1,821	1,518	1,194	1,003	815	5,315
1970	0	46	11,665	48,628	25,218	30,839	30,575	16,559	10,261	6,411	5,122	4,385	4,415	3,612	3,451	1,747	1,461	1,196	945	805	5,710
1971	0	395	1,590	19,910	45,418	16,374	24,724	14,666	7,949	4,612	2,956	2,496	2,115	1,876	1,776	841	729	607	504	396	3,124
1972	0	23	14,477	3,008	21,026	33,703	15,087	13,680	8,057	4,104	2,445	1,670	1,398	1,036	1,074	504	408	355	295	246	1,961
1973	0	17	1,523	45,714	5,430	25,993	52,528	14,271	12,899	7,193	3,758	2,381	1,596	1,162	1,026	519	419	339	298	247	2,040
1974	0	254	1,219	5,317	88,610	7,213	43,978	54,421	14,756	12,473	7,082	3,979	2,449	1,442	1,239	533	466	376	306	268	2,307
1975	0	11	11,302	2,790	6,772	78,866	8,042	30,331	36,506	9,306	8,059	4,893	2,703	1,473	1,014	426	317	275	224	181	1,680
1976	0	65	539	32,146	3,788	6,774	99,751	5,999	23,219	27,616	6,809	6,029	3,660	1,935	1,058	772	562	416	365	295	2,671
1977	0	3	1,908	984	27,835	2,420	5,574	48,468	3,013	11,430	13,164	3,315	2,944	1,705	911	526	305	223	166	146	1,286
1978	0	138	137	4,825	1,199	25,149	2,823	3,821	34,403	2,110	7,696	9,020	2,283	1,939	1,131	642	345	200	146	109	1,009
1979	0	2	8,279	521	8,809	1,618	43,392	2,901	4,078	35,831	2,106	7,890	9,319	2,253	1,926	1,189	575	309	179	131	1,080
1980	0	20	81	16,961	510	6,393	1,510	23,973	1,655	2,286	19,415	1,166	4,369	4,934	1,201	1,096	565	273	146	85	623
1981	0	444	1,505	383	38,124	849	13,593	1,910	31,464	2,125	2,848	24,603	1,480	5,313	6,057	1,567	1,241	638	309	166	875
1982	0	4	15,489	3,320	399	29,693	847	8,009	1,163	18,781	1,223	1,669	14,483	838	3,028	3,637	869	684	360	172	640
1983	0	4	148	38,045	3,895	349	33,090	561	5,491	785	12,169	808	1,112	9,218	533	2,043	2,186	523	411	215	542
1984	0	7	207	521	64,638	4,888	566	31,677	559	5,329	735	11,679	774	1,018	8,525	524	1,700	1,820	437	346	700
1985	0	230	304	514	618	56,834	5,558	378	21,994	377	3,497	494	7,849	498	657	5,854	318	1,028	1,091	266	689
1986	0	3	17,559	1,460	1,180	1,043	123,226	7,172	505	28,818	479	4,532	641	9,739	620	873	6,799	370	1,182	1,267	1,220
1987	0	5	157	59,622	2,367	1,412	1,597	111,257	6,677	461	25,485	433	4,104	556	8,497	574	668	5,177	280	900	1,912
1988	0	226	267	517	92,414	2,730	2,057	1,367	99,106	5,832	388	21,897	374	3,384	460	7,502	494	574	4,447	240	2,454
1989	0	95	14,036	1,029	944	124,772	4,606	2,073	1,432	100,951	5,742	391	22,158	360	3,288	474	6,157	407	469	3,658	2,286
1990	0	4	3,596	32,875	1,157	767	128,851	2,812	1,305	876	59,993	3,468	237	12,856	211	2,047	288	3,740	247	284	3,630
1991	0	250	525	48,119	67,082	1,509	1,184	115,994	2,593	1,179	766	53,797	3,112	205	11,158	192	1,320	186	2,422	159	2,550
1992	0	49	7,738	1,077	32,785	60,768	2,101	1,112	112,205	2,474	1,082	721	50,578	2,794	186	10,717	247	1,684	236	3,089	3,468
1993	0	2	1,217	34,950	971	18,871	53,445	966	530	52,693	1,112	501	335	22,484	1,249	87	3,310	76	523	73	2,038
1994	0	67	113	4,798	67,646	1,187	33,689	96,783	1,810	969	93,210	2,030	913	580	39,327	2,319	169	6,384	148	1,005	4,077
1995	0	78	2,615	345	8,134	65,020	1,323	19,405	58,190	1,064	549	54,167	1,171	507	326	23,371	1,430	104	3,926	90	3,133
1996	0	110	26,487	42,474	1,323	13,542	79,018	1,127	17,152	50,069	884	469	46,204	963	419	285	14,078	857	62	2,353	1,951
1997	0	43	1,536	70,281	73,708	1,621	28,882	53,817	796	11,776	33,352	603	318	30,092	626	291	178	8,900	540	39	2,738
1998	0	55	5,697	41,246	64,580	91,638	2,171	18,392	35,343	511	7,257	21,250	384	193	18,557	407	177	109	5,420	330	1,697
1999	0	135	12,183	47,651	41,814	74,109	51,571	1,515	13,405	25,172	350	5,143	14,915	257	131	13,291	375	160	100	4,922	1,851
2000	0	292	3,860	16,885	27,940	18,115	64,401	38,201	1,178	10,101	18,256	263	3,817	10,658	186	101	7,638	217	92	58	3,893
2001	0	8	17,562	30,042	30,076	38,047	16,056	37,556	23,071	693	5,739	10,669	153	2,148	5,988	111	62	4,693	133	57	2,435
2002	0	18	213	67,364	29,523	16,087	17,923	6,880	16,567	9,946	287	2,443	4,559	62	878	2,621	50	27	2,096	58	1,116
2003	0	0	453	775	121,650	26,115	10,113	12,136	4,781	11,339	6,612	195	1,658	2,958	41	610	1,700	32	18	1,357	765
2004	0	61	92	14,959	11,838	223,024	31,961	10,780	13,409	5,210	11,920	7,075	209	1,707	3,053	45	603	1,675	31	18	2,099
2005	0	1	1,465	230	24,820	7,238	250,202	27,111	9,494	11,530	4,320	10,101	6,015	171	1,403	2,662	38	508	1,411	27	1,782
2006	0	225	328	34,695	1,048	38,100	5,713	212,993	23,868	8,216	9,597	3,686	8,618	4,919	140	1,228	2,324	33	444	1,231	1,580
2007	0	101	15,050	890	48,666	762	28,066	3,842	148,174	16,256	5,418	6,452	2,486	5,557	3,194	97	712	1,350	19	258	1,637
2008	0	2	9,197	72,451	878	53,790	1,207	22,880	3,228	122,401	12,960	4,396	5,273	1,937	4,368	2,668	80	587	1,110	16	1,568
2009	0	213	68	43,752	54,194	456	24,127	358	7,061	976	35,827	3,877	1,311	1,513	560	1,341	808	24	177	337	482
2010	0	46	26,698	416	80,697	71,156	431	14,524	220	4,308	574	21,682	2,341	755	876	347	686	416	12	91	423
2011	0	1,553	4,930	205,058	441	21,906	23,247	257	9,028	134	2,522	346	13,019	1,344	436	538	188	377	228	7	283
2012	0	26	50,305	17,882	88,120	204	12,846	16,395	186	6,440	94	1,785	246	8,814	918	316	402	142	282	170	218
2013	0	36	519	169,222	15,102	40,270	255	15,375	20,225	227	7,535	111	2,131	281	10,201	1,128	327	416	146	292	404
2014	0	18	5,627	7,284	179,884	16,708	51,802	159	9,721	12,552	135	4,610	69	1,251	166	6,371	632	186	233	82	391
2015	0	1,242	792	12,912	3,797	137,758	7,862	16,689	53	3,168	3,947	43	1,488	21	388	54	2,023	200	59	74	151
2016	0	11	108,582	3,965	23,410	5,074	144,706	9,607	20,970	65	3,777	4,801	53	1,734	25	484	65	2,431	241	71	272
2017	0	3,818	543	138,594	7,335	25,815	6,379	195,664	13,462	28,767	86	5,109	6,521	69	2,267	35	622	84	3,119	309	443
2018	0	4,901	76,251	536	120,000	3,516	28,000	4,252	134,248	9,050	18,693	57	3,402	4,149	44	1,543	22	404	55	2,025	491

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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+
2019	0	46	26,902	84,516	497	139,366	6,510	20,554	3,242	100,146	6,506	13,766	42	2,399	2,958	33	1,010	15	263	36	1,645
2020	0	5	313	13,251	146,704	426	116,830	4,185	13,648	2,108	63,115	4,182	8,897	26	1,493	1,948	18	540	8	142	903
2021	0	637	630	2,330	32,843	127,122	492	86,246	3,189	10,242	1,519	46,613	3,109	6,303	19	1,130	1,191	11	331	5	641
2022	0	196	60,860	1,437	3,139	27,669	105,326	367	67,133	2,426	7,527	1,144	35,153	2,235	4,561	14	770	817	7	225	440
2023	0	67	47,681	65,253	1,563	2,582	26,768	54,495	197	35,191	1,227	3,892	595	17,458	1,112	2,430	7	367	389	4	319

Table 22. 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, Natural Mortality 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.

Age	Start Biomass (kt)	Catch Weight (kt)	Natural Mortality (kt)	Surviving Biomass (kt)
2021 cohort				
0	211.8	0.0	43.9	167.8
1	824.8	0.2	173.7	650.9
2	1,693.1			
2020 cohort				
0	119.3	0.0	25.1	94.2
1	461.3	0.6	95.9	364.7
2	1,043.6	60.9	212.0	770.7
3	1,134.5			
2016 cohort				
0	124.0	0.0	26.0	98.0
1	503.7	3.8	105.0	394.9
2	1,143.1	76.3	230.9	836.0
3	1,151.2	84.5	233.0	833.7
4	1,029.4	146.7	197.6	685.1
5	814.6	127.1	155.5	532.0
6	596.2	105.3	112.8	378.0
7	381.9			
2014 cohort				
0	192.3	0.0	40.4	151.9
1	577.5	1.2	121.1	455.2
2	1,244.4	108.6	249.7	886.1
3	1,500.6	138.6	298.5	1,063.5
4	1,370.7	120.0	273.6	977.1
5	992.0	139.4	191.4	661.3
6	718.2	116.8	137.2	464.2
7	513.9	86.2	97.6	330.0
8	379.6	67.1	72.0	240.5
9	246.3			
2010 cohort				
0	286.3	0.0	60.2	226.1
1	1,038.1	1.6	217.8	818.7
2	2,266.1	50.3	470.4	1,745.5
3	2,888.9	169.2	587.3	2,132.4
4	2,816.0	179.9	571.2	2,064.9
5	1,906.7	137.8	383.4	1,385.6
6	1,483.7	144.7	294.9	1,044.2
7	1,213.7	195.7	232.5	785.6
8	914.1	134.2	176.2	603.6
9	578.4	100.1	109.9	368.4
10	388.7	63.1	74.1	251.4
11	278.4	46.6	52.9	178.9
12	199.6	35.2	38.2	126.3
13	122.4			
1999 cohort				
0	229.7	0.0	48.0	181.8
1	1,104.2	0.3	231.7	872.2

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Age	Start Biomass (kt)	Catch Weight (kt)	Natural Mortality (kt)	Surviving Biomass (kt)
2	2,464.7	17.6	515.0	1,932.2
3	3,044.3	67.4	628.0	2,348.9
4	2,547.3	121.6	518.7	1,907.0
5	1,996.9	223.0	390.6	1,383.2
6	1,449.7	250.2	273.9	925.6
7	995.5	213.0	182.9	599.7
8	618.4	148.2	112.8	357.5
9	435.8	122.4	76.4	237.0
10	241.7	35.8	46.5	159.3
11	179.5	21.7	34.9	122.9
12	128.1	13.0	25.6	89.5
13	92.3	8.8	18.4	65.2
14	71.5	10.2	13.9	47.4
15	56.1	6.4	11.2	38.5
16	32.8	2.0	6.6	24.1
17	25.2	2.4	5.0	17.8
18	19.6	3.1	3.8	12.7
19	14.0	2.0	0.5	11.4
20	9.6			

Table 23. 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 - $\text{SPR}_{40\%}$) such that values below 100% represent fishing below $F_{40\%}$. In the last row, dashes (–) indicate quantities requiring 2024 catch which has not taken place yet.

Year	Female spawning biomass (kt)	Relative spawning biomass (%)	Total biomass (kt)	Age-2+ biomass (kt)	Age-0 recruits (millions)	Relative fishing intensity (%)	Exploitation fraction (%)
1966	954	49.9	2,389	2,171	1,633	47.2	6.3
1967	959	50.8	2,504	2,230	4,651	64.6	9.6
1968	967	51.1	2,674	2,245	3,128	46.5	5.4
1969	1,097	57.8	3,022	2,762	717	57.0	6.5
1970	1,255	66.4	3,286	3,028	9,385	62.7	7.7
1971	1,296	68.7	3,525	2,812	860	46.4	5.5
1972	1,462	77.2	3,985	3,909	554	35.0	3.0
1973	1,747	92.5	4,136	3,962	6,282	38.5	4.1
1974	1,712	90.4	4,043	3,568	353	44.9	5.9
1975	2,123	112.0	5,056	4,985	1,948	40.9	4.4
1976	2,415	127.4	5,358	5,181	215	40.8	4.6
1977	2,165	113.9	4,827	4,634	6,980	27.6	2.9
1978	1,809	95.2	4,297	3,690	138	26.6	2.8
1979	1,952	102.9	4,857	4,815	1,446	29.9	2.8
1980	1,725	90.8	4,193	3,755	17,672	24.8	2.4
1981	1,663	87.5	4,687	3,433	274	36.1	4.1
1982	1,772	93.4	5,106	5,086	325	30.9	2.1
1983	2,265	119.6	5,180	5,155	564	26.2	2.2
1984	2,327	122.5	5,122	4,823	14,415	28.9	2.9
1985	2,325	122.3	5,783	4,665	139	22.9	2.4
1986	2,316	122.1	6,114	6,100	191	34.0	3.5
1987	2,388	125.6	5,454	5,313	6,785	38.8	4.4

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Year	Female spawning biomass (kt)	Relative spawning biomass (%)	Total biomass (kt)	Age-2+ biomass (kt)	Age-0 recruits (millions)	Relative fishing intensity (%)	Exploitation fraction (%)
1988	2,375	124.8	5,403	4,858	2,144	40.1	5.1
1989	2,111	110.8	5,031	4,876	114	47.4	6.1
1990	2,056	108.0	4,666	4,570	4,395	39.8	5.7
1991	1,864	98.0	4,206	3,853	1,261	58.7	8.3
1992	1,687	88.6	3,944	3,838	127	56.7	7.8
1993	1,314	68.9	2,961	2,895	3,230	46.4	6.9
1994	1,267	66.5	2,926	2,617	3,331	59.8	13.8
1995	1,147	60.2	2,946	2,634	1,271	50.8	9.5
1996	1,087	57.1	2,783	2,654	1,864	63.7	11.5
1997	1,081	56.8	2,596	2,438	1,027	68.4	13.3
1998	912	48.0	2,175	2,059	2,013	81.5	15.6
1999	783	41.1	2,097	1,730	12,898	92.2	18.0
2000	886	46.5	3,104	1,993	315	66.1	11.5
2001	1,284	67.4	4,236	4,170	1,256	67.6	5.5
2002	1,896	99.8	4,574	4,448	44	47.7	4.1
2003	1,754	92.4	3,833	3,786	1,715	43.7	5.4
2004	1,454	76.5	3,127	2,981	43	70.9	11.5
2005	1,145	60.3	2,553	2,496	2,857	68.3	14.5
2006	926	48.8	2,159	1,923	2,076	85.1	18.8
2007	705	37.1	1,787	1,666	25	86.9	17.5
2008	736	38.9	1,858	1,762	5,629	91.5	18.3
2009	616	32.6	1,686	1,316	1,371	79.7	13.6
2010	746	39.4	2,224	1,841	15,979	87.6	12.4
2011	729	38.5	2,849	1,803	384	87.0	15.9
2012	890	47.1	3,744	3,684	1,575	71.2	5.6
2013	1,662	88.0	4,277	4,138	371	66.8	6.9
2014	1,977	104.9	4,415	4,189	8,256	62.3	7.1
2015	1,448	76.9	3,487	2,908	34	45.5	6.7
2016	1,223	65.0	3,708	3,582	5,638	73.6	9.3
2017	1,646	87.5	3,998	3,452	1,565	79.3	12.8
2018	1,711	90.9	4,164	3,987	397	72.2	10.4
2019	1,402	74.5	3,417	3,378	273	80.3	12.2
2020	1,350	71.5	2,940	2,788	4,748	62.5	13.6
2021	1,118	58.9	2,939	2,251	10,187	62.4	14.5
2022	1,116	58.6	3,661	2,786	1,881	61.8	11.6
2023	1,335	69.9	4,246	4,009	979	55.1	6.6
2024	1,885	98.7	4,758	4,460	980	–	–

Table 24. Time-series of 95% posterior credibility intervals for the quantities shown in Table 23. In the last row, dashes (–) indicate quantities requiring 2024 catch which has not taken place yet.

Year	Female spawning biomass (kt)	Relative spawning biomass	Total biomass (kt)	Age-2+ biomass (kt)	Age-0 recruits (millions)	Relative fishing intensity	Exploitation fraction
1966	576-1,816	29.2-89.5%	1,501-4,529	1,284-4,196	57-10,657	25.2-71.9%	3.3-10.7%
1967	587-1,833	29.7-89.7%	1,589-4,908	1,354-4,337	214-14,910	36.9-91.2%	4.9-15.8%
1968	590-1,921	29.9-91.8%	1,672-5,380	1,338-4,588	209-10,277	23.6-71.7%	2.7-9.1%
1969	685-2,191	34.0-104.8%	1,878-6,113	1,703-5,558	39-4,067	30.2-83.1%	3.2-10.6%
1970	773-2,529	38.7-122.3%	2,018-6,698	1,875-6,065	4,722-22,796	33.5-90.2%	3.9-12.5%
1971	785-2,623	39.5-126.6%	2,110-7,269	1,698-5,683	83-3,161	22.6-72.9%	2.7-9.1%
1972	879-2,960	44.3-143.1%	2,378-8,208	2,325-8,053	67-1,969	16.1-59.2%	1.5-5.1%
1973	1,054-3,509	52.6-170.3%	2,478-8,371	2,390-8,002	3,235-14,699	18.2-63.3%	2.0-6.8%
1974	1,036-3,412	51.5-164.9%	2,417-8,132	2,151-7,092	37-1,425	22.1-71.7%	3.0-9.8%
1975	1,261-4,207	63.1-204.6%	2,994-10,097	2,956-9,952	934-4,575	20.0-67.0%	2.2-7.5%
1976	1,436-4,754	71.8-231.9%	3,183-10,618	3,084-10,258	24-920	19.6-67.8%	2.3-7.7%
1977	1,286-4,231	64.5-206.6%	2,864-9,463	2,748-9,060	3,706-14,871	12.8-49.2%	1.5-4.8%

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Year	Female spawning biomass (kt)	Relative spawning biomass	Total biomass (kt)	Age-2+ biomass (kt)	Age-0 recruits (millions)	Relative fishing intensity	Exploitation fraction
1978	1,089-3,449	54.6-169.9%	2,585-8,235	2,224-7,057	18-718	12.5-47.2%	1.5-4.7%
1979	1,196-3,640	59.8-181.3%	2,966-9,108	2,940-9,023	547-3,485	14.5-51.3%	1.5-4.7%
1980	1,074-3,153	53.1-157.1%	2,601-7,643	2,330-6,878	10,315-34,580	12.1-43.3%	1.3-3.9%
1981	1,053-2,952	51.5-149.0%	2,991-8,310	2,177-6,071	32-1,121	18.7-58.8%	2.3-6.4%
1982	1,151-3,057	55.7-155.7%	3,324-8,880	3,310-8,841	54-1,059	16.0-51.0%	1.2-3.3%
1983	1,510-3,816	72.6-196.9%	3,453-8,742	3,438-8,707	96-1,601	13.7-43.2%	1.3-3.3%
1984	1,593-3,805	75.3-199.2%	3,500-8,416	3,301-7,898	9,172-25,635	15.6-46.6%	1.8-4.2%
1985	1,630-3,696	76.1-197.1%	4,048-9,253	3,268-7,415	19-575	12.4-37.1%	1.5-3.4%
1986	1,671-3,583	77.4-192.8%	4,385-9,491	4,379-9,472	25-692	19.7-51.5%	2.2-4.8%
1987	1,758-3,609	80.6-196.5%	4,004-8,270	3,904-8,045	4,345-11,598	23.2-56.7%	2.9-6.0%
1988	1,784-3,503	80.8-193.8%	4,036-8,004	3,651-7,174	1,128-3,995	24.4-58.1%	3.5-6.8%
1989	1,610-3,051	72.1-171.2%	3,827-7,287	3,693-7,062	17-439	29.9-66.1%	4.2-8.1%
1990	1,588-2,914	70.0-166.1%	3,609-6,633	3,538-6,480	2,871-7,189	24.8-56.4%	4.0-7.4%
1991	1,470-2,584	63.7-149.8%	3,306-5,891	3,041-5,349	598-2,398	37.5-89.4%	6.0-10.5%
1992	1,345-2,321	57.8-134.6%	3,125-5,461	3,040-5,311	16-524	36.3-88.6%	5.6-9.9%
1993	1,055-1,786	45.1-104.2%	2,367-4,045	2,319-3,933	2,200-5,169	28.8-74.7%	5.1-8.6%
1994	1,033-1,693	43.5-100.4%	2,366-3,955	2,129-3,486	2,273-5,264	40.7-82.2%	10.4-17.0%
1995	930-1,539	39.3-91.3%	2,367-4,002	2,125-3,558	770-2,150	34.3-69.0%	7.0-11.7%
1996	886-1,454	37.1-86.6%	2,255-3,754	2,153-3,569	1,199-3,064	44.9-86.5%	8.6-14.2%
1997	883-1,441	37.1-86.0%	2,111-3,489	1,991-3,264	565-1,845	49.5-88.4%	10.0-16.3%
1998	745-1,219	31.2-72.4%	1,764-2,931	1,678-2,764	1,276-3,417	61.9-99.3%	11.6-19.1%
1999	633-1,060	26.7-62.3%	1,663-2,909	1,394-2,353	8,949-20,678	71.2-110.1%	13.3-22.4%
2000	698-1,227	30.3-70.3%	2,387-4,460	1,564-2,766	95-714	47.3-84.2%	8.3-14.6%
2001	1,001-1,811	43.9-102.2%	3,274-6,056	3,227-5,961	849-2,062	47.9-86.5%	3.8-7.1%
2002	1,499-2,643	65.3-150.9%	3,610-6,406	3,513-6,208	13-127	31.7-65.1%	2.9-5.1%
2003	1,422-2,382	60.5-139.1%	3,102-5,244	3,067-5,161	1,173-2,804	28.5-60.0%	4.0-6.7%
2004	1,207-1,930	50.2-115.0%	2,583-4,183	2,473-3,958	12-144	48.4-96.2%	8.6-13.8%
2005	957-1,511	39.6-90.7%	2,114-3,424	2,073-3,329	1,987-4,786	47.4-91.2%	10.9-17.5%
2006	770-1,240	32.1-73.4%	1,775-2,951	1,597-2,578	1,422-3,416	60.3-117.1%	14.0-22.7%
2007	575-976	24.4-56.0%	1,445-2,527	1,352-2,335	6-95	61.2-117.8%	12.5-21.6%
2008	587-1,056	25.4-58.6%	1,474-2,698	1,405-2,543	3,966-9,328	67.4-114.0%	12.7-23.0%
2009	479-914	21.1-49.8%	1,303-2,520	1,026-1,940	770-2,706	55.0-103.3%	9.2-17.4%
2010	579-1,114	25.6-60.3%	1,690-3,415	1,427-2,755	10,711-28,567	61.0-117.2%	8.3-16.0%
2011	560-1,105	25.1-59.3%	2,124-4,501	1,390-2,737	150-898	59.5-116.0%	10.5-20.7%
2012	665-1,403	30.5-73.4%	2,761-6,026	2,715-5,929	1,006-2,973	46.0-99.0%	3.5-7.6%
2013	1,246-2,641	57.0-137.2%	3,197-6,839	3,099-6,585	133-881	42.9-88.2%	4.3-9.2%
2014	1,496-3,143	68.1-163.1%	3,322-7,081	3,172-6,686	5,667-14,926	39.3-85.8%	4.5-9.4%
2015	1,105-2,310	50.0-119.8%	2,632-5,615	2,218-4,629	9-122	26.4-66.6%	4.2-8.7%
2016	940-1,954	42.2-101.5%	2,805-6,043	2,721-5,814	3,715-10,991	47.7-98.3%	5.7-12.2%
2017	1,248-2,721	56.4-139.1%	2,990-6,728	2,618-5,704	849-3,553	50.4-113.5%	7.7-16.8%
2018	1,259-2,948	57.8-148.5%	3,023-7,297	2,917-6,920	112-1,287	44.1-103.0%	6.0-14.2%
2019	1,004-2,501	46.5-125.4%	2,405-6,183	2,387-6,115	47-1,015	49.7-107.8%	6.7-17.3%
2020	911-2,566	43.3-125.4%	1,954-5,628	1,874-5,317	2,063-12,728	36.3-87.3%	7.2-20.3%
2021	699-2,269	34.3-110.0%	1,770-6,247	1,406-4,561	4,085-29,499	35.3-87.7%	7.2-23.2%
2022	627-2,453	31.7-118.5%	1,954-8,518	1,517-6,238	289-8,859	33.0-91.4%	5.2-21.3%
2023	652-3,225	34.2-154.7%	2,056-10,368	1,915-10,002	43-20,272	26.7-87.2%	2.6-13.8%
2024	853-4,828	45.0-229.8%	2,162-11,986	2,022-11,288	47-20,193	–	–

Table 25. Select parameters, derived quantities, and reference point posterior median estimates for the (2024) base model compared to the previous assessment's (2023) base model. Dashes (–) in column for the previous assessment indicate quantities that were not available in that assessment

Parameter, Quantity, or Reference point	Base model	2023 Base model
Parameters		

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Parameter, Quantity, or Reference point	Base model	2023 Base model
Natural mortality (M)	0.235	0.233
Unfished recruitment (R_0, millions)	2,600	2,547
Steepness (h)	0.812	0.808
Additional biomass index SD	0.322	0.286
Catchability: biomass index (q_b)	0.838	0.833
Additional age-1 index SD	0.381	0.375
Catchability: age-1 index (q_1)	0.490	0.398
Dirichlet-multinomial fishery (log θ_{fish})	-0.663	-0.629
Dirichlet-multinomial survey (log θ_{surv})	2.770	2.595
Derived Quantities		
2014 recruitment (millions)	8,256	9,165
2016 recruitment (millions)	5,638	6,374
2020 recruitment (millions)	4,748	11,409
Unfished female spawning biomass (B_0, kt)	1,919	1,815
2009 relative spawning biomass	32.6%	34.8%
2023 relative spawning biomass	69.9%	104%
2024 relative spawning biomass	98.7%	–
2023 rel. fishing intensity: (1 - SPR)/(1 - $\text{SPR}_{40\%}$)	55.1%	–
Reference Points based on $F_{SPR=40\%}$		
Female spawning biomass at $F_{\text{SPR=40\%}}$ ($B_{\text{SPR=40\%}}$, kt)	681	642
SPR at $F_{\text{SPR=40\%}}$ (kt)	40.0%	40.0%
Exploitation fraction corresponding to SPR	19.1%	18.6%
Yield at $B_{\text{SPR=40\%}}$ (kt)	317	309

Table 26. Summary of median and 95% credibility intervals of equilibrium conceptual reference points for the base assessment model. Equilibrium reference points were computed using 1975–2023 averages for mean weight-at-age and baseline selectivity-at-age (1966–1990; prior to time-varying deviations). Dashes (–) indicate values that are static at one value and do not have a credible interval associated with them.

Quantity	2.5%	Median	97.5%
Unfished female spawning biomass (B_0, kt)	1,235	1,919	3,132
Unfished recruitment (R_0, millions)	1,394	2,600	5,383
Reference points (equilibrium) based on $F_{SPR=40\%}$			
Female spawning biomass at $F_{\text{SPR=40\%}}$ ($B_{\text{SPR=40\%}}$, kt)	409	681	1,127
SPR at $F_{\text{SPR=40\%}}$	–	40%	–
Exploitation fraction corresponding to $F_{\text{SPR=40\%}}$	16.3%	19.1%	22.0%
Yield associated with $F_{\text{SPR=40\%}}$ (kt)	180	317	594
Reference points (equilibrium) based on $B_{40\%}$ (40% of B_0)			
Female spawning biomass ($B_{40\%}$, kt)	494	767	1,253
SPR at $B_{40\%}$	40.7%	43.5%	50.8%
Exploitation fraction resulting in $B_{40\%}$	12.9%	16.8%	20.2%
Yield at $B_{40\%}$ (kt)	177	309	580
Reference points (equilibrium) based on estimated MSY			
Female spawning biomass (B_{MSY}, kt)	297	490	867
SPR at MSY	22.8%	29.6%	45.1%
Exploitation fraction corresponding to SPR at MSY	15.8%	27.0%	36.5%
MSY (kt)	188	336	639

Table 27. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year. Catch alternatives are defined by letters a-o and are a constant value across all forecasted years unless otherwise defined in the first column. Acronyms are defined in the glossary (Appendix C).

Catch alternative	Catch year	Catch (t)	Biomass at start of year	Relative spawning biomass 5%	50%	95%
			Start of 2024	0.51	0.99	2.01
a:	2024	0	Start of 2025	0.57	1.11	2.23
	2025	0	Start of 2026	0.59	1.13	2.35
	2026	0	Start of 2027	0.57	1.12	2.45
b:	2024	180,000	Start of 2025	0.53	1.06	2.18
	2025	180,000	Start of 2026	0.50	1.04	2.26
	2026	180,000	Start of 2027	0.46	1.00	2.32
c:	2024	225,000	Start of 2025	0.52	1.05	2.16
	2025	225,000	Start of 2026	0.48	1.02	2.23
	2026	225,000	Start of 2027	0.43	0.97	2.29
d:	2024	320,000	Start of 2025	0.50	1.02	2.14
10% reduction	2025	288,000	Start of 2026	0.45	0.98	2.20
each year	2026	259,200	Start of 2027	0.39	0.93	2.24
e:	2024	264,000	Start of 2025	0.51	1.04	2.15
2023 catch	2025	264,000	Start of 2026	0.47	1.00	2.21
	2026	264,000	Start of 2027	0.41	0.94	2.26
f:	2024	350,000	Start of 2025	0.49	1.01	2.13
	2025	350,000	Start of 2026	0.42	0.96	2.17
	2026	350,000	Start of 2027	0.35	0.88	2.20
g:	2024	350,000	Start of 2025	0.49	1.01	2.13
10% reduction	2025	315,000	Start of 2026	0.43	0.97	2.18
each year	2026	283,500	Start of 2027	0.37	0.91	2.23
h:	2024	380,000	Start of 2025	0.49	1.01	2.12
	2025	380,000	Start of 2026	0.41	0.94	2.16
	2026	380,000	Start of 2027	0.33	0.86	2.17
i:	2024	380,000	Start of 2025	0.49	1.01	2.12
10% reduction	2025	342,000	Start of 2026	0.42	0.95	2.17
each year	2026	307,800	Start of 2027	0.36	0.89	2.21
j:	2024	430,000	Start of 2025	0.47	0.99	2.11
	2025	430,000	Start of 2026	0.39	0.92	2.14
	2026	430,000	Start of 2027	0.30	0.83	2.13
k:	2024	545,000	Start of 2025	0.45	0.96	2.08
2022 TAC	2025	545,000	Start of 2026	0.33	0.86	2.08
	2026	545,000	Start of 2027	0.22	0.75	2.05
l:	2024	625,000	Start of 2025	0.43	0.94	2.06
2023 TAC	2025	625,000	Start of 2026	0.30	0.83	2.03
	2026	625,000	Start of 2027	0.18	0.70	1.99
m:	2024	875,262	Start of 2025	0.37	0.88	1.99
Fishing intensity	2025	861,614	Start of 2026	0.22	0.71	1.91
at 100%	2026	782,426	Start of 2027	0.13	0.57	1.86
n:	2024	747,588	Start of 2025	0.40	0.91	2.02
Default HR	2025	772,111	Start of 2026	0.24	0.76	1.97
($F_{\text{SPR}=40\%}$–40:10)	2026	717,464	Start of 2027	0.14	0.62	1.91
o:	2024	767,382	Start of 2025	0.39	0.90	2.02
Equal catch	2025	767,382	Start of 2026	0.24	0.76	1.96
($C_{2024} \approxeq C_{2025}$)	2026	712,782	Start of 2027	0.14	0.62	1.91

Table 28. Forecast quantiles of Pacific Hake relative fishing intensity (1 - SPR)/(1 - $SPR_{40\%}$), expressed as a proportion. Catch alternatives are defined by letters a-o and are a constant value across all forecasted years unless otherwise defined in the first column. Acronyms are defined in the glossary (Appendix C).

Catch alternative	Catch year	Catch (t)	Relative fishing intensity 5%	50%	95%
a:	2024	0	0.00	0.00	0.00
	2025	0	0.00	0.00	0.00
	2026	0	0.00	0.00	0.00
b:	2024	180,000	0.22	0.43	0.69
	2025	180,000	0.18	0.37	0.63
	2026	180,000	0.16	0.33	0.59
c:	2024	225,000	0.27	0.50	0.78
	2025	225,000	0.22	0.44	0.72
	2026	225,000	0.20	0.40	0.69
d:	2024	320,000	0.35	0.62	0.91
10% reduction	2025	288,000	0.27	0.53	0.83
each year	2026	259,200	0.23	0.46	0.78
e:	2024	264,000	0.30	0.55	0.84
2023 catch	2025	264,000	0.25	0.49	0.79
	2026	264,000	0.23	0.46	0.77
f:	2024	350,000	0.38	0.66	0.94
	2025	350,000	0.32	0.60	0.92
	2026	350,000	0.29	0.57	0.92
g:	2024	350,000	0.38	0.66	0.94
10% reduction	2025	315,000	0.30	0.56	0.88
each year	2026	283,500	0.25	0.49	0.83
h:	2024	380,000	0.40	0.69	0.97
	2025	380,000	0.34	0.63	0.96
	2026	380,000	0.31	0.60	0.97
i:	2024	380,000	0.40	0.69	0.97
10% reduction	2025	342,000	0.32	0.59	0.92
each year	2026	307,800	0.26	0.52	0.88
j:	2024	430,000	0.44	0.73	1.02
	2025	430,000	0.38	0.68	1.02
	2026	430,000	0.35	0.66	1.05
k:	2024	545,000	0.51	0.82	1.11
2022 TAC	2025	545,000	0.45	0.78	1.13
	2026	545,000	0.42	0.78	1.20
l:	2024	625,000	0.56	0.87	1.16
2023 TAC	2025	625,000	0.50	0.85	1.20
	2026	625,000	0.47	0.85	1.26
m:	2024	875,262	0.68	1.00	1.27
Fishing intensity	2025	861,614	0.62	1.00	1.30
at 100%	2026	782,426	0.57	1.00	1.31
n:	2024	747,588	0.62	0.94	1.22
Default HR	2025	772,111	0.58	0.94	1.28
($F_{SPR=40\%}$–40:10)	2026	717,464	0.53	0.94	1.30
o:	2024	767,382	0.63	0.95	1.23
Equal catch	2025	767,382	0.58	0.94	1.28
($C_{2024} \approxeq C_{2025}$)	2026	712,782	0.53	0.94	1.30

Table 29. Probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options (catch options explained in Table 27).

	Catch (t) in 2024	$B_{2025} < B_{2024}$	$B_{2025} < B_{40\%}$	$B_{2025} < B_{25\%}$	$B_{2025} < B_{10\%}$	**2024 Fishing intensity > 100%**	**2025 Default HR catch > 2024 catch**
a:	0	0.03	0.00	0.00	0.00	0.00	0.00
b:	180,000	0.22	0.01	0.00	0.00	0.00	0.00
c:	225,000	0.29	0.01	0.00	0.00	0.00	0.00
d:	320,000	0.44	0.02	0.00	0.00	0.02	0.03
e:	264,000	0.36	0.01	0.00	0.00	0.00	0.01
f:	350,000	0.49	0.02	0.00	0.00	0.03	0.04
g:	350,000	0.49	0.02	0.00	0.00	0.03	0.04
h:	380,000	0.53	0.02	0.00	0.00	0.04	0.06
i:	380,000	0.53	0.02	0.00	0.00	0.04	0.06
j:	430,000	0.60	0.02	0.00	0.00	0.07	0.10
k:	545,000	0.71	0.03	0.00	0.00	0.16	0.23
l:	625,000	0.76	0.04	0.00	0.00	0.24	0.33
m:	875,262	0.87	0.07	0.01	0.00	0.50	0.61
n:	747,588	0.83	0.05	0.01	0.00	0.37	0.48
o:	767,382	0.83	0.05	0.01	0.00	0.39	0.50

Table 30. Probabilities related to spawning biomass, relative fishing intensity, and the 2026 default harvest policy catch for alternative 2025 catch options, given the 2024 catch level shown in Table 29 (catch options explained in Table 27).

	Catch (t) in 2025	$B_{2026} < B_{2025}$	$B_{2026} < B_{40\%}$	$B_{2026} < B_{25\%}$	$B_{2026} < B_{10\%}$	**2025 Fishing intensity > 100%**	**2026 Default HR catch > 2025 catch**
a:	0	0.59	0.00	0.00	0.00	0.00	0.00
b:	180,000	0.70	0.02	0.00	0.00	0.00	0.00
c:	225,000	0.72	0.02	0.00	0.00	0.00	0.00
d:	288,000	0.75	0.03	0.00	0.00	0.01	0.01
e:	264,000	0.74	0.03	0.00	0.00	0.00	0.01
f:	350,000	0.77	0.04	0.00	0.00	0.02	0.04
g:	315,000	0.76	0.03	0.00	0.00	0.01	0.03
h:	380,000	0.78	0.05	0.01	0.00	0.03	0.06
i:	342,000	0.76	0.04	0.01	0.00	0.02	0.04
j:	430,000	0.79	0.06	0.01	0.00	0.06	0.10
k:	545,000	0.82	0.09	0.02	0.00	0.15	0.25
l:	625,000	0.84	0.11	0.03	0.00	0.23	0.35
m:	861,614	0.87	0.20	0.07	0.00	0.50	0.64
n:	772,111	0.86	0.16	0.06	0.00	0.39	0.54
o:	767,382	0.86	0.16	0.06	0.00	0.39	0.54

Table 31. Probabilities related to spawning biomass, relative fishing intensity, and the 2027 default harvest policy catch for alternative 2026 catch options, given the 2024 and 2025 catch levels shown in Tables 29 and 30 (catch options explained in Table 27).

	Catch (t) in 2026	$B_{2027} < B_{2026}$	$B_{2027} < B_{40\%}$	$B_{2027} < B_{25\%}$	$B_{2027} < B_{10\%}$	**2026 Fishing intensity > 100%**	**2027 Default HR catch > 2026 catch**
a:	0	0.66	0.00	0.00	0.00	0.00	0.00
b:	180,000	0.73	0.03	0.00	0.00	0.00	0.00
c:	225,000	0.74	0.04	0.00	0.00	0.00	0.00
d:	259,200	0.75	0.05	0.01	0.00	0.01	0.01
e:	264,000	0.75	0.05	0.01	0.00	0.01	0.01
f:	350,000	0.78	0.07	0.02	0.00	0.03	0.05
g:	283,500	0.75	0.06	0.01	0.00	0.01	0.02
h:	380,000	0.78	0.09	0.02	0.00	0.04	0.07
i:	307,800	0.76	0.07	0.01	0.00	0.02	0.03
j:	430,000	0.79	0.11	0.03	0.00	0.07	0.12
k:	545,000	0.82	0.17	0.06	0.01	0.18	0.29
l:	625,000	0.83	0.21	0.09	0.01	0.27	0.41
m:	782,426	0.84	0.35	0.19	0.03	0.50	0.65
n:	717,464	0.84	0.29	0.14	0.02	0.41	0.56
o:	712,782	0.84	0.29	0.15	0.02	0.41	0.56

Table 32. 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.

Parameter, Quantity, or Reference point	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)	0.235	0.239	0.234	0.231	0.237	0.290	0.312	0.315
Unfished recruitment (R_0, millions)	2,600	2,772	2,535	1,870	3,201	5,477	7,873	8,476
Steepness (h)	0.812	0.541	–	0.813	0.808	0.797	0.793	0.787
Additional biomass index SD	0.322	0.324	0.319	0.313	0.324	0.338	0.347	0.350
Catchability: biomass index (q_b)	0.838	0.819	0.844	0.860	0.828	0.575	0.468	0.443
Additional age-1 index SD	0.381	0.380	0.376	0.394	0.383	0.354	0.346	0.342
Catchability: age-1 index (q_1)	0.490	0.474	0.495	0.472	0.496	0.294	0.228	0.216
Dirichlet-multinomial fishery ($\log \theta_{\text{fish}}$)	-0.663	-0.667	-0.660	-0.716	-0.647	-0.662	-0.663	-0.659
Dirichlet-multinomial survey ($\log \theta_{\text{surv}}$)	2.770	2.783	2.795	2.736	2.758	2.775	2.782	2.782
Derived Quantities								
2014 recruitment (millions)	8,256	8,610	8,177	7,875	8,462	14,408	19,228	20,470
2016 recruitment (millions)	5,638	5,875	5,578	5,363	5,784	9,934	13,212	14,096
2020 recruitment (millions)	4,748	5,006	4,672	4,254	4,964	8,886	12,136	12,939
Unfished female spawning biomass (B_0, kt)	1,919	1,992	1,886	1,426	2,325	2,716	3,373	3,519
2009 relative spawning biomass	32.6%	32.1%	32.9%	42.5%	27.2%	35.4%	36.1%	36.1%
2023 relative spawning biomass	69.9%	70.7%	70.4%	86.8%	59.8%	80.9%	84.4%	85.3%
2024 relative spawning biomass	98.7%	99.7%	99.3%	118.8%	85.3%	114.1%	119.0%	120.0%
2023 rel. fishing intensity: $(1 - \text{SPR})/(1 - \text{SPR}_{40\%})$	55.1%	53.0%	55.7%	57.7%	53.9%	32.9%	25.0%	23.6%
Reference Points based on $F_{SPR=40\%}$								
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, kt)	681	450	754	510	826	948	1,172	1,195
SPR at $F_{\text{SPR}=40\%}$ (kt)	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	19.1%	19.3%	19.0%	18.8%	19.2%	22.6%	23.9%	24.1%
Negative log likelihoods								
Yield at $B_{\text{SPR}=40\%}$ (kt)	317	212	351	233	389	551	736	761
Total	2,225.16	2,226.82	2,234.82	2,228.62	2,227.44	2,225.16	2,225.15	2,225.19
Survey index	-4.40	-4.39	-4.40	-3.64	-4.52	-4.40	-4.40	-4.39
Survey age compositions	305.08	305.07	305.08	305.70	304.96	305.07	305.07	305.08
Fishery age compositions	1,840.11	1,840.15	1,840.08	1,846.84	1,838.33	1,840.10	1,840.09	1,840.12
Recruitment	63.85	65.02	63.53	58.22	68.38	63.87	63.89	63.83
Parameter priors	1.13	1.60	11.14	1.11	1.15	1.14	1.14	1.15
Parameter deviations	19.38	19.38	19.39	20.40	19.14	19.37	19.37	19.40

Table 33. 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.

Parameter, Quantity, or Reference point	Base model	Remove Age 1 Index	Downweight Fishery Comps
Parameters			
Natural mortality (M)	0.235	0.233	0.236
Unfished recruitment (R_0, millions)	2,600	2,384	2,748
Steepness (h)	0.812	0.805	0.806
Additional biomass index SD	0.322	0.299	0.316
Catchability: biomass index (q_b)	0.838	0.889	0.875
Additional age-1 index SD	0.381	–	0.351
Catchability: age-1 index (q_1)	0.490	–	0.474
Dirichlet-multinomial fishery (log θ_{fish})	-0.663	-0.658	–
Dirichlet-multinomial survey (log θ_{surv})	2.770	2.787	–
Derived Quantities			
2014 recruitment (millions)	8,256	7,611	8,117
2016 recruitment (millions)	5,638	5,053	5,613
2020 recruitment (millions)	4,748	3,659	4,451
Unfished female spawning biomass (B_0, kt)	1,919	1,801	2,021
2009 relative spawning biomass	32.6%	33.6%	29.3%
2023 relative spawning biomass	69.9%	57.8%	61.8%
2024 relative spawning biomass	98.7%	78.4%	84.9%
2023 rel. fishing intensity: (1 - SPR)/(1 - $\text{SPR}_{40\%}$)	55.1%	65.1%	59.5%
Reference Points based on $F_{SPR=40\%}$			
Female spawning biomass at $F_{\text{SPR=40\%}}$($B_{\text{SPR=40\%}}$, kt)	681	635	713
SPR at $F_{\text{SPR=40\%}}$ (kt)	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	19.1%	18.9%	19.2%
Negative log likelihoods			
Yield at $B_{\text{SPR=40\%}}$ (kt)	317	294	335
Total	2,225.16	2,219.13	216.94
Survey index	-4.40	-8.94	-5.62
Survey age compositions	305.08	305.25	38.64
Fishery age compositions	1,840.11	1,839.04	117.06
Recruitment	63.85	63.42	56.25
Parameter priors	1.13	1.14	-0.02
Parameter deviations	19.38	19.22	10.63

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.

Parameter, Quantity, or Reference point	Base model	Phi t.v. selectivity (0.21)	Phi t.v. selectivity (0.70)	Phi t.v. selectivity (2.10)
Parameters				
Natural mortality (M)	0.235	0.221	0.229	0.239
Unfished recruitment (R_0, millions)	2,600	2,433	2,461	2,717
Steepness (h)	0.812	0.810	0.807	0.807
Additional biomass index SD	0.322	0.369	0.329	0.316
Catchability: biomass index (q_b)	0.838	0.857	0.859	0.823
Additional age-1 index SD	0.381	0.441	0.440	0.352
Catchability: age-1 index (q_1)	0.490	0.495	0.508	0.477
Dirichlet-multinomial fishery (log θ_{fish})	-0.663	-0.976	-0.724	-0.640
Dirichlet-multinomial survey (log θ_{surv})	2.770	2.833	2.707	2.791
Derived Quantities				
2014 recruitment (millions)	8,256	8,126	8,012	8,484
2016 recruitment (millions)	5,638	6,128	5,500	5,799
2020 recruitment (millions)	4,748	6,605	5,288	4,470
Unfished female spawning biomass (B_0, kt)	1,919	2,009	1,928	1,952
2009 relative spawning biomass	32.6%	28.2%	31.3%	32.7%
2023 relative spawning biomass	69.9%	85.8%	72.2%	68.9%
2024 relative spawning biomass	98.7%	120.7%	99.4%	98.9%
2023 rel. fishing intensity: (1 - SPR)/(1 - $\text{SPR}_{40\%}$)	55.1%	54.3%	58.2%	53.0%
Reference Points based on $F_{\text{SPR}=40\%}$				
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, kt)	681	714	670	689
SPR at $F_{\text{SPR}=40\%}$ (kt)	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	19.1%	18.1%	18.7%	19.3%
Negative log likelihoods				
Yield at $B_{\text{SPR}=40\%}$ (kt)	317	312	306	326
Total	2,225.16	2,356.78	2,259.11	2,210.95
Survey index	-4.40	-1.35	-2.95	-4.77
Survey age compositions	305.08	304.79	306.21	304.95
Fishery age compositions	1,840.11	1,940.60	1,859.39	1,831.04
Recruitment	63.85	63.44	64.69	63.06
Parameter priors	1.13	1.33	1.12	1.13
Parameter deviations	19.38	47.97	30.65	15.54

Table 35. 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.

Parameter, Quantity, or Reference point	Base model	-1 year	-2 years	-3 years	-4 years	-5 years
Parameters						
Natural mortality (M)	0.235	0.233	0.231	0.231	0.231	0.229
Unfished recruitment (R_0, millions)	2,600	2,520	2,477	2,434	2,448	2,384
Steepness (h)	0.812	0.805	0.804	0.805	0.805	0.804
Additional biomass index SD	0.322	0.292	0.296	0.321	0.320	0.333
Catchability: biomass index (q_b)	0.838	0.863	0.864	0.860	0.897	0.938
Additional age-1 index SD	0.381	0.343	0.338	0.292	0.267	0.281
Catchability: age-1 index (q_1)	0.490	0.413	0.440	0.408	0.407	0.400
Dirichlet-multinomial fishery ($\log \theta_{\text{fish}}$)	-0.663	-0.645	-0.595	-0.599	-0.573	-0.554
Dirichlet-multinomial survey ($\log \theta_{\text{surv}}$)	2.770	2.620	2.634	2.448	2.444	2.198
Derived Quantities						
2014 recruitment (millions)	8,256	8,761	8,838	9,727	10,098	9,922
2016 recruitment (millions)	5,638	6,180	6,073	5,287	4,829	4,527
2020 recruitment (millions)	4,748	11,230	6,001	930	950	946
Unfished female spawning biomass (B_0, kt)	1,919	1,901	1,886	1,859	1,870	1,838
2009 relative spawning biomass	32.6%	33.2%	33.3%	34.4%	33.3%	32.9%
2023 relative spawning biomass	69.9%	107.9%	–	–	–	–
2024 relative spawning biomass	98.7%	–	–	–	–	–
2023 rel. fishing intensity: (1 - SPR)/(1 - $\text{SPR}_{40\%}$)	55.1%	–	–	–	–	–
Reference Points based on $F_{SPR=40\%}$						
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, kt)	681	669	663	658	660	651
SPR at $F_{\text{SPR}=40\%}$ (kt)	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	19.1%	18.9%	18.8%	18.8%	18.8%	18.7%
Negative log likelihoods						
Yield at $B_{\text{SPR}=40\%}$ (kt)	317	308	305	301	302	295
Total	2,225.16	2,156.46	2,098.34	2,035.58	1,987.54	1,921.37
Survey index	-4.40	-6.05	-6.15	-6.21	-6.68	-5.06
Survey age compositions	305.08	288.23	288.38	269.94	269.51	251.84
Fishery age compositions	1,840.11	1,793.52	1,736.78	1,694.15	1,648.11	1,599.10
Recruitment	63.85	62.96	62.45	61.20	60.97	60.28
Parameter priors	1.13	0.99	0.97	0.82	0.84	0.68
Parameter deviations	19.38	16.82	15.91	15.67	14.79	14.53

7 FIGURES

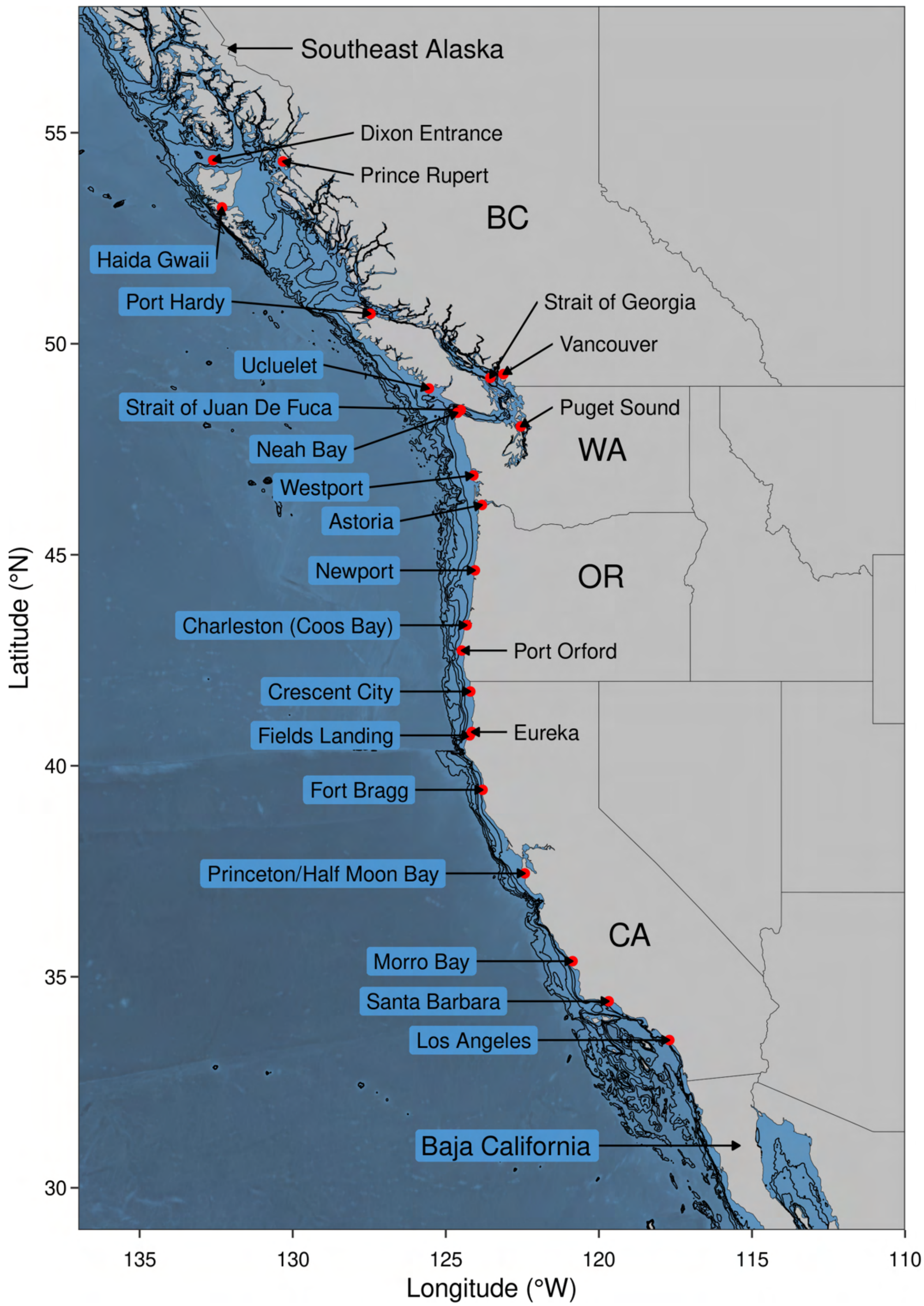


Figure 1. Overview map of the area in the Northeast Pacific Ocean occupied by Pacific Hake. Ports and areas of interest referred to in this document or past assessment documents are shown.

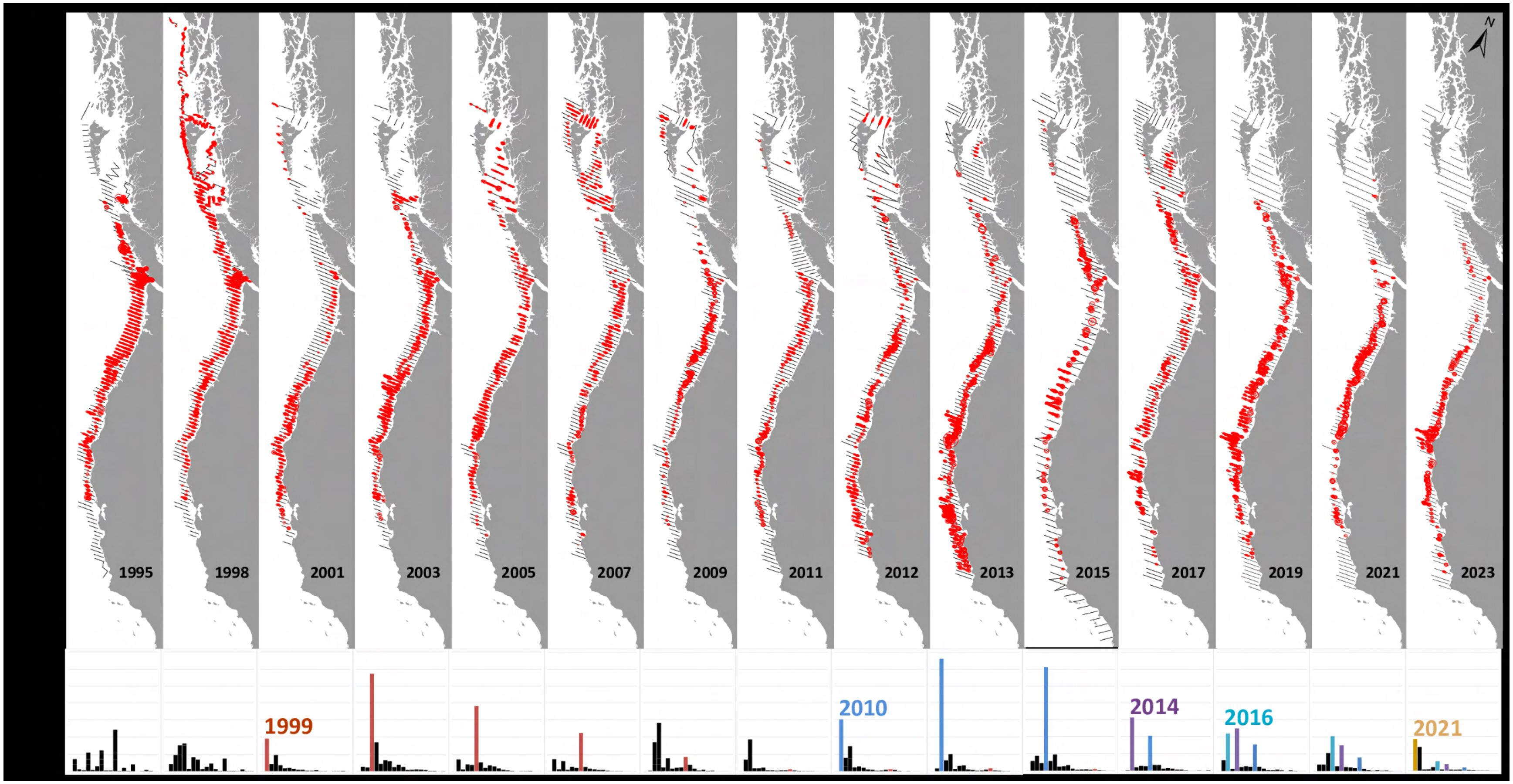


Figure 2. Spatial distribution of acoustic backscatter attributable to age-2 and older Pacific Hake from the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey (1995–2023). Area of the circle is roughly proportional to observed backscatter. Bar plots show survey-estimated biomass for ages 2 to 20, with major cohorts highlighted in color. Figure produced by Julia Clemons (NOAA).

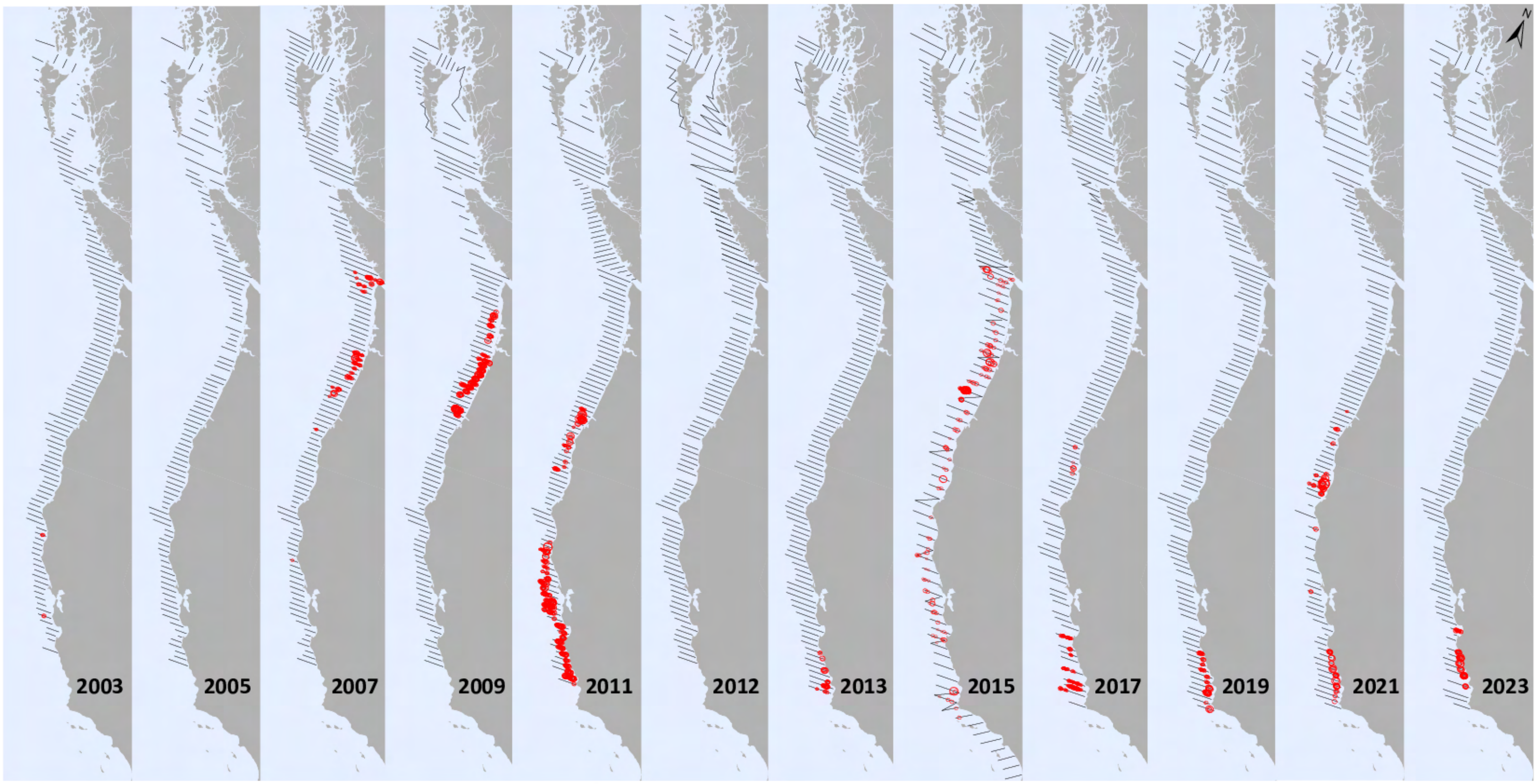


Figure 3. Spatial distribution of acoustic backscatter attributable to aggregations of age-1 Pacific Hake from the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey 2003–2023 (spatial details are not available for survey years 1995, 1998, and 2001). Age-1 Pacific Hake are not fully sampled during the acoustic survey and were not explicitly considered during establishment of the survey sampling design. Additional backscatter from age-1 fish intermixed with older fish is not shown. 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, 1966–2023. U.S. tribal catches are included in the sectors where they are represented.

Figure 5. 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 2019–2023. Horizontal lines in each box represent the median depth and boxes encompass the middle 50% of the data. Whiskers encompass the 95% quantiles.

Figure 6. Distribution of fishing depths (left) and bottom depths (right), in meters, of hauls targeting Pacific Hake in the Canadian fleets from 2019–2023. Horizontal lines in each box represent the median depth and boxes encompass the middle 50% of the data. Whiskers encompass the 95% quantiles.

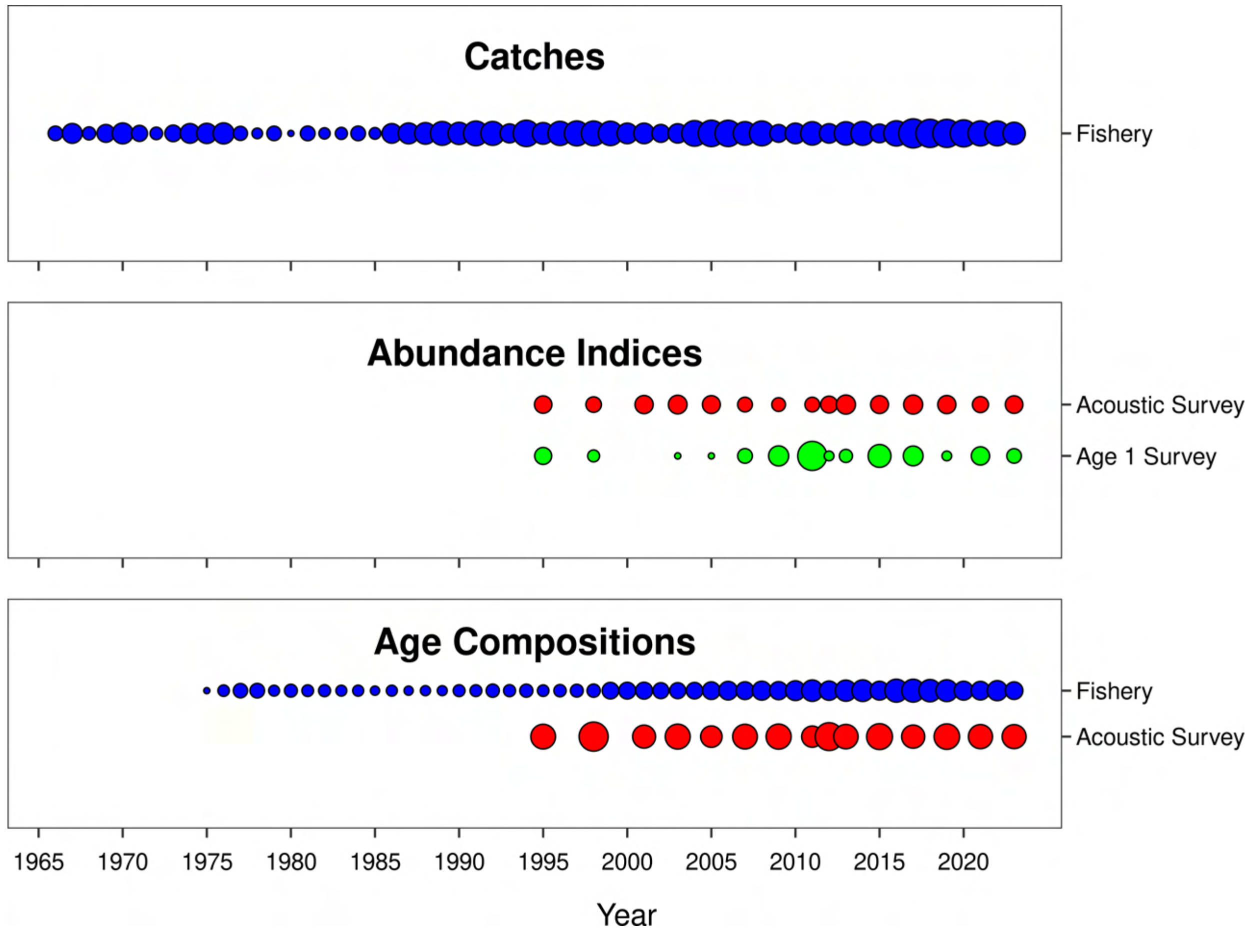


Figure 7. Overview of data used in this assessment. Circle areas are proportional to total catch for the fishery data, precision for the indices, and total sample size for the age compositions (and cannot be compared across data types). Additionally, mean weight-at-age data (1975–2023; not depicted here but see Figure 13 for sample sizes) are used to account for time-varying growth.

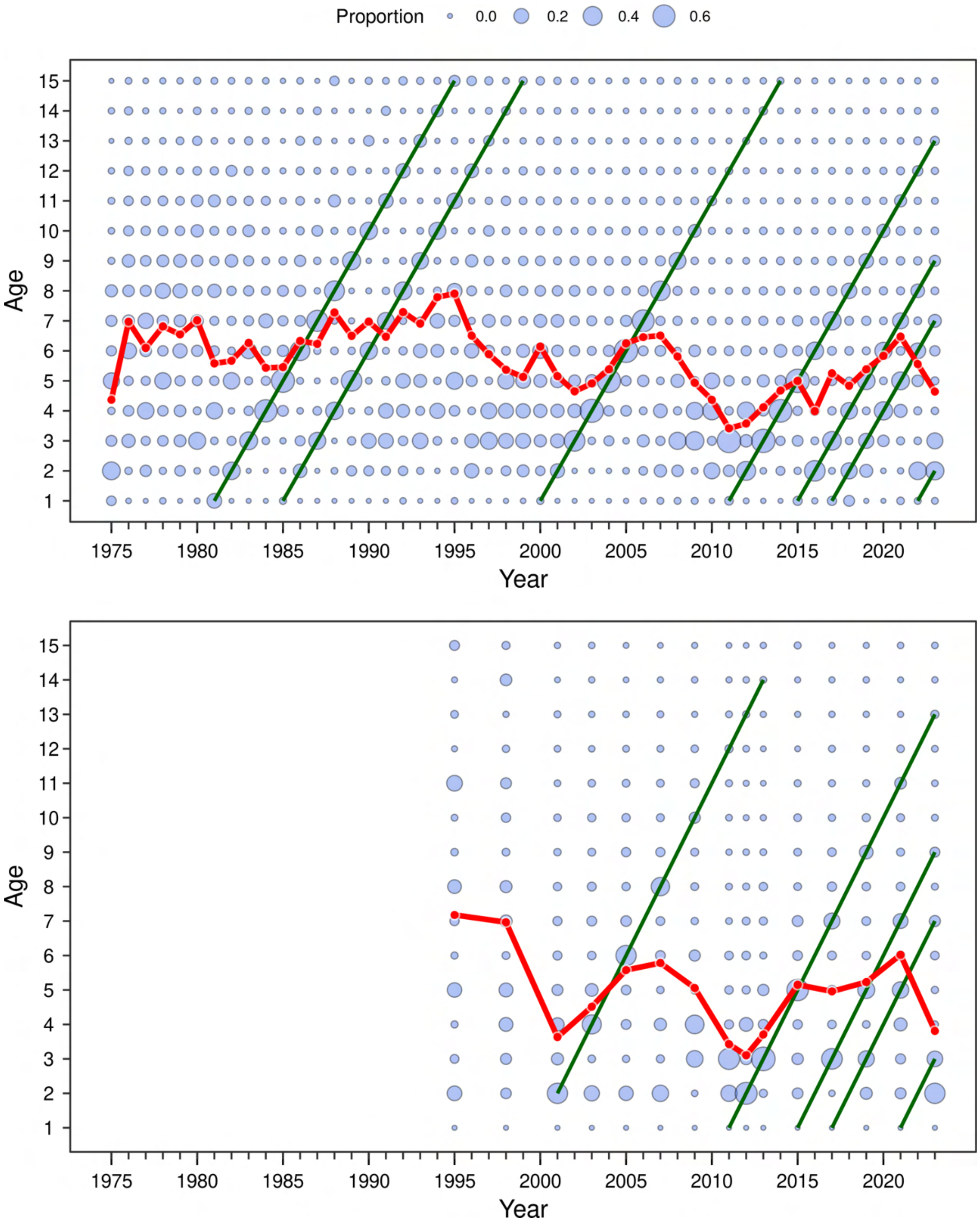


Figure 8. Age compositions for the aggregate fishery (top, all sectors combined) and acoustic survey (bottom) for the years 1975–2023. Proportions in each year sum to 1.0 and area of the bubbles are proportional to the proportion and consistent in both panels (see key at top). The largest bubble in the fishery data is 0.72 for age 3 in 2011 and in the survey data is 0.75 for age 3 in 2013. Green lines track large cohorts.

Figure 9. Acoustic survey biomass index of age-2+ fish (Mt, Table 12). Approximate 95% confidence intervals are based on sampling variability (intervals without the additional squid/hake apportionment uncertainty included in 2009, black line).

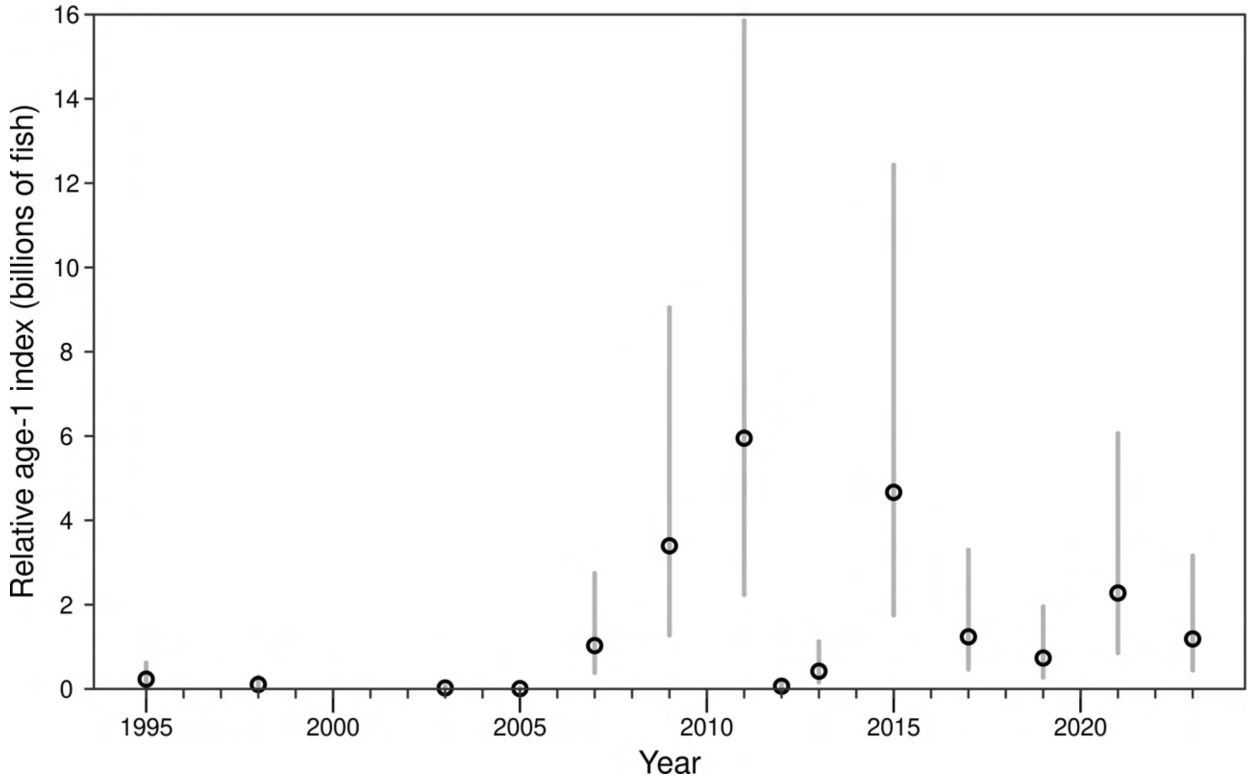
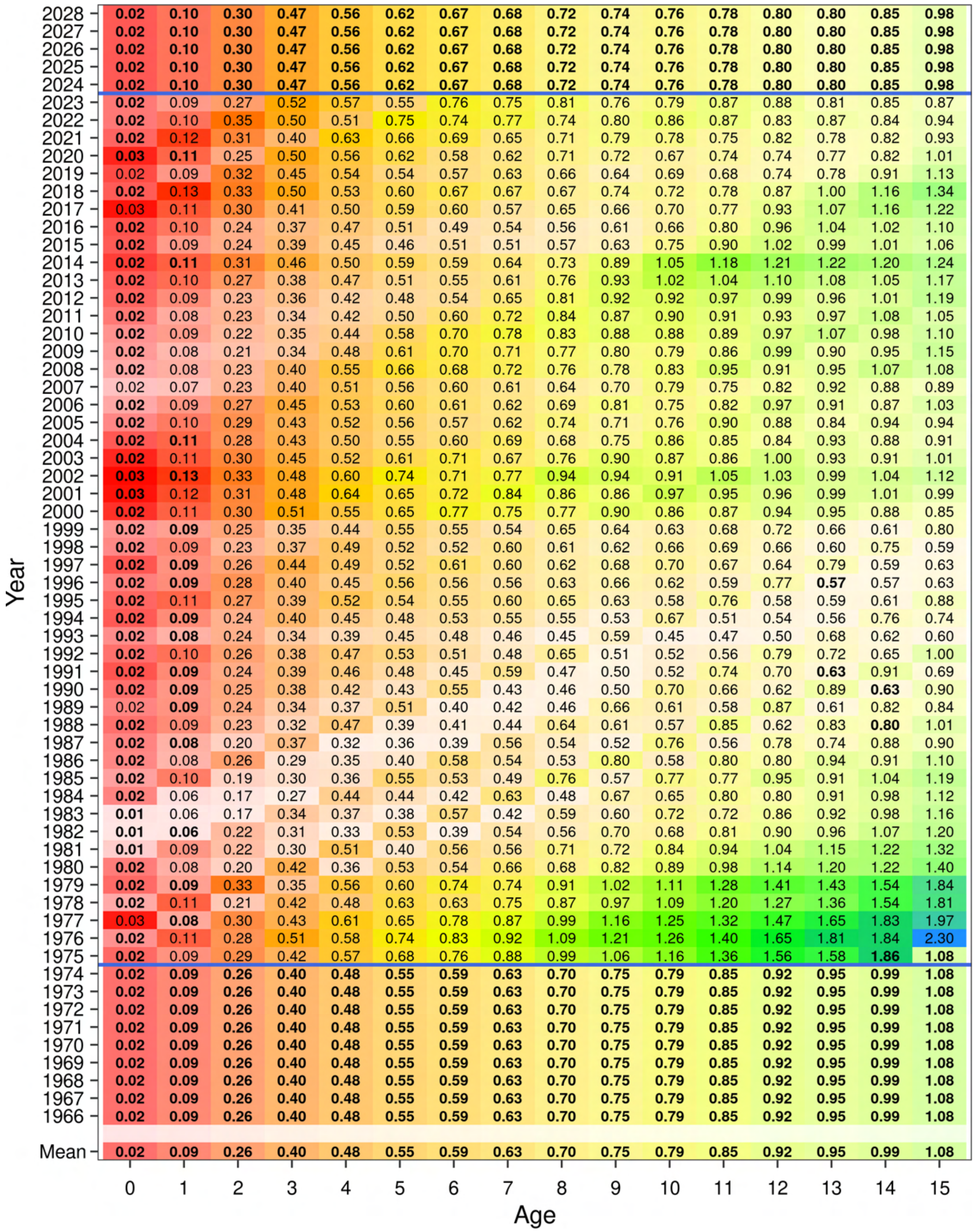


Figure 10. Relative index of age-1 fish (numbers of fish, Table 12) and approximate 95% confidence intervals based on sampling variability. The index is relative because the survey does not attempt to sample all available age-1 fish and the analysis does not include kriging as is done to estimate age-2+ biomass.

Figure 11. Maturity ogives by year used in the assessment. The thick black line shows the equilibrium ogive which is an average of all years; the thick red line shows the forecast ogive which is an average of the last five years (2019–2023). The colors of the year lines move from orange in 2009 through the spectrum to dark blue in 2023.



Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2028	**0.02**	**0.10**	**0.30**	**0.47**	**0.56**	**0.62**	**0.67**	**0.68**	**0.72**	**0.74**	**0.76**	**0.78**	**0.80**	**0.80**	**0.85**	**0.98**
2027	**0.02**	**0.10**	**0.30**	**0.47**	**0.56**	**0.62**	**0.67**	**0.68**	**0.72**	**0.74**	**0.76**	**0.78**	**0.80**	**0.80**	**0.85**	**0.98**
2026	**0.02**	**0.10**	**0.30**	**0.47**	**0.56**	**0.62**	**0.67**	**0.68**	**0.72**	**0.74**	**0.76**	**0.78**	**0.80**	**0.80**	**0.85**	**0.98**
2025	**0.02**	**0.10**	**0.30**	**0.47**	**0.56**	**0.62**	**0.67**	**0.68**	**0.72**	**0.74**	**0.76**	**0.78**	**0.80**	**0.80**	**0.85**	**0.98**
2024	**0.02**	**0.10**	**0.30**	**0.47**	**0.56**	**0.62**	**0.67**	**0.68**	**0.72**	**0.74**	**0.76**	**0.78**	**0.80**	**0.80**	**0.85**	**0.98**
2023	**0.02**	0.09	0.27	0.52	0.57	0.55	0.76	0.75	0.81	0.76	0.79	0.87	0.88	0.81	0.85	0.87
2022	**0.02**	0.10	0.35	0.50	0.51	0.75	0.74	0.77	0.74	0.80	0.86	0.87	0.83	0.87	0.84	0.94
2021	**0.02**	0.12	0.31	0.40	0.63	0.66	0.69	0.65	0.71	0.79	0.78	0.75	0.82	0.78	0.82	0.93
2020	**0.03**	**0.11**	0.25	0.50	0.56	0.62	0.58	0.62	0.71	0.72	0.67	0.74	0.74	0.77	0.82	1.01
2019	0.02	0.09	0.32	0.45	0.54	0.54	0.57	0.63	0.66	0.64	0.69	0.68	0.74	0.78	0.91	1.13
2018	**0.02**	0.13	0.33	0.50	0.53	0.60	0.67	0.67	0.67	0.74	0.72	0.78	0.87	1.00	1.16	1.34
2017	0.03	0.11	0.30	0.41	0.50	0.59	0.60	0.57	0.65	0.66	0.70	0.77	0.93	1.07	1.16	1.22
2016	**0.02**	0.10	0.24	0.37	0.47	0.51	0.49	0.54	0.56	0.61	0.66	0.80	0.96	1.04	1.02	1.10
2015	**0.02**	0.09	0.24	0.39	0.45	0.46	0.51	0.51	0.57	0.63	0.75	0.90	1.02	0.99	1.01	1.06
2014	**0.02**	**0.11**	0.31	0.46	0.50	0.59	0.59	0.64	0.73	0.89	1.05	1.18	1.21	1.22	1.20	1.24
2013	**0.02**	0.10	0.27	0.38	0.47	0.51	0.55	0.61	0.76	0.93	1.02	1.04	1.10	1.08	1.05	1.17
2012	**0.02**	0.09	0.23	0.36	0.42	0.48	0.54	0.65	0.81	0.92	0.92	0.97	0.99	0.96	1.01	1.19
2011	**0.02**	0.08	0.23	0.34	0.42	0.50	0.60	0.72	0.84	0.87	0.90	0.91	0.93	0.97	1.08	1.05
2010	**0.02**	0.09	0.22	0.35	0.44	0.58	0.70	0.78	0.83	0.88	0.88	0.89	0.97	1.07	0.98	1.10
2009	**0.02**	0.08	0.21	0.34	0.48	0.61	0.70	0.71	0.77	0.80	0.79	0.86	0.99	0.90	0.95	1.15
2008	**0.02**	0.08	0.23	0.40	0.55	0.66	0.68	0.72	0.76	0.78	0.83	0.95	0.91	0.95	1.07	1.08
2007	0.02	0.07	0.23	0.40	0.51	0.56	0.60	0.61	0.64	0.70	0.79	0.75	0.82	0.92	0.88	0.89
2006	**0.02**	0.09	0.27	0.45	0.53	0.60	0.61	0.62	0.69	0.81	0.75	0.82	0.97	0.91	0.87	1.03
2005	**0.02**	0.10	0.29	0.43	0.52	0.56	0.57	0.62	0.74	0.71	0.76	0.90	0.88	0.84	0.94	0.94
2004	**0.02**	**0.11**	0.28	0.43	0.50	0.55	0.60	0.69	0.68	0.75	0.86	0.85	0.84	0.93	0.88	0.91
2003	**0.02**	0.11	0.30	0.45	0.52	0.61	0.71	0.67	0.76	0.90	0.87	0.86	1.00	0.93	0.91	1.01
2002	**0.03**	**0.13**	0.33	0.48	0.60	0.74	0.71	0.77	0.94	0.94	0.91	1.05	1.03	0.99	1.04	1.12
2001	**0.03**	0.12	0.31	0.48	0.64	0.65	0.72	0.84	0.86	0.86	0.97	0.95	0.96	0.99	1.01	0.99
2000	**0.02**	0.11	0.30	0.51	0.55	0.65	0.77	0.75	0.77	0.90	0.86	0.87	0.94	0.95	0.88	0.85
1999	**0.02**	**0.09**	0.25	0.35	0.44	0.55	0.55	0.54	0.65	0.64	0.63	0.68	0.72	0.66	0.61	0.80
1998	**0.02**	0.09	0.23	0.37	0.49	0.52	0.52	0.60	0.61	0.62	0.66	0.69	0.66	0.60	0.75	0.59
1997	**0.02**	**0.09**	0.26	0.44	0.49	0.52	0.61	0.60	0.62	0.68	0.70	0.67	0.64	0.79	0.59	0.63
1996	**0.02**	**0.09**	0.28	0.40	0.45	0.56	0.56	0.56	0.63	0.66	0.62	0.59	0.77	**0.57**	0.57	0.63
1995	**0.02**	0.11	0.27	0.39	0.52	0.54	0.55	0.60	0.65	0.63	0.58	0.76	0.58	0.59	0.61	0.88
1994	**0.02**	**0.09**	0.24	0.40	0.45	0.48	0.53	0.55	0.55	0.53	0.67	0.51	0.54	0.56	0.76	0.74
1993	**0.02**	**0.08**	0.24	0.34	0.39	0.45	0.48	0.46	0.45	0.59	0.45	0.47	0.50	0.68	0.62	0.60
1992	**0.02**	0.10	0.26	0.38	0.47	0.53	0.51	0.48	0.65	0.51	0.52	0.56	0.79	0.72	0.65	1.00
1991	**0.02**	**0.09**	0.24	0.39	0.46	0.48	0.45	0.59	0.47	0.50	0.52	0.74	0.70	**0.63**	0.91	0.69
1990	**0.02**	**0.09**	0.25	0.38	0.42	0.43	0.55	0.43	0.46	0.50	0.70	0.66	0.62	0.89	**0.63**	0.90
1989	0.02	**0.09**	0.24	0.34	0.37	0.51	0.40	0.42	0.46	0.66	0.61	0.58	0.87	0.61	0.82	0.84
1988	**0.02**	0.09	0.23	0.32	0.47	0.39	0.41	0.44	0.64	0.61	0.57	0.85	0.62	0.83	**0.80**	1.01
1987	**0.02**	**0.08**	0.20	0.37	0.32	0.36	0.39	0.56	0.54	0.52	0.76	0.56	0.78	0.74	0.88	0.90
1986	**0.02**	0.08	0.26	0.29	0.35	0.40	0.58	0.54	0.53	0.80	0.58	0.80	0.80	0.94	0.91	1.10
1985	**0.02**	0.10	0.19	0.30	0.36	0.55	0.53	0.49	0.76	0.57	0.77	0.77	0.95	0.91	1.04	1.19
1984	**0.02**	0.06	0.17	0.27	0.44	0.44	0.42	0.63	0.48	0.67	0.65	0.80	0.80	0.91	0.98	1.12
1983	**0.01**	0.06	0.17	0.34	0.37	0.38	0.57	0.42	0.59	0.60	0.72	0.72	0.86	0.92	0.98	1.16
1982	**0.01**	**0.06**	0.22	0.31	0.33	0.53	0.39	0.54	0.56	0.70	0.68	0.81	0.90	0.96	1.07	1.20
1981	**0.01**	0.09	0.22	0.30	0.51	0.40	0.56	0.56	0.71	0.72	0.84	0.94	1.04	1.15	1.22	1.32
1980	**0.02**	0.08	0.20	0.42	0.36	0.53	0.54	0.66	0.68	0.82	0.89	0.98	1.14	1.20	1.22	1.40
1979	**0.02**	**0.09**	0.33	0.35	0.56	0.60	0.74	0.74	0.91	1.02	1.11	1.28	1.41	1.43	1.54	1.84
1978	**0.02**	0.11	0.21	0.42	0.48	0.63	0.63	0.75	0.87	0.97	1.09	1.20	1.27	1.36	1.54	1.81
1977	0.03	**0.08**	0.30	0.43	0.61	0.65	0.78	0.87	0.99	1.16	1.25	1.32	1.47	1.65	1.83	1.97
1976	**0.02**	0.11	0.28	0.51	0.58	0.74	0.83	0.92	1.09	1.21	1.26	1.40	1.65	1.81	1.84	2.30
1975	**0.02**	0.09	0.29	0.42	0.57	0.68	0.76	0.88	0.99	1.06	1.16	1.36	1.56	1.58	**1.86**	**1.08**
1974	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1973	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1972	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1971	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1970	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1969	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1968	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1967	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
1966	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**
Mean	**0.02**	**0.09**	**0.26**	**0.40**	**0.48**	**0.55**	**0.59**	**0.63**	**0.70**	**0.75**	**0.79**	**0.85**	**0.92**	**0.95**	**0.99**	**1.08**

Axis labels: Year (rows); Age (columns)

Figure 12. Empirical weight-at-age (kg) values used for the base model as predicted from the time-varying 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 1975–2023. Values based on assumptions for the pre-1975 and forecast years are shown outside the blue lines. Bold values between 1975–2023 represent unavailable data such that weights were predicted from the time-varying model. The bottom row (mean) is the mean weight-at-age over all years of data.

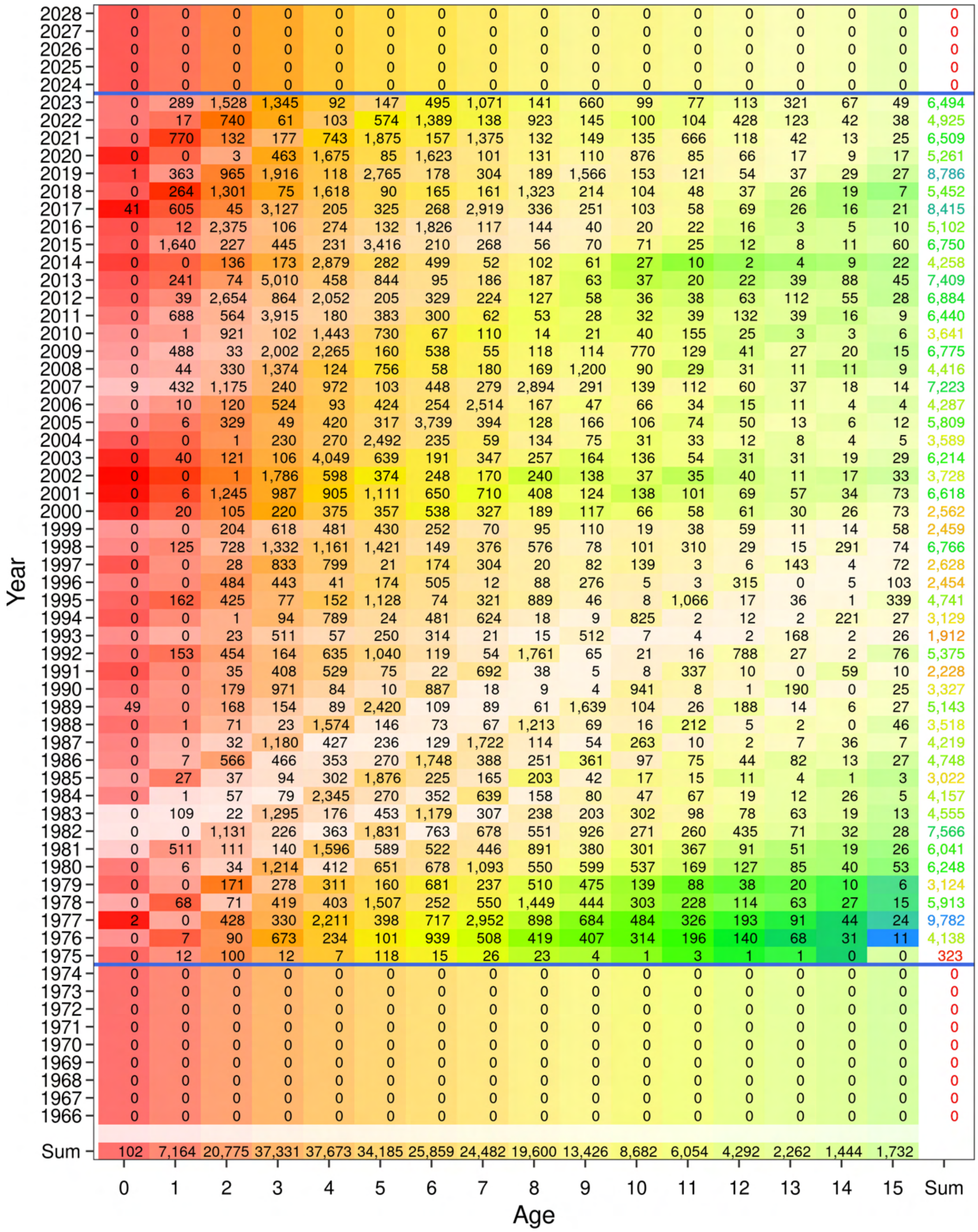


Figure 13. Sample sizes of empirical weight-at-age measurements used to fit the time-varying model used to estimate mean weight-at-age that is used in the base model. Colors and transparency are identical to Figure 12. Sample sizes of zero highlight years for which data are not available, i.e., pre 1975 and post 2023. The total sample sizes for each age used in the model 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.

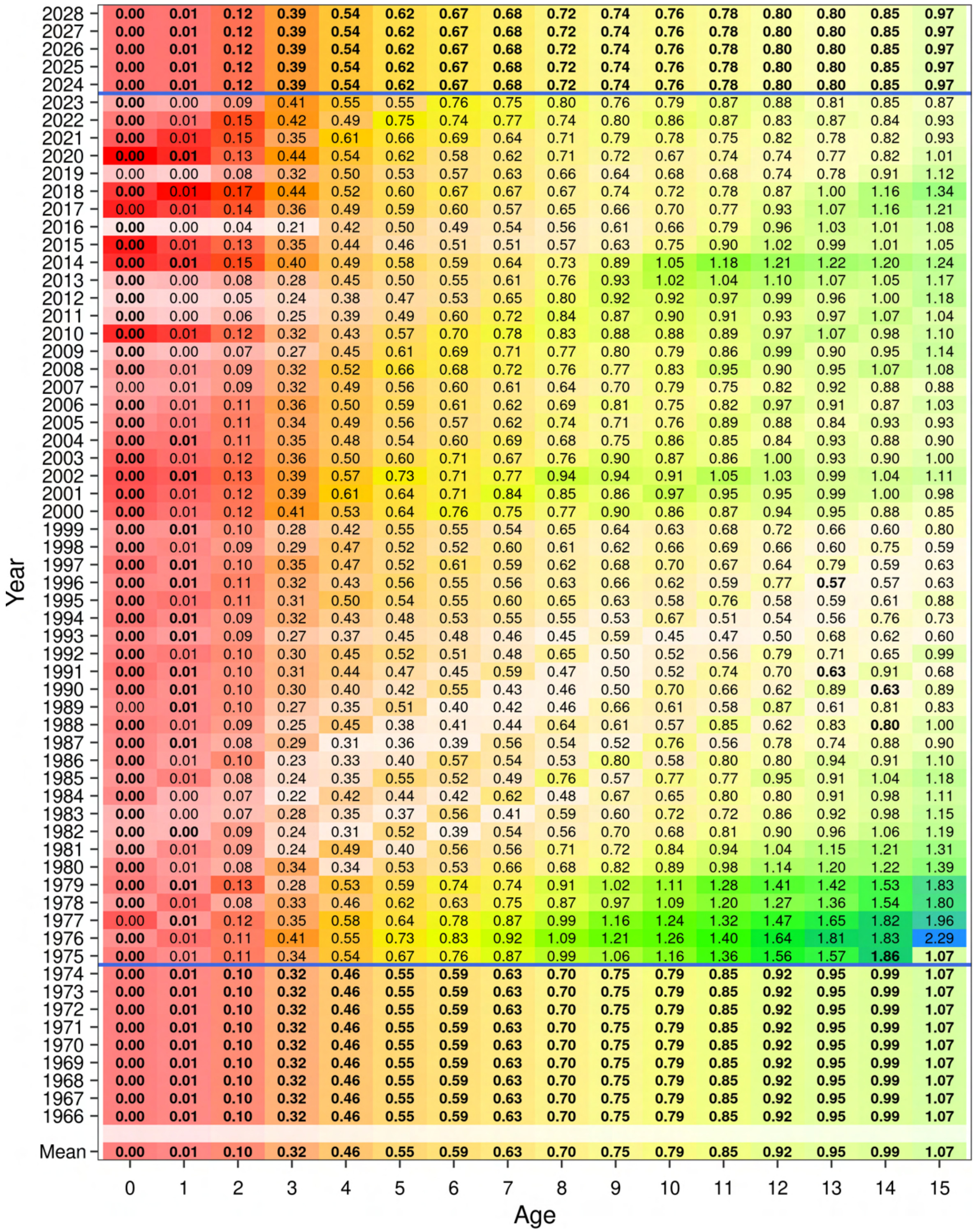


Figure 14. Fecundity-at-age values used for the base model. Colors correspond to the values, with red being the least fecund fish (across all years and ages) and blue being the most fecund fish. For each age, the most transparent cells indicate the least fecund fish of that age. Fecundity is the product of maturity and weight-at-age. Weight-at-age data are only available from 1975–2023. Values based on assumptions for the pre-data and forecast years are shown outside the blue lines. Bold values between 1975–2023 represent year/age combinations where weight-at-age data were unavailable to fit the model such that weights were predicted rather than estimated.

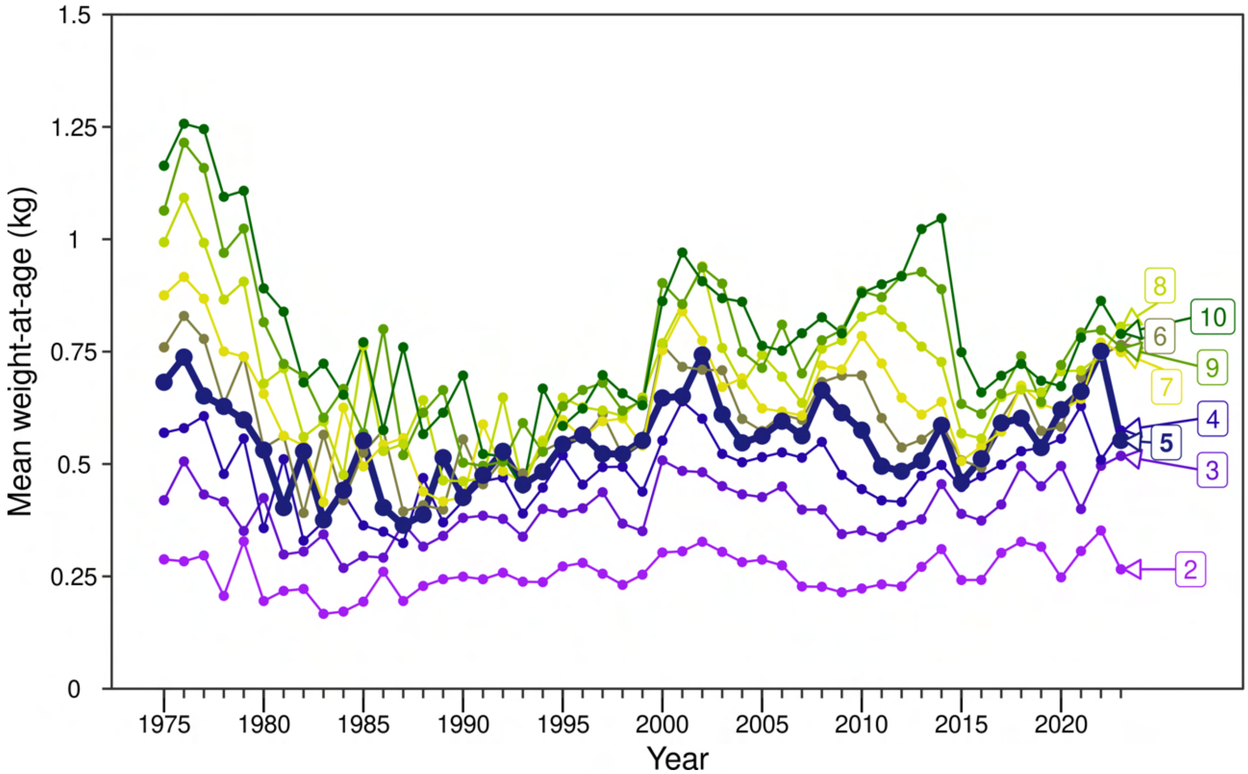


Figure 15. Empirical mean weight-at-age (kg) values for ages 2–10 used for the base model, as in Figure 12 but shown as time series. Purple lines are for the youngest ages and green lines are for the oldest ages shown, with age-5 having a thicker line and larger points as a visual aid.

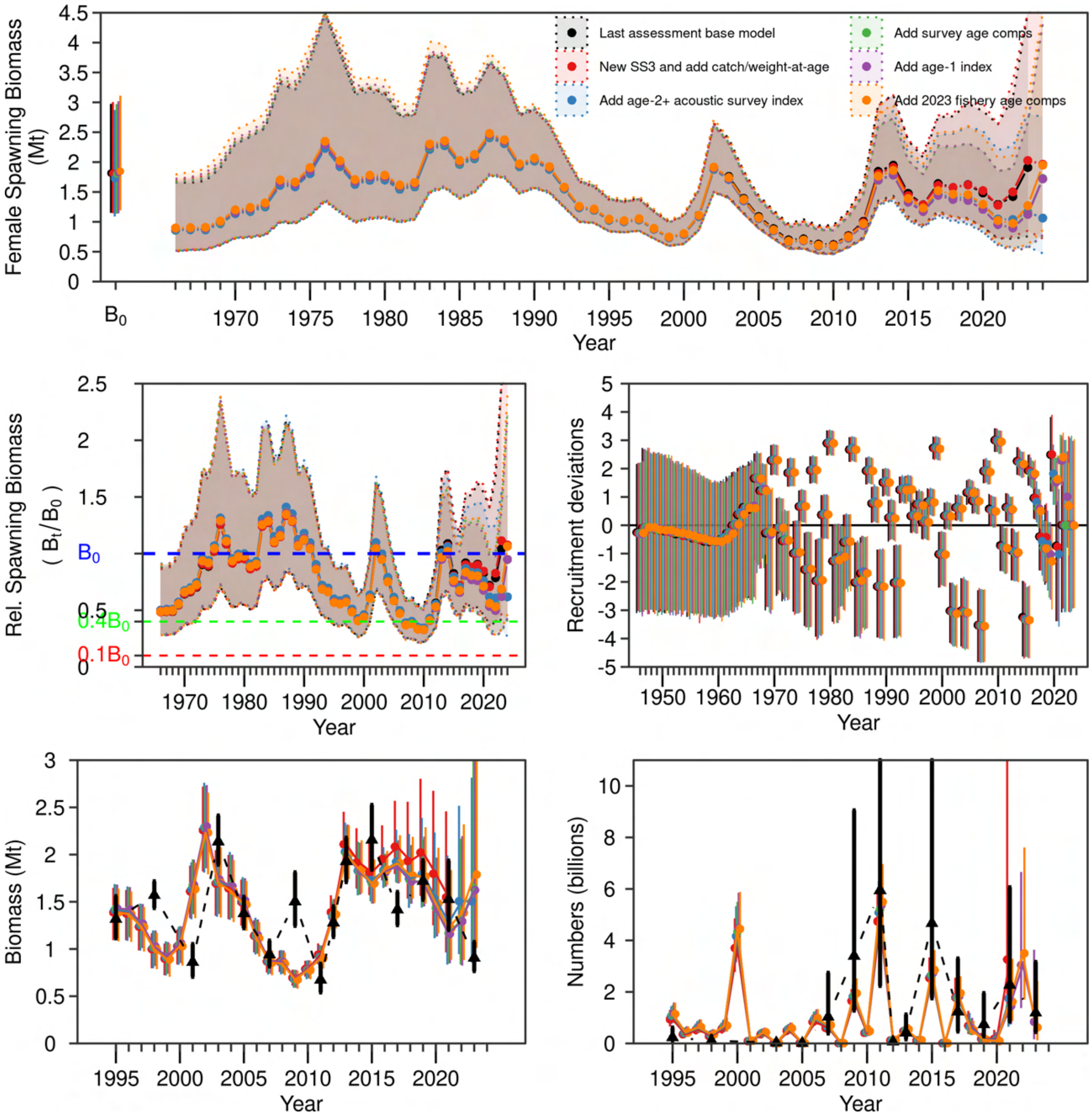


Figure 16. Bridging models showing some of the sequential steps made towards the base model from the 2023 base model. Models include shifting to the newest version of Stock Synthesis, amending older data sources, and adding new data. Panels are spawning biomass (upper panel); relative spawning biomass (spawning biomass in each year relative to the unfished equilibrium spawning biomass, middle left); recruitment deviations (middle right); and age-2+ survey biomass (lower left) and age-1 (lower right) indices, with triangles representing the observed survey indices. Note that in the top panel the red circle for 2024 is obscured by the orange circle.

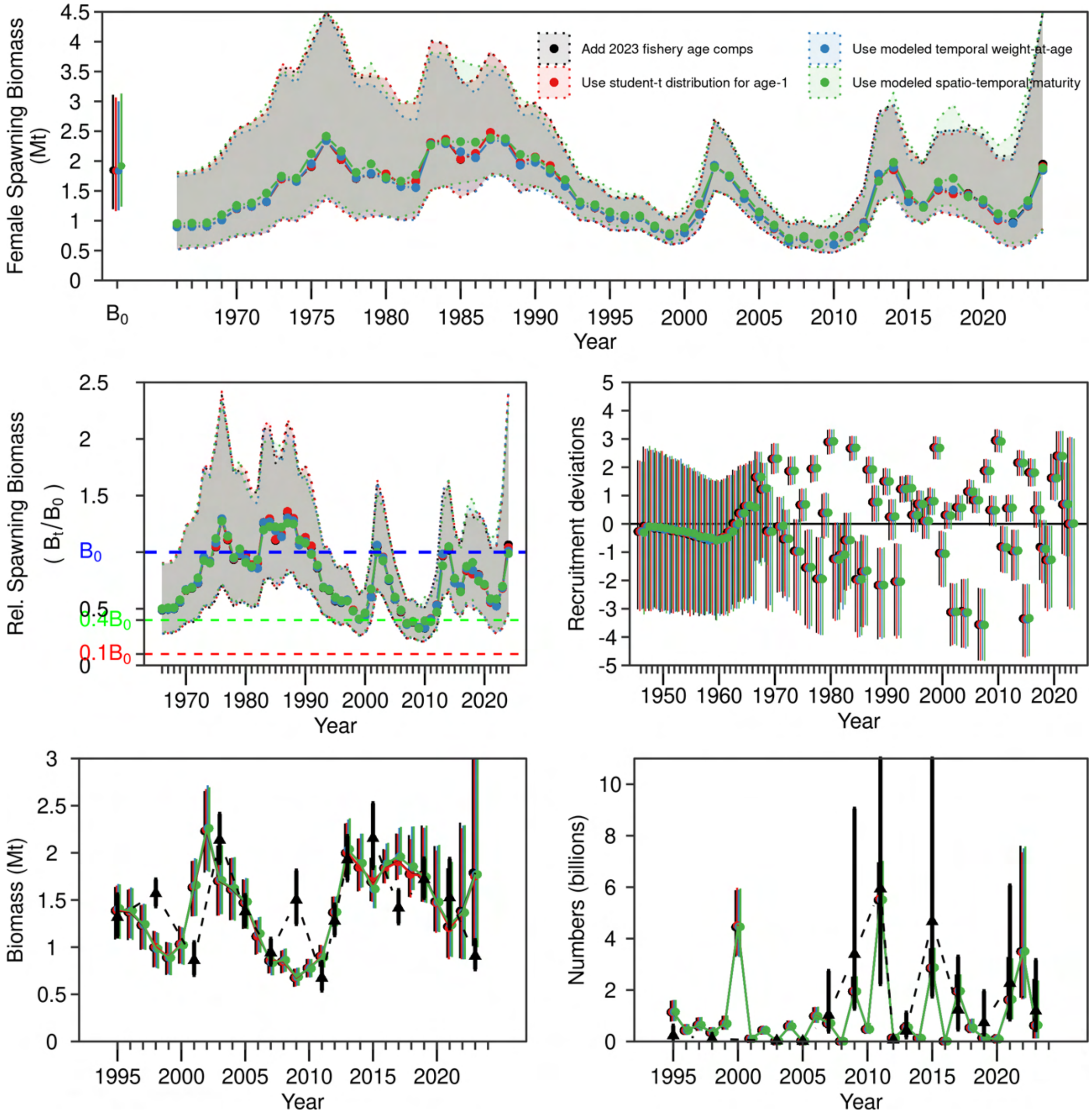


Figure 17. Bridging models showing some of the sequential steps made towards the base model from the 2023 base model. Models include the last step from the previous figure of adding new data, changes to working up data inputs, and structural changes to the model. Panels are spawning biomass (upper panel); relative spawning biomass (spawning biomass in each year relative to the unfished equilibrium spawning biomass, middle left); recruitment deviations (middle right); and age-2+ survey biomass (lower left) and age-1 (lower right) indices, with triangles representing the observed survey indices.

Figure 18. Fits (thin black lines) to the acoustic survey (points) with input 95% intervals around the observations. The thin black lines are the results of a random subset of individual Markov chain Monte Carlo (MCMC) samples. Thick, vertical black lines around observed survey points indicate 95% lognormal uncertainty intervals estimated by the kriging method and are used as input to the assessment model. Thin, vertical black lines indicate estimated 95% uncertainty intervals that account for the model estimate of additional uncertainty.

Figure 19. Assessment model fit to the relative age-1 index data that was produced from acoustic survey observations. Age-1 index observations (black dots) are input into the assessment model with uncertainty arising from sampling variability (thick vertical black lines). Additional uncertainty is estimated within the stock assessment model (thin vertical black lines) and added to the input sampling variability. A time series of the assessment model fit to the observations (blue line) represents the median of the posterior Markov chain Monte Carlo (MCMC) samples. A random subset of the individual MCMC time series samples are shown (thin blue lines) to provide context for the description of the median MCMC estimate.

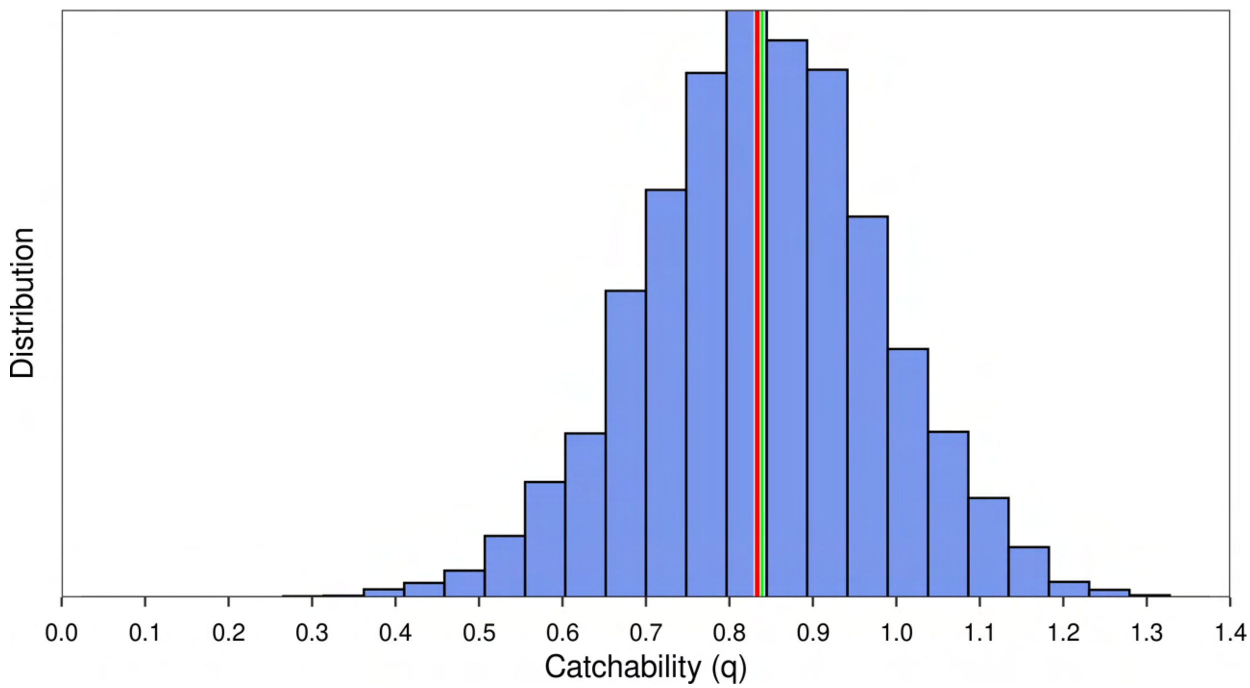


Figure 20. Density of the Catchability (q) parameter for the acoustic survey index. The green vertical line is the median of the posterior for 2024, which is 0.838; the red line is the median of the posterior for the last assessment year, 2023, which was 0.833.

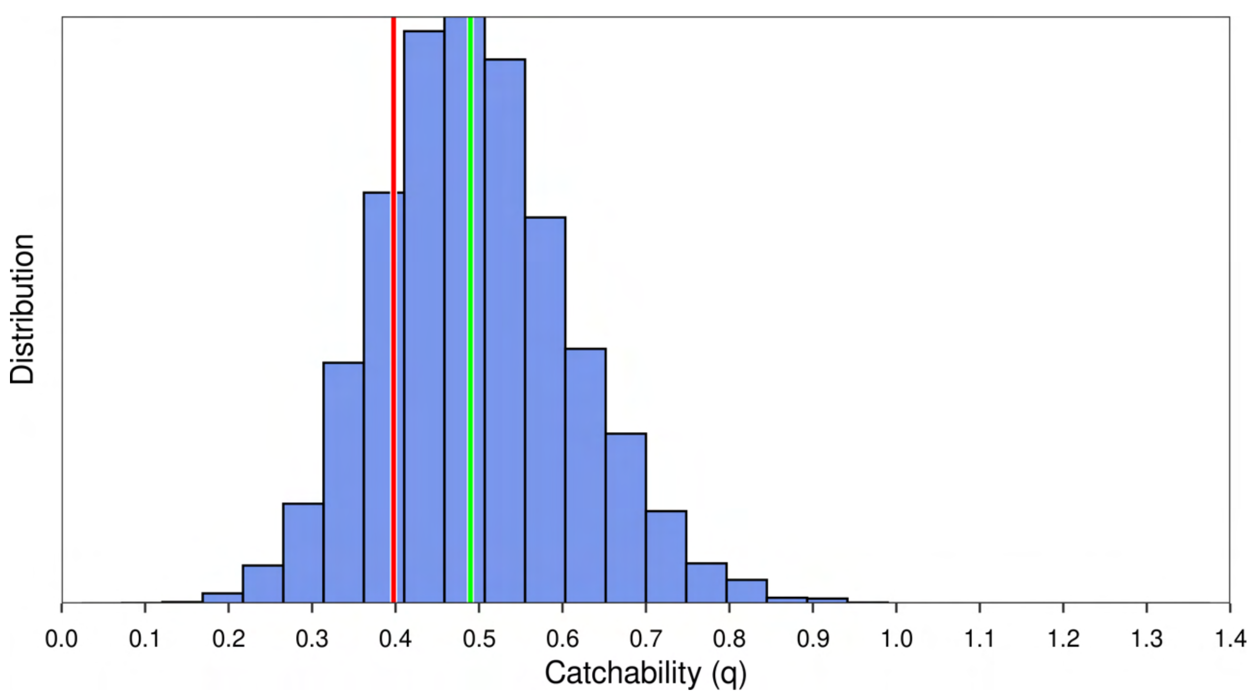


Figure 21. Density of the Catchability (q) parameter for the age-1 index. The green vertical line is the median of the posterior for 2024, which is 0.490; the red line is the median of the posterior for the last assessment year, 2023, which was 0.398.

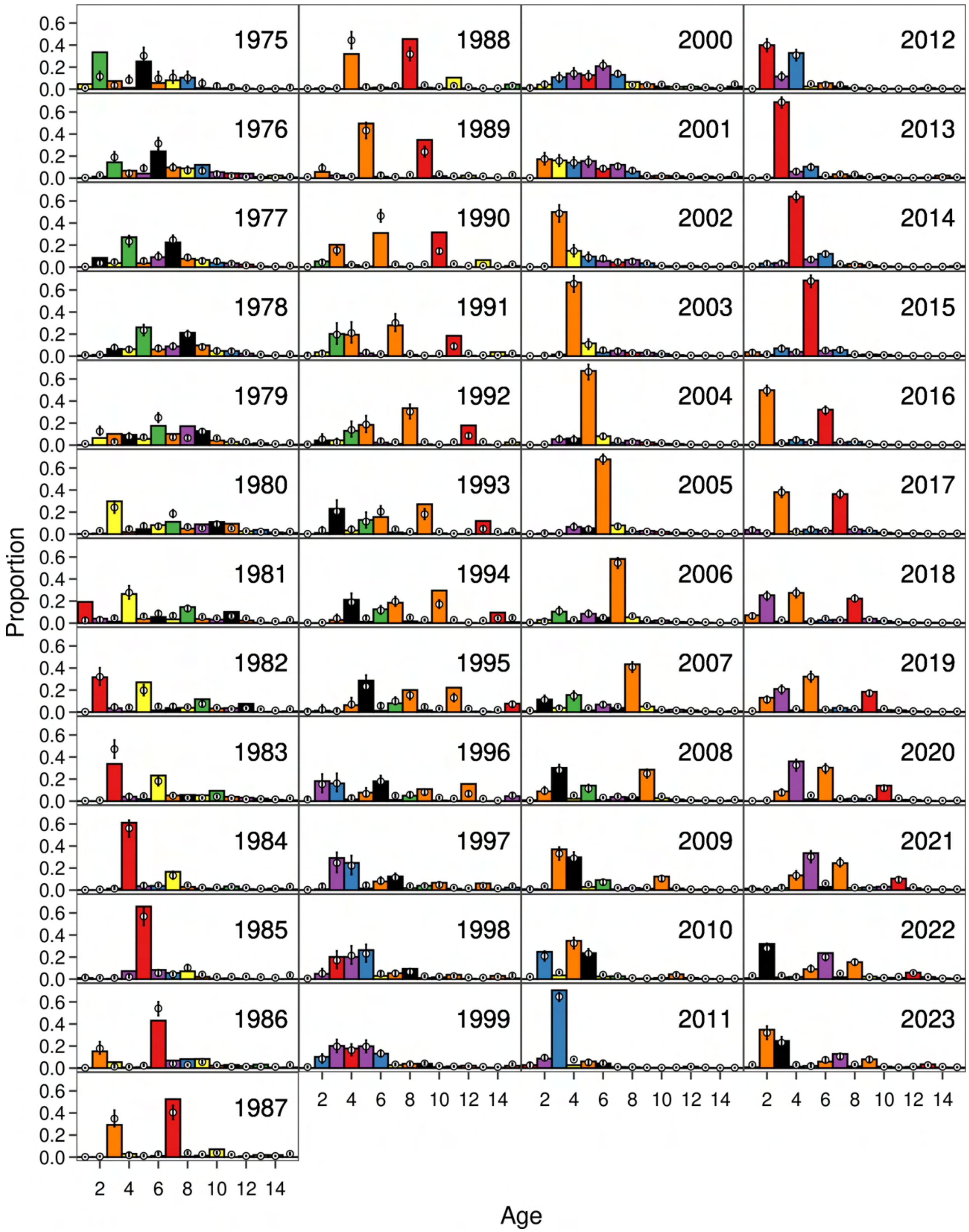


Figure 22. Base model fits to the fishery age-composition data. Colored bars show observed proportions with colors following each cohort across years. Points with intervals indicate median expected proportions and 95% credibility intervals from the Markov chain Monte Carlo calculations.

Figure 23. Base model fits to the acoustic survey 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 Markov chain Monte Carlo calculations.

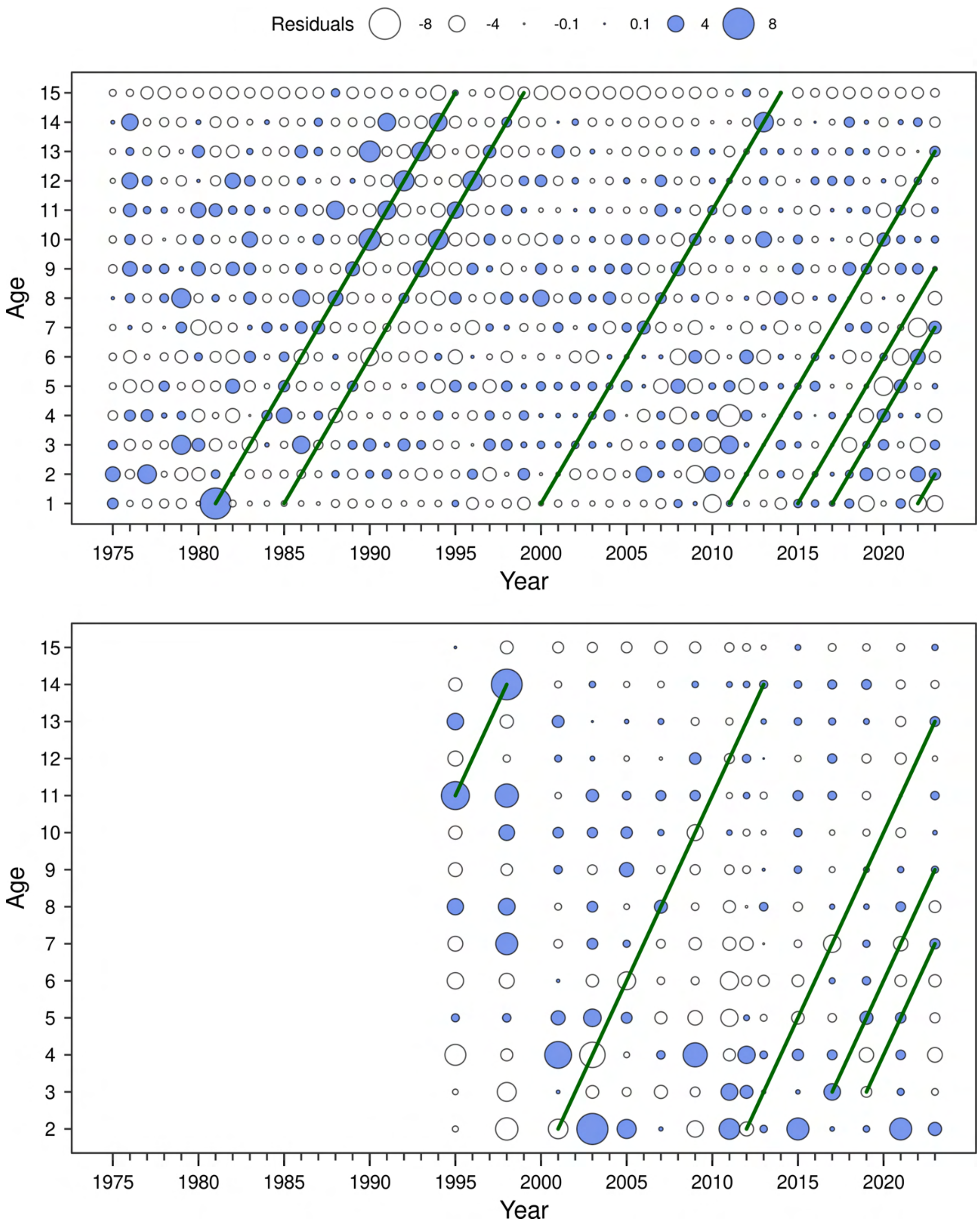


Figure 24. Pearson residuals for base model fits to the age-composition data for the medians of the Markov chain Monte Carlo posteriors for the fishery (top) and acoustic survey (bottom). Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected). Green lines track cohorts from years of large recruitment events.

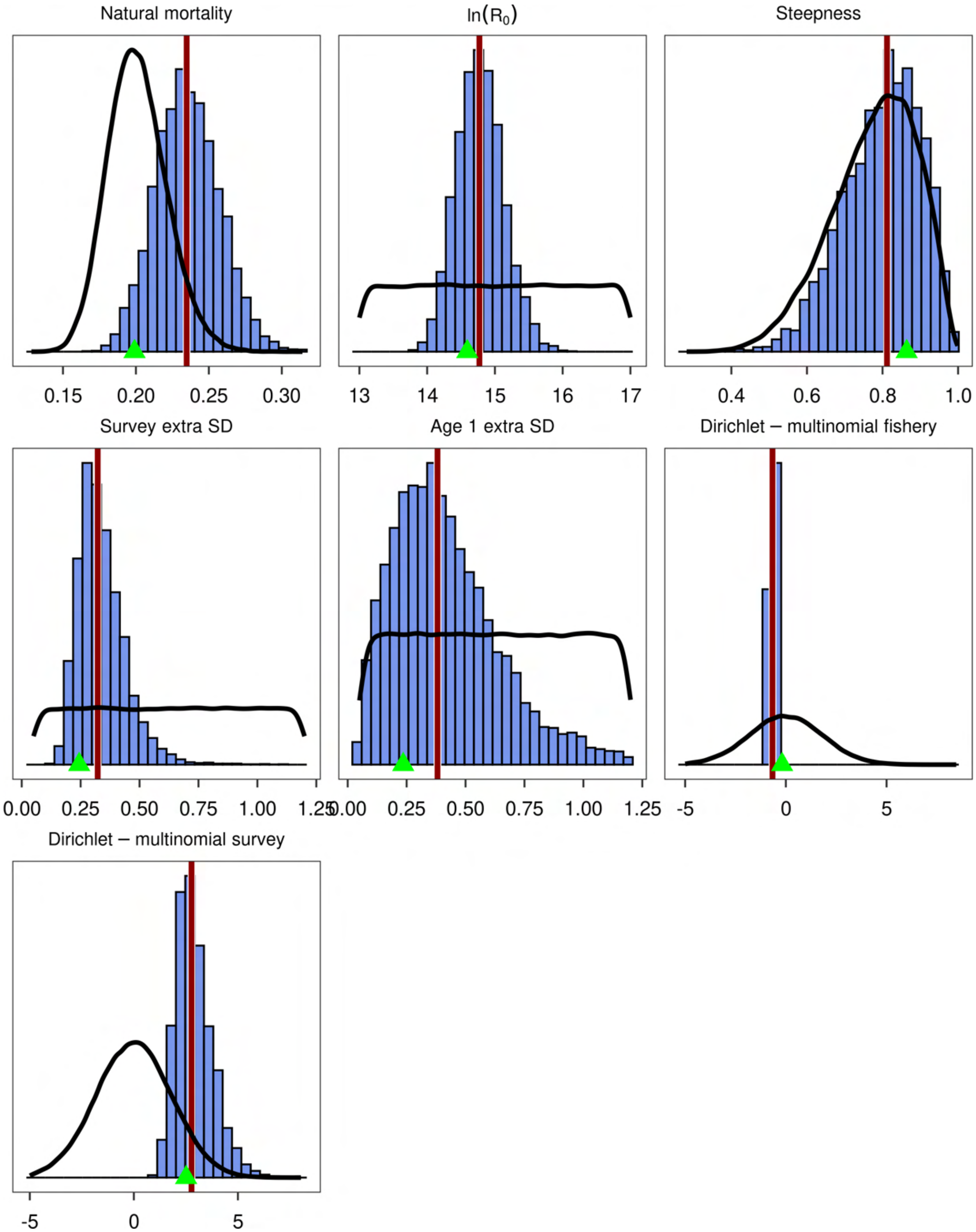


Figure 25. Prior (black lines) and posterior (blue histograms) distributions for natural mortality (M), equilibrium log recruitment ($\ln R_0$), steepness (h), the additional process-error standard deviation (SD) for the acoustic survey and the age-1 index, and the Dirichlet-multinomial parameters for the fishery ($\log \theta_{\text{fish}}$) and the survey ($\log \theta_{\text{surv}}$). Green triangles signify the initial value for each parameter. Red vertical lines represent the median of the posterior. The small downturns at the ends of the uniform priors for $ln(R_0)$, and the Survey and age-1 extra SD parameters represent the hard limits set for the priors in the Stock Synthesis control file.

Figure 26. As for Figure 25 but the x axis of each panel is truncated to the range of the posterior distribution, and thus, there is the potential for the full range of the prior and the initial value to be missing from individual panels.

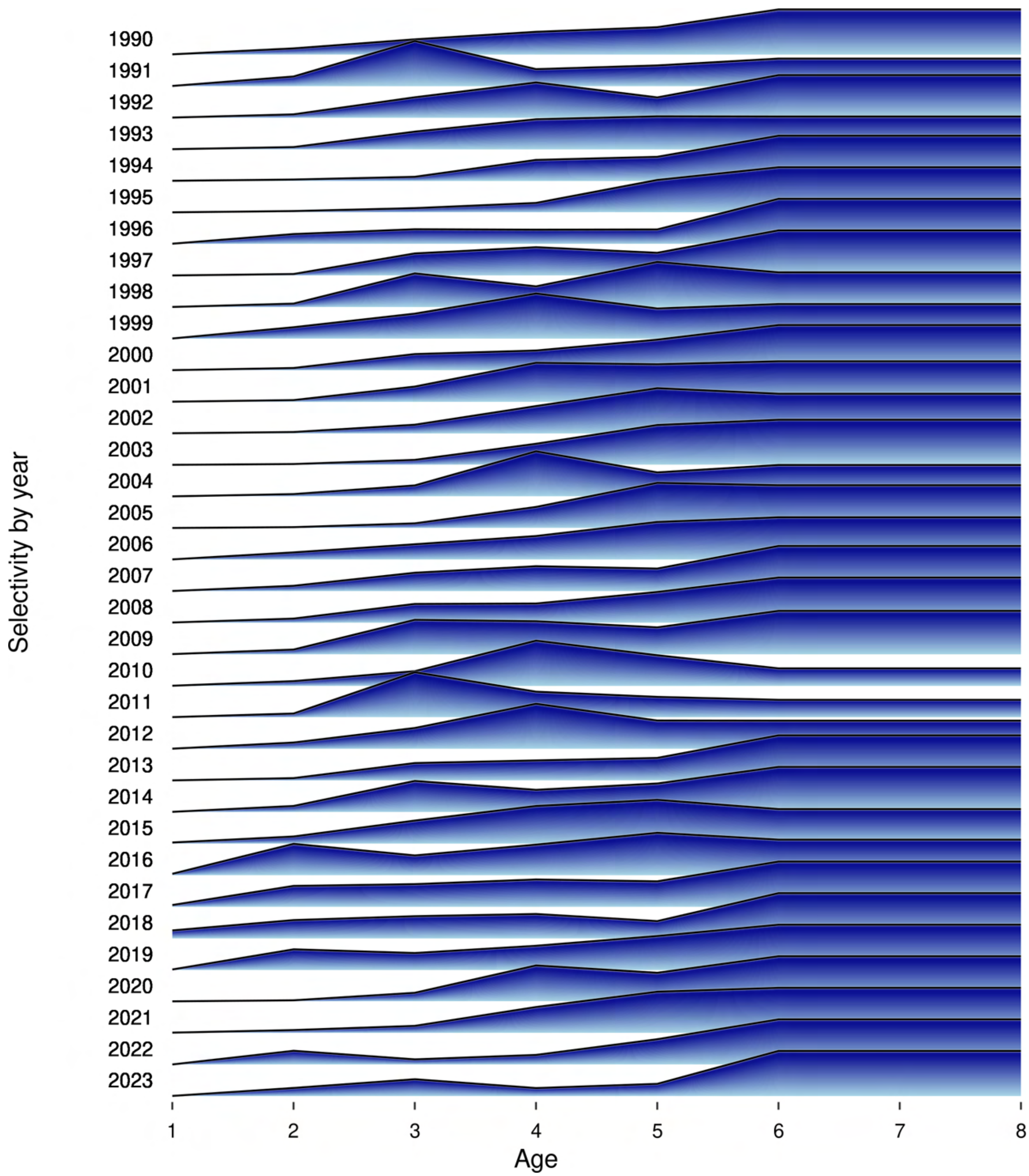


Figure 27. Mountains plot of median fishery selectivity in each year for the base model. The range of selectivity is scaled to be between 0 and 1 in each year.

Figure 28. 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. The range of selectivity is scaled to be between 0 and 1 in each year. Selectivity for 1990 is shared for all years from 1966 to 1990.

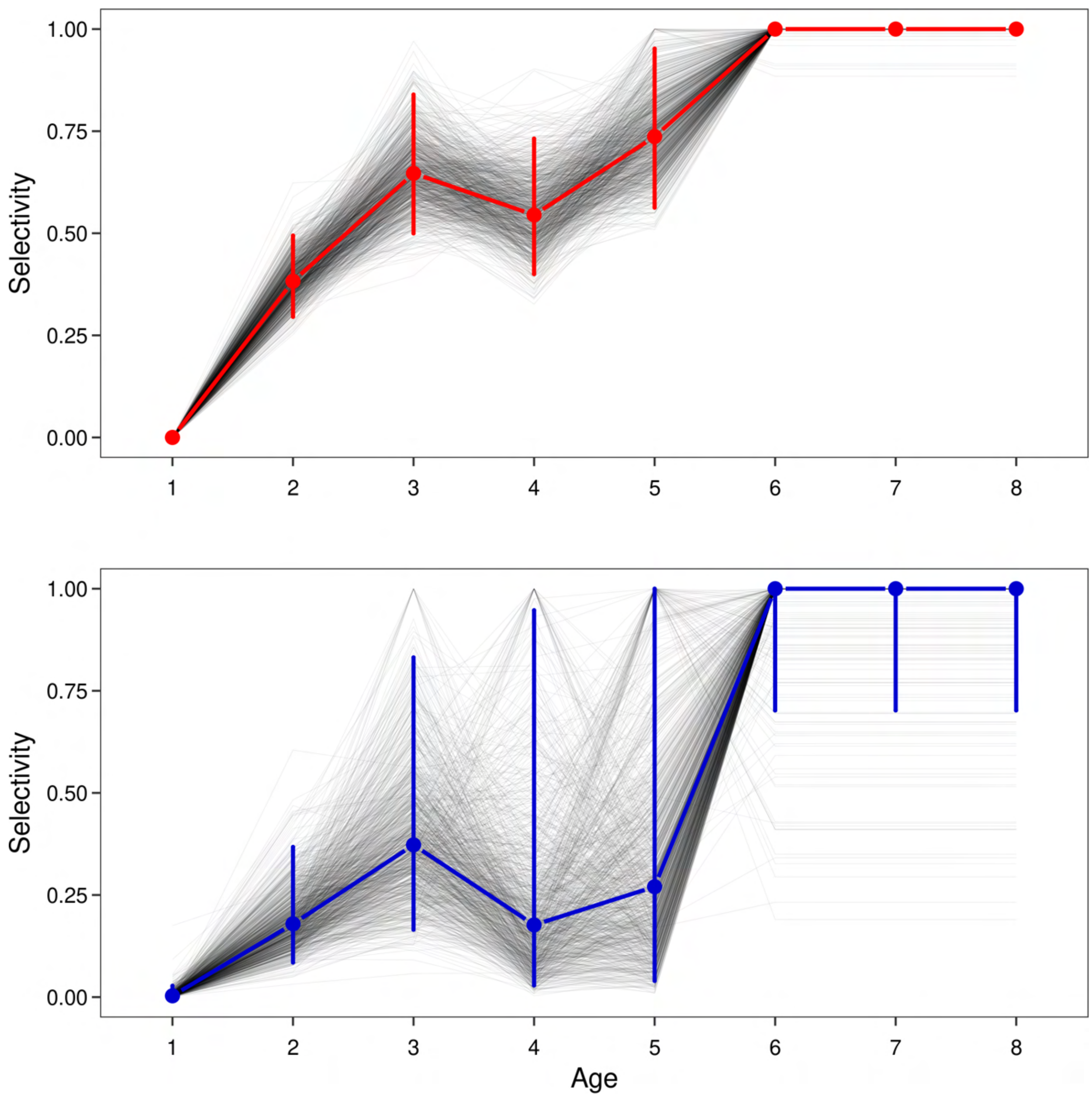


Figure 29. Estimated selectivities for the acoustic survey age-2+ biomass index (top, with selectivity of zero for age-1 fish) and fishery (bottom – shown for 2023 only, age-1 and older) from a subsample of 1,000 draws from the posterior distribution for the base model.

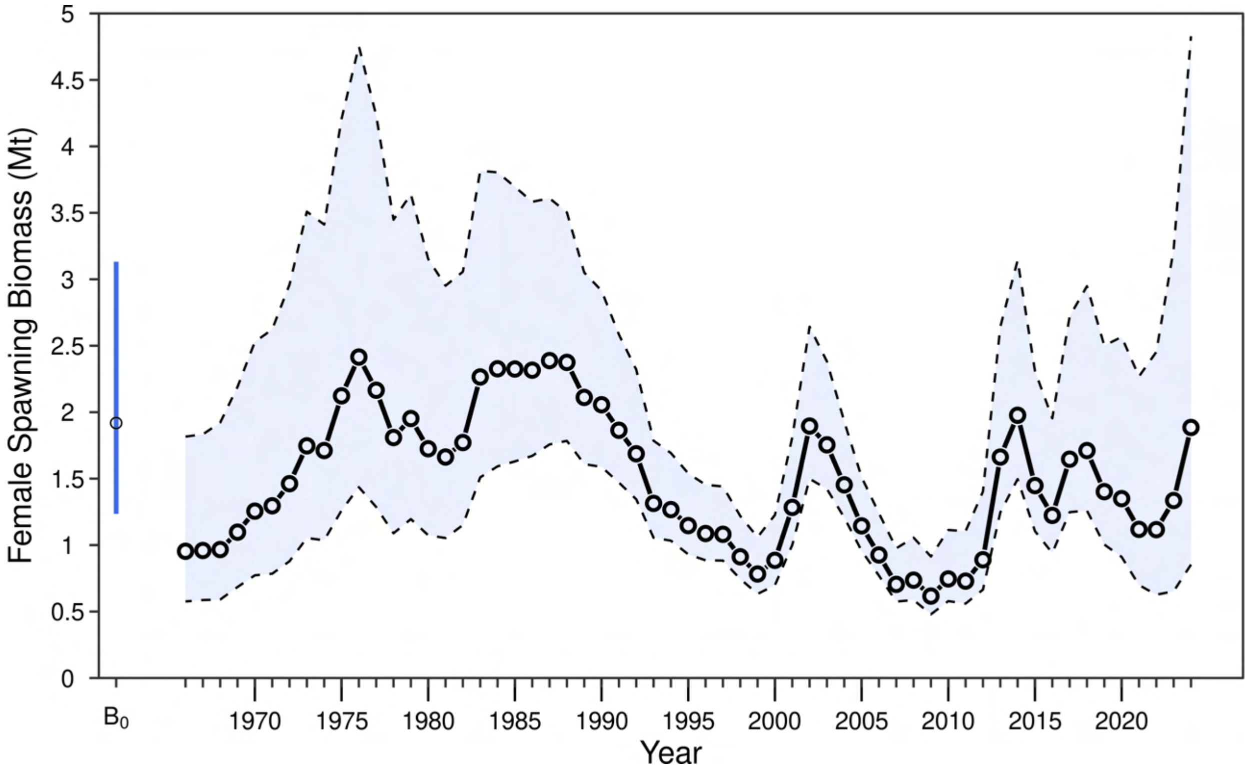


Figure 30. Median (solid line) of the posterior distribution for beginning of the year female spawning biomass (B_t in year t; Mt) through 2024 (solid line) with 95% posterior credibility intervals (shaded area). The left-most circle with a 95% posterior credibility interval is the estimated unfished equilibrium biomass, B_0.

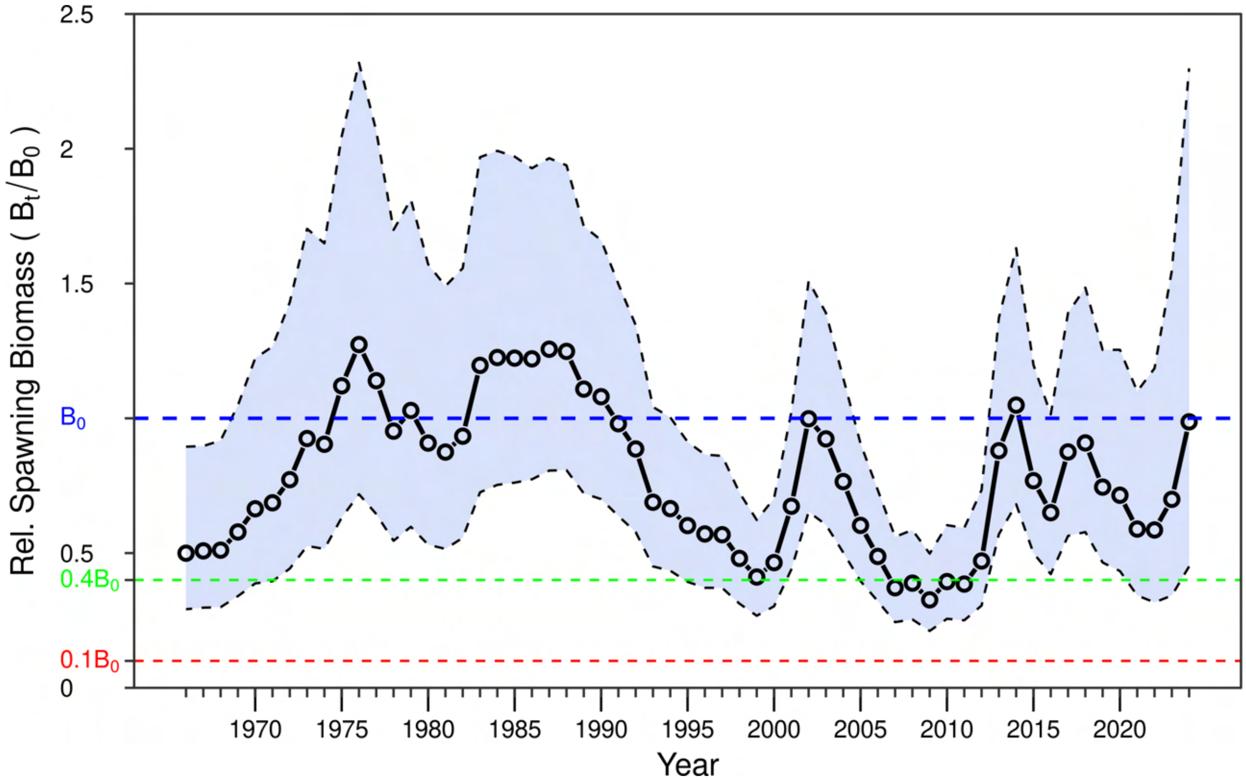


Figure 31. Median (solid line) of the posterior distribution for relative spawning biomass (B_t/B_0) through 2024 with 95% posterior credibility intervals (shaded area). Dashed horizontal lines show 10%, 40%, and 100% of the unfished equilibrium (B_0).

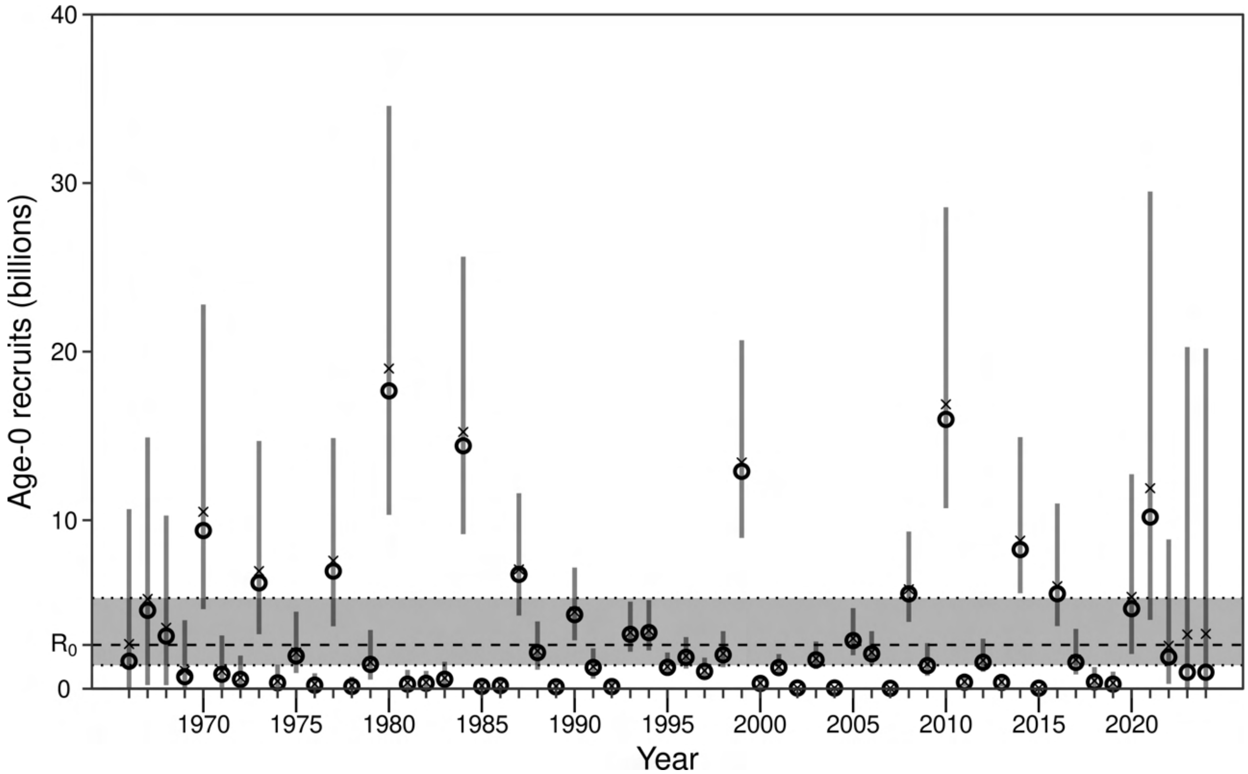


Figure 32. Medians (solid circles) and means (X) of the posterior distribution for recruitment (billions of age-0 fish) with 95% posterior credibility intervals (vertical lines). The median of the posterior distribution for mean unfished equilibrium recruitment (R_0) is shown as the horizontal dashed line with the 95% posterior credibility interval shaded between the dotted lines.

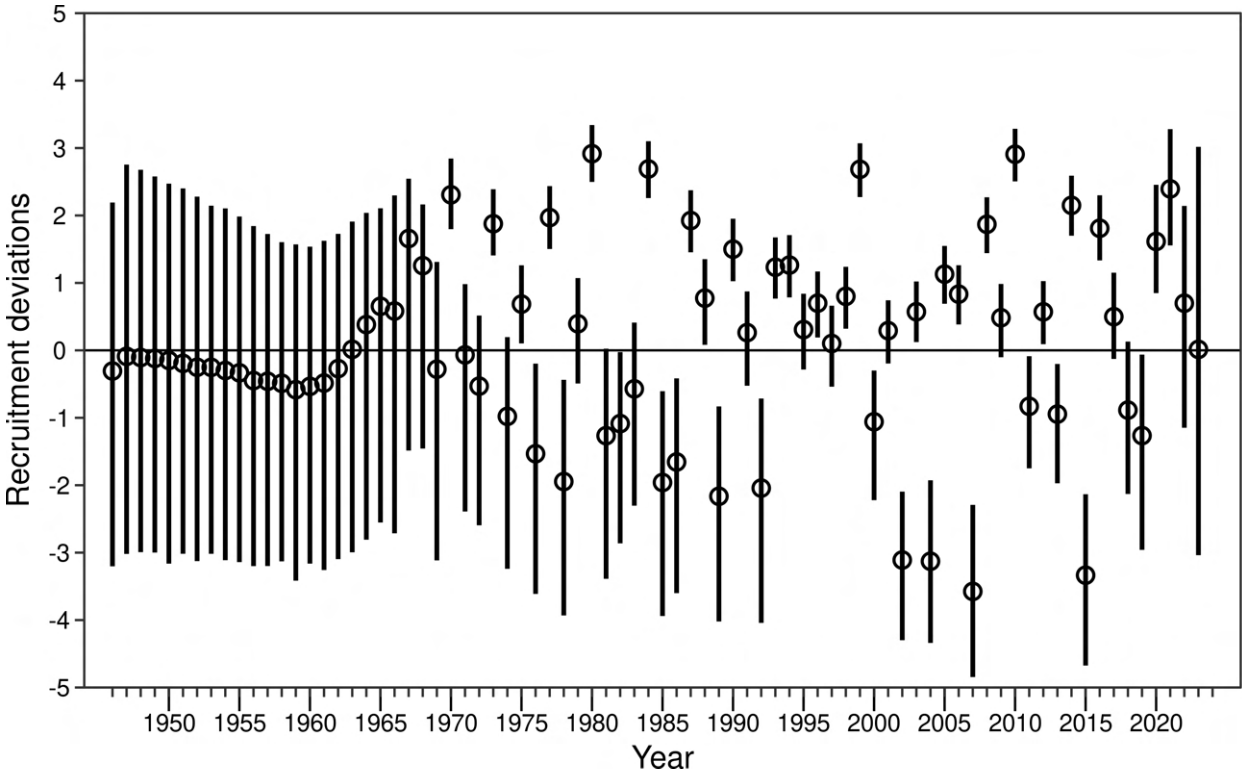


Figure 33. Medians (solid circles) of the posterior distribution for log-scale recruitment deviations with 95% posterior credibility intervals (vertical lines). Recruitment deviations for the years 1946–1965 are used to calculate the numbers at age in 1966, the initial year of the model.

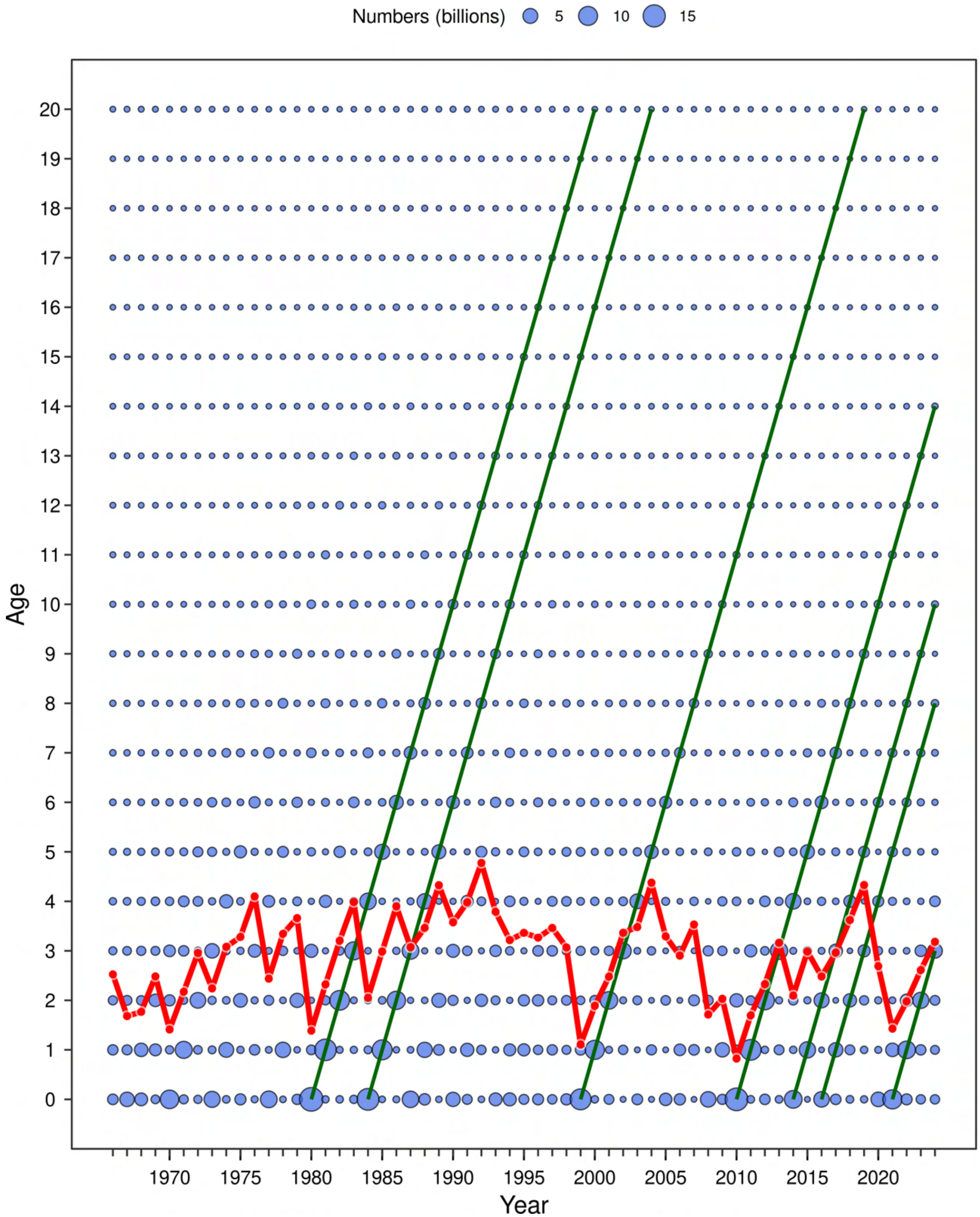


Figure 34. Bubble plot of the medians of the posterior distributions of population numbers at age at the beginning of each year, where green diagonal lines follow each larger-than-usual year-class through time. The red line represents the mean age. The scale of the bubbles is represented in the key where the units are billions of fish; the largest overall bubble represents the 17.7 billion age-0 recruits in 1980. See Table 17 for values.

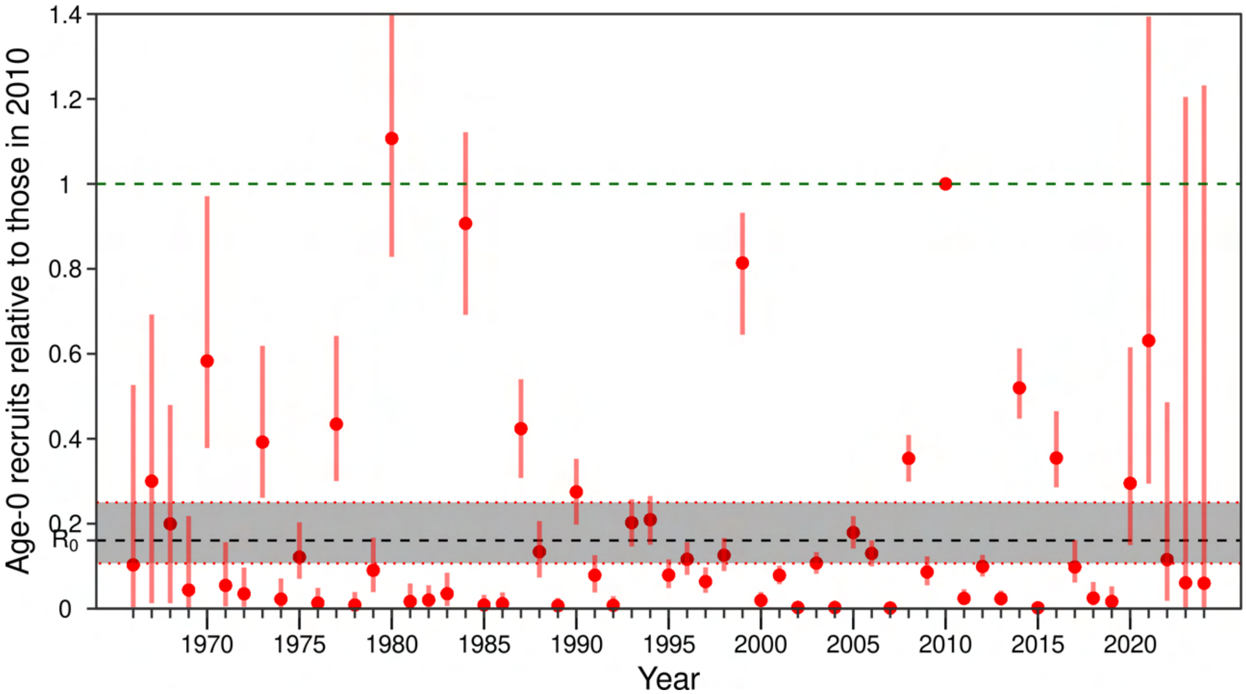


Figure 35. Medians (circles) of the posterior distribution of annual recruitment relative to recruitment in 2010 (recruitment divided by the 2010 recruitment for every MCMC sample), with 95% posterior credibility intervals (red lines). This procedure somewhat scales out the uncertainty due to uncertainty 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 (horizontal green dashed line). 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 36. Estimated stock–recruitment 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 lognormal distribution (median). Shading around the stock–recruitment relationship indicates uncertainty in shape associated with distribution of the steepness parameter (h). The blue polygon on the right indicates the expected distribution of absolute recruitments.

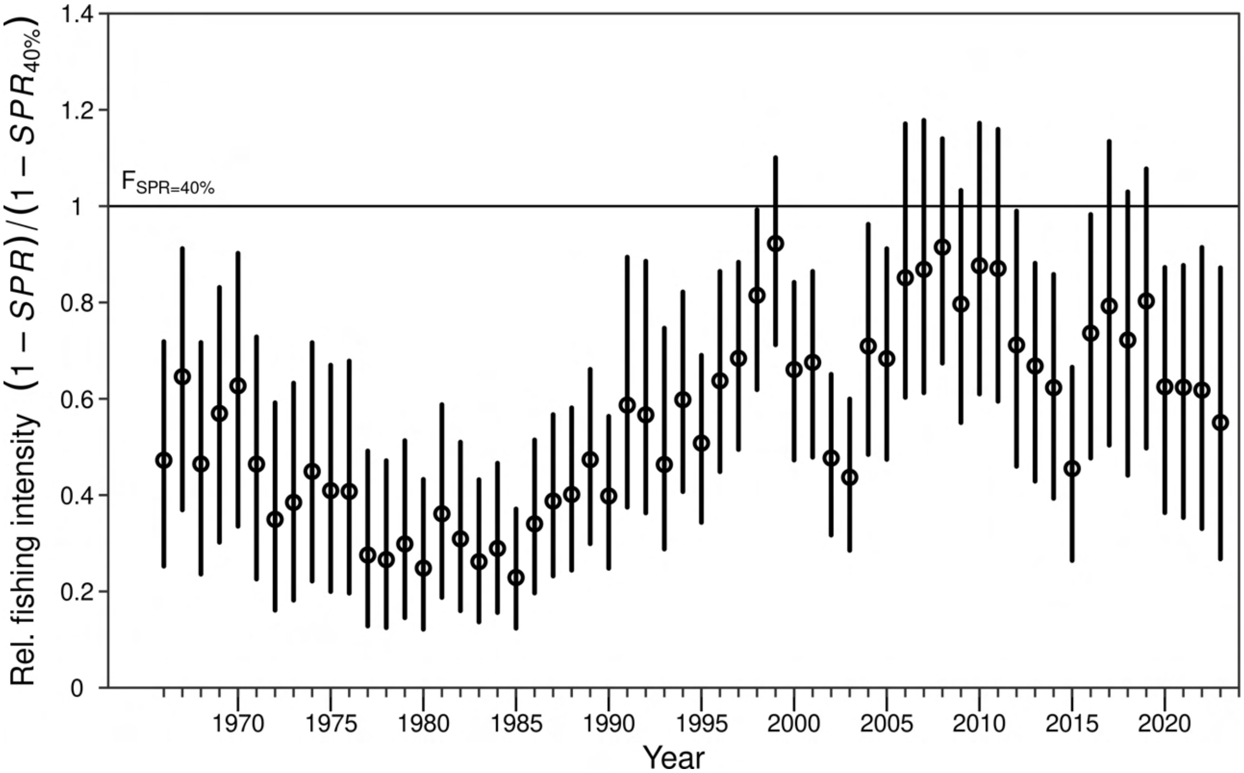


Figure 37. Trend in median relative fishing intensity (relative to the $F_{\text{SPR}=40\%}$ management level) through 2023 with 95% posterior credibility intervals. The $F_{\text{SPR}=40\%}$ management level defined in the Joint U.S.-Canada Agreement for Pacific Hake is shown as a horizontal line at 1.0.

Figure 38. Trend in median exploitation fraction (catch divided by age-2+ biomass) through 2023 with 95% posterior credibility intervals.

Figure 39. Estimated historical path of median relative spawning biomass at the beginning of year t and corresponding median relative fishing intensity in fishing year $t-1$ leading up to year t. Labels show the time series start and end years; labels correspond to year t (i.e., year of the relative spawning biomass). Gray bars span the 95% credibility intervals for 2024 relative spawning biomass (horizontal) and 2023 relative fishing intensity (vertical).

Figure 40. The posterior distribution of the default 2024 catch limit calculated using the default harvest policy ($F_{40\%}$–40:10). The median is 747,588 t (vertical line), with the dark shaded area ranging from the 2.5% quantile to the 97.5% quantile, covering the range 298,355–2,124,832 t.

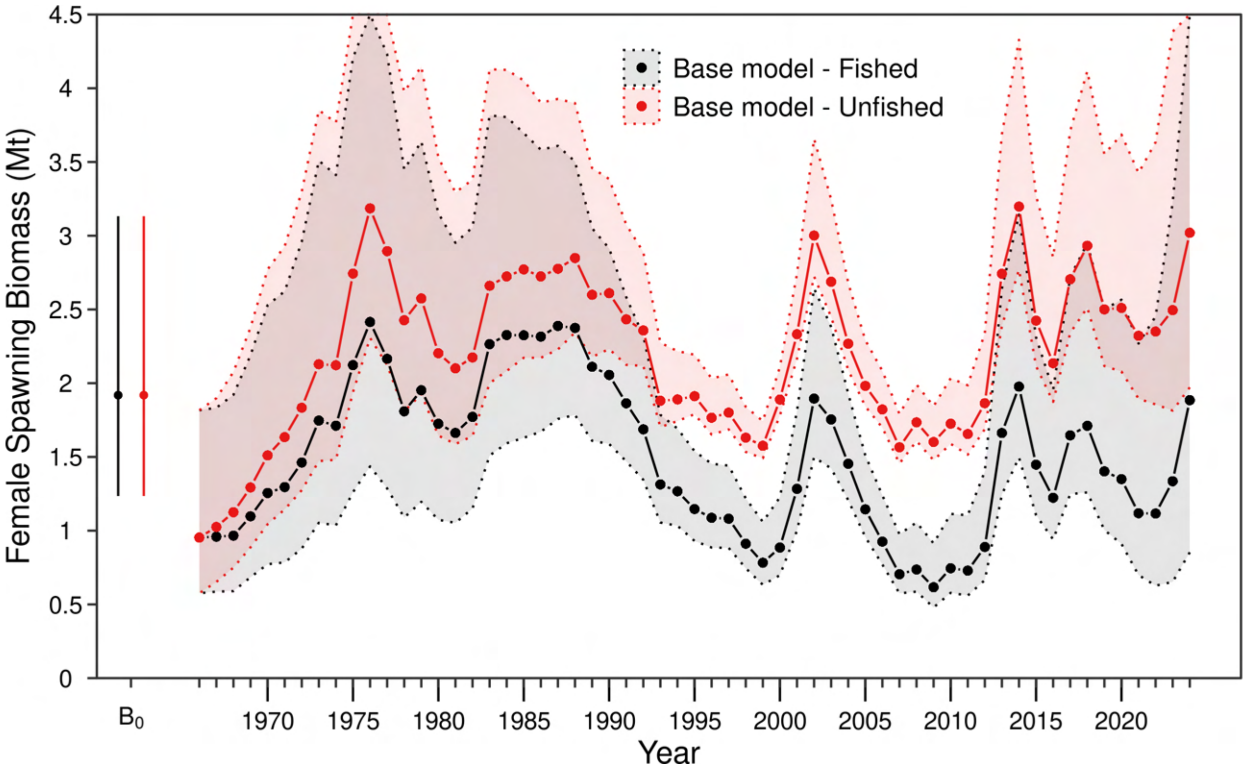


Figure 41. A comparison of female spawning stock biomass with fishing (black; as in Figure 30) and when the effects of fishing on the population are removed (red; unfished time series). Medians (solid lines) of the posterior distribution for beginning of the year female spawning biomass (B_t in year t; Mt) through 2024 (solid lines) with 95% posterior credibility intervals (shaded areas). The left-most circles with 95% posterior credibility intervals show the estimated unfished equilibrium biomass, B_0. The difference between the two lines shows the impact of removing fishing mortality from the population.

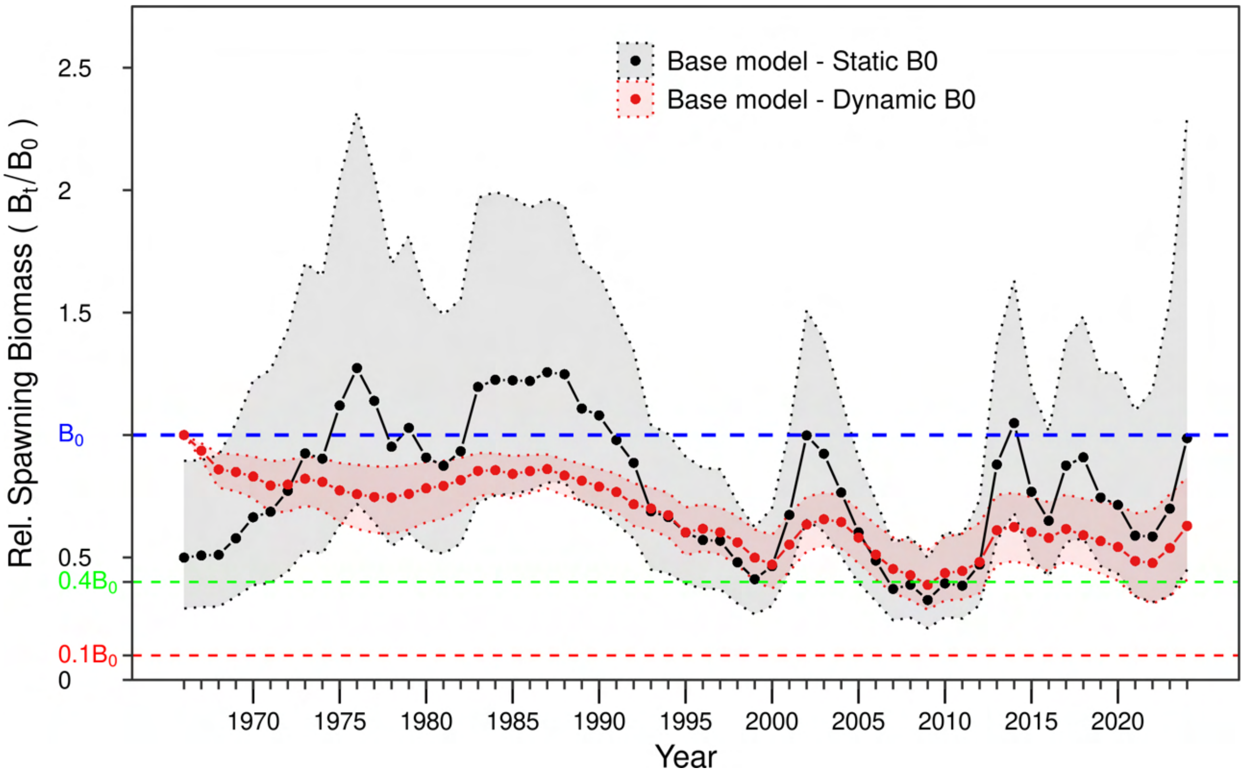


Figure 42. A comparison of relative spawning biomass when spawning biomass in year t is related to unfished equilibrium biomass, B_0 (static B_0, black; as in Figure 31) and when spawning biomass in year t is related to the unfished biomass time series in year t (dynamic B_0, red). Median (solid lines) of the posterior distribution for each calculation of relative spawning biomass through 2024 with 95% posterior credibility intervals (shaded areas). Dashed horizontal lines show 10%, 40%, and 100% of the unfished equilibrium (B_0). The default $F_{40\%}$–40:10 harvest policy uses relative spawning biomass based on a static B_0 determination of stock status.

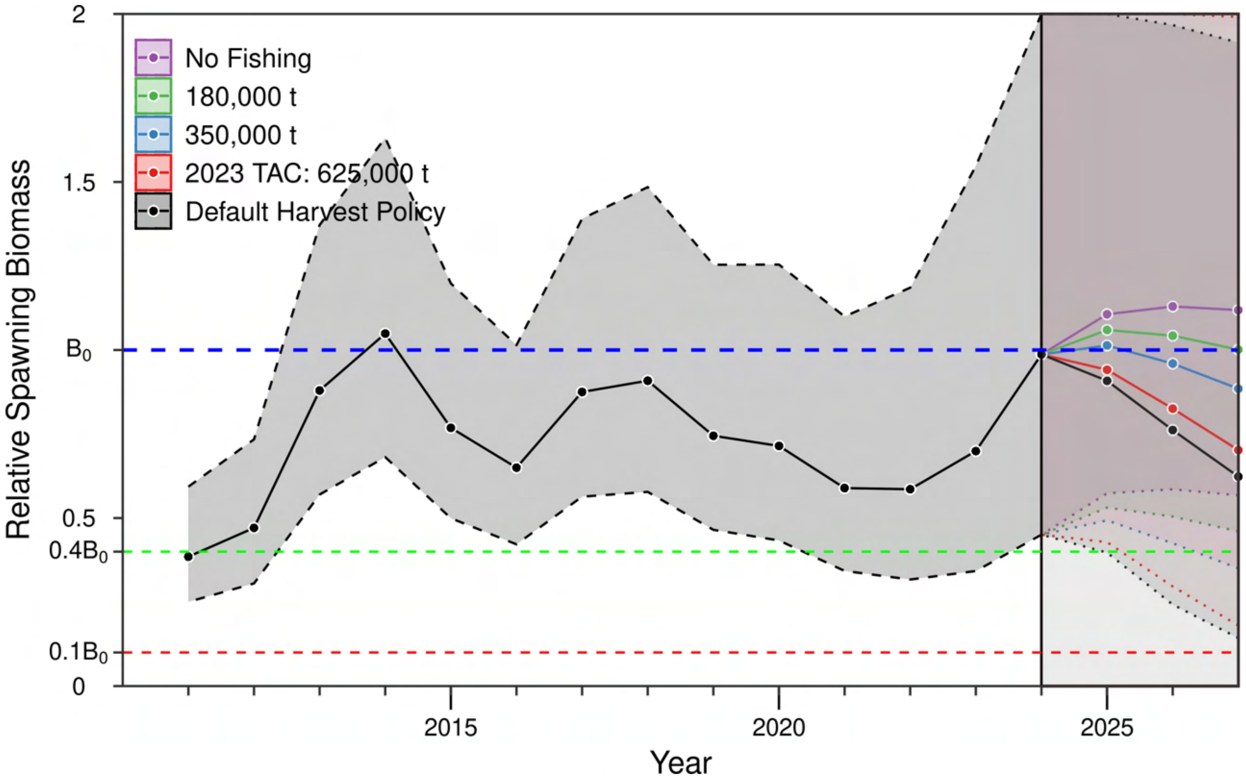


Figure 43. Median and 95% posterior credibility intervals of estimated relative spawning biomass to the start of 2024 from the base model and projections to the start of 2027 (vertical shaded rectangle) for several management actions, which are defined in the decision tables. The default harvest policy catches are 747,588 t in 2024, 772,111 t in 2025, and 717,464 t in 2026.

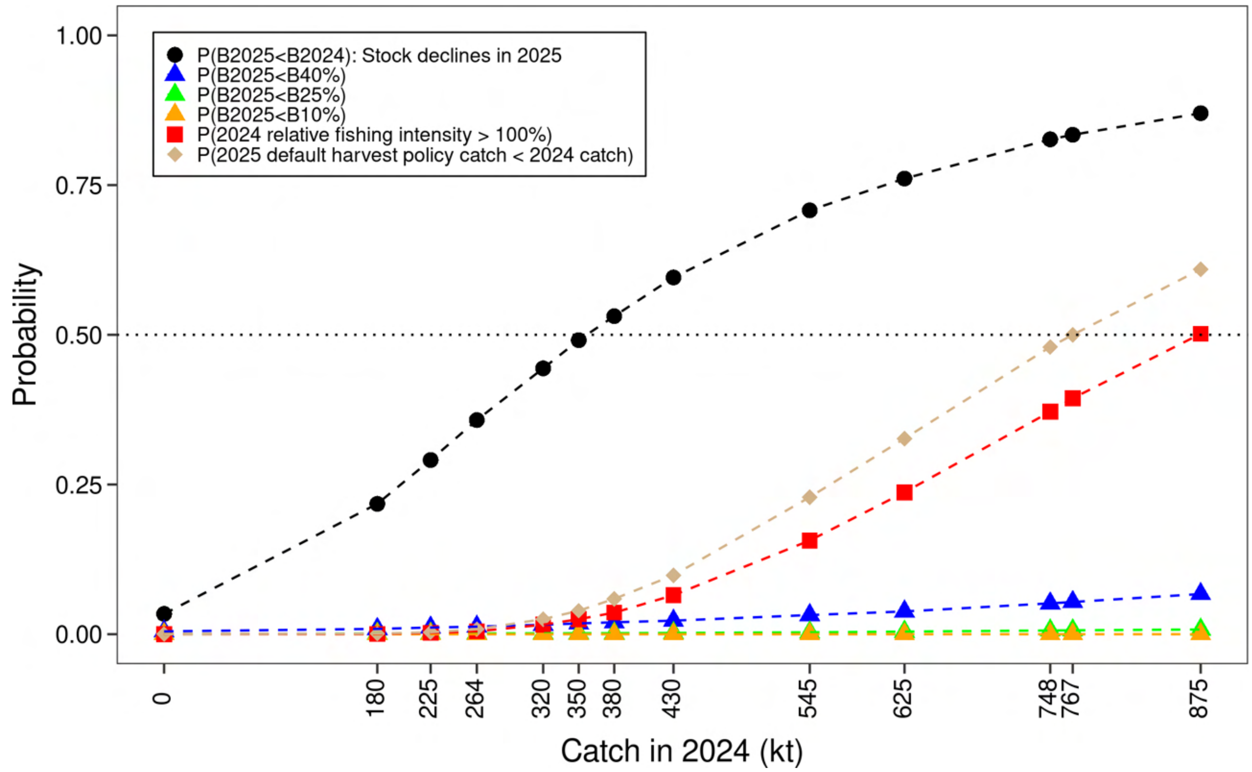


Figure 44. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options (explained in Table 27) as listed in Table 29. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

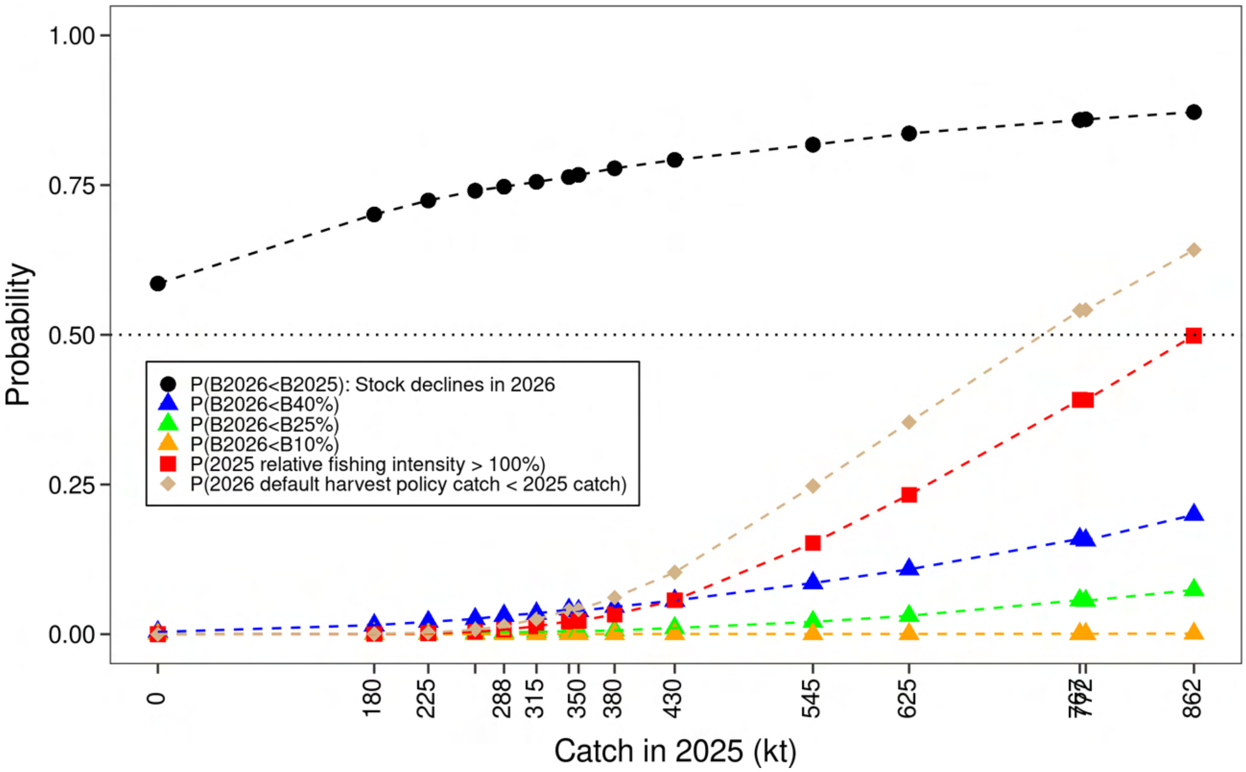


Figure 45. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2026 default harvest policy catch for alternative 2025 catch options (including associated 2024 catch; catch options explained in Table 27) as listed in Table 30. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

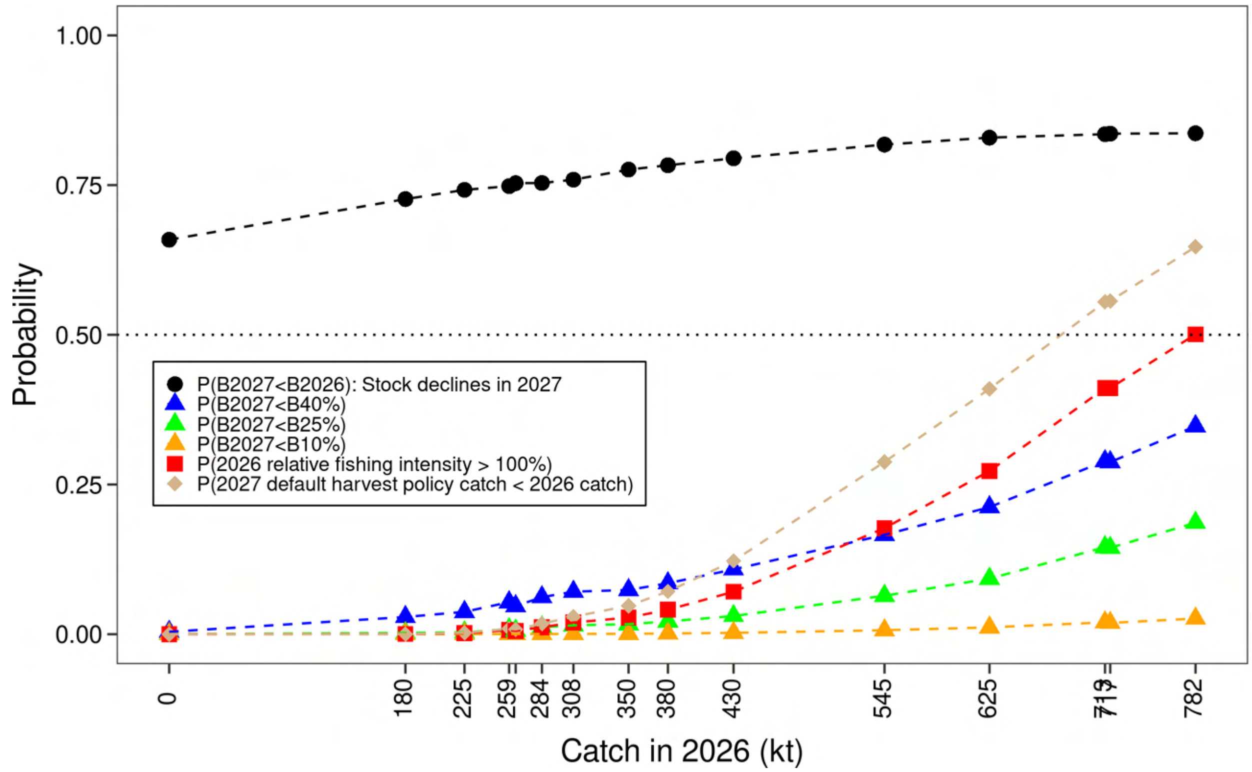


Figure 46. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2027 default harvest policy catch for alternative 2026 catch options (including associated 2024 and 2025 catches; catch options explained in Table 27) as listed in Table 31. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Figure 47. Forecast age compositions in numbers and in weight for the 2024 fishery catch (combined across all sectors in both countries). Light blue 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 2024 (see Table 17 for the Markov chain Monte Carlo 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.

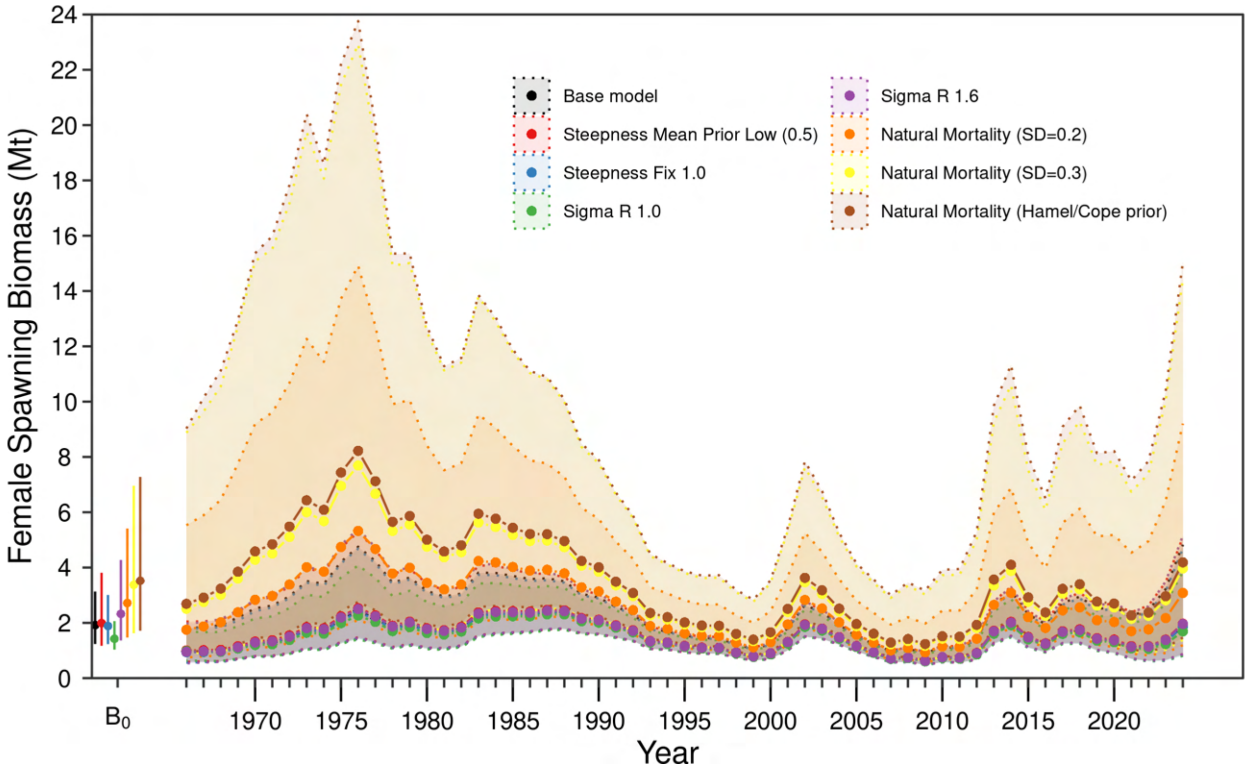


Figure 48. Markov chain Monte Carlo estimates of spawning biomass for the base model and alternative sensitivity runs representing changing the mean of the prior for steepness from 1.0 to 0.5, fixing steepness at 1.0, lower (1.0) and higher (1.6) levels of variation assumed about the stock–recruitment relationship (σ_r), changing the standard deviation of the prior for natural mortality, and using the Hamel/Cope prior distribution for natural mortality.

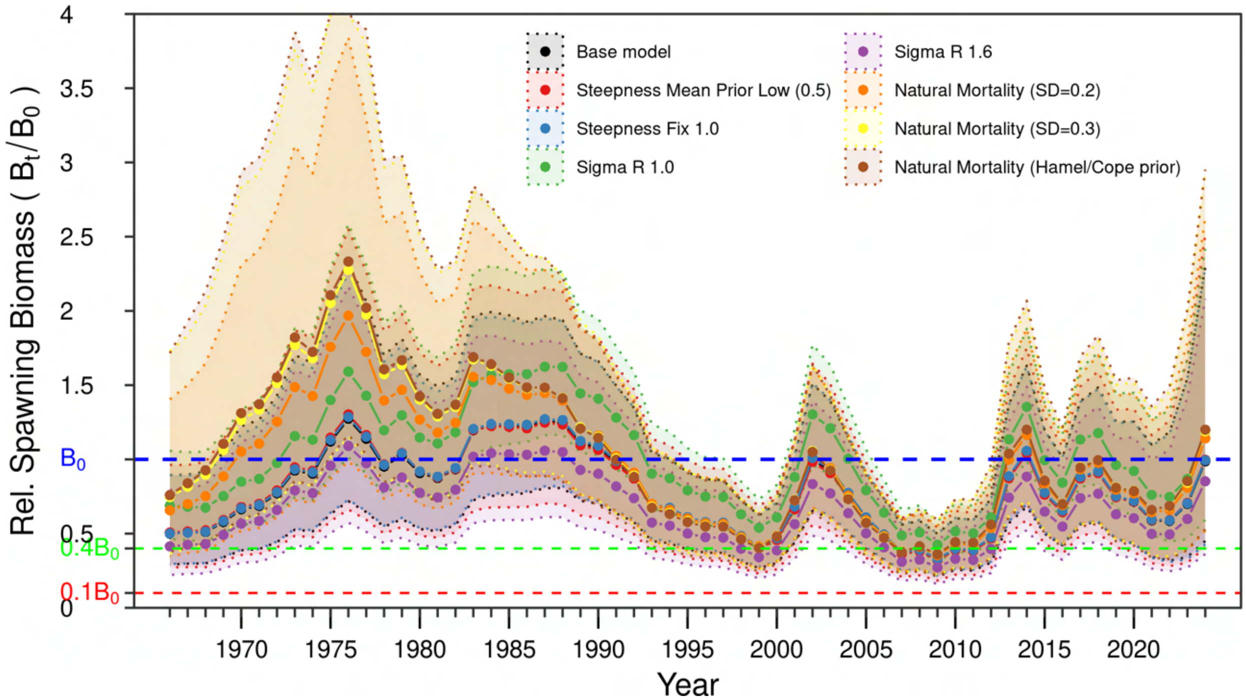


Figure 49. Markov chain Monte Carlo estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity runs representing changing key parameters. See Figure 48 for sensitivity descriptions.

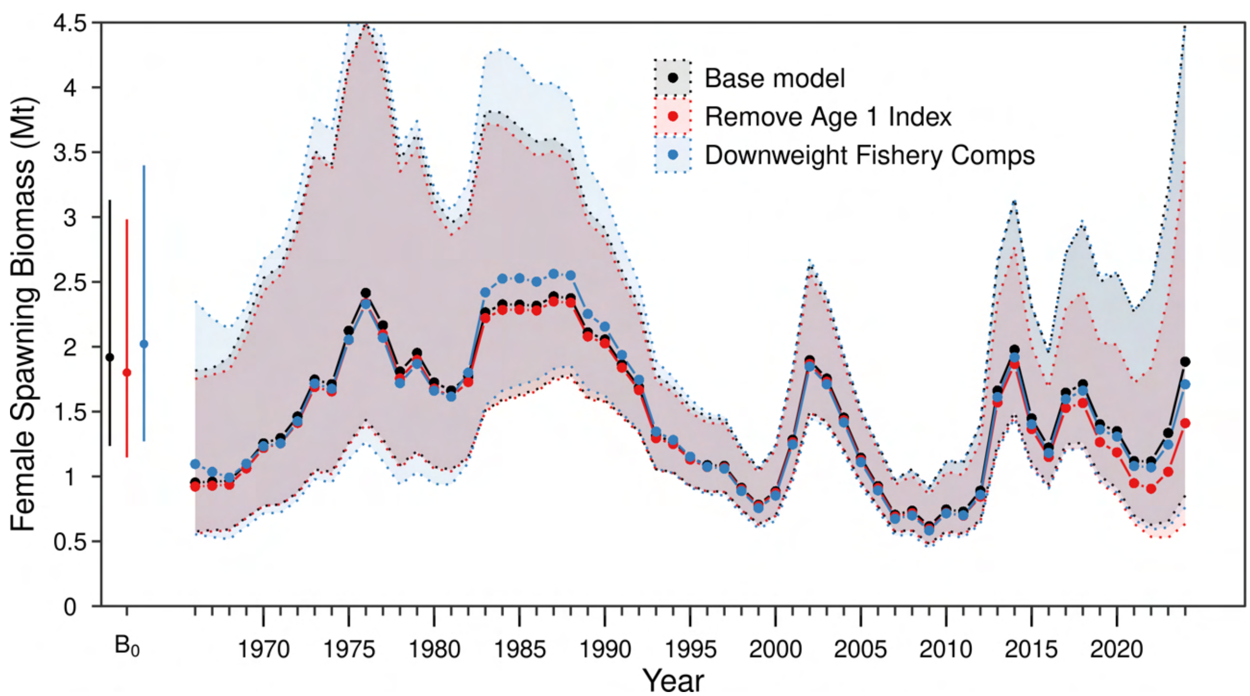


Figure 50. Markov chain Monte Carlo estimates of spawning biomass for the base model and alternative sensitivity models that represent the following changes in data: removing the index of age-1 fish and down-weighting fishery composition data using the McAllister-Ianelli method.

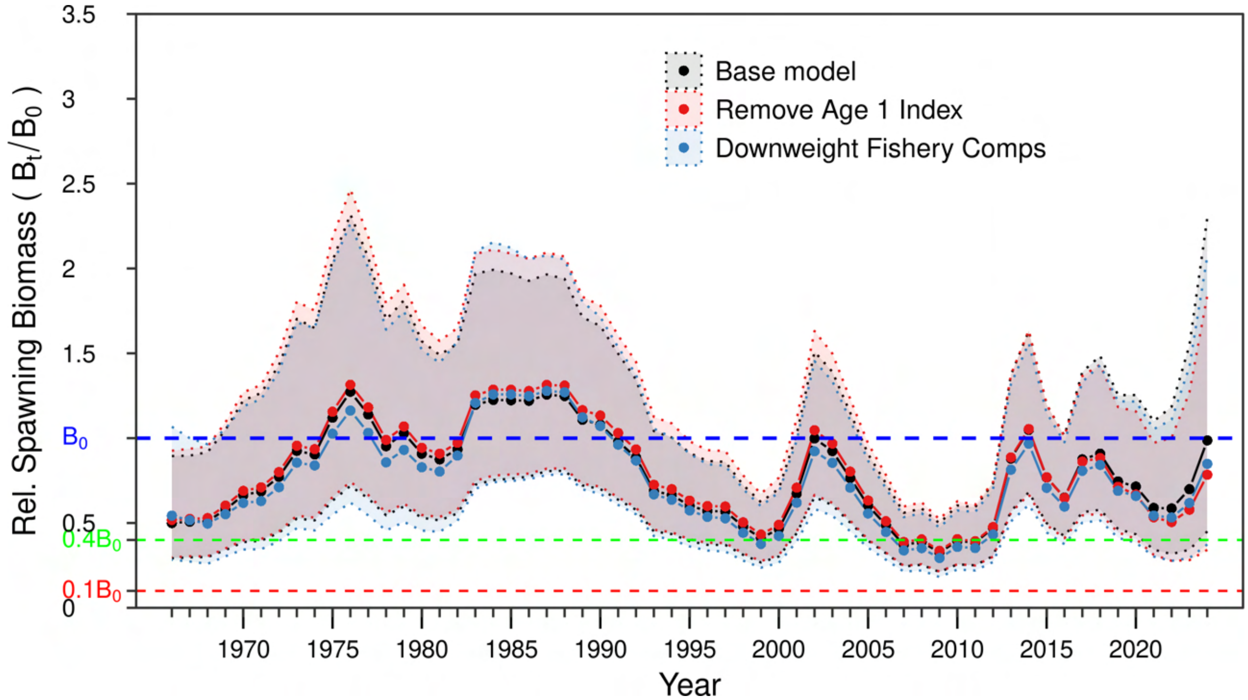


Figure 51. Markov chain Monte Carlo estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity models that represent changes in data. See Figure 50 for sensitivity descriptions.

Figure 52. Markov chain Monte Carlo estimates of recruitment deviations for the base model and alternative sensitivity runs that represent changes in data. See Figure 50 for sensitivity descriptions.

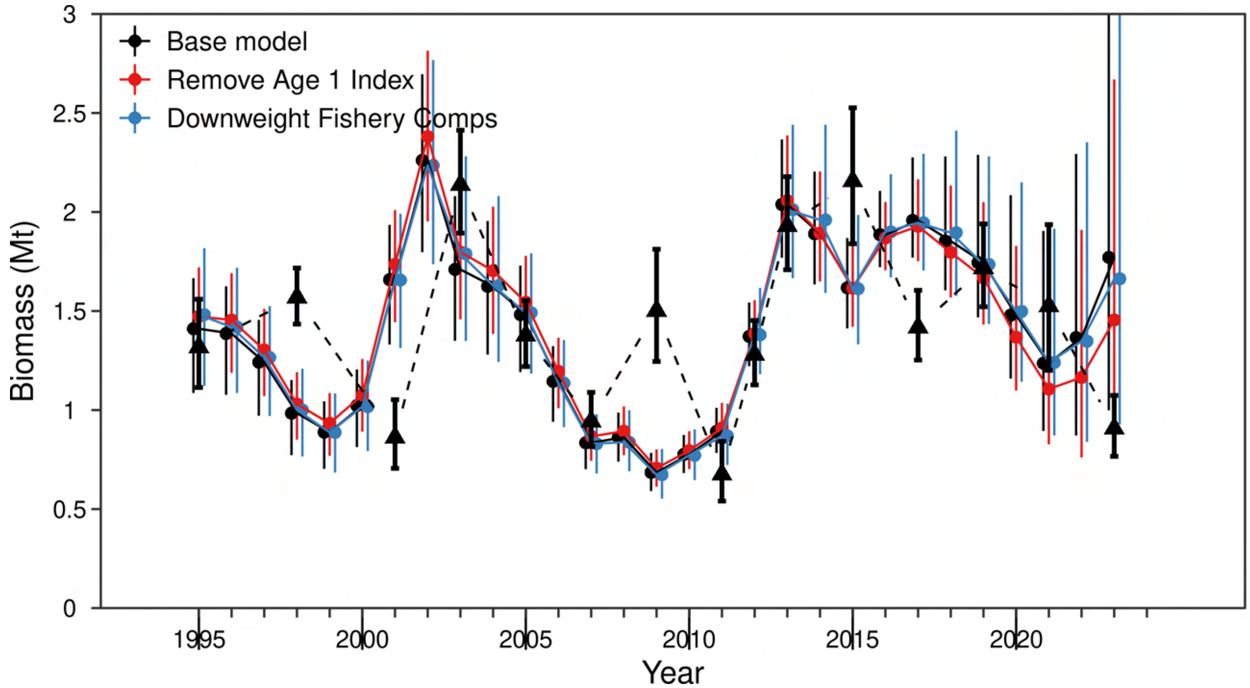


Figure 53. Markov chain Monte Carlo estimates of the fit to the acoustic survey biomass time series for the base model and alternative sensitivity runs that represent changes in data. See Figure 50 for sensitivity descriptions.

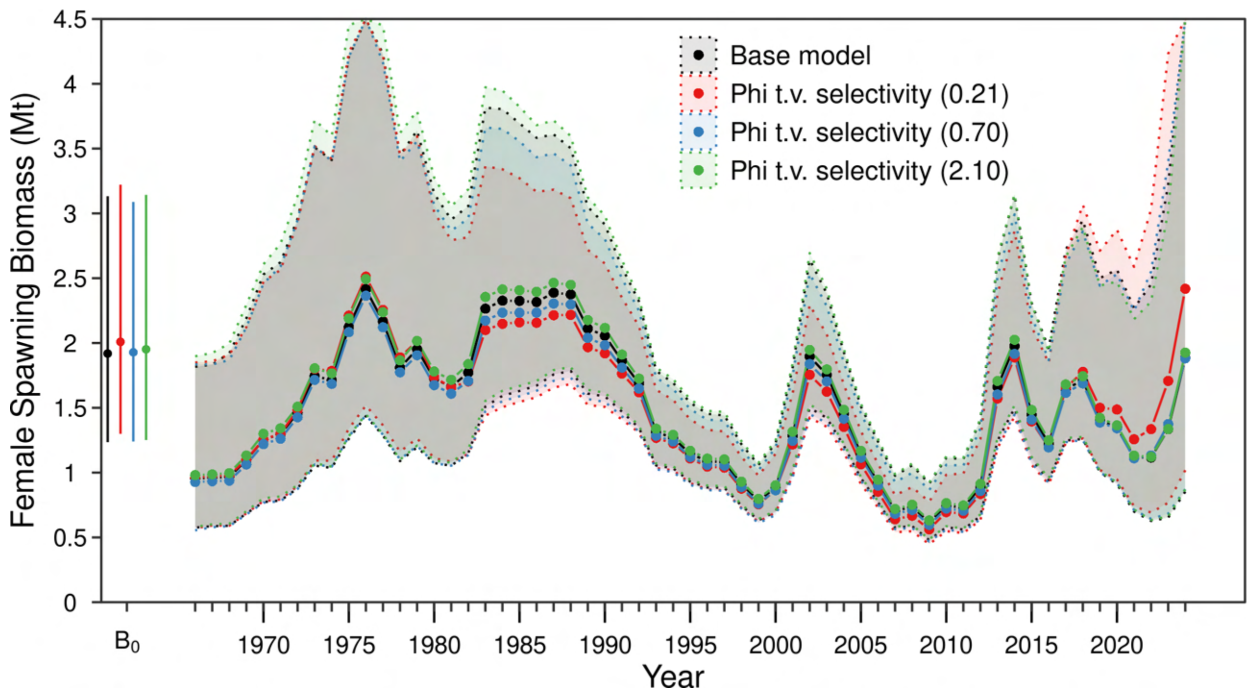


Figure 54. Markov chain Monte Carlo estimates of spawning biomass for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. Standard deviations examined are below (0.21 and 0.70) and above (2.10) the base model value of 1.4.

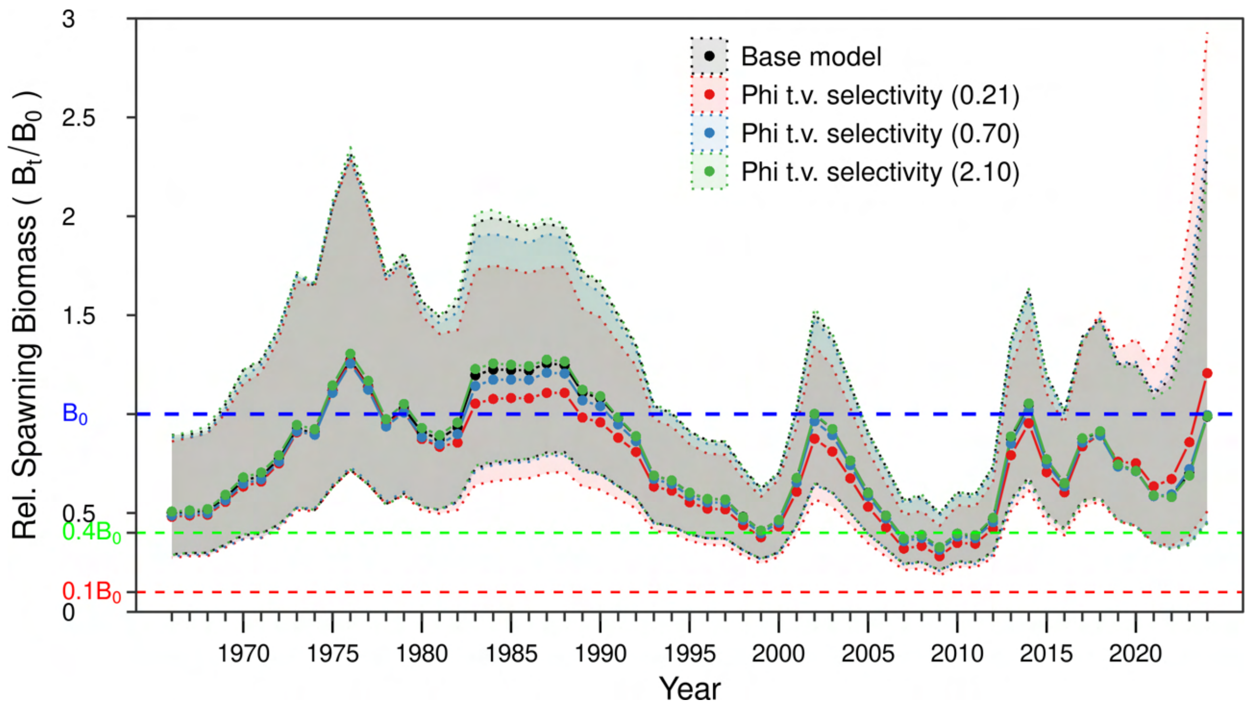


Figure 55. Markov chain Monte Carlo estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 54 for sensitivity descriptions.

Figure 56. Markov chain Monte Carlo estimates of recruitment for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 54 for sensitivity descriptions.

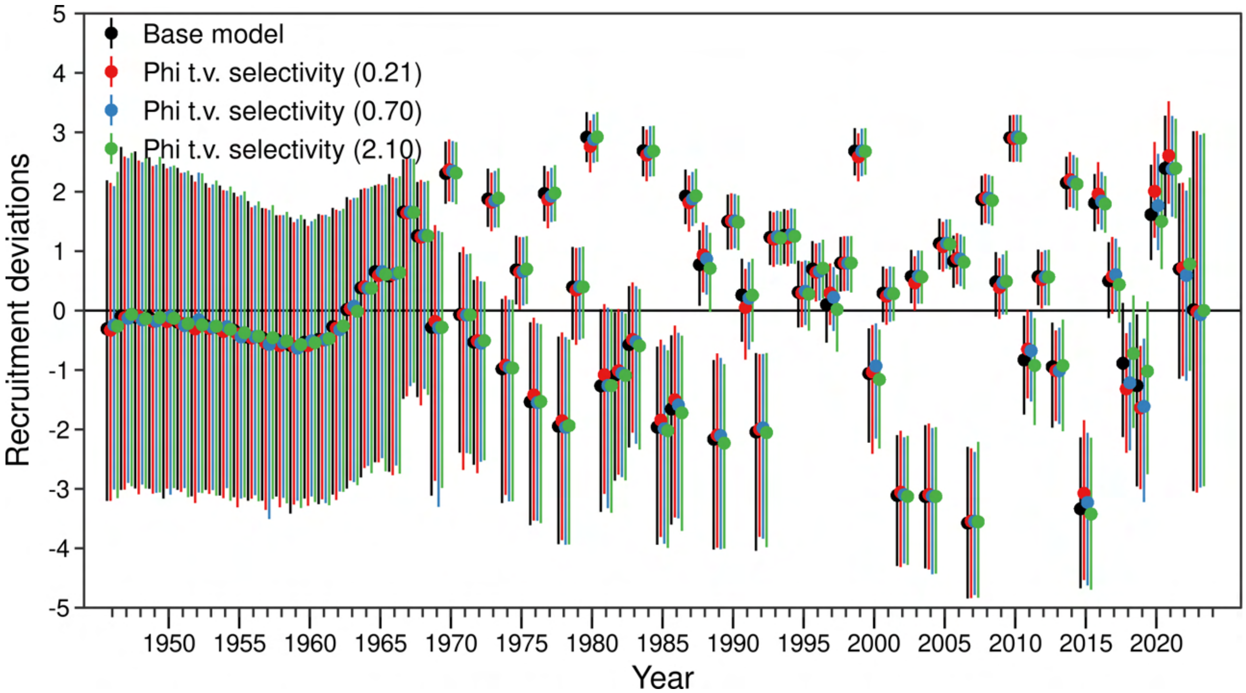


Figure 57. Markov chain Monte Carlo estimates of recruitment deviations for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 54 for sensitivity descriptions.

Figure 58. Markov chain Monte Carlo 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 54 for sensitivity descriptions.

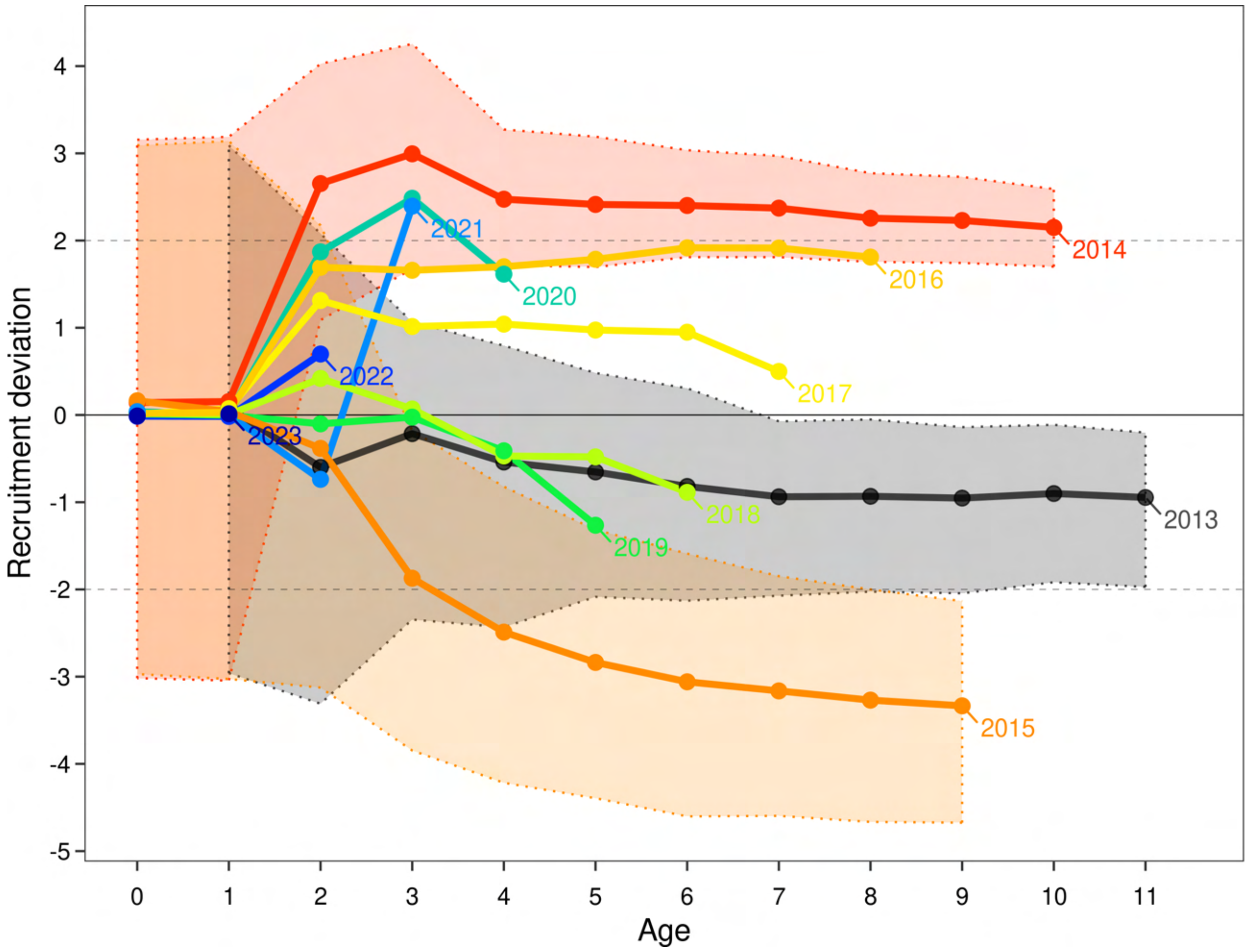


Figure 59. Retrospective analysis of recruitment deviations from Markov chain Monte Carlo models over the last 10 years. Recruitment deviations are the median log-scale differences between recruitment estimated by the model and expected recruitment from the stock-recruitment relationship (shading represents 95% posterior credibility intervals for a select low, moderate, and high deviation). Age-0 recruitment deviations are non-zero because Markov chain Monte Carlo allows for sampling from the full lognormal distribution. Lines represent estimated recruitment deviations for cohorts born from 2013 to 2023, with cohort birth year marked at the right of each color-coded line. For example, the right-most point for the 2016 cohort shows the cohort at age-8 (i.e., at the start of 2024, which represents the base model and includes data through 2023). The next point to the left is the 2016 cohort at age-7, calculated by removing one year of data (so includes data up to 2022). 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 $cohort\ birth\ year + cohort\ age - 1$.

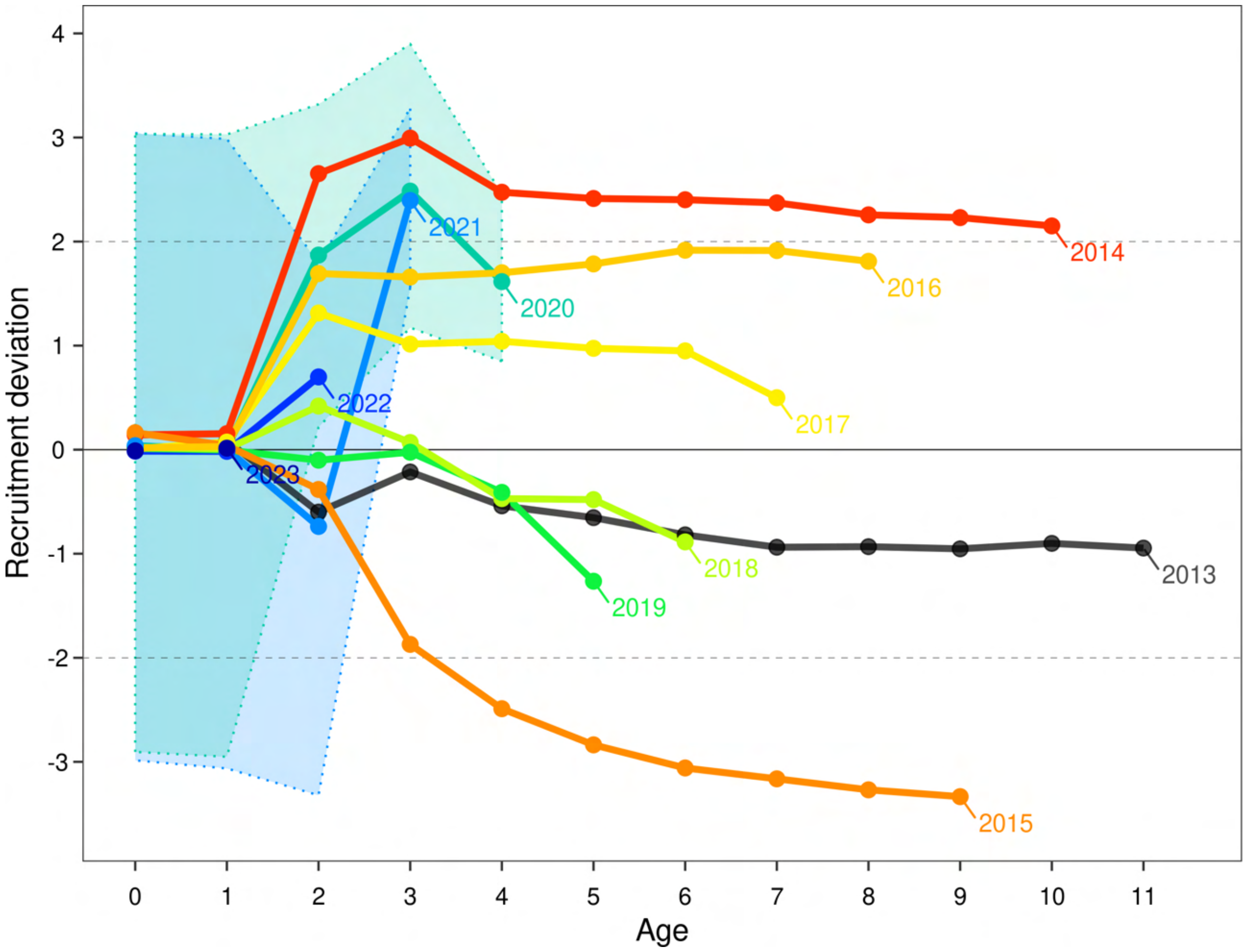


Figure 60. As for Figure 59 but with the credibility intervals shown for the 2020 and 2021 cohorts.

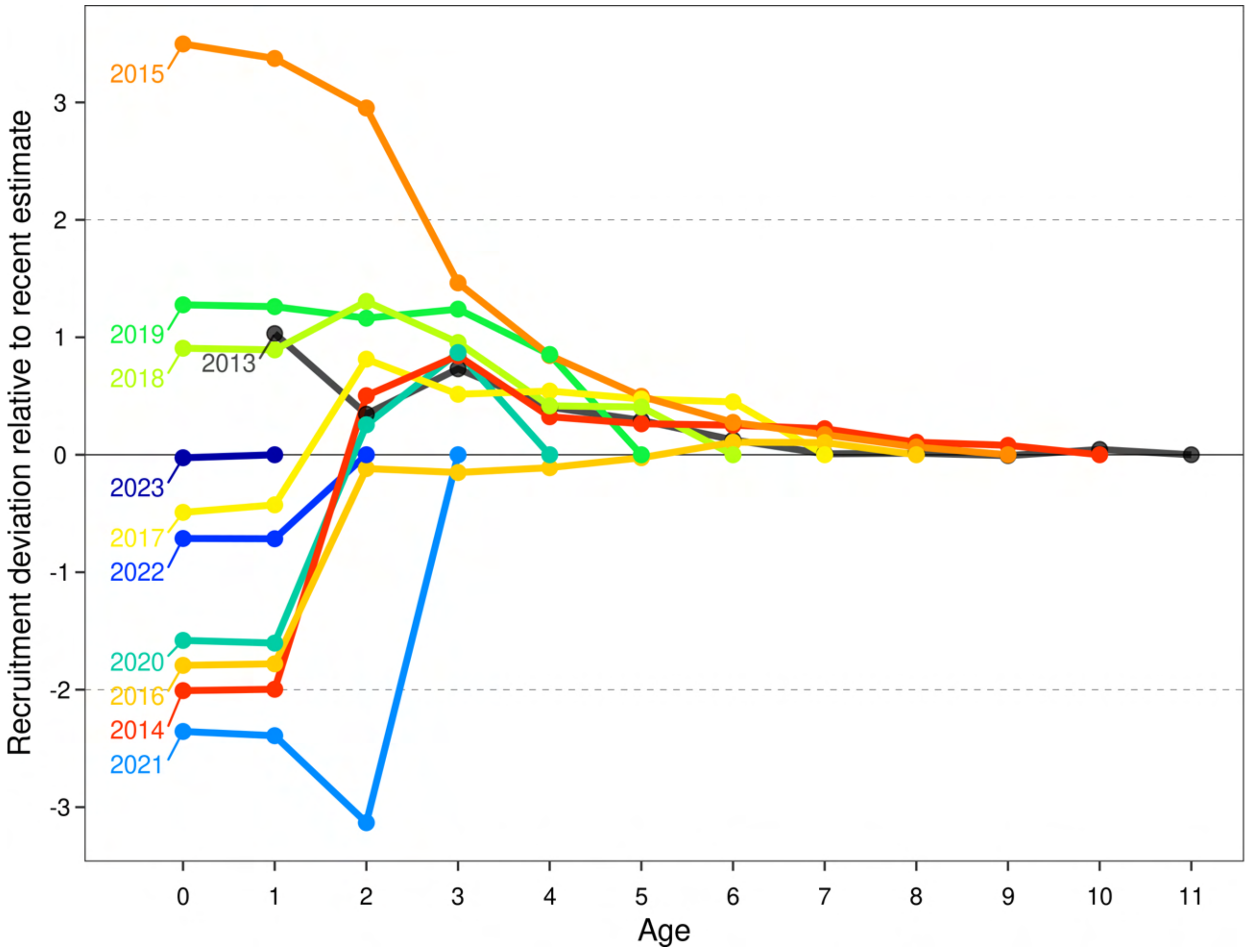


Figure 61. Retrospective recruitment estimates shown in Figure 59 scaled relative to the most recent estimate of the strength of each cohort.

Figure 62. Markov chain Monte Carlo estimates of spawning biomass at the start of each year (top) and recruitment (bottom) for the base model and 5-year retrospective runs.

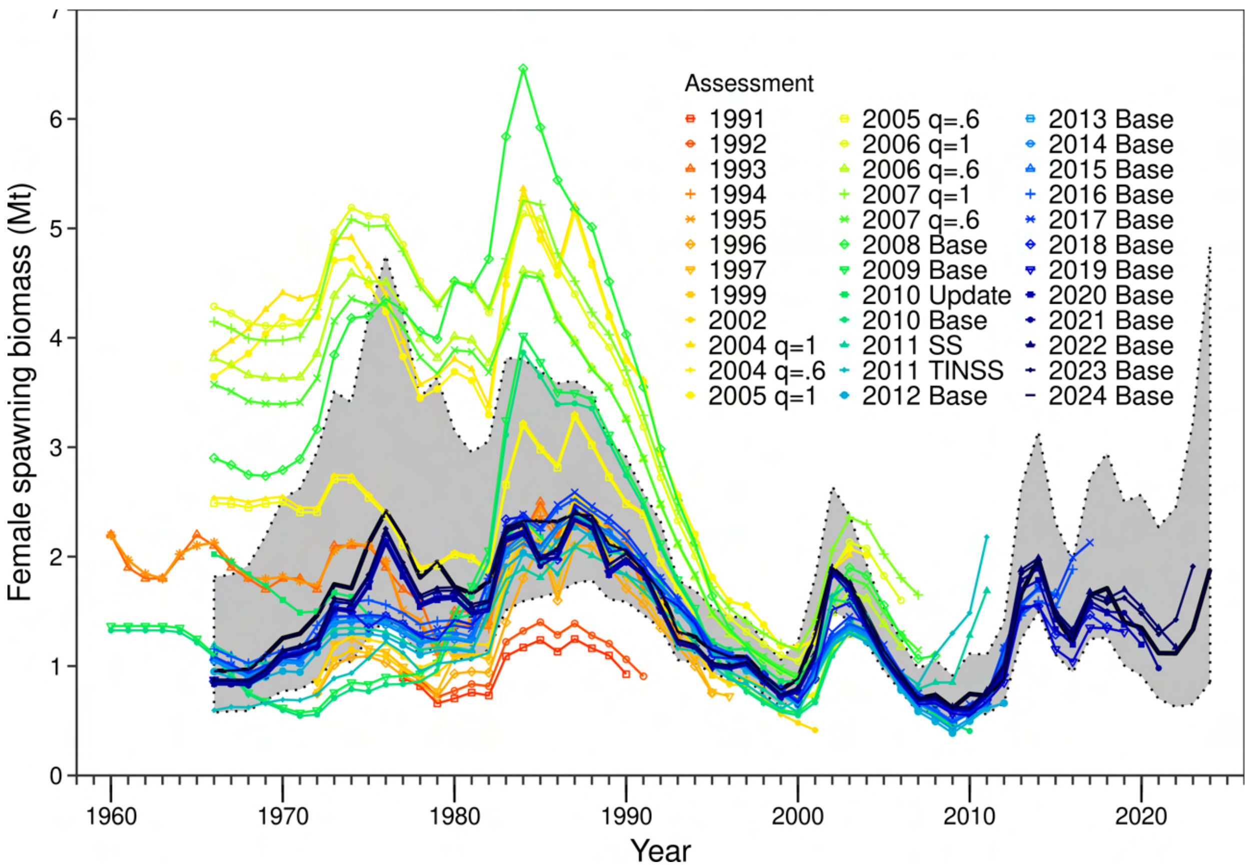


Figure 63. Summary of historical Pacific Hake assessment estimates of spawning biomass. Estimates are MLEs or Markov chain Monte Carlo medians depending on the model structure. Shading represents the 95% credible interval from the 2024 base model. Line colors are shades of orange for the oldest models, yellow shades for the 2000's, green shades for the 2010's and into blue shades from 2013 to present.

Figure 64. 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 (Q_1: 25th percentile) to quartile 3 (Q_3: 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 $(Q_3 - Q_1)/(Q_1 + Q_3)$.

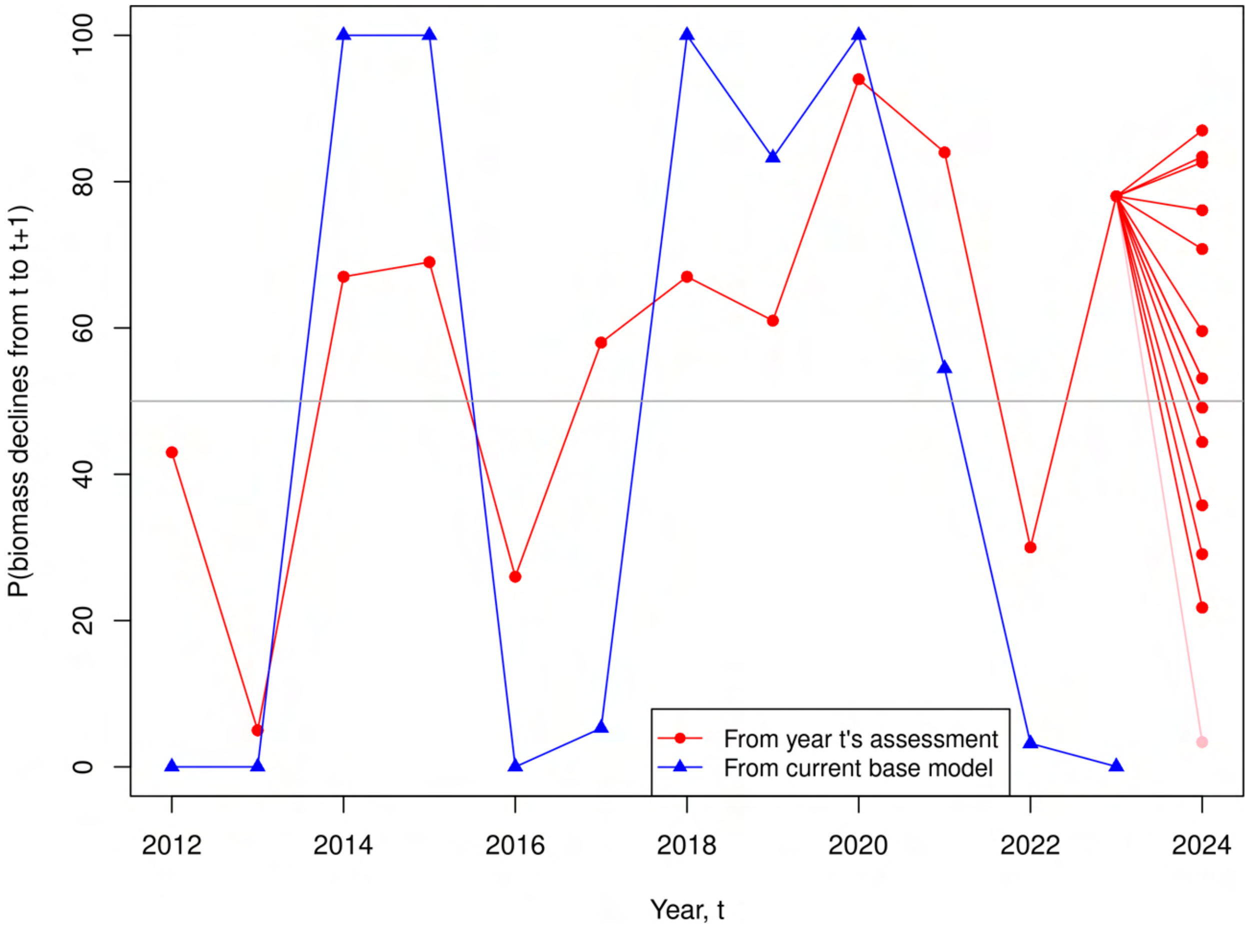


Figure 65. For each year t, $\mathrm{P}(B_{t+1} < B_t)$ is the probability that the spawning biomass at the start of $t+1$ is below that at the start of t. It is calculated in two ways. Red circles: the probability is taken from year t's stock assessment document, from the row in the decision table corresponding to the consequent catch in year t (with interpolation if necessary). Blue triangles: the probability is calculated using the current 2024 base model. The grey horizontal line is the 50% value. For each year except 2017 and 2023, 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 2024 assessment the probabilities are shown for all catch alternatives for 2024, as described in Table 27, with 0 t being the lowest probability, shown in pink.

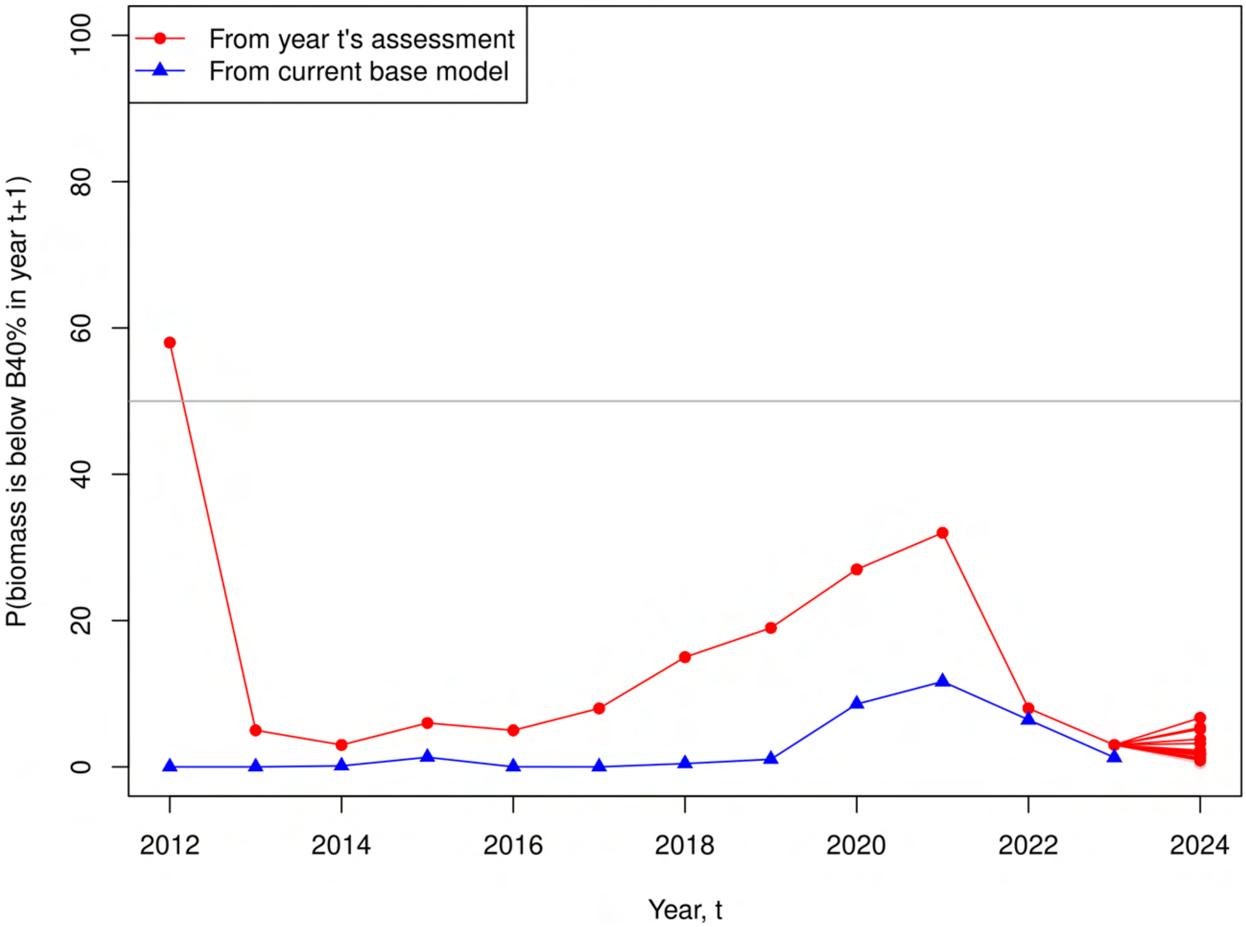


Figure 66. For each year t, $\mathrm{P}(B_{t+1} < B_{40\%})$ is the probability that the spawning biomass at the start of $t+1$ is below $B_{40\%}$. The red circles and blue triangles represent probabilities calculated analogously to Figure 65. The grey horizontal line is the 50% value. For each year 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 2024 assessment the probabilities are shown for all catch alternatives for 2024, as described in Table 27, with 0 t shown in pink.

A BASE MODEL MCMC DIAGNOSTICS

Figure A.1. Summary of Markov chain Monte Carlo diagnostics for natural mortality (upper 4 panels) and the natural log of mean unfished equilibrium recruitment ($\ln(R_0)$; lower 4 panels) in the base model. Top sub-panels show the trace of the sampled values across iterations (absolute values, top left; cumulative running median with 2.5$^{\text{th}}$ and 97.5$^{\text{th}}$ percentiles, top right). The lower left sub-panel indicate 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).

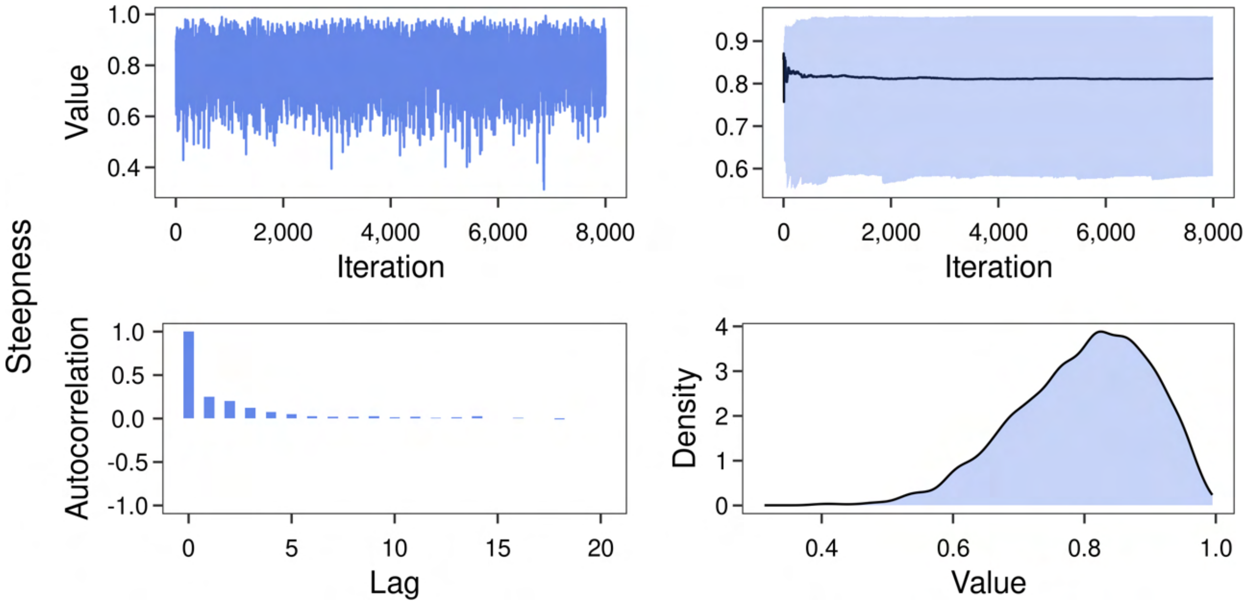


Figure A.2. Summary of Markov chain Monte Carlo diagnostics for steepness in the base model. Sub-panel descriptions as in Figure A.1.

Figure A.3. Summary of Markov chain Monte Carlo diagnostics for the additional standard deviation (SD) in the biomass index (upper 4 panels) and for the age-1 index (lower 4 panels) in the base model. Sub-panel descriptions as in Figure A.1.

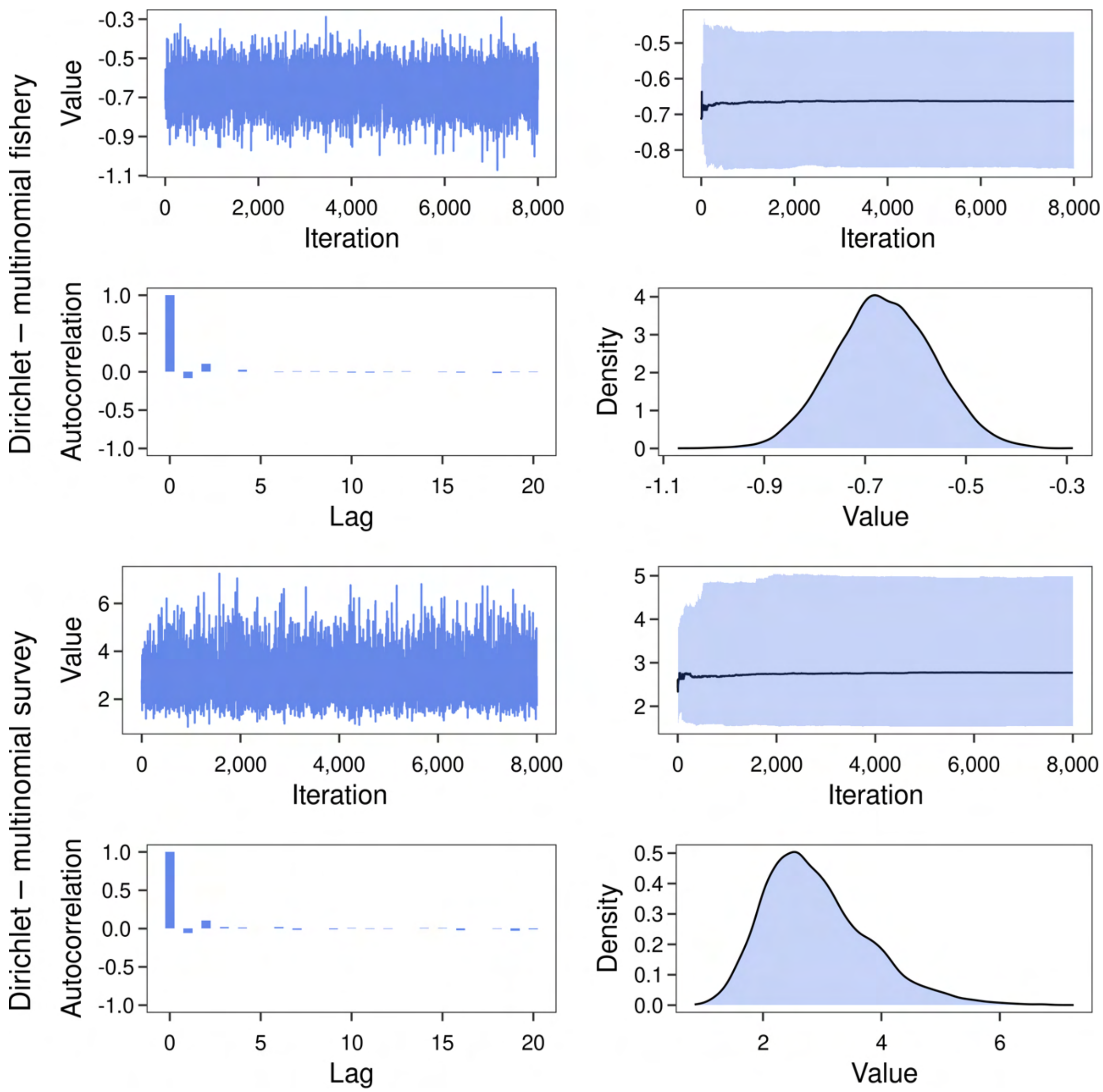


Figure A.4. Summary of Markov chain Monte Carlo diagnostics for the Dirichlet-multinomial age-composition parameters for the fishery (θ_{fish}, upper 4 panels) and the survey (θ_{surv}, lower 4 panels) in the base model. Sub-panel descriptions as in Figure A.1.

Figure A.5. Summary histograms of Markov chain Monte Carlo 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. Values for the unfished equilibrium recruitment (R_0) are explicitly highlighted. Values inside the bars represent the number of parameters counted in that bin.

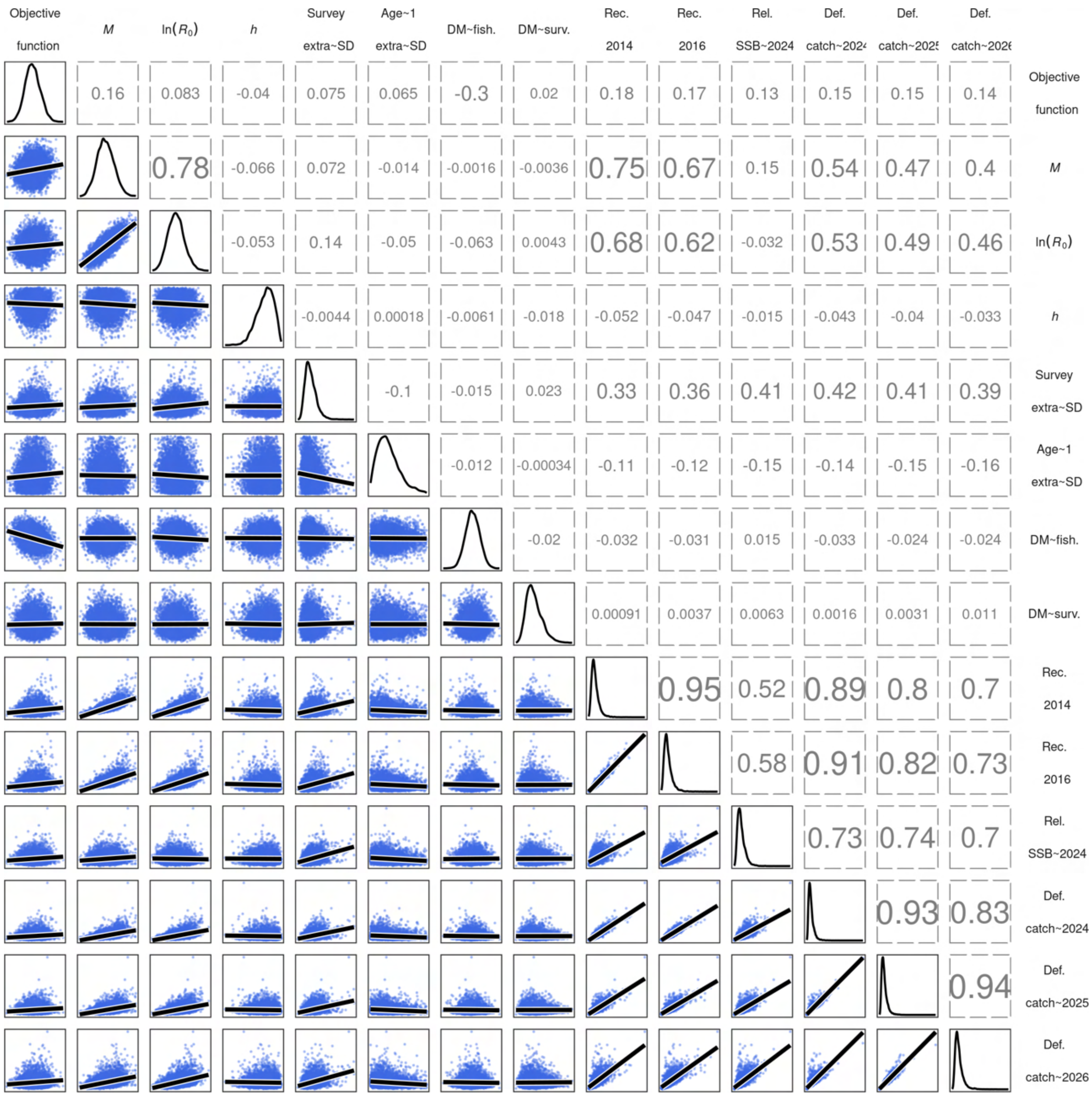


Figure A.6. Posterior correlations among the objective function which is minimized during model fitting, key base-model parameters, and derived quantities. Numbers refer to the absolute correlation coefficients, with font size proportional to the square root of the coefficient. Straight lines on the scatterplots are linear regressions.

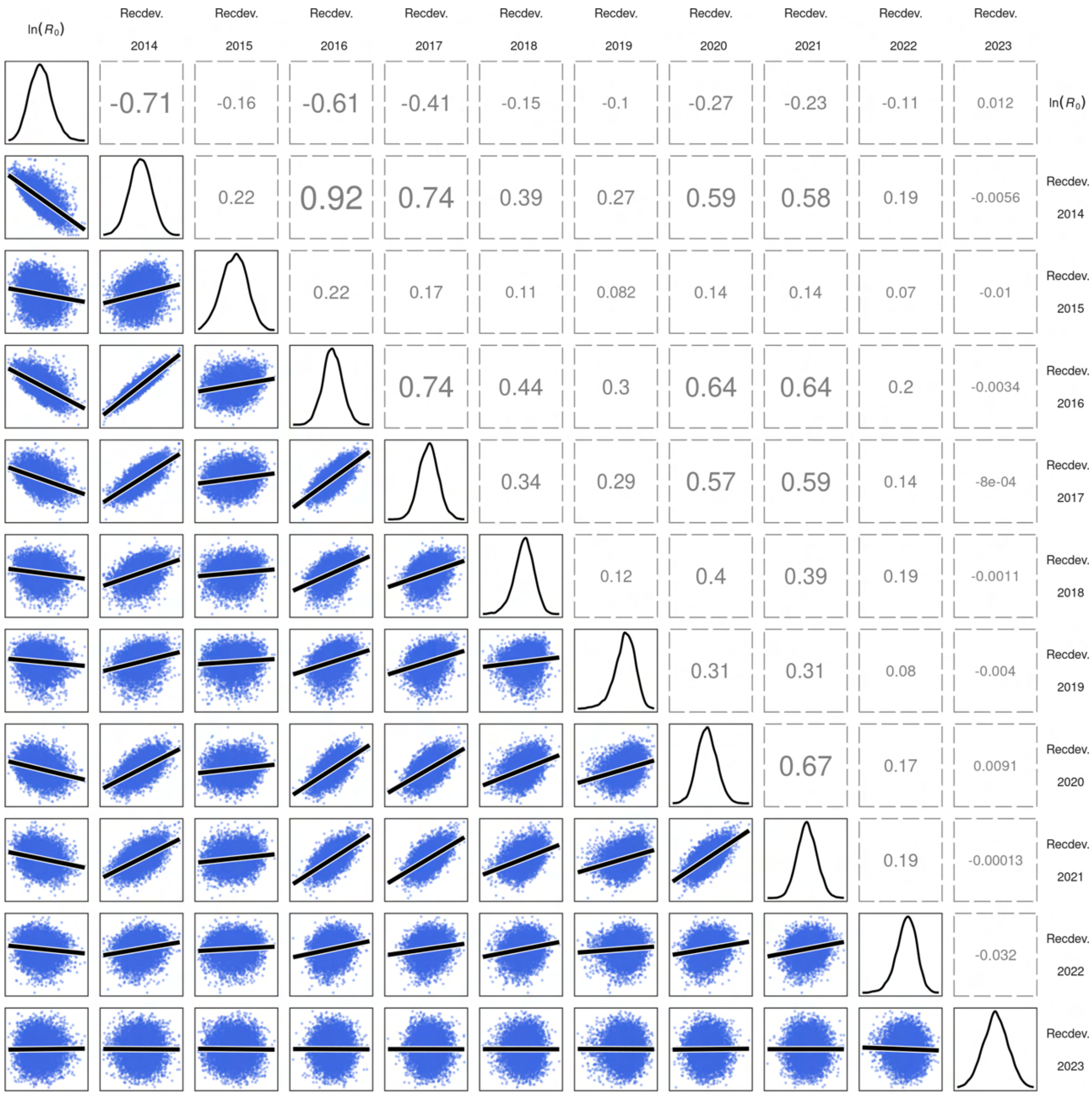


Figure A.7. Posterior correlations among recruitment deviations from recent years and mean unfished equilibrium recruitment. Numbers refer to the absolute correlation coefficients, with font size proportional to the square root of the coefficient. Straight lines on the scatterplots are linear regressions.

B SCIENTIFIC REVIEW GROUP (SRG) REQUESTS

This appendix summarizes results produced in response to Scientific Review Group requests made during the meeting held from February 6–9, 2024.

B.1 Day 1

Request 1

List the sample sizes for males, females and unsexed (for the weight-at-age), for the U.S. and Canada. This will help to understand the effect of averaging unsexed fish into empirical weight-at-age and provide some insight into the differences spatially of weight-at-age.

JTC Response

The JTC provided two tables, one for each country containing the weight-at-age sample sizes for each sex code(Male = M, Female = F, Unsexed = U; Tables B.1 and B.2).

The weight-at-age for two years, 2018 and 2023 are shown in Figure B.1. During the meeting, this plot contained unsexed fish as well, which were all much heavier than both males and females. On investigation, the JTC discovered that the data file for Canada had been modified to have all the sex data set to **U** (unsexed). This was fixed and Figures B.2 and B.3 show assessment model results.

Table B.1. Canadian sample sizes for weight-at-age data. F = Female, M = Male, and U = Unsexed.

Year	F Fishery	F Survey	M Fishery	M Survey	U Survey	U Fishery
1982	133	0	67	0	0	0
1989	102	0	97	0	0	0
1990	133	0	91	0	0	0
1995	0	287	0	163	0	0
1998	0	645	0	555	1	0
2001	0	220	0	176	0	0
2002	294	0	179	0	0	0
2003	0	1,619	0	1,384	3	0
2004	161	0	124	0	0	0
2005	181	0	170	0	0	0
2009	0	291	0	275	0	0
2011	37	216	34	162	0	0
2012	5	322	2	253	0	0
2013	0	97	0	15	0	0
2015	0	155	0	203	0	0
2016	85	0	91	0	0	0
2017	323	148	331	110	42	0
2018	422	0	297	0	0	0
2019	214	259	162	132	0	0
2020	872	0	566	0	0	0
2021	0	94	0	55	0	0
2022	727	0	289	0	0	0
2023	657	172	229	90	0	0

Table B.2. U.S. sample sizes for weight-at-age data. F = Female, M = Male, and U = Unsexed. Samples from the Poland survey are included in the fisheries data.

Year	F Fishery	F Survey	M Fishery	M Survey	U Survey	U Fishery
1975	204	0	119	0	0	0
1976	2,362	0	1,720	0	0	56
1977	4,142	0	3,524	0	0	2,116
1978	3,164	0	2,668	0	0	81
1979	1,652	0	1,472	0	0	0
1980	3,011	0	3,233	0	0	4
1981	2,748	0	3,289	0	0	4
1982	3,596	0	3,770	0	0	0
1983	2,386	0	2,169	0	0	0
1984	2,165	0	1,982	0	0	10
1985	1,491	0	1,521	0	0	10
1986	2,398	38	2,232	15	0	65
1987	2,100	0	2,119	0	0	0
1988	1,677	0	1,819	0	0	22
1989	1,742	728	1,647	778	49	0
1990	1,849	0	1,254	0	0	0
1991	1,219	0	1,009	0	0	0
1992	1,675	976	1,516	1,208	0	0
1993	929	0	983	0	0	0
1994	1,487	0	1,642	0	0	0
1995	1,021	1,131	1,106	1,032	1	0
1996	1,250	0	1,204	0	0	0
1997	1,290	0	1,338	0	0	0
1998	1,502	1,245	1,646	1,172	0	0
1999	1,314	0	1,145	0	0	0
2000	1,336	0	1,226	0	0	0
2001	2,089	1,134	1,993	1,006	0	0
2002	1,839	0	1,416	0	0	0
2003	1,473	0	1,735	0	0	0
2004	1,501	0	1,803	0	0	0
2005	1,676	898	1,928	956	0	0
2006	1,924	0	2,363	0	0	0
2007	1,851	1,642	2,021	1,668	42	0
2008	2,129	0	2,277	0	0	10
2009	1,627	1,067	2,081	1,427	6	1
2010	1,518	0	2,110	0	0	13
2011	1,770	854	2,165	1,200	1	1
2012	1,522	1,373	1,852	1,553	1	1
2013	2,101	1,282	2,424	1,489	0	1
2014	1,718	0	2,540	0	0	0
2015	1,510	1,385	1,984	1,459	27	30
2016	2,281	0	2,645	0	0	2
2017	2,503	1,031	2,807	1,109	7	4
2018	2,435	0	2,295	0	0	4
2019	2,464	1,354	2,687	1,507	5	2
2020	1,826	0	1,995	0	0	2
2021	2,248	1,019	1,972	1,118	2	1
2022	2,095	0	1,809	0	0	5
2023	1,682	1,076	1,366	1,219	0	3

Request 2

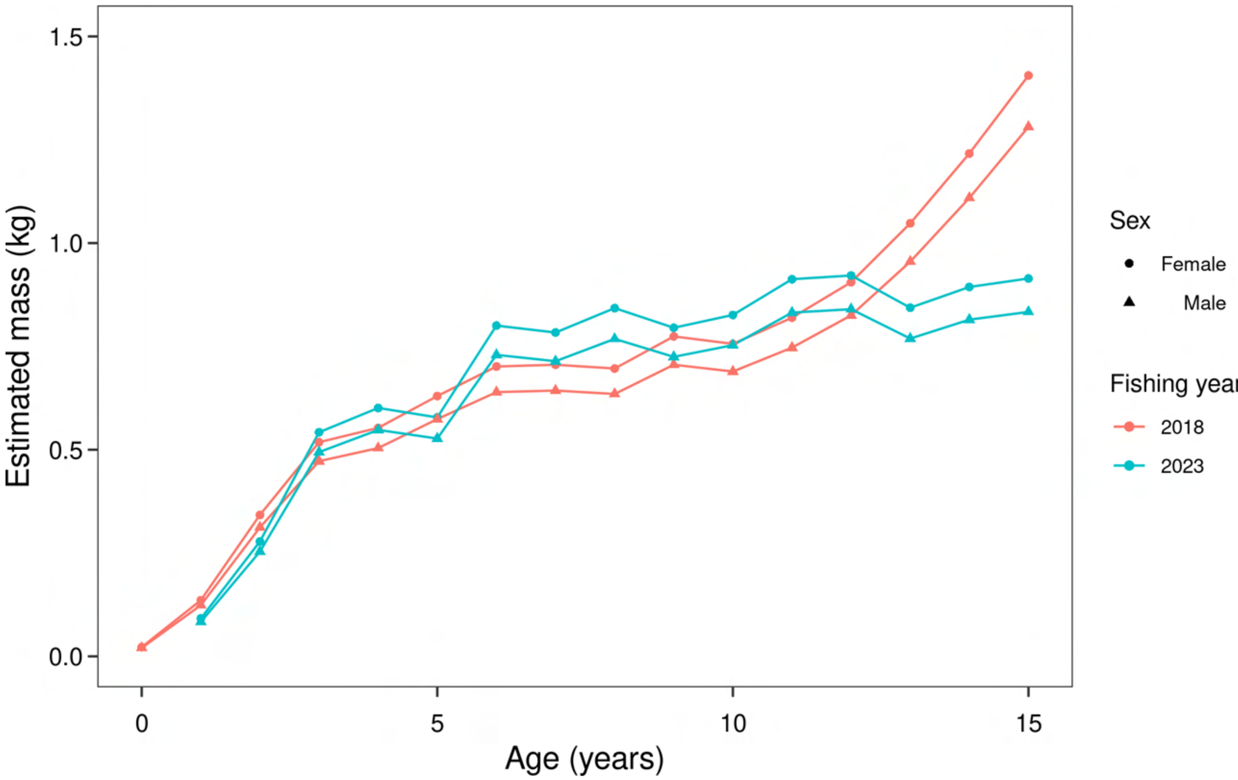


Figure B.1. Weight-at-age by sex (shapes) for two fishing years, 2018 and 2023 (colors).

On Figure G.10 add the data for proportion mature at age-2 (if possible) and age-3 to the model prediction of maturity at age-2 (if possible) and age-3 from the temperature-based model.

JTC Response

The JTC provided two figures showing the proportion mature by year and temperature.

- Figure B.4 shows empirical results for age two and Figure B.5 shows empirical results for age three. For each year (denoted on the smooth line) the points representing the raw data from non-ASHOP samples appear above or below the labeled point from the same year.
- We do not expect the points to overlap or lie on the line because the curve represents the marginal effect of temperature (e.g., predicted maturity from non-ASHOP samples collected from an average sample location on July 1 but predicted to the 278th day of the year).
- Changing the reference date from July 1 to a later date for age-3 fish shifted the curve up closer to the points because the non-ASHOP samples occur later in the year (25% before July1/75% after). The points are also affected by variable sampling effort year to year.
- In conclusion, we would never really expect the empirical estimates to perfectly match the model-based ones. Sampling varies across space and time, and the empirical estimates do not account for any of this variation.

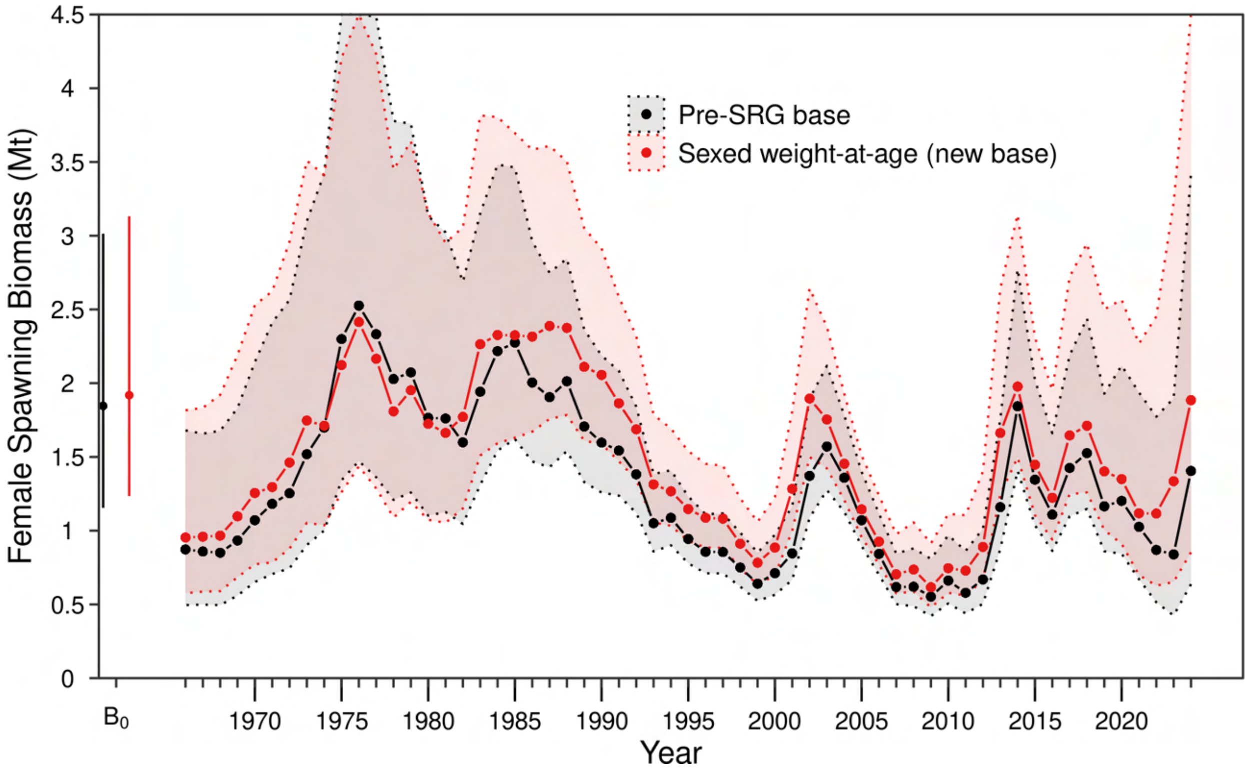


Figure B.2. Female spawning biomass for the pre-SRG base model compared to the final base model, where the latter model excluded unsexed fish in the weight-at-age data.

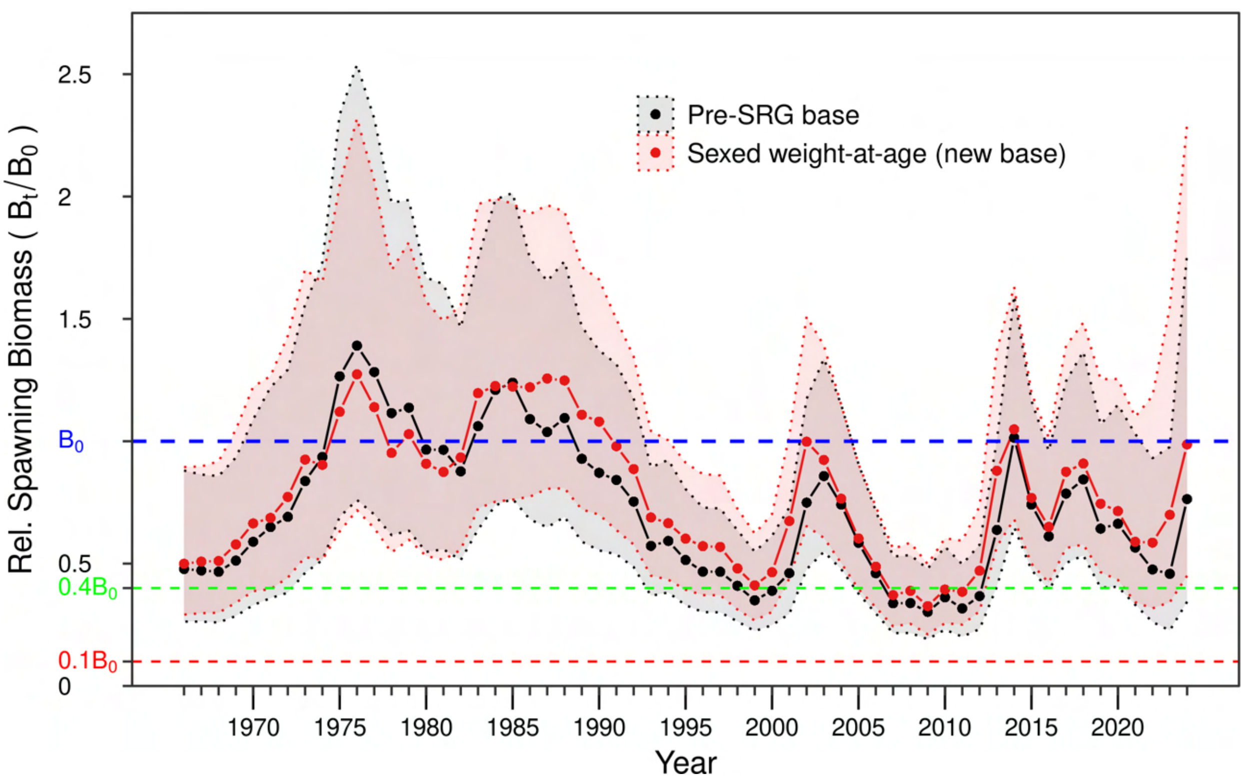


Figure B.3. Relative female spawning biomass for the pre-SRG base model compared to the final base model, where the latter model excluded unsexed fish in the weight-at-age data.

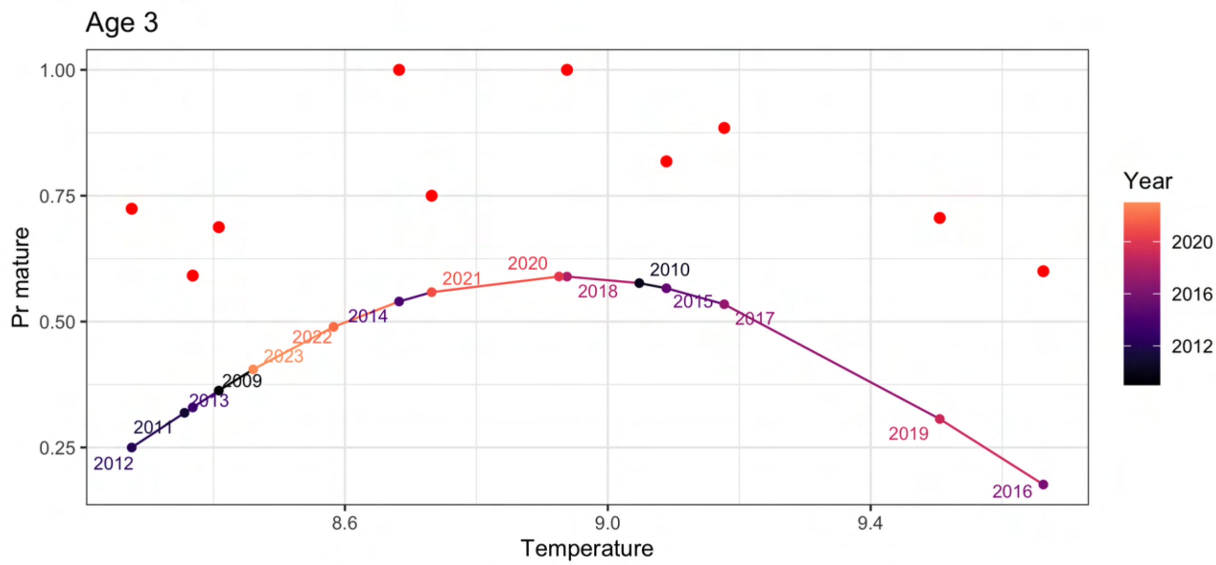


Figure B.4. Proportion of age-2 fish mature by year and sea temperature (Celcius).

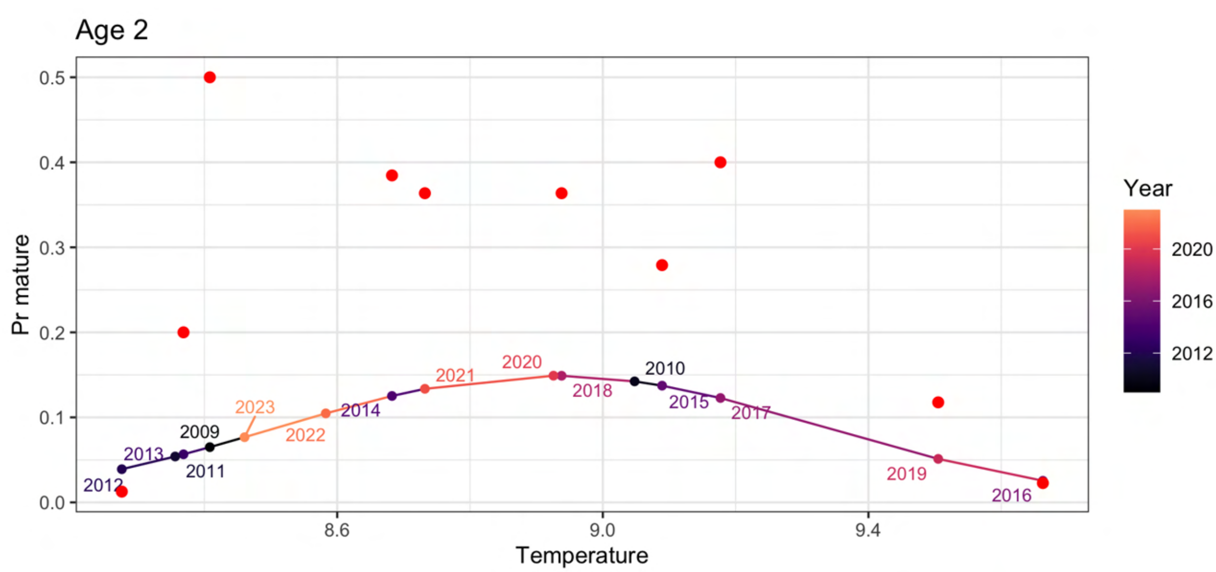


Figure B.5. Proportion of age-3 fish mature by year and sea temperature (Celcius).

Request 3

Add B_{2023}/B_0 to Table 25 comparing the 2023 and 2024 assessments.

JTC Response

The JTC provided an updated table, and updated the table in the assessment to match it. See Table 25. All other similar tables in the document containing parameter estimates now have this row as well.

Request 4

The SRG requests data to better understand the presence of clean hake trawls and mixed species trawls in the 2023 acoustic survey by area (such as INPFC area). This will help understand where hake were in 2023 and the potential effects of mixed trawls on the determination of biomass.

JTC Response

In 2023, the acoustic-trawl survey had 13 regions out of 282 that were classified as 'hake mix'. These regions were associated with 4 separate trawls. The hake percentages in those hake mix trawls ranged from 55% to 76% hake (all mixed with rockfish).

Of the un-Kriged biomass (3.1%), 22.9 kt out of the 735 kt came from hake mixes in 2023.

Request 5

The SRG requests maturity-at-age in a tabular format from 2008 to 2026. These numbers will help understand the variability of maturity-at-age without the effect of changes in weight-at-age used to calculate fecundity. It will also help understand how the projected maturity-at-age relates to estimated values.

JTC Response

The actual years that are included are 2009–2023 and 4 projection years. The projections use the mean of the maturity-at-age for 2019–2023. Figure B.6 shows the requested table in a heatmap format to match the other figures in the document depicting weight-at-age, sample sizes of weight-at-age, and fecundity.

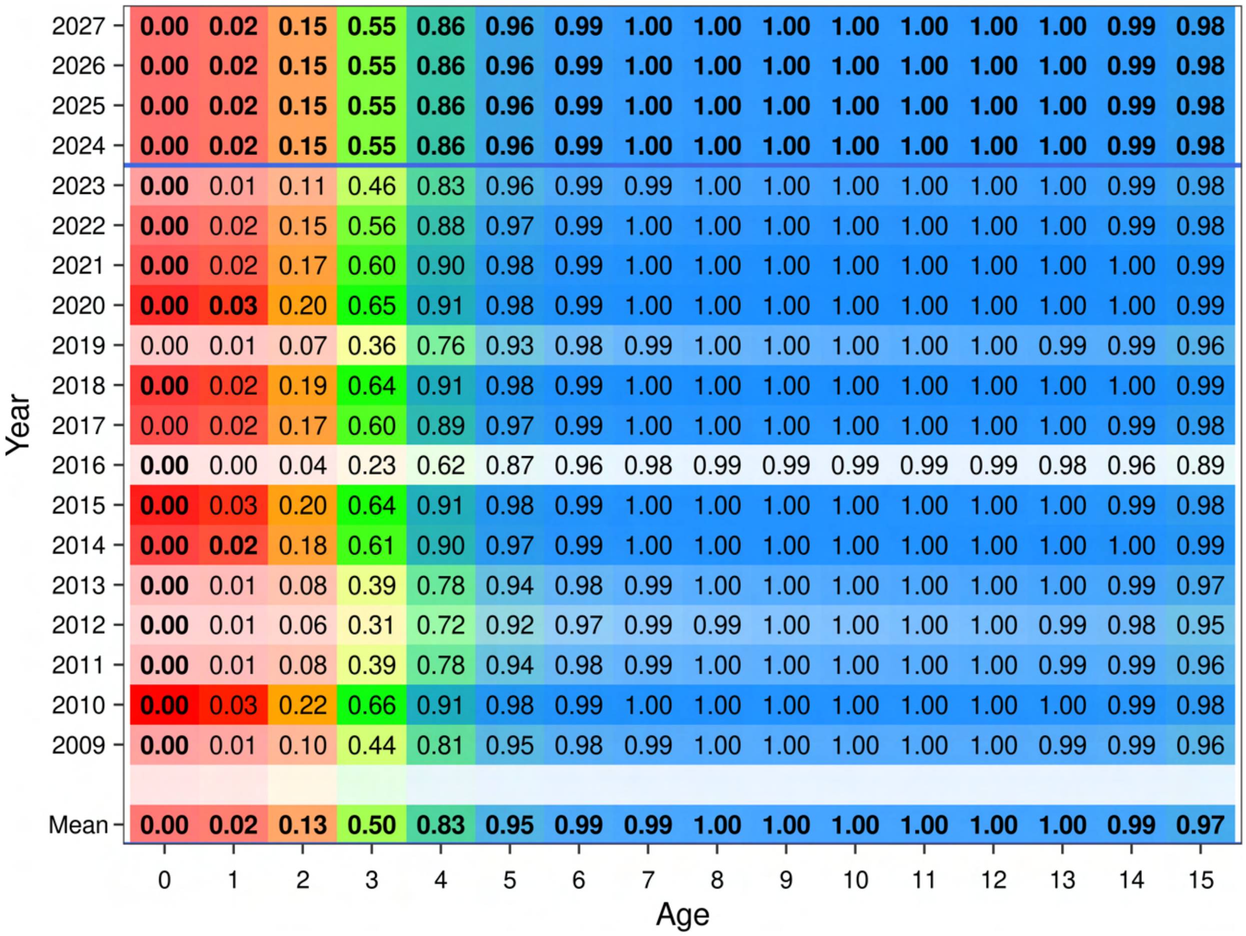


Figure B.6. Heatmap showing maturity-at-age by year in the same format as the other heatmaps for weight-at-age, sample size, and fecundity found in this document (Figures 12–14). The Projected years (2024–2027) are set to the mean values of the previous 5 years (2019–2023). The years prior to the initial year shown (2009) are set to the mean of the entire time series and are shown in the **Mean** row.

Request 6

The SRG requests that the JTC add a new run seriously downweighting the age composition sample sizes to increase the influence of the survey biomass index. For example, an effective sample size of no more than 50, which would mean dividing the sample size by about 100. Alternatively, use a lambda of 0.05 on survey and fishery age composition data. Report the additional survey variance as well.

JTC Response

A lambda value of 0.05 was multiplied by the age-composition likelihood component to calculate the overall negative log likelihood to be minimized. The bulleted list below provides parameter estimates for the base model and the requested model run, respectively. Figures B.7–B.12 were provided to the SRG to fulfill the request thoroughly. While substantially downweighting age-composition data results in an improved survey fit, the model loses critical information on recruitment and thus overall population scale.

- DM fishery: 0.341 (base); 0.035 (lambda)
- DM survey: 0.942; 0.271
- DM ratio: 0.362; 0.129
- Extra SD survey: 0.313; 0.202
- Extra SD age-1 index: 0.385; 0.371
- Age Likelihood: 2,144; 131
- Approximate run time: 2 hours; 17 hours

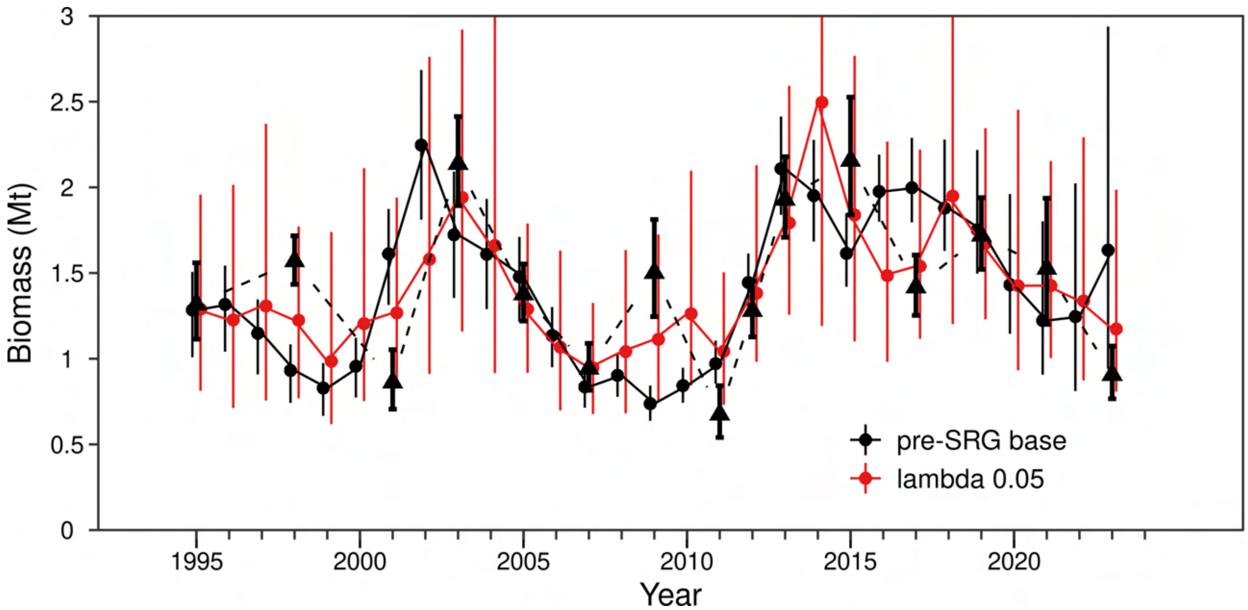


Figure B.7. Fits to the acoustic age 2+ survey observations (triangles) for the base model (black) and the adjusted lambda = 0.05 model (red).

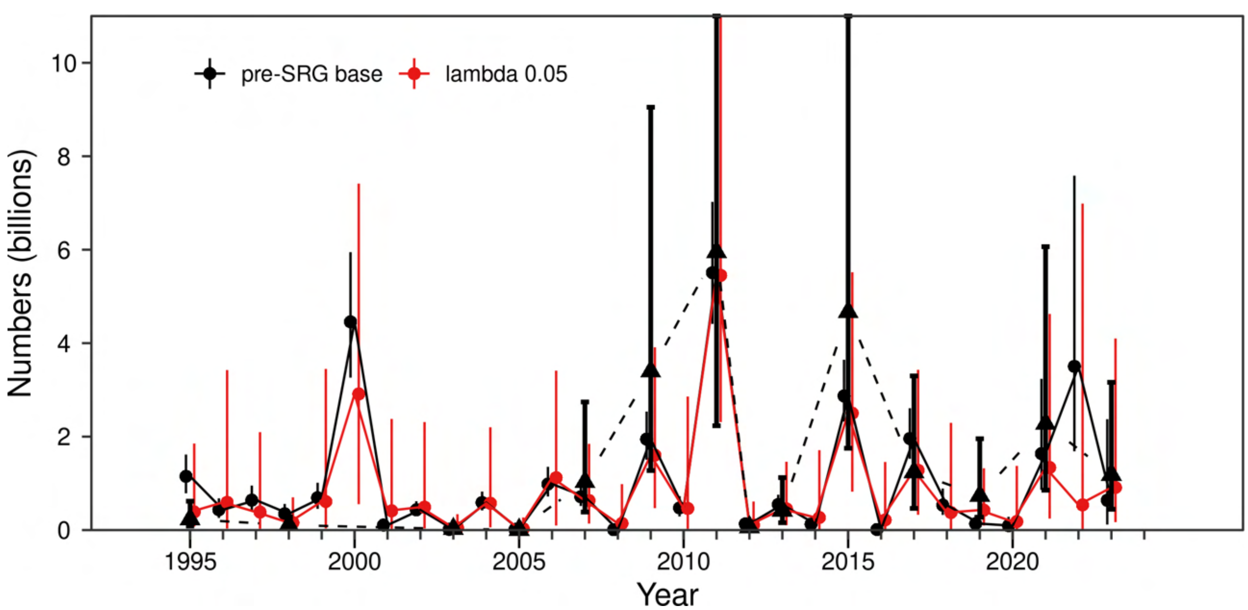


Figure B.8. Fits to the relative age 1 index observations (triangles) for the base model (black) and the adjusted lambda = 0.05 model (red).

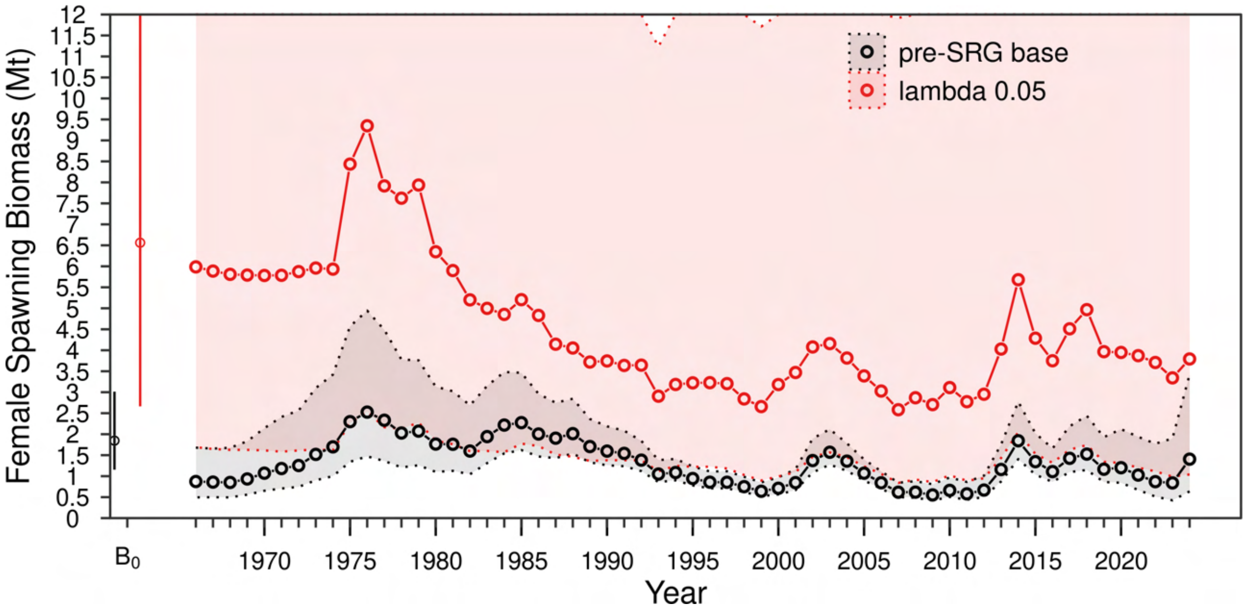


Figure B.9. Estimated female spawning biomass for the base model (black) and the adjusted lambda = 0.05 model (red). The shaded areas represent the 95% credible interval.

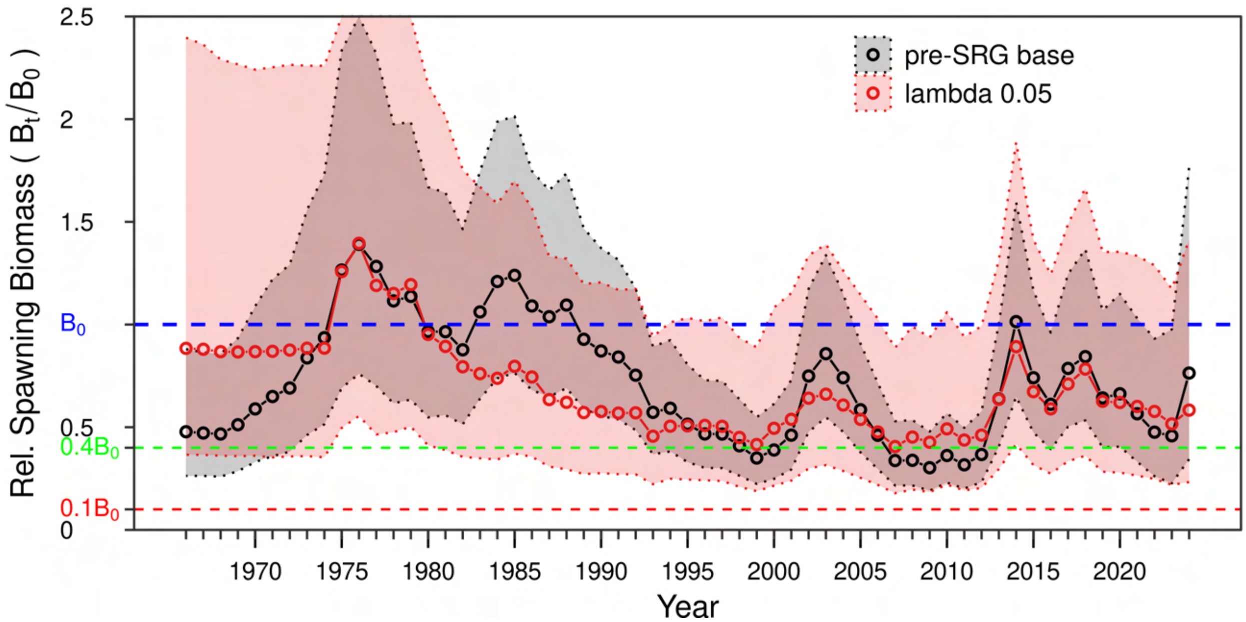


Figure B.10. Estimated relative female spawning biomass for the base model (black) and the adjusted lambda = 0.05 model (red). The shaded areas represent the 95% credible interval.

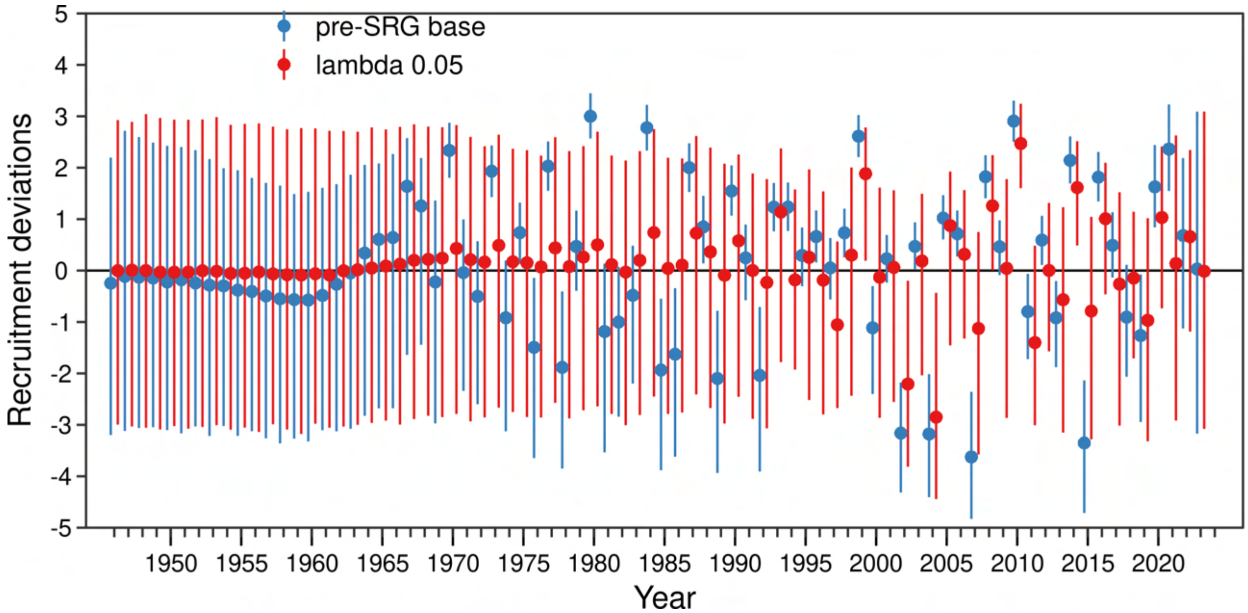


Figure B.11. Estimated recruitment deviations for the base model (black) and the adjusted lambda = 0.05 model (red). The bars represent the 95% credible interval.

Figure B.12. Estimated absolute recruitment for the base model (black) and the adjusted lambda = 0.05 model (red). The bars represent the 95% credible interval.

Request 7

The SRG would like to see the proportion of survey biomass and catch estimated in Canada.

JTC Response

The JTC provided two tables to show the catch-at-age in each country, which were calculated by multiplying the input proportions-at-age with the the annual catch in each country (Tables B.3 and B.4).

To show the proportion of biomass in Canada as determined by the acoustic survey, a figure (Figure B.13) and two tables (Tables B.6 and B.5) were provided.

Table B.3. Fishery catch-at-age for Canada (t).

Year	Catch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2007	73,590	43	225	315	5,477	1,482	4,147	3,196	38,261	7,415	1,448	3,853	4,383	1,098	373	1,872
2008	71,010	0	501	2,759	653	4,874	885	2,917	3,385	41,070	5,284	3,978	916	1,432	153	2,202
2009	13,223	0	79	4,740	2,881	552	1,349	64	196	26	2,634	358	68	260	17	0
2010	48,934	0	250	921	7,957	23,635	3,540	2,332	567	329	966	5,408	1,951	670	281	128
2011	56,073	0	0	32,542	1,030	6,979	6,754	2,009	1,574	213	677	194	3,230	231	248	391
2012	47,059	0	262	4,200	21,222	2,376	8,960	3,760	1,071	1,014	397	576	241	2,078	285	616
2013	52,249	0	0	1,019	2,799	5,074	2,107	12,282	4,975	2,800	5,810	622	1,297	2,247	9,871	1,346
2014	35,118	0	0	276	6,103	4,393	9,220	2,807	4,282	2,849	769	1,026	195	492	343	2,361
2015	39,684	454	0	1,215	872	23,386	4,154	5,516	871	1,587	1,047	259	150	0	58	115
2016	69,743	177	3,210	551	3,403	4,551	44,086	4,433	4,974	1,228	997	57	668	464	95	849
2017	81,113	3,016	342	6,191	1,670	3,362	5,067	39,733	10,348	6,668	1,479	1,490	1,038	144	137	427
2018	92,689	295	4,576	1,271	18,810	1,657	3,934	5,172	37,048	10,282	4,453	2,323	1,019	759	858	233
2019	95,013	21	15,182	12,823	3,155	22,764	2,266	3,908	3,575	23,296	3,847	2,613	958	409	197	0
2020	30,085	0	12	2,885	5,957	412	9,073	814	1,049	771	7,240	861	636	67	144	163
2021	45,807	0	0	0	7,907	10,994	3,087	12,537	1,318	1,318	4,355	2,460	514	0	1,318	0
2022	31,671	0	0	5	123	2,257	7,044	2,485	5,614	2,283	1,384	1,866	5,133	2,298	892	285
2023	23,557	0	11	242	130	745	3,816	5,451	1,238	4,387	1,265	741	1,616	3,109	503	301

Table B.4. Fishery catch-at-age for U.S.A. (t).

Year	Catch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2008	248,395	2,349	26,390	88,573	6,174	39,451	2,671	9,195	7,945	57,070	4,244	1,601	1,340	463	533	396
2009	121,324	1,333	795	43,582	36,762	3,436	11,084	930	2,658	1,804	15,765	1,757	375	569	235	237
2010	170,960	45	50,951	6,367	66,392	32,785	2,365	3,531	347	673	1,260	5,016	828	94	126	180
2011	230,219	9,198	29,296	160,492	5,950	11,887	7,744	1,496	927	563	358	142	1,710	243	101	115
2012	159,696	463	87,120	16,632	41,442	3,103	4,407	2,536	1,371	594	178	320	428	465	304	333
2013	232,561	80	1,806	182,689	13,275	23,566	1,779	2,634	2,858	983	669	410	142	341	859	469
2014	263,945	0	10,532	10,893	187,047	15,985	25,963	2,720	4,844	2,934	1,357	343	77	125	353	772
2015	154,160	5,139	1,885	13,262	6,493	112,388	5,633	5,277	1,065	1,185	1,195	236	127	84	0	191
2016	261,582	973	152,082	4,763	12,658	5,582	71,932	4,087	5,685	1,602	684	759	524	90	111	51
2017	354,129	16,571	2,820	170,171	8,308	14,398	7,812	109,815	8,885	7,254	3,442	886	2,377	696	313	383
2018	318,306	33,394	94,236	3,995	91,906	4,574	7,674	7,332	58,134	7,687	3,790	1,922	1,393	1,089	976	202
2019	317,002	0	38,011	72,616	3,591	115,220	4,809	12,484	4,981	53,575	4,246	3,660	1,411	1,161	663	572
2020	287,813	0	161	25,494	115,322	5,563	85,014	4,438	5,549	5,841	34,093	2,671	2,555	789	74	248
2021	268,556	4,092	1,294	5,927	33,341	98,939	5,502	61,806	4,291	5,614	6,011	33,179	5,328	1,605	520	1,109
2022	291,702	2,902	111,429	4,878	6,513	25,074	65,665	3,098	43,032	5,333	2,325	1,887	13,145	4,077	1,310	1,034
2023	240,424	3,077	100,090	67,936	2,711	3,381	11,777	23,375	2,626	14,349	1,999	912	1,403	5,537	862	388

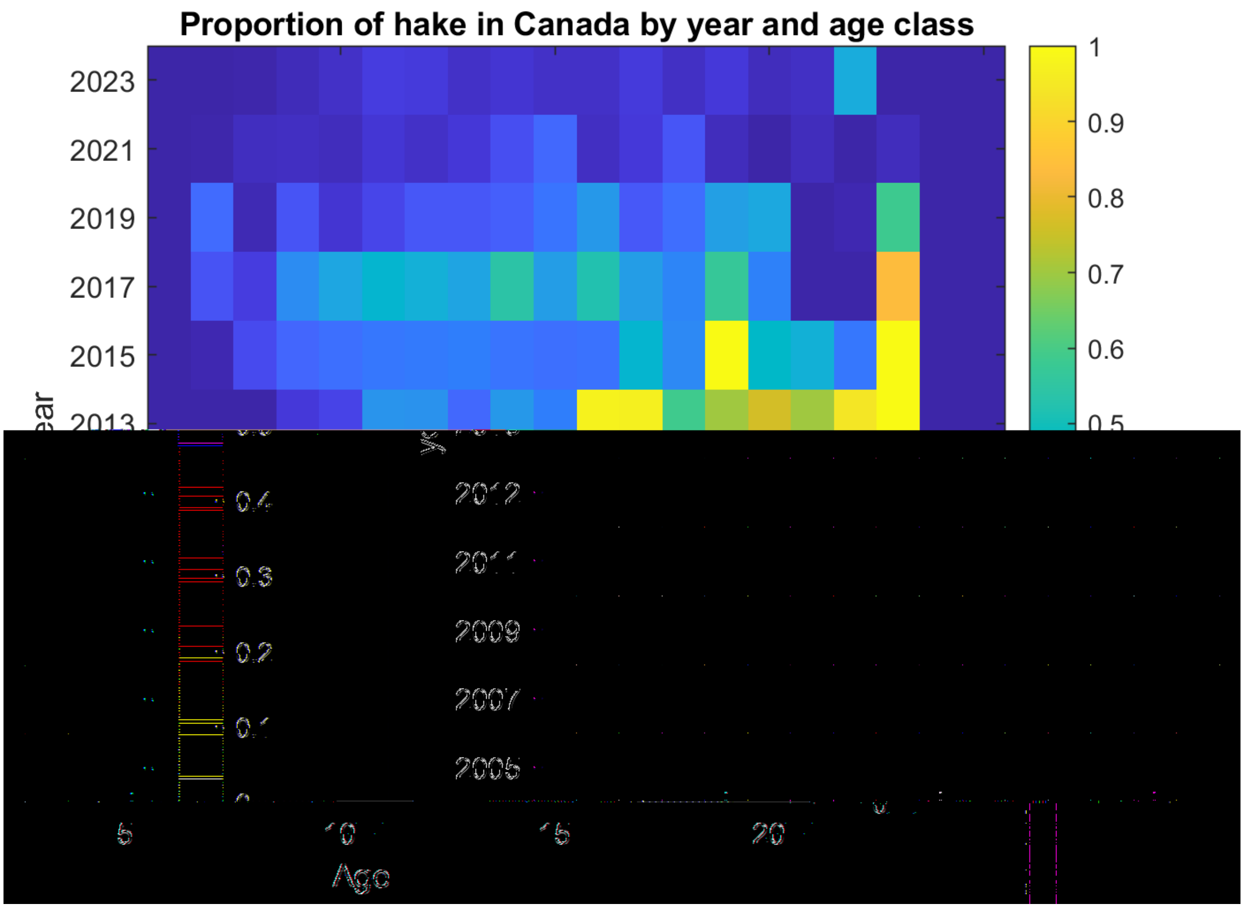


Figure B.13. The proportion of Pacific Hake in Canadian waters by year and age. The yellow tiles mean that all the fish at that age were found in the Canadian part of the survey only. Dark blue means that all fish of that age were found in the U.S. part of the survey only, or for ages 19 and 20, that there were no data. Figure produced by Rebecca Thomas (NOAA).

Table B.5. Proportion of survey biomass estimated in the U.S.A.

Year	Biomass	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2005	707,378	0	76,133	10,331	49,462	36,282	401,433	45,855	15,065	26,367	19,430	11,565	9,384	655	3,242	0	470	584	1,119	0	0
2007	682,827	0	126,820	15,197	100,304	11,749	38,143	25,269	298,298	29,490	14,727	10,392	4,704	5,546	2,186	0	0	0	0	0	0
2009	1,104,157	0	3,424	345,098	580,433	13,521	67,320	5,293	8,109	17,164	39,179	12,572	4,840	2,994	4,008	95	108	0	0	0	0
2011	602,165	0	138,137	370,905	24,062	19,958	24,340	4,652	4,385	1,456	2,135	0	10,548	1,171	416	0	0	0	0	0	0
2012	1,140,742	0	614,258	139,229	253,797	33,700	37,162	23,940	16,112	2,376	2,980	2,874	3,200	7,858	3,254	0	0	0	0	0	0
2013	1,805,243	0	44,844	1,323,574	108,111	170,667	16,315	40,496	59,942	13,214	13,058	82	133	5,092	7,072	1,821	790	33	0	0	0
2015	1,698,059	0	119,473	135,552	68,994	980,876	93,396	153,672	34,322	35,177	35,855	22,023	1,715	4,975	0	2,533	6,470	3,025	0	0	0
2017	1,028,202	0	6,443	556,809	28,241	36,013	32,431	242,600	40,633	27,601	12,706	9,815	18,289	9,043	3,447	2,132	0	0	452	0	1,547
2019	1,527,135	0	101,995	382,877	22,970	509,596	43,528	54,597	47,642	279,611	39,302	17,226	6,442	6,574	8,340	3,986	0	2,174	274	0	0
2021	1,458,573	0	103,310	86,591	201,176	400,084	50,190	297,866	49,639	29,699	26,877	165,189	24,819	4,760	3,739	7,775	1,165	4,333	1,361	0	0
2023	885,014	0	335,555	250,521	11,566	13,620	33,344	93,009	11,854	64,783	9,473	7,550	8,630	31,719	5,980	4,870	1,306	183	1,052	0	0

Table B.6. Proportion of survey biomass estimated in Canada

Year	Biomass	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2005	668,721	0	56,703	3,392	18,366	32,614	347,059	64,653	27,257	45,003	34,090	20,770	8,601	7,364	2,199	0	141	175	336	0	0
2007	259,894	0	440	2,035	18,629	3,224	17,398	12,669	152,072	18,048	11,027	9,710	6,024	4,918	2,258	717	262	461	0	0	0
2009	398,117	0	967	4,483	30,399	22,526	74,367	15,335	22,546	22,742	114,687	52,557	23,060	3,092	6,660	1,490	3,208	0	0	0	0
2011	72,409	0	0	10,007	2,114	7,143	9,038	2,663	3,959	2,388	3,792	7,557	14,532	5,892	2,569	393	196	169	0	0	0
2012	138,679	0	520	6,816	21,233	5,640	28,505	19,490	10,281	6,776	3,452	4,116	8,292	13,778	7,801	1,222	0	757	0	0	0
2013	123,992	0	23	2,101	8,258	19,331	7,947	19,406	15,465	6,858	4,669	2,936	4,427	7,227	16,463	5,877	1,866	540	597	0	0
2015	457,794	0	1,738	19,326	17,273	282,824	30,457	52,041	12,237	10,888	10,401	6,637	1,381	2,063	2,027	2,179	4,820	975	527	0	0
2017	389,610	0	1,108	51,919	12,181	22,813	26,322	178,693	24,911	32,341	7,116	10,756	10,203	3,583	4,510	789	0	0	2,362	0	0
2019	190,892	0	27,387	7,271	4,064	33,244	5,224	10,259	9,043	62,313	12,260	8,901	1,247	1,848	4,782	2,637	0	27	386	0	0
2021	66,069	0	696	2,864	7,984	12,852	3,464	13,410	3,667	4,693	6,860	6,598	1,912	860	107	29	33	0	39	0	0
2023	22,079	0	829	1,150	296	633	3,099	7,706	544	4,138	457	363	703	1,355	476	148	56	125	0	0	0

B.2 Day 2

Request 1

The SRG requests rerunning the GLM for weight-at-age without unsexed hake, and creating a weight-at-age matrix using the updated outputs by averaging Males and Females equally.

JTC Response

- The GLMM was run after filtering the data to remove unsexed fish.
- The model output was truncated to just produce males and females given unsexed fish were no longer in the data used to fit the GLMM.
- Results for males and females were averaged.
- The weight-at-age file for SS3 was updated.
- The updated weight-at-age file was used to process the fishery-composition data.

Request 2

The SRG requests a plot of the day effect in the maturity analysis for age-3 hake for any given year, assuming the peak of maturity is the same in all years (please confirm this assumption).

JTC Response

The formula used for the non-spatial effects of the maturity-at-age model looks like the following:

$$maturity_{functional} \sim -1 + s(doy) + age + age^2 + temp + temp^2$$

where there is **NO** interaction with the smoother on the day of the year. Thus, the shape of the relationship (G.5) does not change with time or temperature in this case.

Request 3

The SRG requests that the maturity plot be recalculated for Day 278, peak of maturity.

JTC Response

The updated figure was presented at the SRG meeting and Figure 11 was also updated.

Request 4

The SRG asks for a presentation of the recalculated probability mature by age matrix.

JTC Response

The JTC created a heatmap-type plot (Figure B.14) which is similar to the figures in the document for weight-at-age and fecundity-at-age.

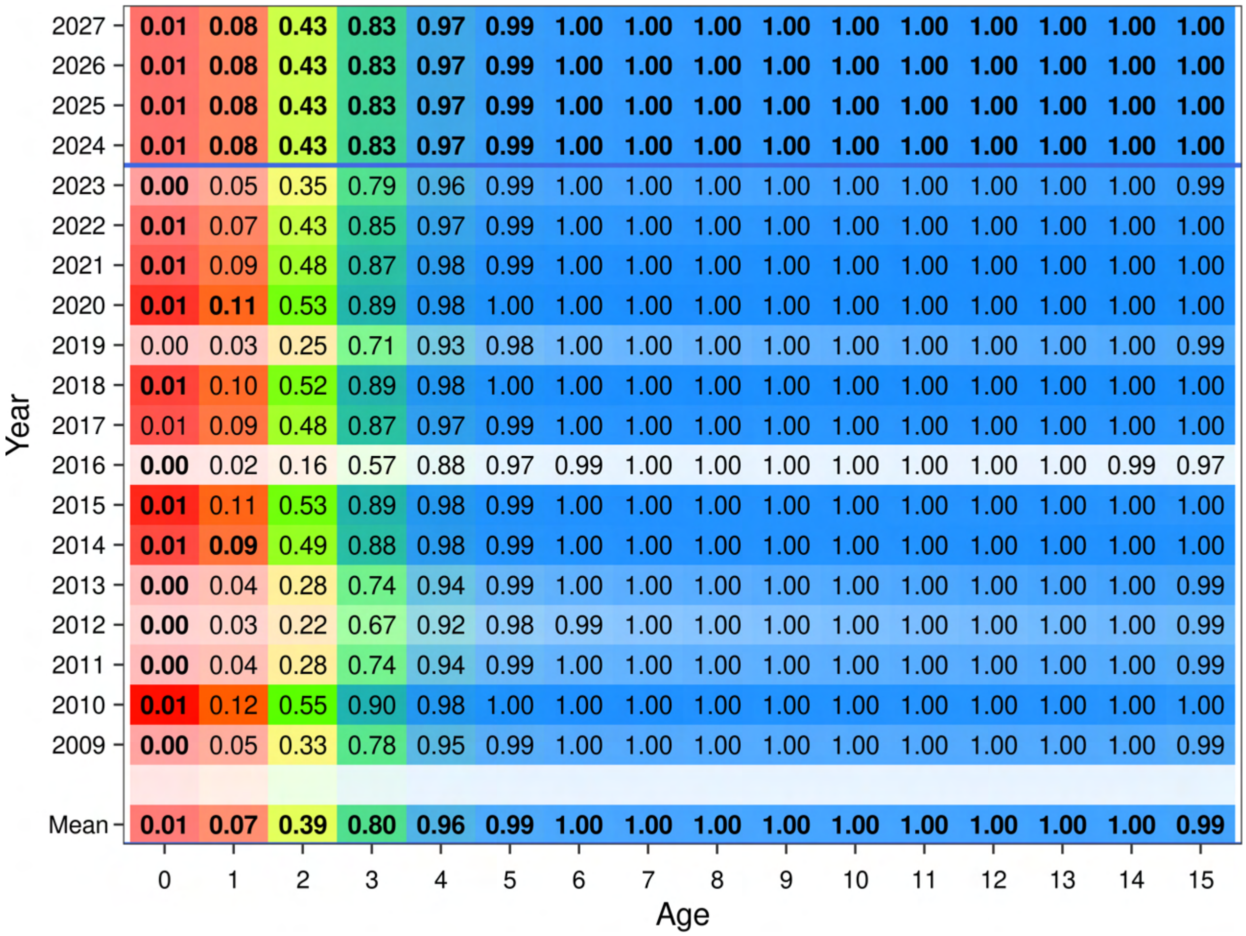


Figure B.14. Heatmap showing the maturity-at-age by year. Projected years (2024–2027) are the means of the previous five years (2019–2023). Values used for years prior to 2009 are the means or the values by age for 2009–2023.

Request 5

The SRG requests rerunning the base assessment model with updated weight-at-age and fecundity matrices based on day 278. Updated harvest scenario tables if possible.

JTC Response

The JTC ran the modified base model and presents the following figures.

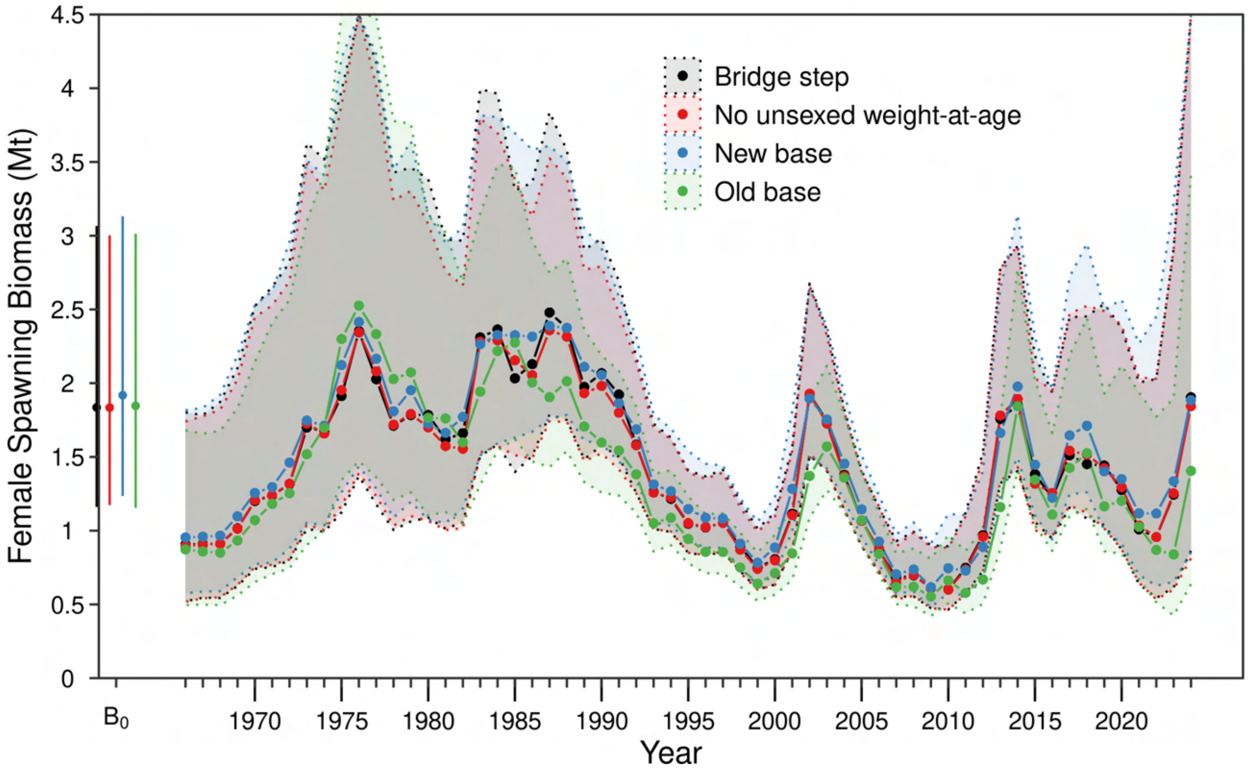


Figure B.15. Female spawning biomass across time for the terminal bridging steps to the new base model, as well as the pre-SRG base model. The bridge model is the step in which the student-t distribution was used for the relative age-1 index of numbers of fish. Weight-at-age data were then updated, followed by fecundity using the new maturity ogives to create the new base model.

Request 6

The SRG requests a new executive summary based on the updated base model.

JTC Response

The JTC completed the new Executive Summary and submitted it to the SRG in an unchecked, draft form. It has been since completed and is the new Executive Summary for this document.

Notes:

- The forecast for a constant catch of 270,000 t was removed and the TAC from 2022 (545,000 t) was added. This results in the row letters being different for roughly half of the forecast catch streams in the tables when compared with the submitted pre-SRG Executive Summary.
- The One-page summary has been modified, in particular the penultimate bullet point.

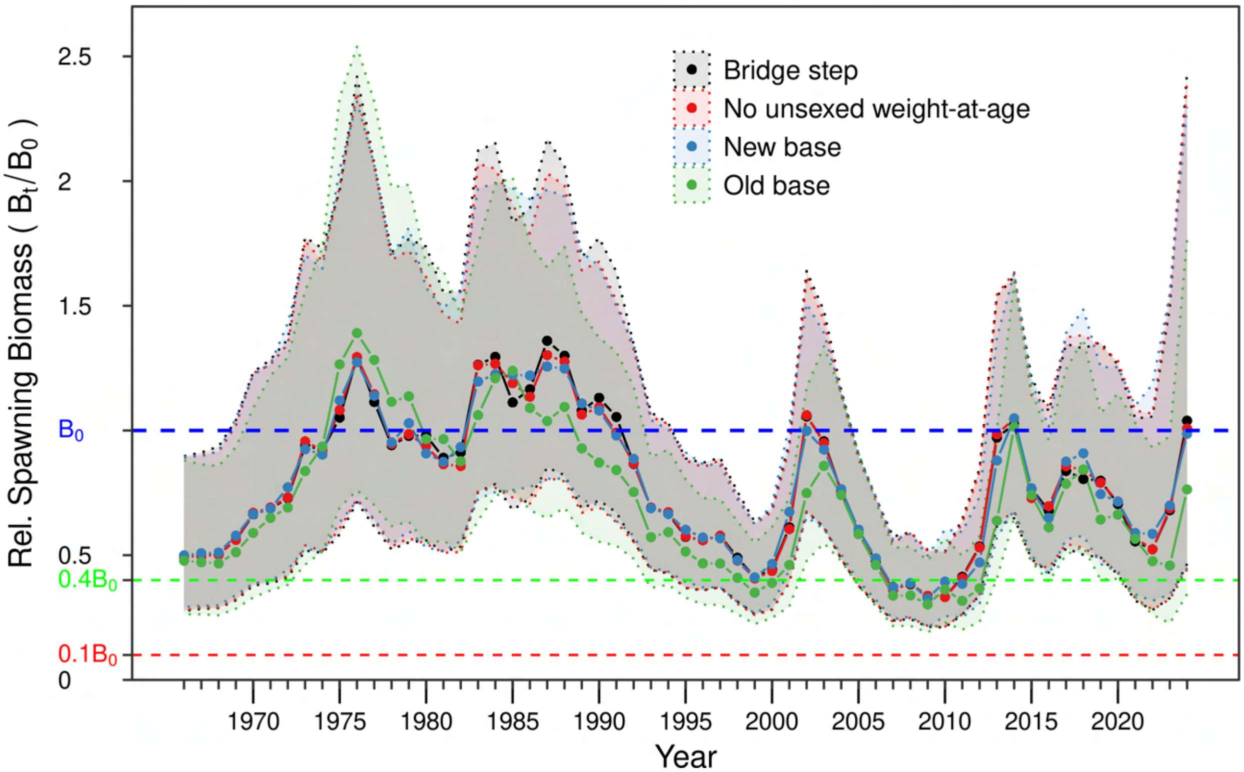


Figure B.16. Female spawning biomass relative to unfished female spawning biomass across time for the terminal bridging steps to the new base model, as well as the pre-SRG base model. The bridge model is the step in which the student-t distribution was used for the relative age-1 index of numbers of fish. Weight-at-age data were then updated, followed by fecundity using the new maturity ogives to create the new base model.

C GLOSSARY OF TERMS 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.

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 the maximum sustainable yield from the estimated vulnerable biomass. 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 the total allowable catch or allocations that account for carryovers of uncaught catch from previous years.

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 in Seattle, Washington, on November 21, 2003 and entered into force June 25, 2008.

Alaska Fisheries Science Center (AFSC): One of six regional NOAA Fisheries Science Centers, primarily in Seattle, Washington but also present throughout Alaska.

B_0: 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 total allowable catch is set to 0, based on the 40:10 adjustment.

$B_{40\%}$: 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 total allowable catch is decreased from the value associated with $F_{\text{SPR}=40\%}$, based on the 40:10 adjustment.

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

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.

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

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 some of these unharvested allocations to be carried over into the next year's allocation process. The Agreement states that "If, in any year, a Party's catch is less than its individual total allowable catch, an amount equal to the shortfall shall be added to its individual total allowable catch in the following year, unless otherwise recommended by the Joint Management Committee. Adjustments under this sub-paragraph shall in no case exceed 15 percent of a Party's unadjusted individual total allowable catch for the year in which the shortfall occurred."

Catchability (q): The parameter defining the proportionality between a relative index of abundance (often a fishery-independent survey) and the estimated 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 abundance in the absence of fishery-independent indices and/or where the two types of indices 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 total allowable catch, an acceptable biological catch, the median result of applying the default harvest policy, or some other number. The Joint Technical Committee welcomes input from the Joint Management Committee on the best terminology to use for these quantities.

Closed-loop simulation: A subset of a management strategy evaluation that iteratively simulates a population using an operating model, generates data from that population and passes it to an estimation method, uses the estimation method 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.

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

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.

Default harvest policy (rate): The application of $F_{\text{SPR}=40\%}$ with the 40:10 adjustment. Having considered any advice provided by the Joint Technical Committee, Scientific Review Group, or Advisory Panel, the Joint Management Committee may recommend a different harvest rate if the scientific evidence demonstrates that a different rate is necessary to sustain the resource.

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

Depletion: Prior to the 2015 assessment, depletion was used instead of relative spawning biomass. 'Relative depletion' was also used.

El Niño: Abnormally warm ocean climate conditions in the California Current Ecosystem 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 assessment; note that in some previous assessments it was 3+). This value is not equivalent to the instantaneous rate of fishing mortality or the spawning potential ratio.

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

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

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

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

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

Fisheries and Oceans Canada (DFO): Federal organization that delivers programs and services to support sustainable use and development of Canada's waterways and aquatic resources. Was previously called Department of Fisheries and Oceans.

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 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 (Figures C.1 and C.2) is the fishing intensity relative to that at the SPR fishing rate $F_{\text{SPR}=40\%}$, where $F_{\text{SPR}=40\%}$ is the F that gives an SPR of 40% such that, by definition, SPR($F_{40\%}$) = 40% (the benchmark spawning ratio). Therefore

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

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

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

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

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

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, percent annual removal, or the spawning potential ratio.

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

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 acceptable biological catch from a stock assessment. Also see default harvest policy.

Joint Management Committee (JMC): The Joint Management Committee is established by the Agreement.

Joint Technical Committee (JTC): The Joint Technical Committee established by the Agreement. The formal name is 'Joint Technical Committee of the Pacific Hake/Whiting Agreement Between the Governments of the United States and Canada'.

Kilotonne (kt). Metric abbreviation for 1,000 metric tonnes.

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 (MSFCMA): 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.

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

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 population under equilibrium ecological and environmental conditions.

Megatonne (Mt): Metric abbreviation for 1,000,000 metric tonnes.

Metric tonne (t): A unit of mass (often referred to as weight) equal to 1,000 kilograms or 2,204.62 pounds. Some previous stock assessments used the abbreviation 'mt'.

National Marine Fisheries Service (NMFS): See NOAA Fisheries.

No-U-Turn Sampler (NUTS): An advanced Hamiltonian Bayesian Markov chain Monte Carlo sampling algorithm used to efficiently create posterior distributions and used in Pacific Hake Bayesian assessments beginning in 2021.

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.

North Pacific Groundfish and Halibut Observer Program Database (NORPAC): A database that stores data collected at sea by U.S. fishery observers.

Northwest Fisheries Science Center (NWFSC): One of six regional NOAA Fisheries Science Centers, primarily in Seattle, Washington but also in various locations in Oregon and Washington.

Not available (NA): Something that is not available, e.g., an entry in a table.

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

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

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

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 population 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 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 Markov chain Monte Carlo sampling.

Prior distribution: A 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, uninformative priors can be constructed which allow the data to dominate the posterior distribution. For other parameters, informative priors can be constructed based on auxiliary information and/or expert knowledge or opinions.

R_0: Estimated annual recruitment at unfished equilibrium.

Random walk Metropolis Hastings (rwMH): Bayesian Markov chain Monte Carlo sampling algorithm used to create posterior distributions used in Pacific Hake Bayesian stock assessment models prior to 2021.

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–recruitment relationship; values occur on a logarithmic scale and are relative to the expected recruitment at a given female spawning biomass.

Relative fishing intensity: See 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). Thus, lower values are associated with fewer mature female fish. This term was introduced in the 2015 stock assessment as a replacement for 'depletion'.

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

Scientific and Statistical Committee (SSC): The scientific advisory committee to the Pacific Fishery Management Council. The Magnuson–Stevens Fishery Conservation and Management Act requires that each council maintain a Scientific and Statistical Committee to assist in gathering and analyzing statistical, biological, ecological, economic, social, and other scientific information that is relevant to the management of the Council.

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 Markov chain Monte Carlo, for a particular model (e.g., the base model).

Spawning biomass: Abbreviated term for female spawning biomass.

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.

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. Often expressed as a percentage, it achieves a value of 100% in the absence of fishing and declines toward zero as fishing intensity increases (Figure C.2).

Standard deviation (sd): A measure of variability within a sample.

Steepness (h): A parameter of the stock–recruitment relationship 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 strength (TS): The amount of backscatter from an individual acoustic target.

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 for the U.S. share and 26.12% for the Canadian share.

Vulnerable biomass: The demographic portion of the population 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 the spawning potential ratio (SPR; top axis) and 1-SPR (bottom axis); given the benchmark SPR of 40%, the solid blue line is simply $1/0.6$, as shown in equation (C.3).

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 Markov chain Monte Carlo (MCMC) estimates of natural mortality, selectivity, and fishing mortality in the final year of the base model used in this year's assessment. The light blue bars represent unfished values, the dark blue bars represent fished values.

D REPORT OF THE 2023 PACIFIC HAKE FISHERY IN CANADA

Prepared by the Canadian Advisory Panel and submitted on February 13, 2024 for inclusion in this assessment document.

The Canadian Offshore Pacific Hake fishery was very poor in 2023. The 2023 year recorded the lowest catch since the fishery began in the late 1970s, with slightly more than 22,000 tonnes caught, or 21% of the 105,000 tonne TAC for the fishery. This is down from the 31,000 tonnes caught in 2022 when 29% of the 105,000 tonne TAC was harvested. Generally, the fishermen found the fishing very poor and similar or worse than 2022. Catches were inconsistent and usually very scratchy. Most of the fishing occurred around Father Charles and the Finger Bank and south of there. The fish encountered were large older fish and small fish were rarely encountered. The bycatch was primarily Yellowtail rockfish, pollock, and herring. The market for HGT was also poor.

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

Prepared by the United States Advisory Panel on 17 January 2024 for inclusion in this assessment document.

Based on data from the Pacific Fisheries Information Network (PacFIN), total U.S. harvest in the 2023 whiting fishery was 240,189 t, which is 52% of the U.S. allocation of 461,750 t. Total U.S. harvest from these same sectors in the 2022 whiting fishery was 289,726 t. Compared to 2022, total U.S. catch was down 17% in 2023 (see Tables E.1 and E.2).

Shoreside (SS) Fishery: Spring fishing in the SS sector started strong shortly after May 1 but slowed considerably by the end of May, and didn't pick back up until later in the year. Spring fishing was described as very spotty for both the fleet fishing around the Columbia River and north, as well as the fleet fishing out of Newport, Oregon. By June, almost all of the fish were observed to be off Newport and well to the south. The most consistent volumes in the SS fishery were observed from late June to early September, and the majority of the SS late summer and fall fishery occurred off the central OR coast and closer to the California border. Fishing in the SS sector slowed by October, which is normal.

Larger fish were reported further north during the times when fish were up north. The fleet fishing north of the Columbia River and in WA landed fish as large as 900 grams. Fish caught off the south coast of OR and CA were reported to be sub-450 gram at best and got smaller later in the season.

Bycatch encounters in the SS sector consisted primarily of Chinook salmon, sablefish, darkblotched rockfish, yellowtail rockfish, and some mackerel off Newport late in the season. The SS whiting cooperative implemented several hot spot closures/advisory areas during the season to avoid/minimize bycatch.

Overall, the total 2023 SS whiting catch (100,392 t) represented 56% of the 2023 SS allocation and was slightly lower than total 2022 SS catch (104,323 t).

At-Sea Fishery: The U.S. at-sea fishery is comprised of the Mothership (MS) and Catcher Processor (CP) sectors.

Mothership (MS) Sector – In the spring fishery, one MS fleet was on the grounds on May 2, and another joined on May 10. Two other platforms joined on May 15. Spring fishing was strong until late May, and all four MS fleets concluded operations by May 30.

The size of whiting in the MS spring fishery generally ranged from 400–600 grams. However, location of fish further south and in shallower waters during the spring increased bycatch. By the end of May, slower fishing rates combined with high bycatch encounters and restrictive bycatch movement rules led to an early end to the spring fishery for the MS sector.

In the "fall" fishery (which began mid-summer this year), one MS fleet was on the grounds on August 11, with another joining on September 27. Fall catch occurred primarily off of

Table E.1. Final 2022 allocations (after reallocation of tribal quota) and catch totals (tonnes, t). Note that 402,646 t U.S. TAC is reduced by 750 t 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. Source: 2023 Whiting Stock Assessment Report and PacFIN Whiting Report.

	U.S. TAC	Shoreside	Catcher Processor	Mothership	Tribal
Allocation (t)	401,896	156,002	126,287	89,144	30,463
Catch (t)	289,726	104,323	126,247	59,157	1,174
Utilization (%)	72.1%	66.9%	100.0%	66.4%	3.9%

Oregon, with clean fishing and low bycatch encounters, but smaller fish size, averaging around 300 grams. The 2023 MS fishery concluded on November 1.

Overall, the total 2023 MS sector catch (32,744 t) represented 32% of the 2023 MS allocation and was significantly lower than the total 2022 MS catch (59,157 t). Four out of six MS platforms participated in the 2023 fishery, with one MS platform changing ownership mid-year.

Catcher Processor (CP) Sector – In the spring fishery, the first CPs were on the grounds on May 5. The CP sector ended their spring fishery the first week of June, as vessels transition to the Alaska pollock fishery which begins June 10. Overall, spring whiting harvest rates for the CPs were lower as fish were mostly absent from the WA and northern OR coastlines. Whiting were mainly schooled in southern OR and shallower than previous years. The shoreward and more shallow distribution of whiting contributed to much higher levels of incidental catch. The CPs observed higher encounters with Chinook salmon compared to previous years and record high encounters with some rockfish species during the spring fishery. The average whiting size in the spring CP fishery was approximately 450 grams.

The fall fishery began with the first CPs arriving in OR late August and continued through the beginning of November. Unlike spring fishing efforts, the fall was a turnaround for whiting harvest levels. A greater abundance of whiting were seen further north into OR and more normal depths. Southern OR exhibited steady fishing with good catch per unit effort (CPUE), and far lower bycatch than the spring fishery. Overall, there was very little CP catch and effort off Washington. The observed fish size in the fall fishery was smaller compared to the spring fishery, averaging approximately 350 grams.

Overall, the total 2023 CP sector catch (107,053 t) represented 74% of the 2023 CP allocation and was lower than total 2022 CP catch (126,247 t), due to two vessels not participating during the 2023 whiting fishery. One CP vessel underwent repairs during the fall. Another vessel experienced a fire and was not operational in the whiting fishery this year.

Table E.2. Final 2023 allocations (after reallocation of tribal quota) and catch totals (tonnes, t). Note that 461,750 t U.S. TAC is reduced by 750 t 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. Source: PacFIN Whiting Report.

	U.S. TAC	Shoreside	Catcher Processor	Mothership	Tribal
Allocation (t)	461,000	178,581	144,566	102,047	35,806
Catch (t)	240,190	100,392	107,053	32,744	0
Utilization (%)	52.1%	56.2%	74.1%	32.1%	0.0%

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	0.2348
SR_LN(R0)	14.7710
SR_BH_steep	0.8118
Q_extraSD_Acoustic_Survey(2)	0.3225
Q_extraSD_Age1_Survey(3)	0.3810
ln(DM_theta)_Age_P1	-0.6631
ln(DM_theta)_Age_P2	2.7705
Early_InitAge_20	-0.3065
Early_InitAge_19	-0.0891
Early_InitAge_18	-0.1063
Early_InitAge_17	-0.1203
Early_InitAge_16	-0.1496
Early_InitAge_15	-0.1937
Early_InitAge_14	-0.2506
Early_InitAge_13	-0.2520
Early_InitAge_12	-0.2990
Early_InitAge_11	-0.3331
Early_InitAge_10	-0.4485
Early_InitAge_9	-0.4587
Early_InitAge_8	-0.4887
Early_InitAge_7	-0.5836
Early_InitAge_6	-0.5343
Early_InitAge_5	-0.4851
Early_InitAge_4	-0.2706
Early_InitAge_3	0.0148
Early_InitAge_2	0.3822
Early_InitAge_1	0.6536
Early_RecrDev_1966	0.5827
Early_RecrDev_1967	1.6581
Early_RecrDev_1968	1.2563
Early_RecrDev_1969	-0.2794
Main_RecrDev_1970	2.3070
Main_RecrDev_1971	-0.0674
Main_RecrDev_1972	-0.5308
Main_RecrDev_1973	1.8778
Main_RecrDev_1974	-0.9790
Main_RecrDev_1975	0.6857
Main_RecrDev_1976	-1.5334
Main_RecrDev_1977	1.9687
Main_RecrDev_1978	-1.9460
Main_RecrDev_1979	0.3948

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Parameter	Posterior median
Main_RecrDev_1980	2.9165
Main_RecrDev_1981	-1.2655
Main_RecrDev_1982	-1.0860
Main_RecrDev_1983	-0.5714
Main_RecrDev_1984	2.6899
Main_RecrDev_1985	-1.9600
Main_RecrDev_1986	-1.6559
Main_RecrDev_1987	1.9252
Main_RecrDev_1988	0.7740
Main_RecrDev_1989	-2.1642
Main_RecrDev_1990	1.5005
Main_RecrDev_1991	0.2631
Main_RecrDev_1992	-2.0430
Main_RecrDev_1993	1.2331
Main_RecrDev_1994	1.2647
Main_RecrDev_1995	0.3080
Main_RecrDev_1996	0.6996
Main_RecrDev_1997	0.1019
Main_RecrDev_1998	0.8010
Main_RecrDev_1999	2.6847
Main_RecrDev_2000	-1.0589
Main_RecrDev_2001	0.2921
Main_RecrDev_2002	-3.1098
Main_RecrDev_2003	0.5723
Main_RecrDev_2004	-3.1280
Main_RecrDev_2005	1.1299
Main_RecrDev_2006	0.8335
Main_RecrDev_2007	-3.5752
Main_RecrDev_2008	1.8693
Main_RecrDev_2009	0.4833
Main_RecrDev_2010	2.9079
Main_RecrDev_2011	-0.8300
Main_RecrDev_2012	0.5710
Main_RecrDev_2013	-0.9457
Main_RecrDev_2014	2.1502
Main_RecrDev_2015	-3.3347
Main_RecrDev_2016	1.8102
Main_RecrDev_2017	0.4993
Main_RecrDev_2018	-0.8865
Main_RecrDev_2019	-1.2643
Main_RecrDev_2020	1.6148
Main_RecrDev_2021	2.3944
Main_RecrDev_2022	0.6988

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Parameter	**Posterior median**
Late_RecrDev_2023	0.0142
ForeRecr_2024	-0.0152
ForeRecr_2025	0.0616
ForeRecr_2026	0.0164
ForeRecr_2027	0.0017
AgeSel_P3_Fishery(1)	3.0812
AgeSel_P4_Fishery(1)	0.8957
AgeSel_P5_Fishery(1)	0.4069
AgeSel_P6_Fishery(1)	0.1832
AgeSel_P7_Fishery(1)	0.4995
AgeSel_P4_Acoustic_Survey(2)	0.5250
AgeSel_P5_Acoustic_Survey(2)	-0.1734
AgeSel_P6_Acoustic_Survey(2)	0.3007
AgeSel_P7_Acoustic_Survey(2)	0.3055
AgeSel_P3_Fishery(1)_DEVadd_1991	0.5162
AgeSel_P3_Fishery(1)_DEVadd_1992	0.0062
AgeSel_P3_Fishery(1)_DEVadd_1993	-0.0147
AgeSel_P3_Fishery(1)_DEVadd_1994	0.0846
AgeSel_P3_Fishery(1)_DEVadd_1995	-0.1565
AgeSel_P3_Fishery(1)_DEVadd_1996	0.3852
AgeSel_P3_Fishery(1)_DEVadd_1997	0.0602
AgeSel_P3_Fishery(1)_DEVadd_1998	0.1898
AgeSel_P3_Fishery(1)_DEVadd_1999	0.9011
AgeSel_P3_Fishery(1)_DEVadd_2000	0.4173
AgeSel_P3_Fishery(1)_DEVadd_2001	0.0514
AgeSel_P3_Fishery(1)_DEVadd_2002	0.0801
AgeSel_P3_Fishery(1)_DEVadd_2003	0.0060
AgeSel_P3_Fishery(1)_DEVadd_2004	0.2656
AgeSel_P3_Fishery(1)_DEVadd_2005	0.0085
AgeSel_P3_Fishery(1)_DEVadd_2006	0.5499
AgeSel_P3_Fishery(1)_DEVadd_2007	0.5194
AgeSel_P3_Fishery(1)_DEVadd_2008	-0.0130
AgeSel_P3_Fishery(1)_DEVadd_2009	0.3617
AgeSel_P3_Fishery(1)_DEVadd_2010	0.8387
AgeSel_P3_Fishery(1)_DEVadd_2011	-0.2112
AgeSel_P3_Fishery(1)_DEVadd_2012	0.0761
AgeSel_P3_Fishery(1)_DEVadd_2013	0.2066
AgeSel_P3_Fishery(1)_DEVadd_2014	0.2674
AgeSel_P3_Fishery(1)_DEVadd_2015	-0.8431
AgeSel_P3_Fishery(1)_DEVadd_2016	-0.0241
AgeSel_P3_Fishery(1)_DEVadd_2017	-0.4552
AgeSel_P3_Fishery(1)_DEVadd_2018	-1.6229
AgeSel_P3_Fishery(1)_DEVadd_2019	0.6842

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Parameter	Posterior median
AgeSel_P3_Fishery(1)_DEVadd_2020	0.0127
AgeSel_P3_Fishery(1)_DEVadd_2021	-0.5725
AgeSel_P3_Fishery(1)_DEVadd_2022	1.7423
AgeSel_P3_Fishery(1)_DEVadd_2023	0.6769
AgeSel_P4_Fishery(1)_DEVadd_1991	0.3254
AgeSel_P4_Fishery(1)_DEVadd_1992	0.5886
AgeSel_P4_Fishery(1)_DEVadd_1993	0.8088
AgeSel_P4_Fishery(1)_DEVadd_1994	0.1478
AgeSel_P4_Fishery(1)_DEVadd_1995	0.2448
AgeSel_P4_Fishery(1)_DEVadd_1996	-0.3570
AgeSel_P4_Fishery(1)_DEVadd_1997	1.2656
AgeSel_P4_Fishery(1)_DEVadd_1998	0.9667
AgeSel_P4_Fishery(1)_DEVadd_1999	-0.0935
AgeSel_P4_Fishery(1)_DEVadd_2000	0.8008
AgeSel_P4_Fishery(1)_DEVadd_2001	0.9377
AgeSel_P4_Fishery(1)_DEVadd_2002	0.6972
AgeSel_P4_Fishery(1)_DEVadd_2003	0.6910
AgeSel_P4_Fishery(1)_DEVadd_2004	0.4503
AgeSel_P4_Fishery(1)_DEVadd_2005	0.6481
AgeSel_P4_Fishery(1)_DEVadd_2006	-0.1227
AgeSel_P4_Fishery(1)_DEVadd_2007	0.2426
AgeSel_P4_Fishery(1)_DEVadd_2008	0.4494
AgeSel_P4_Fishery(1)_DEVadd_2009	0.7286
AgeSel_P4_Fishery(1)_DEVadd_2010	0.1541
AgeSel_P4_Fishery(1)_DEVadd_2011	1.0462
AgeSel_P4_Fishery(1)_DEVadd_2012	0.2448
AgeSel_P4_Fishery(1)_DEVadd_2013	0.8045
AgeSel_P4_Fishery(1)_DEVadd_2014	0.4961
AgeSel_P4_Fishery(1)_DEVadd_2015	0.1647
AgeSel_P4_Fishery(1)_DEVadd_2016	-0.9255
AgeSel_P4_Fishery(1)_DEVadd_2017	-0.5714
AgeSel_P4_Fishery(1)_DEVadd_2018	-0.5257
AgeSel_P4_Fishery(1)_DEVadd_2019	-0.7931
AgeSel_P4_Fishery(1)_DEVadd_2020	0.8083
AgeSel_P4_Fishery(1)_DEVadd_2021	-0.0104
AgeSel_P4_Fishery(1)_DEVadd_2022	-1.3424
AgeSel_P4_Fishery(1)_DEVadd_2023	-0.1153
AgeSel_P5_Fishery(1)_DEVadd_1991	-0.8527
AgeSel_P5_Fishery(1)_DEVadd_1992	0.0980
AgeSel_P5_Fishery(1)_DEVadd_1993	-0.0093
AgeSel_P5_Fishery(1)_DEVadd_1994	0.8687
AgeSel_P5_Fishery(1)_DEVadd_1995	0.2673
AgeSel_P5_Fishery(1)_DEVadd_1996	-0.3229

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Parameter	Posterior median
AgeSel_P5_Fishery(1)_DEVadd_1997	-0.1132
AgeSel_P5_Fishery(1)_DEVadd_1998	-0.6136
AgeSel_P5_Fishery(1)_DEVadd_1999	0.0951
AgeSel_P5_Fishery(1)_DEVadd_2000	-0.1591
AgeSel_P5_Fishery(1)_DEVadd_2001	0.3224
AgeSel_P5_Fishery(1)_DEVadd_2002	0.5311
AgeSel_P5_Fishery(1)_DEVadd_2003	0.7475
AgeSel_P5_Fishery(1)_DEVadd_2004	0.6686
AgeSel_P5_Fishery(1)_DEVadd_2005	0.7351
AgeSel_P5_Fishery(1)_DEVadd_2006	-0.0276
AgeSel_P5_Fishery(1)_DEVadd_2007	-0.0707
AgeSel_P5_Fishery(1)_DEVadd_2008	-0.3018
AgeSel_P5_Fishery(1)_DEVadd_2009	-0.3118
AgeSel_P5_Fishery(1)_DEVadd_2010	0.5130
AgeSel_P5_Fishery(1)_DEVadd_2011	-0.7007
AgeSel_P5_Fishery(1)_DEVadd_2012	0.1580
AgeSel_P5_Fishery(1)_DEVadd_2013	-0.1910
AgeSel_P5_Fishery(1)_DEVadd_2014	-0.4967
AgeSel_P5_Fishery(1)_DEVadd_2015	-0.0246
AgeSel_P5_Fishery(1)_DEVadd_2016	-0.0070
AgeSel_P5_Fishery(1)_DEVadd_2017	-0.1511
AgeSel_P5_Fishery(1)_DEVadd_2018	-0.2096
AgeSel_P5_Fishery(1)_DEVadd_2019	-0.0752
AgeSel_P5_Fishery(1)_DEVadd_2020	0.6741
AgeSel_P5_Fishery(1)_DEVadd_2021	0.6345
AgeSel_P5_Fishery(1)_DEVadd_2022	0.1278
AgeSel_P5_Fishery(1)_DEVadd_2023	-0.8338
AgeSel_P6_Fishery(1)_DEVadd_1991	-0.0546
AgeSel_P6_Fishery(1)_DEVadd_1992	-0.4801
AgeSel_P6_Fishery(1)_DEVadd_1993	-0.0557
AgeSel_P6_Fishery(1)_DEVadd_1994	-0.0871
AgeSel_P6_Fishery(1)_DEVadd_1995	0.7385
AgeSel_P6_Fishery(1)_DEVadd_1996	-0.1070
AgeSel_P6_Fishery(1)_DEVadd_1997	-0.3419
AgeSel_P6_Fishery(1)_DEVadd_1998	0.3681
AgeSel_P6_Fishery(1)_DEVadd_1999	-0.3918
AgeSel_P6_Fishery(1)_DEVadd_2000	0.1502
AgeSel_P6_Fishery(1)_DEVadd_2001	-0.1392
AgeSel_P6_Fishery(1)_DEVadd_2002	0.1388
AgeSel_P6_Fishery(1)_DEVadd_2003	0.2638
AgeSel_P6_Fishery(1)_DEVadd_2004	-0.5599
AgeSel_P6_Fishery(1)_DEVadd_2005	0.2660
AgeSel_P6_Fishery(1)_DEVadd_2006	0.2131

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Parameter	Posterior median
AgeSel_P6_Fishery(1)_DEVadd_2007	-0.2244
AgeSel_P6_Fishery(1)_DEVadd_2008	0.2367
AgeSel_P6_Fishery(1)_DEVadd_2009	-0.3308
AgeSel_P6_Fishery(1)_DEVadd_2010	-0.3864
AgeSel_P6_Fishery(1)_DEVadd_2011	-0.2272
AgeSel_P6_Fishery(1)_DEVadd_2012	-0.4511
AgeSel_P6_Fishery(1)_DEVadd_2013	-0.0421
AgeSel_P6_Fishery(1)_DEVadd_2014	0.0535
AgeSel_P6_Fishery(1)_DEVadd_2015	-0.0197
AgeSel_P6_Fishery(1)_DEVadd_2016	-0.0199
AgeSel_P6_Fishery(1)_DEVadd_2017	-0.1621
AgeSel_P6_Fishery(1)_DEVadd_2018	-0.3403
AgeSel_P6_Fishery(1)_DEVadd_2019	0.1470
AgeSel_P6_Fishery(1)_DEVadd_2020	-0.3350
AgeSel_P6_Fishery(1)_DEVadd_2021	0.1884
AgeSel_P6_Fishery(1)_DEVadd_2022	0.5586
AgeSel_P6_Fishery(1)_DEVadd_2023	0.1653
AgeSel_P7_Fishery(1)_DEVadd_1991	-0.0949
AgeSel_P7_Fishery(1)_DEVadd_1992	0.0732
AgeSel_P7_Fishery(1)_DEVadd_1993	-0.3617
AgeSel_P7_Fishery(1)_DEVadd_1994	0.0914
AgeSel_P7_Fishery(1)_DEVadd_1995	-0.1230
AgeSel_P7_Fishery(1)_DEVadd_1996	0.4078
AgeSel_P7_Fishery(1)_DEVadd_1997	0.1310
AgeSel_P7_Fishery(1)_DEVadd_1998	-0.5020
AgeSel_P7_Fishery(1)_DEVadd_1999	-0.2628
AgeSel_P7_Fishery(1)_DEVadd_2000	-0.0763
AgeSel_P7_Fishery(1)_DEVadd_2001	-0.2944
AgeSel_P7_Fishery(1)_DEVadd_2002	-0.4180
AgeSel_P7_Fishery(1)_DEVadd_2003	-0.2696
AgeSel_P7_Fishery(1)_DEVadd_2004	-0.1766
AgeSel_P7_Fishery(1)_DEVadd_2005	-0.3799
AgeSel_P7_Fishery(1)_DEVadd_2006	-0.3073
AgeSel_P7_Fishery(1)_DEVadd_2007	0.0703
AgeSel_P7_Fishery(1)_DEVadd_2008	-0.1160
AgeSel_P7_Fishery(1)_DEVadd_2009	-0.0300
AgeSel_P7_Fishery(1)_DEVadd_2010	-0.7561
AgeSel_P7_Fishery(1)_DEVadd_2011	-0.4840
AgeSel_P7_Fishery(1)_DEVadd_2012	-0.2938
AgeSel_P7_Fishery(1)_DEVadd_2013	0.1362
AgeSel_P7_Fishery(1)_DEVadd_2014	-0.0977
AgeSel_P7_Fishery(1)_DEVadd_2015	-0.4649
AgeSel_P7_Fishery(1)_DEVadd_2016	-0.3844

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Parameter	Posterior median
AgeSel_P7_Fishery(1)_DEVadd_2017	-0.0375
AgeSel_P7_Fishery(1)_DEVadd_2018	0.2466
AgeSel_P7_Fishery(1)_DEVadd_2019	-0.1914
AgeSel_P7_Fishery(1)_DEVadd_2020	-0.0499
AgeSel_P7_Fishery(1)_DEVadd_2021	-0.2999
AgeSel_P7_Fishery(1)_DEVadd_2022	0.0538
AgeSel_P7_Fishery(1)_DEVadd_2023	0.5701

G MODELING TEMPORAL AND SPATIAL TRENDS IN HAKE MATURITY-AT-AGE DATA

Contributed by Melissa A. Head, Kelli F. Johnson, Kristin N. Marshall, and Eric J. Ward.

G.1 Methods

G.1.1 Data filtering

We assembled a dataset representing hake functional maturity collected from three sources, the West Coast Groundfish Bottom Trawl Survey (WCGBTS; Keller et al. 2017), the Northwest Fisheries Science Center Integrated Pacific Hake Ecosystem and Acoustic-Trawl Survey, and gonad tissue samples from the At-Sea Hake Observer program (ASHOP). The first two sources represent fishery-independent samples, while ASHOP samples are fishery dependent. After filtering, this dataset consisted of 2836 samples, from years 2009 to 2021 (Table G.1; Figure G.1). An additional 180 samples exist with unknown ages and 394 samples exist with uncertain functional maturity; but, these were omitted from our analysis. Similarly, there are 73 samples that were collected in British Columbia (72 of 73 mature; 70 of 73 age 5 or older) but they have limited temporal coverage (primarily 2013, 2015) and were omitted from our analysis. Note that these samples from British Columbia were included in the 2018 analysis of maturity-at-age that was previously included in the fecundity relationship.

G.1.2 Statistical modeling

As each sample in our dataset is geo-referenced with a unique latitude and longitude, we constructed a series of spatiotemporal models to model variation in Pacific Hake maturity. Our statistical modeling framework can be seen as a version of generalized linear mixed model (GLMM), with a series of fixed and random components. We constructed three models to test hypotheses and help improve understanding of spatiotemporal variability in Pacific Hake maturity; these models can generally be described as

1. a null model representing the status quo, similar to models used in previous Pacific Hake assessments but with additional data and an effect for calendar day;
2. a spatiotemporal model incorporating temporal and spatial trends but no covariates;
3. a spatiotemporal model incorporating temperature as an environmental predictor.

To maintain consistency with the status quo, our null model contained no spatial or temporal variation. We included quadratic effects of age (to account for potential skip spawning of older individuals), a smooth effect of calendar day (modeled with a penalized regression or P-spline; Eilers and Marx 1996), and a linear offset corresponding to the ASHOP samples (allowing for differences between fishery independent and dependent samples). Previous Pacific Hake assessments have not allowed maturity to vary over time or space and have not estimated coefficients corresponding to ASHOP samples. Earlier versions of our first model also included offsets allowing for differences between the WCGBTS and Acoustic-Trawl samples, however these estimates were small in magnitude and had large standard errors, which suggests there were not meaningful differences between these sampling platforms. The null model can be written as

$$E[\mathbf{y}] = g^{-1}\left(\mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{b}\right) \tag{G.1}$$

where $g^{-1}()$ represents the inverse logit function, $\mathbf{X}$ represents the design matrix of fixed effects with estimated parameters $\boldsymbol{\beta}$, and the P-spline is represented with random effect design matrix $\mathbf{Z}$ and corresponding coefficients $\mathbf{b}$.

As a second model, we extended our null model to include spatial and temporal variation. We modeled year effects (intercepts) with a time-varying AR(1) random walk. Spatial effects were modeled using the stochastic partial differential equation (SPDE) approximation to Gaussian Random Fields (Lindgren et al. 2011). This approach can be seen as a predictive process method, where a spatial surface is approximated by a series of estimated random effects (locations referred to knots or vertices) which are then projected to locations of sample collections. Our mesh representing the spatial field used a cutoff distance of 50 km, resulting in 97 mesh vertices. Due to the sparsity of data in some years, we only considered models with spatial, and not spatiotemporal, fields. However, to account for interactions between space and age, we also included spatially varying coefficients in age effects, as a quadratic relationship (spatial fields for the intercept, age, age^2). This model can be written as

$$E[\mathbf{y}] = g^{-1}\left(\mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{b} + \boldsymbol{\omega}_s + \mathbf{x}_{age} * \boldsymbol{\zeta}_{s,age} + \mathbf{x}_{age^2} * \boldsymbol{\zeta}_{s,age^2} + \mathbf{X}_t^{tvc}\boldsymbol{\gamma}_{\mathbf{t}}\right) \tag{G.2}$$

where new components $\boldsymbol{\omega}_s$ represent a constant spatial field shared across years (analogous to a spatial intercept), $\boldsymbol{\zeta}_{s,age}$ and $\boldsymbol{\zeta}_{s,age^2}$ represent spatially varying coefficient effects of age, and $\mathbf{X}_t^{tvc}$ represents the design matrix of year effects with estimated coefficients $\boldsymbol{\gamma}_{\mathbf{t}}$. The $\boldsymbol{\gamma}_{\mathbf{t}}$ terms were modeled as AR(1) terms such as in the example $\gamma_{2010} \sim N\left(\rho\gamma_{2009}, \sqrt{1-\rho^2}\sigma\right)$, where ρ represents the AR(1) parameter.

Our third model also extended the null model to include an estimated spatial field and spatially varying coefficients for the quadratic function of age; but, instead of modeling year effects as a random walk, year effects were modeled as a function of subsurface (at 130.67 m; see below for details) temperature indices in the domain of the WCGBTS survey. Replacing random year effects with a temperature covariate has the potential to add mechanistic relationships to the modeling and also reduce uncertainty in years where no or few samples are collected. We explored several forms of the temperature relationship, including linear, quadratic, or P-splines and chose to use quadratic relationships because these introduced fewer parameters than P-splines, while also allowing for parabolic relationships. This model can be written in the same form as Model 2, without the time varying intercept,

$$E[\mathbf{y}] = g^{-1}\left(\mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{b} + \boldsymbol{\omega}_s + \mathbf{x}_{age} * \boldsymbol{\zeta}_{s,age} + \mathbf{x}_{age^2} * \boldsymbol{\zeta}_{s,age^2}\right) \tag{G.3}$$

where the added quadratic effects of temperature are in the fixed effects components $\mathbf{X}$ and $\boldsymbol{\beta}$.

Parameter estimation was done using the `sdmTMB` package (Anderson et al. 2022) in R (R Core Development Team 2024). `sdmTMB` provides a convenient interface between R and

Template Model Builder (TMB; Kristensen et al. 2016), which allows for fast marginal maximum likelihood estimation. Model convergence was assessed by examining the Hessian and standard errors of parameter estimates and the maximum gradient at convergence. Area under the curve (AUC) estimates were also calculated using the `pROC` package (Robin et al. 2011) in R.

G.1.3 Deriving temperature indices

Subsurface ocean temperature has previously been linked to Pacific Hake distribution (Malick et al. 2020) and co-occurrence of Pacific Hake with prey (Phillips et al. 2003); and, more recently, marine heat waves have been found to delay maturity in other groundfish species (Rosemond 2023). Given that temperature sampling is not done from all sampling platforms, we relied on modeled temperature products. Specifically, we used sea water potential temperature (referred to as 'temperature' throughout) from the `GLORYS12v1` product (1/12° resolution, 50 vertical levels, Global Ocean Physics Reanalysis for 1993–September 2023 and Global Ocean Physics Analysis and Forecast for October 2023–January 2024; Global Ocean Physics Reanalysis 2024, Global Ocean Physics Analysis and Forecast 2024; Lellouche et al. 2021). We processed monthly averages of temperature and used data from a subset of depths corresponding to the vertical distribution of Pacific Hake (25.21 m, 40.34 m, 55.76 m, 77.85 m, 92.33 m, 109.73 m, 130.67 m). These data show that, as expected, temperature generally decreases with depth (Figure G.2) and unlike surface temperature, which is warmest in summer months, the warmest temperatures at depth often occur in winter (Figure G.3). Data from each month–depth combination was alternately used to generate annual indices of temperature to relate to maturity. As a final stratification, we also considered indices generated using (1) coastwide GLORYS12v1 temperatures, (2) temperature north of Point Conception, and (3) temperature south of Point Conception.

Rather than take a spatial average of temperature by year for each month–depth combination, we generated biomass weighted averages of temperature (weighting temperature by the spatial distribution of Pacific Hake biomass, rather than weighting each spatial location equally). To generate biomass weights, we constructed a spatial model of Pacific Hake catch per unit effort (CPUE, kg / km^2), using 2003–2023 data from the WCGBTS. We adopted the same SPDE approach used in modeling maturity. Our biomass model included a smooth effect of calendar day (as a P-spline, dates range from May–October), a time varying intercept modeled with a random walk, a spatial field (representing spatial variation shared across years), and spatiotemporal variation (representing year to year variation in spatial patterning) modeled as an AR(1) process. Given the skewed distribution of catches, we modeled CPUE with a Tweedie distribution (Shono 2008). We identified spatial cells from the GLORYS12v1 re-analysis that were in the spatial domain of the WCGBTS (Keller et al. 2017) and made predictions of biomass to those cells on July 1 of each year (July 1 was arbitrarily chosen as a date in the middle of the WCGBTS survey). Because of the random walk model for year effects, our predictions of Pacific Hake biomass in future years 2024–2025 are identical to 2023. Temperature indices were then generated by taking a weighted average of temperature across space, with estimated Pacific Hake biomass used as weights. As the WCGBTS survey only provides an annual snapshot of biomass, the same biomass weights were used for all depths and months with temperature data. In general, weighted indices remained highly correlated with unweighted temperature indices ($\rho = 0.98$ across all depths and months; Figure G.4).

G.2 Model selection and sensitivity analysis

We performed two main sensitivity analyses across the three models used. First, we evaluated the sensitivity of our model selection results to include (or not) the fishery dependent ASHOP samples. Second, we evaluated a sensitivity to including samples south of Point Conception (previous maturity modeling has imposed a cutoff and did not include samples south of Point Conception). After ensuring that models converged (using the `sanity()` function in `sdmTMB`), we evaluated the relative support of models using Akaike information criterion (AIC; Akaike 1973). Similarly, alternative temperature indices were also compared using AIC, and the model(s) with the lowest AIC values were deemed to have the most support.

G.2.1 Generation of annual maturity at age

To create a single index of maturity for each age–year combination and generate maturity ogives, we used results from the best model selected with temperature as a driver alongside model results for Models 1–2. For each of these three models, we generated model predictions onto the WCGBTS design grid for non-ASHOP samples (with a larger intercept, ASHOP samples have earlier maturity at age) on the 278th day of the year or October 5th (Table G.3). Rather than take a simple average of these estimates (which weights each spatial cell equally), we calculated a weighted average, using biomass weights. Biomass was predicted using the same spatiotemporal model fit to the WCGBTS CPUE data, used in generating weighted indices of temperature. Weights were applied to estimated probabilities of maturity in logit space, and the total weighted average for each age–year combination was converted to normal space with an inverse logit transformation.

G.3 Results

Comparing the spatiotemporal model of Pacific Hake maturity to the baseline model representing the status quo provides an evaluation of support for maturation varying over time and space. In our comparison, most models showed greater support for models that included spatiotemporal processes than the null model (Table G.2). Similarly, we found that the model with the temperature index to predict year effects received the most support when ASHOP samples were included and data south of Pt. Conception were excluded (Table G.2; AIC $>$ 10). For other analysis with different subsets of data, the time varying random walk model without temperature as a driver received more support. For consistency with previous Pacific Hake stock assessment models, we focus the remainder of our results on models that were only fit to data north of Point Conception and included the ASHOP samples.

All three models estimated a similar quadratic effect of age and higher maturity at age in ASHOP samples (Table G.3). All three models had similar high AUC values (Model 1 = 0.951, Model 2 = 0.963, Model 3 = 0.962) indicating high abilities to discriminate between whether or not Pacific Hake are mature. Similarly, all three models estimated similar effects of calendar day, with a rapid increase in maturity estimated in summer months (Figure G.5).

For models that include spatiotemporal variation, we found similar patterns of year effects and spatial variation. Year effects from the time varying model without temperature indicated lower than average maturity in a number of years, including 2012, 2016, and 2019 (Figure G.6). Including spatially varying coefficients of age allowed each age to differ slightly; but, in general, spatial patterning was similar across ages (Figure G.7). Biomass weighted predictions of maturity also appeared similar between the spatiotemporal models with and without temperature effects (Figure G.8). The largest differences between these models appeared to be in years like 2016, when the temperature driven model predicts maturation rates lower than the random walk model (the classification ability of these models in 2016 was nearly identical, AUC = 0.957 for both; Figure G.9).

The estimated marginal effect of temperature in our best model (Tables G.2 and G.3) indicated a concave relationship between temperature and functional maturity (Figure G.10). Temperatures in 2018 and 2020 were near the peak of this relationship, while most years were cooler (maturity increasing with temperature over this region). Temperatures in 2016 and 2019 were high (Figures G.2–G.4), above the threshold corresponding to the peak of the temperature–maturity relationship, and maturity at age was estimated to decline in these years. Contrasts between years can also be seen in the estimated ogives (Figure G.11) with a delay in maturity occurring in years that are both cooler and warmer than 2020 (age at 50% maturity = 2.81 in 2020, versus 3.58 in 2012 or 3.82 in 2016).

The estimate of the spatial variance for the model used to weight spatial estimates based on estimated biomass of Pacific Hake was higher than the estimate of the spatiotemporal variance suggesting that differences in locations are more prominent than differences in locations between years (Table G.4). That is, Pacific Hake have a patchy distribution but those patches appear in largely the same locations year after year. The center of gravity of the distribution was furthest to the north in years that correspond to high temperatures and subsequent decreases in maturity (Figure G.12).

G.4 Citations

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. In B.N. Petrov and F. Csaki (Eds.), Second International Symposium on Information Theory (pp. 267–281). Budapest: Akademiai Kiado.

Anderson, S.C., Ward, E.J., English, P.A., and Barnett, L.A.K. 2022. sdmTMB: an R package for fast, flexible, and user-friendly generalized linear mixed effects models with spatial and spatiotemporal random fields. bioRxiv 2022.03.24.485545. https://doi.org/10.1101/2022.03.24.485545

Eilers, P.H.C., and Marx, B.D. 1996. Flexible smoothing with B-splines and penalties. Statistical Science, 11(2): 89–121. https://doi.org/10.1214/ss/1038425655

Global Ocean Physics Reanalysis. 2024. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). Retrieved January 10, 2024, from https://doi.org/10.48670/moi-00021

Global Ocean Physics Analysis and Forecast. 2024. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). Retrieved January 10, 2024, from https://doi.org/10.48670/moi-00016

Keller, A.A., Wallace, J., and Methot, R. 2017. NWFSC's West Coast groundfish bottom trawl survey: History, design, description. U.S. Dept. Comm., NOAA Tech. Memo. NMFS-NWFSC-136.

Kristensen, K., Nielsen, A., Berg, C.W., Skaug, H., and Bell, B.M. 2016. TMB: Automatic Differentiation and Laplace Approximation. Journal of Statistical Software, 70(5): 1–21. https://doi.org/10.18637/jss.v070.i05

Lellouche, J.-M., Greiner, E., Bourdallé-Badie, R., Garric, G., Melet, A., Drévillon, M., Bricaud, C., Hamon, M., Le Galloudec, O., Regnier, C., Candela, T., Testut, C.-E., Gasparin, F., Ruggiero, G., Benkiran, M., Drillet, Y., and Le Traon, P.-Y. 2021. The Copernicus Global 1/12° Oceanic and Sea Ice GLORYS12 Reanalysis. Frontiers in Earth Science, 9. https://doi.org/10.3389/feart.2021.698876

Lindgren, F., Rue, H., and Lindström, J. 2011. An explicit link between Gaussian fields and Gaussian Markov random fields: The stochastic partial differential equation approach. Journal of the Royal Statistical Society Series B: Statistical Methodology 73: 423–498. https://doi.org/10.1111/j.1467-9868.2011.00777.x

Malick, M. J., Hunsicker, M. E., Haltuch, M. A., Parker-Stetter, S. L., Berger, A. M., and Marshall, K. N. 2020. Relationships between temperature and Pacific hake distribution vary across latitude and life-history stage. Marine Ecology Progress Series 639: 185–197. https://doi.org/10.3354/meps13286

Phillips, E. M., Malick, M. J., Gauthier, S., Haltuch, M. A., Hunsicker, M. E., Parker-Stetter, S. L., and Thomas, R. E. 2023. The influence of temperature on Pacific hake co-occurrence with euphausiids in the California Current Ecosystem. Fisheries Oceanography 32(3): 267–279. https://doi.org/10.1111/fog.12628

R Core Team. 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Robin, N., Turck, N., Hainard, A., Tiberti, N., Lisacek, F., Sanchez, J.C., and Müller, M. 2011. pROC: an open-source package for R and S+ to analyze and compare ROC curves. BMC Bioinformatics 12: 77. https://doi.org/10.1186/1471-2105-12-77

Rosemond, R.C. 2023. Influence of novel ocean conditions on life history characteristics of a nearshore rockfish with implications for population assessment and management. Oregon State University. URL: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/8p58pp02d

Shono, H. 2008. Application of the Tweedie distribution to zero-catch data in CPUE analysis. Fisheries Research 93(1–2): 154–162. https://doi.org/10.1016/j.fishres.2008.03.006

G.5 Tables

Table G.1. Samples included in our analysis (after filtering), by sampling platform and year.

Platform	2009	2012	2013	2014	2015	2016	2017	2018	2019	2021
ASHOP	0	0	135	196	131	194	177	0	0	0
Acoustic	0	181	186	0	160	131	57	54	59	68
WCGBT	244	64	63	197	216	66	102	109	46	0

Table G.2. Comparison of Akaike information criterion (AIC) values from the three models in our analysis. Model 1 represents the baseline model, Model 2 represents the model with spatiotemporal variation but no covariates, and Model 3 represents the model with spatial variation and a temperature effect. For the temperature effect, this table represents estimates from models using temperature in February, at a depth of 130.67 m, and only north of Point Conception. The best models (lowest AIC) for each combination are in bold.

ASHOP	Include South	Model 1	Model 2	Model 3
Y	Y	1440.12	**1334.68**	1366.41
Y	N	1277.58	1209.28	**1195.94**
N	N	1688.75	**893.45**	902.61
N	Y	1912.61	**1014.13**	1025.47

Table G.3. Parameter estimates and standard errors estimated for the three models of maturity in our analyses (including samples from the At-Sea Hake Observer Program (ASHOP) and only samples north of Pt. Conception). Estimates of fixed effects are in logit space. The spatial range and spatial variance (σ_O) are also included for models with those terms.

Model	Term	Estimate	Std Error
1	age	4.460	0.2010
1	age^2	-1.060	0.0557
1	ashopFALSE	3.510	0.1900
1	ashopTRUE	4.290	0.2200
2	age	4.520	0.2840
2	age^2	-1.350	0.1050
2	ashopFALSE	3.740	0.3700
2	ashopTRUE	5.200	0.6910
2	range	191.000	85.4000
2	σ_O	0.653	0.3660
3	age	4.510	0.2880
3	age^2	-1.350	0.1020
3	temp	0.421	0.0994
3	$temp^2$	-0.535	0.0754
3	ashopFALSE	4.360	0.3050
3	ashopTRUE	6.050	0.6770
3	range	202.000	95.2000
3	σ_O	0.544	0.4480

Table G.4. Parameter estimates and standard errors estimated for the model of hake biomass from the West Coast Groundfish Bottom Trawl Survey (WCGBTS). The spatial range is included, with spatial variance (σ_O), spatiotemporal variance (σ_E), and Tweedie parameters (ϕ, p).

Term	Estimate	Std. Error
range	33.50	2.20000
ϕ	21.80	0.36700
σ_O	3.78	0.19700
σ_E	1.68	0.05410
p	1.64	0.00368

G.6 Figures

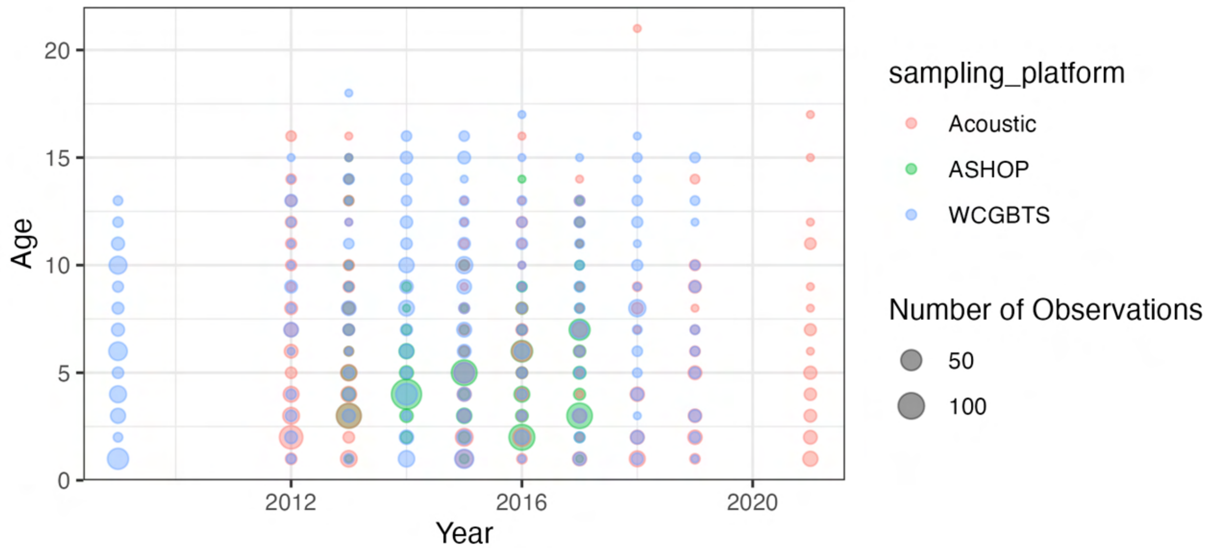

Figure G.1. Breakdown of the number of observations by age, year, and sampling platform (i.e., West Coast Groundfish Bottom Trawl Survey (WCGBTS), At-Sea Hake Observer Program (ASHOP), and the Northwest Fisheries Science Center Integrated Pacific Hake Ecosystem and Acoustic-Trawl Survey).

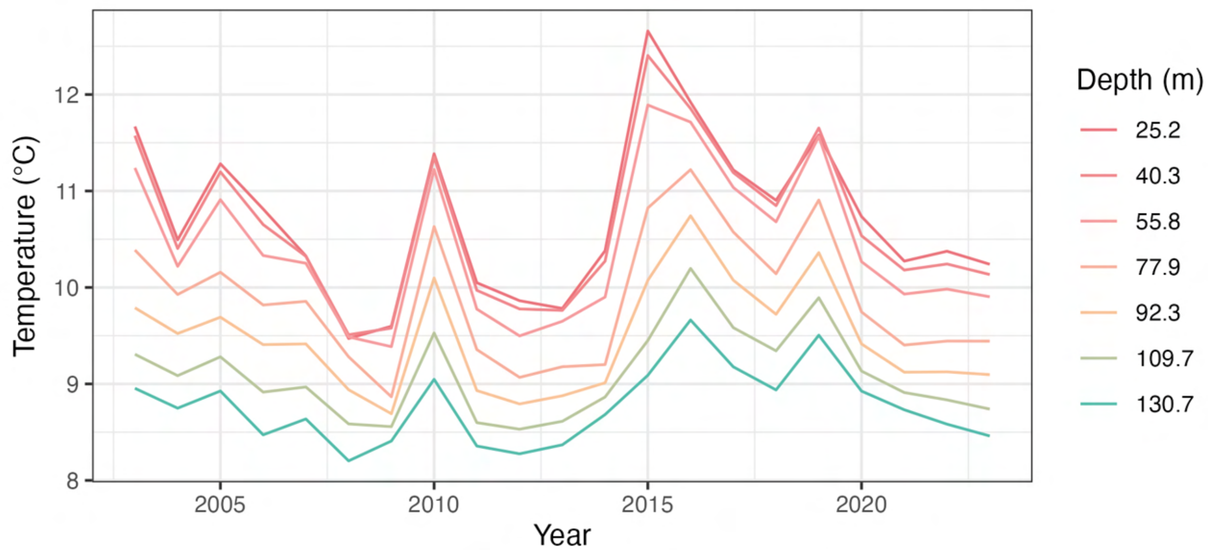

Figure G.2. Average GLORYS12v1 potential temperature (degrees Celsius) within the domain of the West Coast Groundfish Bottom Trawl Survey (WCGBTS) north of Point Conception, in February by depth (m; colors).

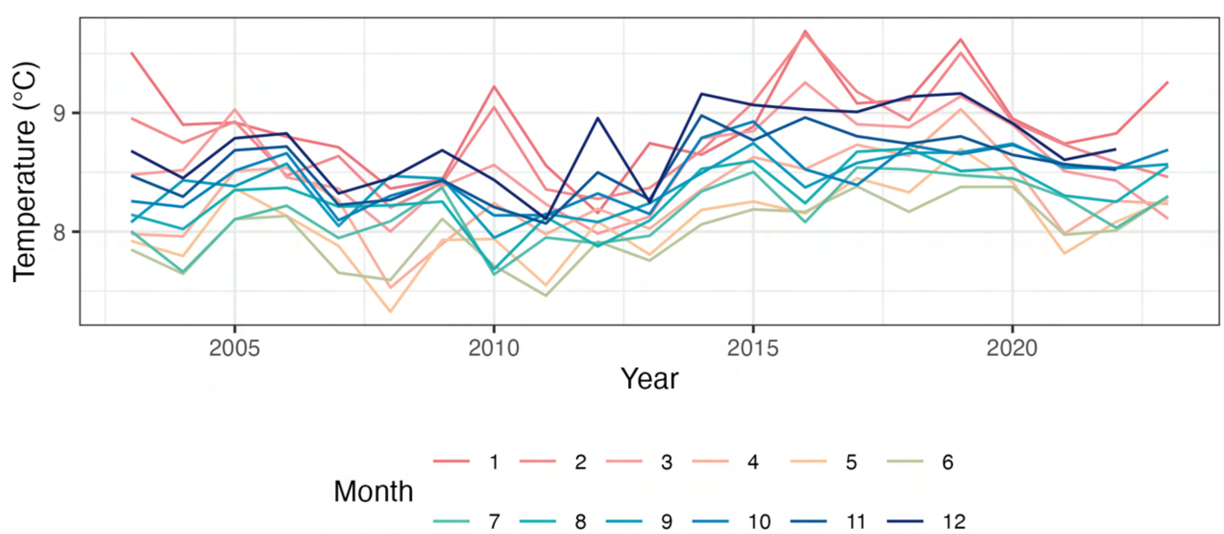

Figure G.3. Average GLORYS12v1 potential temperature (degrees Celsius) within the domain of the West Coast Groundfish Bottom Trawl Survey (WCGBTS) north of Point Conception, at a depth of 130.67 m by month (colors).

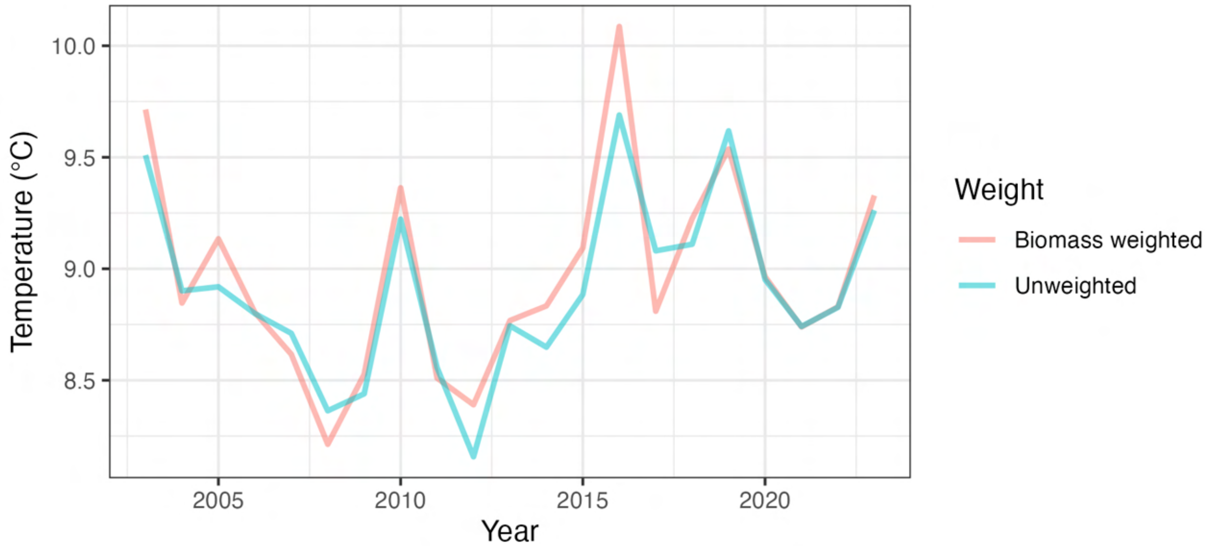

Figure G.4. Comparison of temperature indices (Celsius) using raw averages of temperature (red) and biomass weighted averages of temperature (blue). Shown is temperature at a depth of 130.67 m in January but only for north of Point Conception.

Figure G.5. The estimated effect of day of the year on maturation from Model 3 (see Table G.2) using a penalized spline.

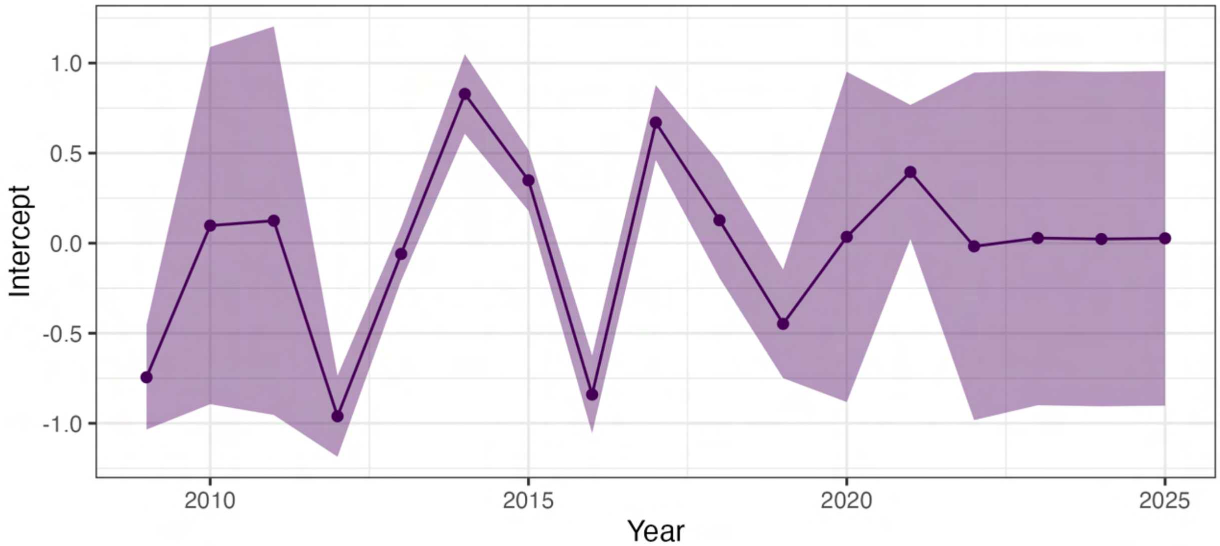

Figure G.6. Estimated and predicted year effects from the spatiotemporal hake maturity model without covariates (Model 2 in Tables G.2 and G.3). Year effects are included as an autocorrelated random walk (variance is larger in years without data, such as 2010–2011 or 2022–2025), and spatiotemporal effects are modeled with an AR(1) process.

Figure G.7. Spatial anomalies in predictions of maturity for ages 1–5. Predictions are centered such that blue represents lower than average maturation and red represents higher than average. Predictions are from Model 3 (see Table G.2) for year 2020. Slight variations between ages are driven by the spatially varying coefficient effect of age.

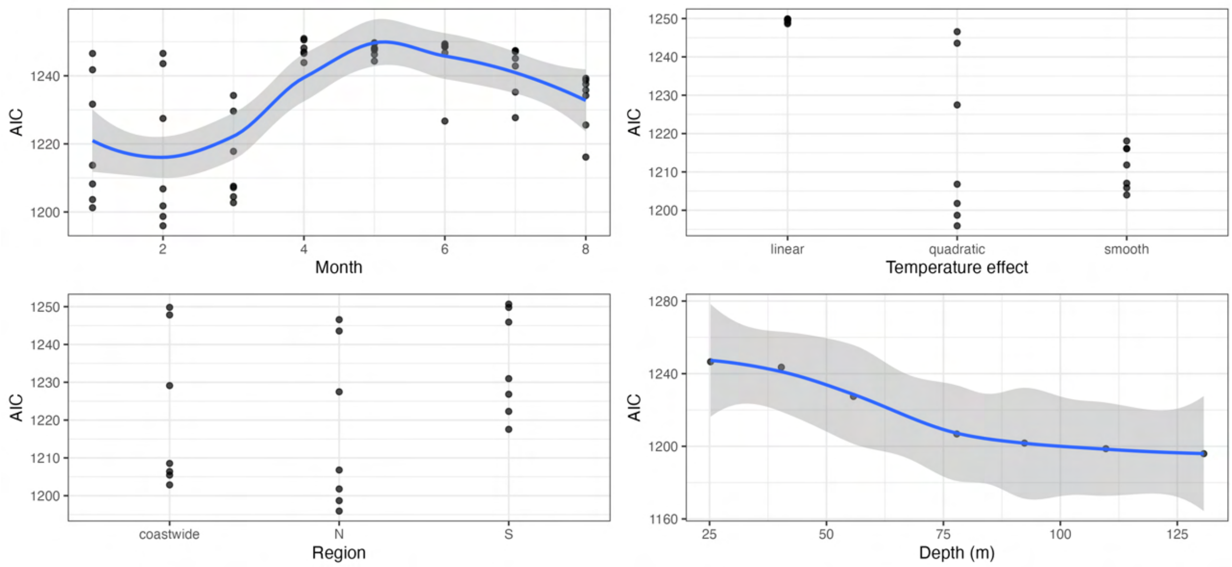

Figure G.8. Sensitivity results for the effect of temperature, with data coming from different months and depths, summarized by different regions (`N` = north of Point Conception, `S` = south of Point Conception) and modeled using different functional relationships (linear, quadratic, and penalized spline, i.e., 'smooth'). In all cases, the raw Akaike information criterion (AIC) values are shown where a lower AIC corresponds to support for the model from the data.

Figure G.9. Biomass weighted estimates of maturity for each of the three models in our analysis (using samples from the At-Sea Hake Observer Program (ASHOP) and data north of Point Conception). Predictions of functional maturity are for non-ASHOP samples.

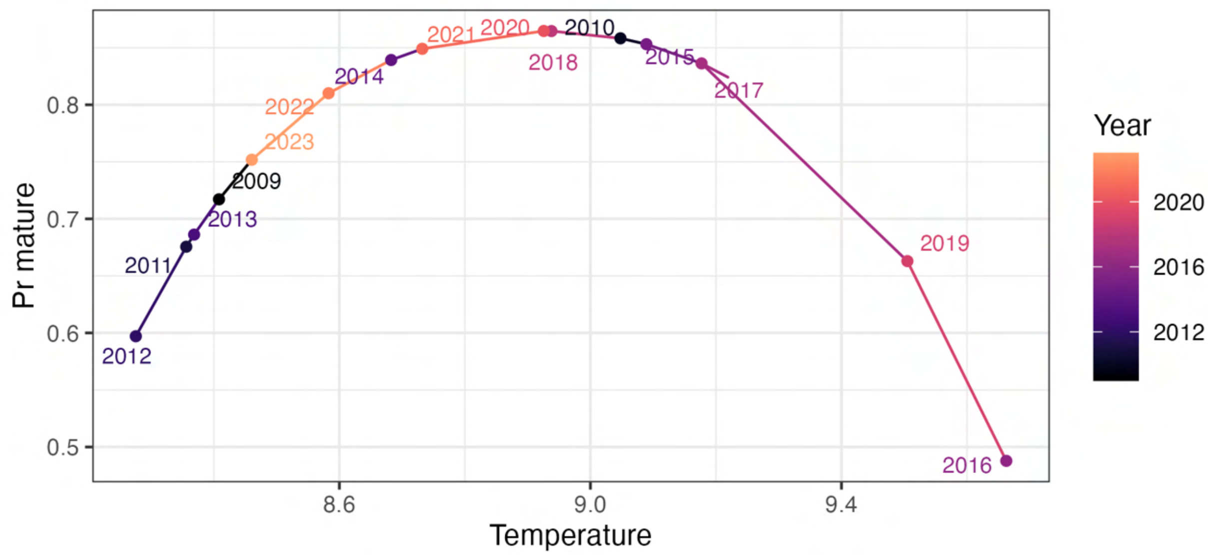

Figure G.10. Estimated marginal effect of February temperature (Celsius) at a depth of 130.67 m when fit to data that included samples from the At-Sea Hake Observer Program (ASHOP) and only data north of Point Conception. Predictions are made for age-3 fish, using coefficients corresponding to the non-ASHOP surveys, and for the 278th day of the year.

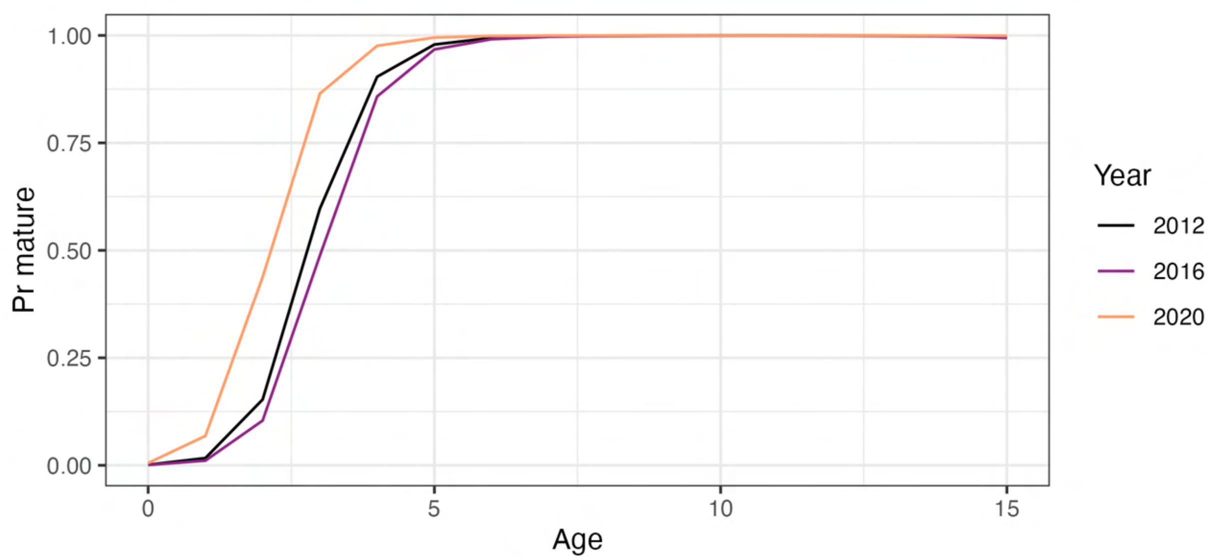

Figure G.11. Estimated ogives in three years representing low temperatures (2012), average temperatures (2020), and high temperatures (2016). The model of maturity used February temperature at a depth of 130.67 m and was fit to data that included samples from the At-Sea Hake Observer Program (ASHOP) and only data north of Point Conception. Ogives represent Pacific Hake not sampled by ASHOP. The estimated age at 50% maturity is 2.81 in 2020, versus 3.58 in 2012, and 3.82 in 2016.

Figure G.12. Estimated center of gravity of Pacific Hake biomass from the West Coast Groundfish Bottom Trawl Survey (WCGBTS), using 2003–2023 data.