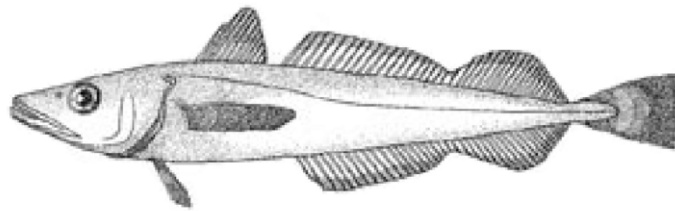


Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2022



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

February 22nd, 2022

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

Authors of this document are (all authors contribute extensively so the order rotates annually):

Andrew M. Edwards¹

Aaron M. Berger²

Chris J. Grandin¹

Kelli F. Johnson³

¹*Pacific Biological Station, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, B.C. V9T 6N7, Canada*

²*Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 2032 SE OSU Dr. Bldg. 955, Newport, OR 97365-5275, USA*

³*Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 2725 Montlake Blvd. East, Seattle, WA 98112-2097, USA*

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ONE-PAGE SUMMARY

- The stock assessment model for 2022 has the same population dynamics structure as the 2021 model. For 2022, it is fit to an acoustic survey index of biomass, an index of age-1 fish, annual commercial catch data, and age-composition data from the survey and commercial fisheries. The addition of the age-1 index is the main change in data streams from 2021.
- Updates to the data include: the new biomass estimate and age-composition data from the acoustic survey conducted in 2021, fishery catch and age-composition data from 2021, weight-at-age data for 2021, the addition of the age-1 index time series (1995–2021), and minor changes to pre-2021 data. Due to staffing issues, age data from 2021 were unavailable from the Canadian freezer-trawler fleet and minimally available for the shoreside fleet.
- Coast-wide catch in 2021 was 326,629 t [t represents metric tons], close to the average over the past decade of 329,035 t, out of a total allowable catch (TAC), adjusted for carryovers, of 473,880 t. Quotas were specified unilaterally in 2021 due to the lack of a bilateral TAC agreement. The U.S. caught 269,553 t (73.0% of their quota) and Canada caught 57,076 t (54.6% of their quota).
- The median estimate of the 2022 relative spawning biomass (female spawning biomass at the start of 2022 divided by that at unfished equilibrium, B_0) is 65% but is highly uncertain (with 95% credible interval from 31% to 135%). The median relative spawning biomass has progressively declined since 2019, due to the aging large cohorts (2010, 2014, and 2016) and relatively high catches. Based on limited data, the 2020 cohort looks likely to be large.
- The median estimate of female spawning biomass at the start of 2022 is 1,171,180 t (with 95% credible interval from 583,632 to 2,584,659 t). This is less than this assessment's median estimate for the 2021 female spawning biomass of 1,347,400 t (with 95% credible interval 743,081–2,896,386 t).
- The estimated probability that spawning biomass at the start of 2022 is below the $B_{40\%}$ (40% of B_0) reference point is 9.5%, and the probability that the relative fishing intensity exceeds its target in 2021 is 0%. The joint probability of both these occurring is 0%.
- Based on the default harvest rule, the estimated median catch limit for 2022 is 715,643 t (with 95% credible interval from 300,110 to 1,882,776 t).
- Projections are highly uncertain due to uncertainty in estimates of recruitment for recent years and so were conducted for a fairly wide range of catch levels. Projections setting the 2022 and 2023 catches equal to the 2021 coast-wide (unilaterally summed) TAC of 473,880 t show the estimated median relative spawning biomass increasing from 65% in 2022 to 71% in 2023 (due to the growth of the expected large 2020 cohort) then decreasing to 64% in 2024, with a 21% chance of the spawning biomass falling below $B_{40\%}$ in 2024. There is an estimated 41% chance of the spawning biomass declining from 2022 to 2023, and a 77% chance of it declining from 2023 to 2024 for these constant catches.

EXECUTIVE SUMMARY

STOCK

This assessment reports the status of the coastal Pacific Hake (or Pacific whiting, *Merluccius productus*) stock off the west coast of the United States and Canada at the start of 2022. This stock exhibits seasonal migratory behavior, ranging from offshore and generally southern waters during the winter spawning season to coastal areas between northern California and northern British Columbia during the spring, summer, and fall when the fishery is conducted. In years with warmer water the stock tends to move farther to the north during the summer. Older hake tend to migrate farther north than younger fish in all years, with catches in the Canadian zone typically consisting of fish greater than four years old. Separate, and much smaller, populations of hake occurring in the major inlets of the northeast Pacific Ocean, including the Strait of Georgia, Puget Sound, and the Gulf of California, are not included in this analysis.

CATCHES

Coast-wide fishery Pacific Hake landings averaged 241,467 t from 1966 to 2021, with a low of 89,930 t in 1980 and a peak of 440,950 t in 2017 (Figure a). Prior to 1966, total removals were negligible compared to the modern fishery. Over the early period (1966–1990) most removals were from foreign or joint-venture fisheries. Across the time series, catch in U.S. waters averaged 183,190 t, (76.2% of the total catch) while catch from Canadian waters averaged 58,277 t. Over the last 10 years, 2012–2021 (Table a), the average coast-wide catch was 329,035 t with U.S. and Canadian catches averaging 262,135 t and 66,900 t, respectively. The coast-wide catch in 2021 was 326,629 t, out of a total allowable catch (TAC, adjusted for carryovers) of 473,880 t. Attainment in the U.S. was 73.0% of its quota and in Canada it was 54.6%.

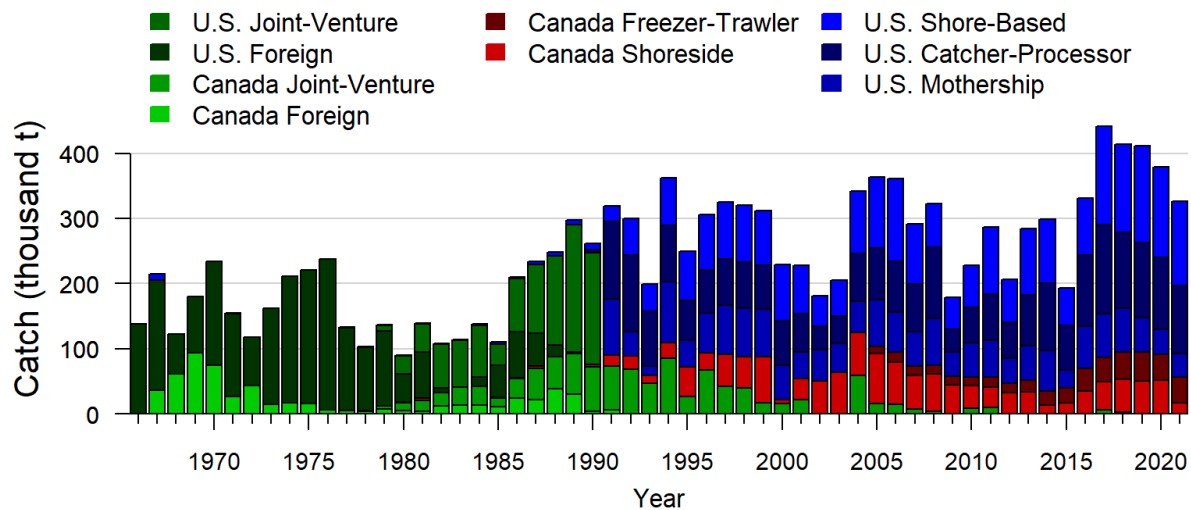


Figure a. Total Pacific Hake catch used in the assessment by sector, 1966–2021. U.S. tribal catches are included in the sectors where they are represented.

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

Year	US Mother- ship	US Catcher- Processor	US Shore- Based	US Research	US Total	CAN Joint- Venture	CAN Shoreside	CAN Freezer- Trawler	CAN Total	Total
2012	38,512	55,264	65,919	448	160,144	0	32,147	14,912	47,059	207,203
2013	52,470	77,950	102,141	1,018	233,578	0	33,665	18,584	52,249	285,828
2014	62,102	103,203	98,640	197	264,141	0	13,326	21,792	35,118	299,259
2015	27,665	68,484	58,011	0	154,160	0	16,775	22,909	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	150,841	0	354,229	5,608	43,427	37,686	86,721	440,950
2018	67,121	116,073	135,112	0	318,306	2,724	50,747	41,942	95,413	413,719
2019	52,646	116,146	148,210	0	317,002	0	50,621	43,950	94,571	411,574
2020	37,978	111,147	138,688	95	287,908	0	51,551	39,812	91,362	379,271
2021	35,219	104,030	130,304	0	269,553	0	16,953	40,123	57,076	326,629

In this stock assessment, the terms catch and landings are used interchangeably. Estimates of discard within the target fishery are included, but discarding of Pacific Hake in non-target fisheries is not. Discard from all fisheries, including those that do not target hake, is estimated to be less than 1% of landings in recent years. During the last five years, catches were considerably above the long-term average catch (241,467 t), with 2017–2020 having the highest catches on record. Landings between 2001 and 2008 were predominantly comprised of fish from the very large 1999 year class, with the cumulative removal (through 2021) from that cohort estimated at approximately 1.29 million t. Through 2021, the cumulative catch of the 2010, 2014, and 2016 year classes is estimated to be about 1.22 million t, 0.72 million t, and 0.43 million t, respectively. In the 2021 catch, the 2016 cohort was the largest (36%), followed by the 2014 cohort (24%), then the 2017 cohort (14%). Due to staffing issues, age data from 2021 were unavailable from the Canadian freezer-trawler fleet and minimally available for the shoreside fleet.

DATA AND ASSESSMENT

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

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

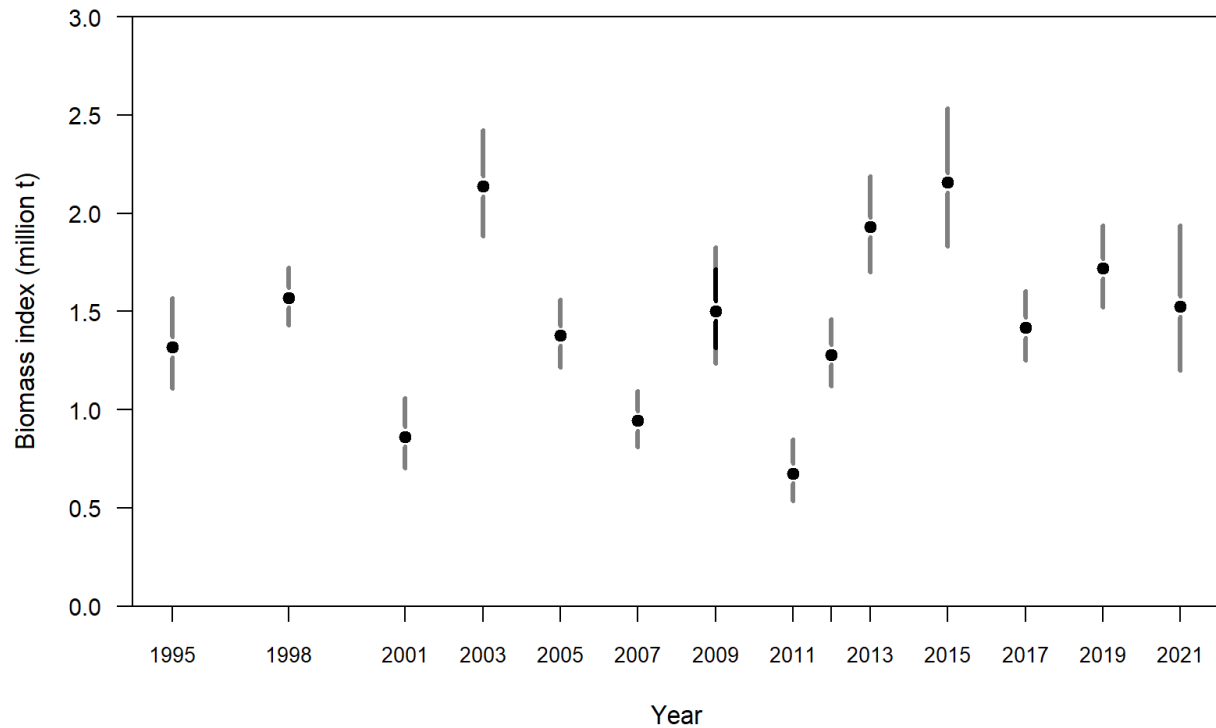


Figure b. Acoustic survey biomass index of age-2+ fish (millions of tons). Approximate 95% confidence intervals are based on sampling variability (intervals without squid/hake apportionment uncertainty in 2009 are displayed in black).

stock productivity), and several other parameters, with likelihoods for the acoustic survey biomass index, acoustic survey age-composition data, the age-1 index, and fishery age-composition data. Integrating the joint posterior distribution over model parameters provides probabilistic inferences about uncertain model parameters and forecasts derived from those parameters; this is done via Markov chain Monte Carlo sampling using the efficient No-U-Turn Sampler (NUTS) that was successfully tested in 2020 and used for the 2021 assessment. Sensitivity analyses are used to identify alternative model assumptions that may also be consistent with the data. This is the first time the entire assessment, including model bridging, sensitivity, and retrospective analyses, has used only Bayesian estimation (rather than some maximum likelihood 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, 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.

This 2022 assessment retains the same general population dynamics structure as the base assessment model from 2021 as well as many of the previous elements as configured in Stock Synthesis. The main change from 2021 is the addition of the age-1 index to help inform recent and current recruitment expectations. Analyses conducted in 2014 showed that allowing for time-varying (rather

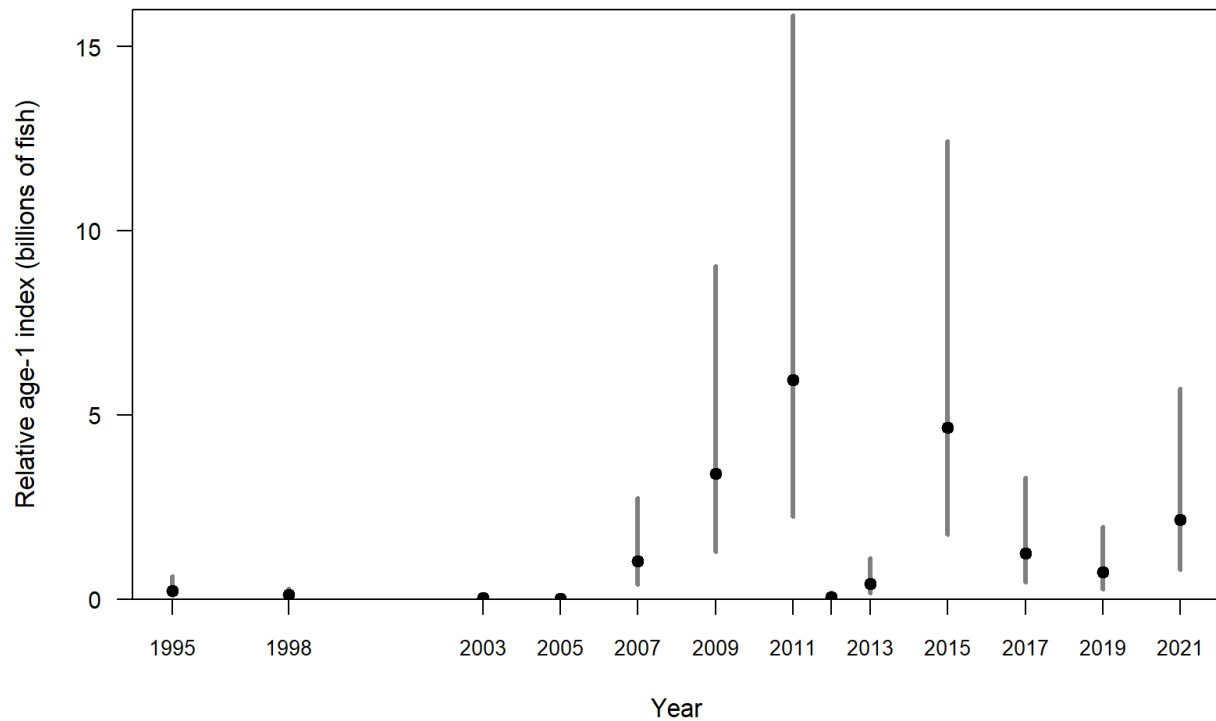


Figure c. Relative acoustic survey index of age-1 fish (numbers of fish) and approximate 95% confidence intervals based on sampling variability. The index is relative because the survey does not attempt to sample all available age-1 fish and the analysis does not include kriging like what is done to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

than fixed) selectivity reduced the magnitude of extreme cohort strength estimates. In closed-loop simulations, management based upon assessment models parameterized with time-varying fishery selectivity led to higher median average catch, lower risk of falling below 10% of unfished biomass, smaller probability of fishery closures, and lower inter-annual variability in catch compared to assessment models parameterized with time-invariant fishery selectivity. Even a small degree of flexibility in the fishery selectivity could reduce the effects of errors caused by assuming selectivity is constant over time. Therefore, we retain time-varying selectivity in this assessment. We retain the Dirichlet-multinomial estimation approach to weighting composition data, and again investigate sensitivity to an alternative data-weighting approach. Time-varying fecundity, which was introduced in 2019, is retained. The weight-at-age information for the forecast period is a representation of the last five years, as for the 2021 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. The stock is estimated to have increased rapidly and was above unfished equilibrium in the mid-1970s and mid-1980s (after two large recruitments

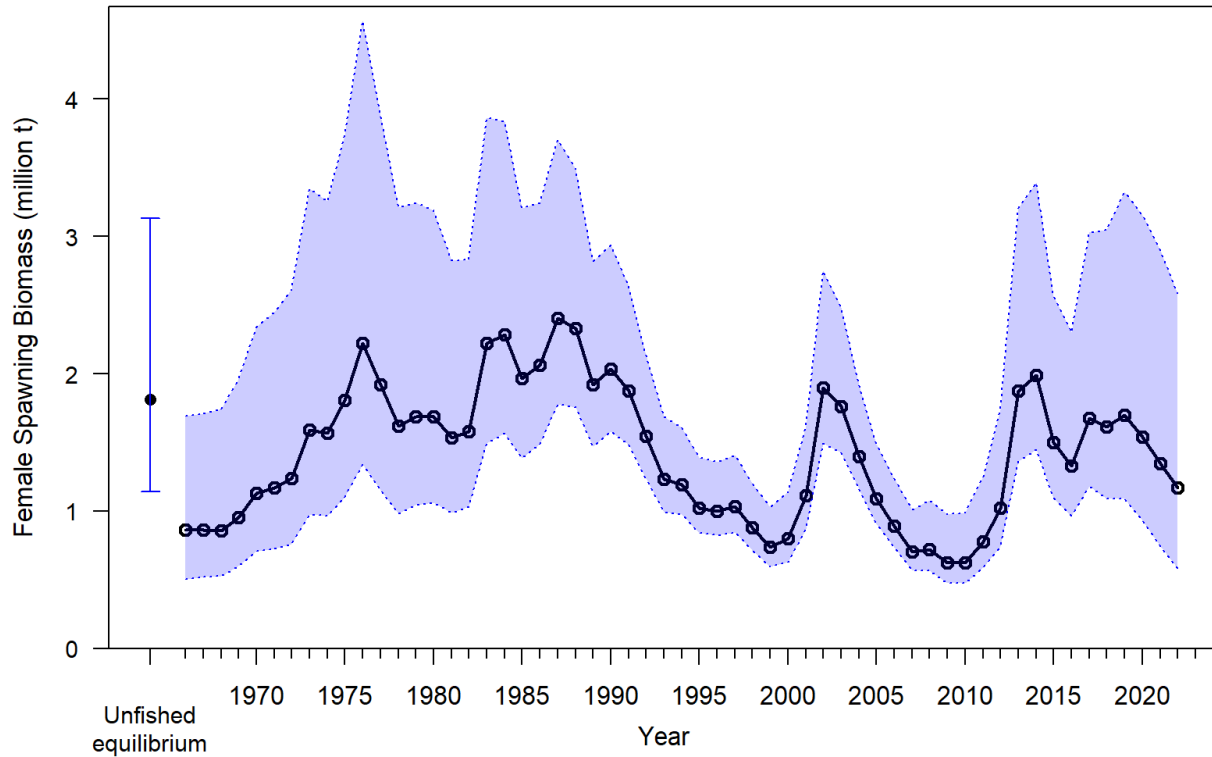


Figure d. Median of the posterior distribution for beginning of the year female spawning biomass (B_t in year t) through 2022 (solid line) with 95% posterior credibility intervals (shaded area). The solid circle with a 95% posterior credibility interval is the estimated unfished equilibrium biomass.

in the early 1980s). It then declined steadily to a low in 1999. This was followed by a brief increase to a peak in 2002 as the very large 1999 year class matured. The 1999 year class largely supported the fishery for several years due to relatively small recruitments between 2000 and 2007. With the aging 1999 year class, median female spawning biomass declined throughout the late 2000s, reaching a time-series low of 0.625 million t in 2010. Median spawning biomass is estimated to have peaked again in 2013 and 2014 due to a very large 2010 year class and an above-average 2008 year class. The subsequent decline from 2014 to 2016 is primarily from the 2010 year class surpassing the age at which 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, increasing the biomass in 2017. The estimated biomass was relatively steady from 2017 to 2019, and then declined in 2020 and 2021 due to the 2014 and 2016 year classes moving through the growth-mortality transition during a period of high catches.

The median estimate of the 2022 relative spawning biomass (spawning biomass at the start of 2022 divided by that at unfished equilibrium, B_0) is 65%. However, the uncertainty is large, with a 95% posterior credibility interval from 31% to 135% (Table b). The median estimate of the 2022 female spawning biomass is 1.171 million t (with a 95% posterior credibility interval from 0.584 to 2.585 million t). The current estimate of the 2021 female spawning biomass is 1.347 (0.743–2.896) million t. This is a somewhat higher median and broader credibility interval than the 0.981

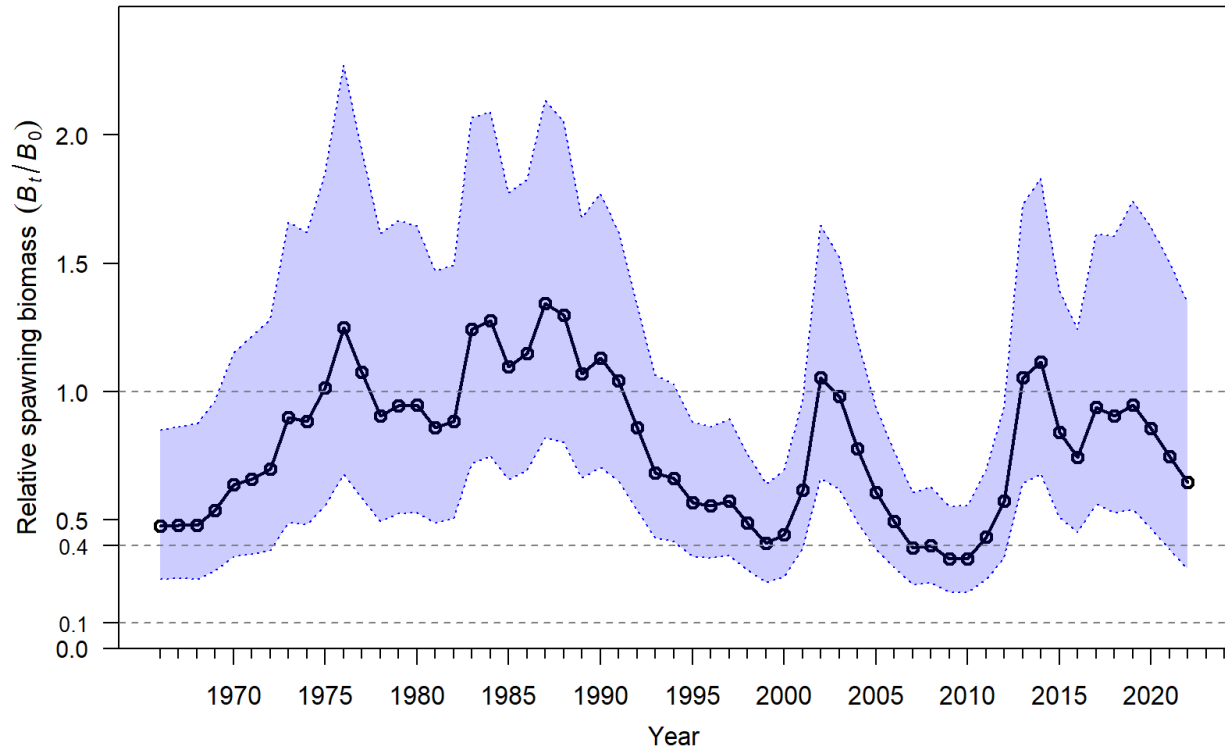


Figure e. Median (solid line) of the posterior distribution for relative spawning biomass (B_t/B_0) through 2022 with 95% posterior credibility intervals (shaded area). Dashed horizontal lines show 10%, 40% and 100% levels.

(0.404–2.388) million t estimated in the 2021 assessment. The increase appears to be due to the addition of survey data, namely the 2021 biomass index and age compositions, plus the full age-1 index.

RECRUITMENT

The new data available and addition of the age-1 index for this assessment do not significantly change the pattern of recruitment estimated in recent assessments. However, estimates of absolute recruitment for some recent years have increased. For example, this assessment’s median estimate of the 2014 recruitment is 0.4 billion fish higher than in last year’s assessment (a 5% increase). Similarly, estimates for the large 2016 and small 2018 recruitments have increased by 33% (1.6 billion fish) and 271% (0.5 billion fish), respectively, but the general notion remains that the 2016 cohort is above average and the 2018 cohort is below average.

Pacific Hake appear to 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. Current estimates continue to indicate a very strong 2010 year class comprising 64% of the coast-wide commercial catch in 2014, 33% of the 2016 catch, 23% of the 2018 catch (all unchanged

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

Year	Spawning biomass (thousand t)			Relative spawning biomass (B_t/B_0)		
	2.5 th percentile	Median	97.5 th percentile	2.5 th percentile	Median	97.5 th percentile
2013	1,365.1	1,878.1	3,207.0	64.4%	105.3%	172.9%
2014	1,450.9	1,986.9	3,391.3	68.0%	111.6%	183.2%
2015	1,095.7	1,501.6	2,569.7	51.2%	84.1%	139.3%
2016	965.0	1,327.8	2,299.7	45.2%	74.5%	124.5%
2017	1,181.8	1,676.4	3,028.3	56.3%	93.9%	161.4%
2018	1,088.8	1,615.0	3,048.6	52.9%	90.4%	160.7%
2019	1,093.3	1,697.2	3,323.3	54.0%	94.7%	174.2%
2020	929.5	1,538.2	3,154.6	46.7%	85.7%	164.3%
2021	743.1	1,347.4	2,896.4	38.6%	74.8%	150.5%
2022	583.6	1,171.2	2,584.7	31.1%	64.7%	134.7%

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

Year	Absolute recruitment (millions)			Recruitment deviations		
	2.5 th percentile	Median	97.5 th percentile	2.5 th percentile	Median	97.5 th percentile
2012	1,048.6	1,715.6	3,473.4	0.129	0.650	1.178
2013	123.2	381.2	1,003.2	-2.035	-0.919	-0.088
2014	6,019.1	9,311.6	18,581.6	1.771	2.281	2.805
2015	8.7	42.5	177.5	-4.614	-3.112	-1.768
2016	3,791.0	6,417.8	13,868.6	1.370	1.940	2.556
2017	1,197.7	2,575.9	6,597.6	0.196	1.001	1.799
2018	171.5	664.6	2,100.0	-1.652	-0.360	0.686
2019	235.3	1,002.1	3,515.6	-1.356	0.038	1.217
2020	935.0	5,224.0	24,333.3	0.022	1.702	3.171
2021	45.3	934.4	20,814.4	-3.008	0.014	3.025

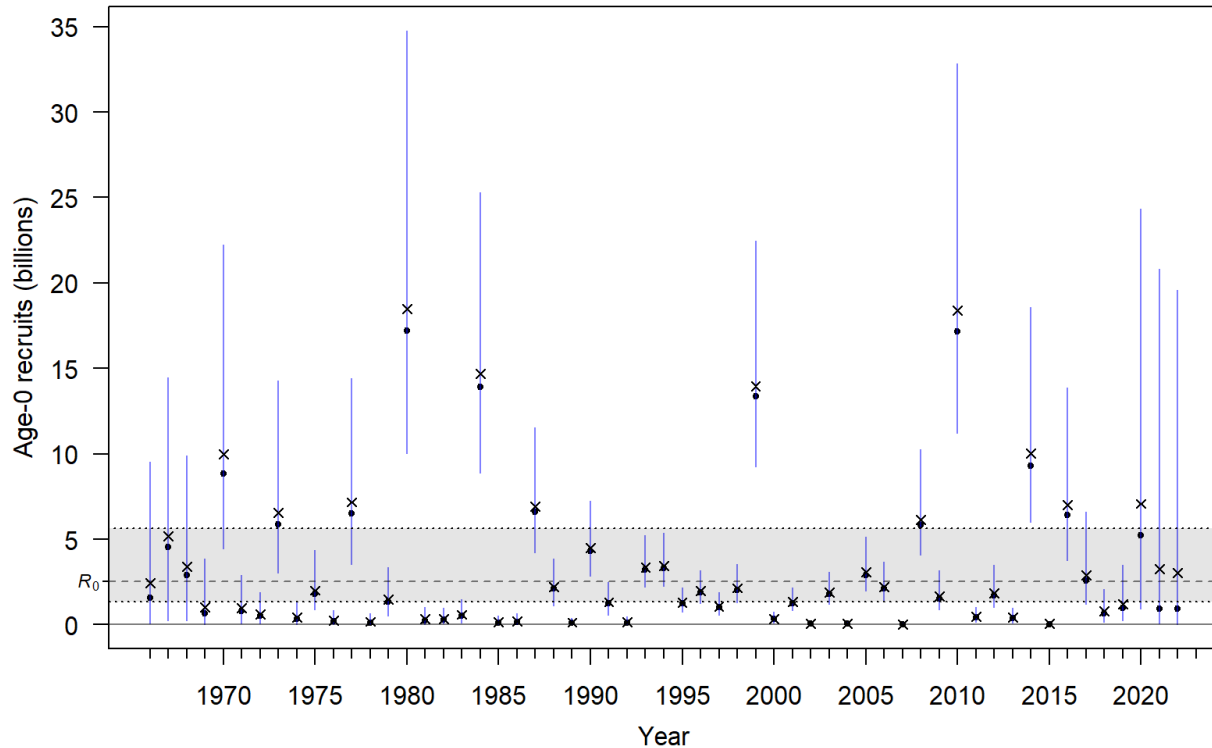


Figure f. Medians (solid circles) and means (\times) of the posterior distribution for recruitment (billions of age-0) with 95% posterior credibility intervals (blue lines). The median of the posterior distribution for mean unfishes equilibrium recruitment (R_0) is shown as the horizontal dashed line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

from last year's assessment), and 14% of the 2020 catch. The decline from 2014 to 2016 was partly due to the large influx of the 2014 year class (50% of the 2016 catch was age-2 fish from the 2014 year class; this was larger than the proportion of age-2 fish, 41%, from the 2010 year class in 2012). The median estimate of the 2010 year class is very slightly below the highest ever (for 1980), with a 50% probability that the 2010 year class is larger than the 1980 year class (this probability was 46% for last year's assessment). Since 2010, the model currently estimates small 2011, 2012, 2013, 2015, 2017, 2018, and 2019 year classes (median recruitment well below the mean of all median recruitments).

The 2014 and 2016 year classes are likely both larger than average, with a very high chance (99%) that 2014 is larger than 2016, but zero chance that it is larger than 2010. With the addition of the age-1 index, there is information beyond just fishery encounters in the data to estimate the size of the 2020 year class. Collectively, these data indicate that the 2020 year class is likely above average, while the 2019 year class is informed by the 2021 biomass index and fishery data, but has no age-1 index. There is no information in the data to estimate the sizes of the 2021 and 2022 year classes. Retrospective analyses of year class strength for young fish have shown the estimates of recent recruitment to be unreliable prior to at least model age-3 (observed at age-2) without a survey in the most recent year and age-2 (observed at age-1) with a survey.

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

Year	Relative fishing intensity			Exploitation fraction		
	2.5 th percentile	Median	97.5 th percentile	2.5 th percentile	Median	97.5 th percentile
2012	0.383	0.639	0.916	0.031	0.054	0.074
2013	0.374	0.614	0.826	0.038	0.065	0.090
2014	0.344	0.587	0.820	0.039	0.066	0.091
2015	0.234	0.433	0.654	0.034	0.058	0.080
2016	0.408	0.694	0.950	0.049	0.086	0.119
2017	0.440	0.735	1.072	0.064	0.117	0.166
2018	0.389	0.683	0.999	0.050	0.094	0.140
2019	0.387	0.681	0.969	0.051	0.100	0.157
2020	0.317	0.587	0.840	0.054	0.112	0.186
2021	0.276	0.528	0.786	0.050	0.107	0.196

DEFAULT HARVEST POLICY

The default $F_{SPR=40\%}$ -40:10 harvest policy prescribes the maximum rate of fishing mortality to equal $F_{SPR=40\%}$. This rate gives a spawning potential ratio (SPR) of 40%, meaning that the spawning biomass per recruit with $F_{SPR=40\%}$ is 40% of that without fishing. If 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 $(1 - SPR(F))/(1 - SPR_{40\%})$, where $SPR_{40\%}$ is the target SPR of 40%; it is reported here interchangeably as a decimal proportion or a percentage.

EXPLOITATION STATUS

The median estimated relative fishing intensity on the stock is below the target of 1.0 for all years (see Table d for recent years and Figure g). Median exploitation fraction (catch divided by biomass of fish of age-2 and above) peaked in 2006 and reached similar levels in 1999 and 2008 (Figure h). Over the last five years, the median estimated exploitation fraction was the highest in 2017 followed closely by 2020 and 2021 (Table d). Note that in earlier assessments the exploitation fraction was often defined in terms of fish age-3 and above, but since the 2018 assessment the definition age was lowered to age-2, because these fish are often caught by the fishery. Median relative fishing intensity is estimated to have declined from 90.5% in 2010 to 43.3% in 2015, and then it leveled off around 70% from 2016 to 2019 before dropping to 58.7% in 2020 and 52.8% in 2021. The median exploitation fraction has increased from a recent low of 0.05 in 2012 to 0.12 in 2017 and has remained relatively stable since then (dropping no further than 0.09). There is a considerable amount of uncertainty around estimates of relative fishing intensity, with the 95% posterior credibility interval reaching above the SPR management target (of 1.0) in 2017 (Figure g).

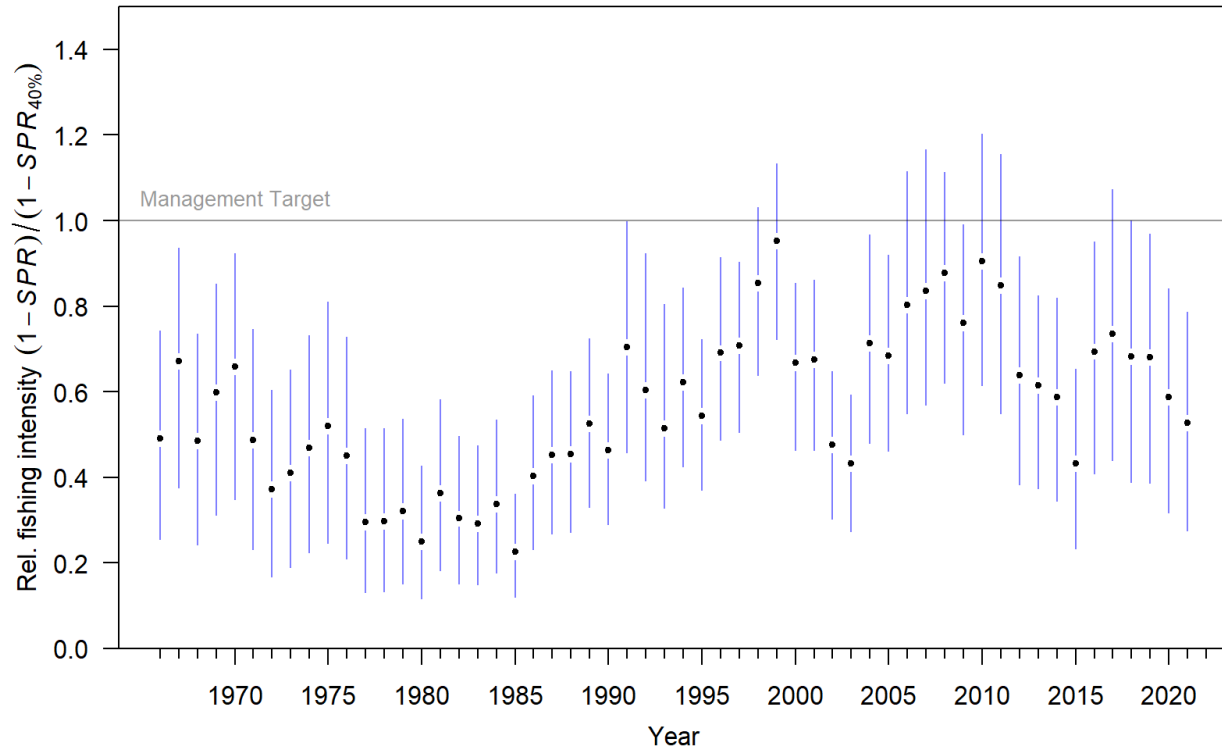


Figure g. Trend in median relative fishing intensity (relative to the SPR management target) through 2021 with 95% posterior credibility intervals. The management target defined in the Joint U.S.-Canada Agreement for Pacific Hake is shown as a horizontal line at 1.0.

MANAGEMENT PERFORMANCE

Over the last decade (2012–2021), the mean coast-wide utilization rate (proportion of catch target removed) has been 69.4% (Table e). Over the last five years (2017 to 2021), the mean utilization rates were 73.0% for the United States and 63.9% for Canada. 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 2021 U.S. catch target was 77.95% of the total coast-wide catch target, and the Canada catch target was 22.05%. These percentages are different to the usual 73.88% and 26.12% as specified in the Joint U.S.-Canada Agreement for Pacific Hake.

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

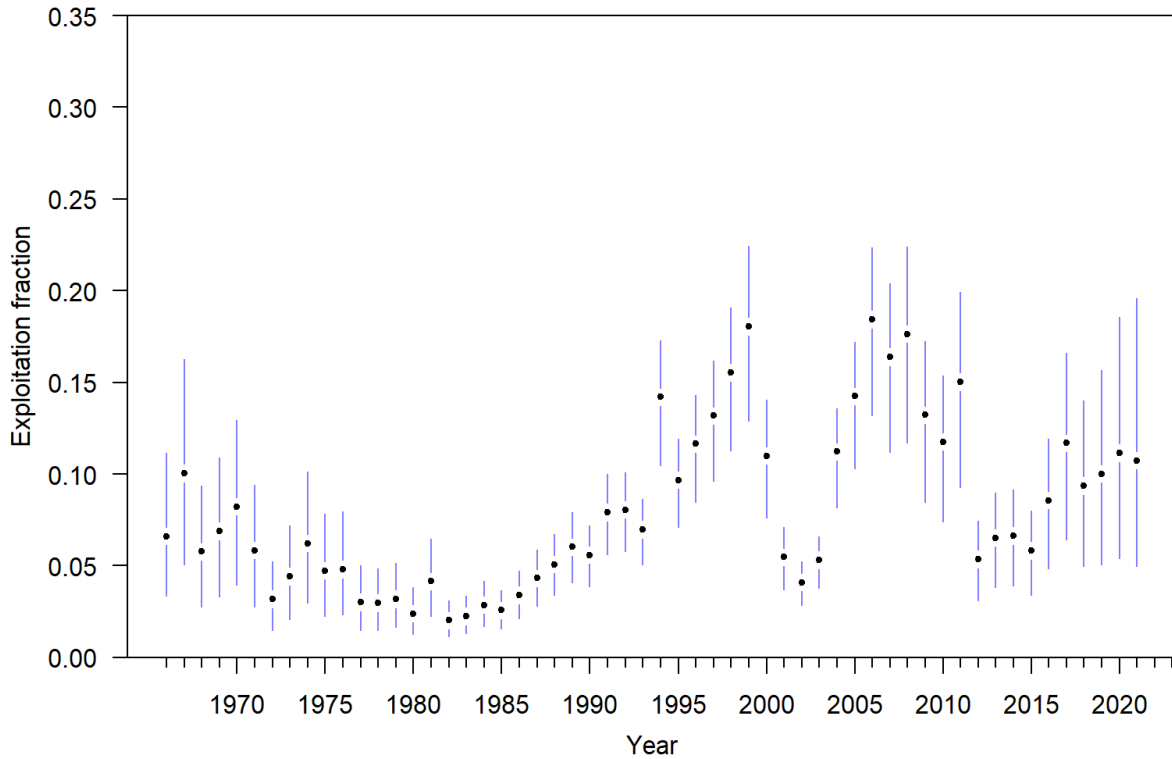


Figure h. Trend in median exploitation fraction (catch divided by age-2+ biomass) through 2021 with 95% posterior credibility intervals.

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

Year	U.S. landings (t)	Canada landings (t)	Total landings (t)	U.S. proportion of total catch	Canada proportion of total catch	U.S. catch target (t)	Canada catch target (t)	Coast-wide catch target (t)	U.S. proportion of catch target removed	Canada proportion of catch target removed	Total proportion of catch target removed
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	354,229	86,721	440,950	80.3%	19.7%	441,433	156,067	597,500	80.2%	55.6%	73.8%
2018	318,306	95,413	413,719	76.9%	23.1%	441,433	156,067	597,500	72.1%	61.1%	69.2%
2019	317,002	94,571	411,574	77.0%	23.0%	441,433	156,067	597,500	71.8%	60.6%	68.9%
2020	287,908	91,362	379,271	75.9%	24.1%	424,810	104,480	529,290	67.8%	87.4%	71.7%
2021	269,553	57,076	326,629	82.5%	17.5%	369,400	104,480	473,880	73.0%	54.6%	68.9%

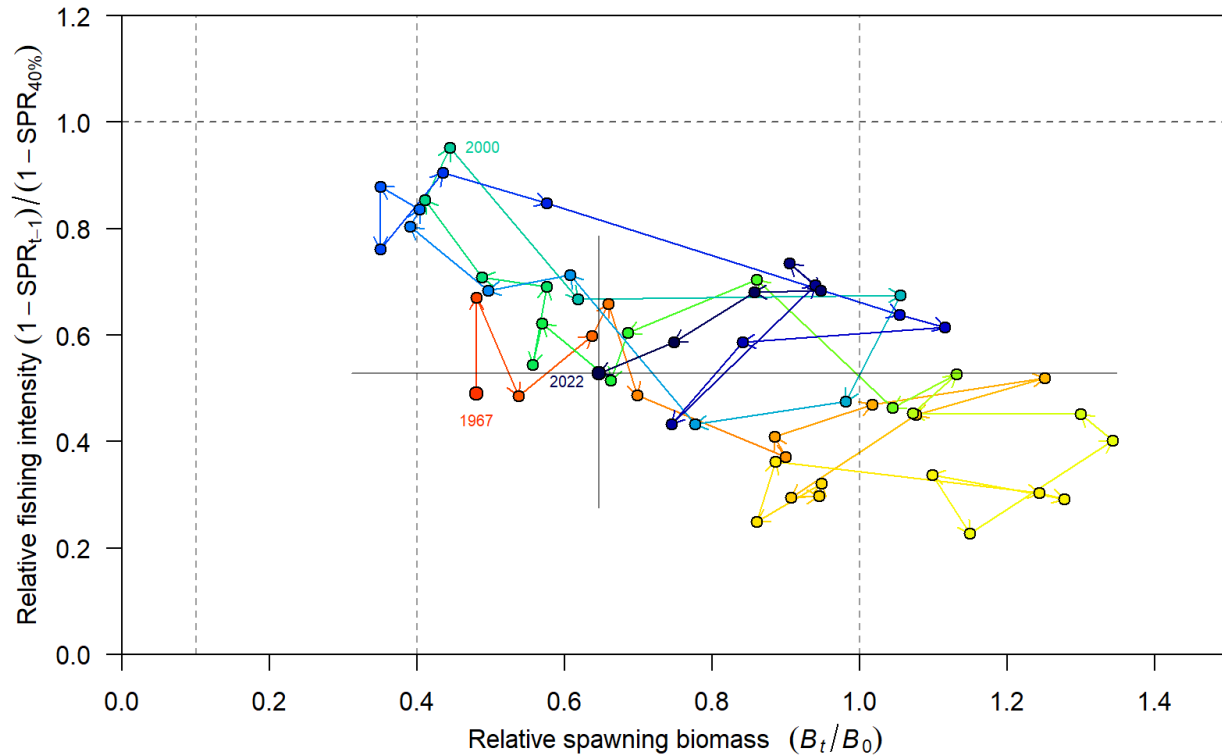


Figure i. Estimated historical path of median relative spawning biomass in year t and corresponding median relative fishing intensity in year $t - 1$. Labels show the start year, end year and year of highest relative fishing intensity; labels correspond to year t (i.e., year of the relative spawning biomass). Gray bars span the 95% credibility intervals for 2022 relative spawning biomass (horizontal) and 2021 relative fishing intensity (vertical).

The median relative fishing intensity was below target in all years (Figures g and i). The median relative female spawning biomass was above the $B_{40\%}$ reference point in all years except 2007, 2009, and 2010 (Figures e and i). The median relative fishing intensity has never been above the target of 1.0 (Figure i). This highlights the highly dynamic nature of the stock due to high variation in recruitment strength. The target fishing mortality ($F_{SPR=40\%}$) and $B_{40\%}$ result in different population sizes (see Table f), highlighting that there are subtle differences in these conceptual reference points. Between 2007 and 2010, median relative fishing intensity ranged from 76% to 91% and median relative spawning biomass between 0.35 and 0.40. Biomass has risen from the 2010 low with the 2008, 2010, 2014, and 2016 recruitments, and median relative spawning biomass has been above the reference point of 40% since 2011.

While there is large uncertainty in the estimates of relative fishing intensity and relative spawning biomass, the model estimates a 0% joint probability of being both above the target relative fishing intensity in 2021 and below the $B_{40\%}$ relative spawning biomass level at the start of 2022.

Table f. Summary of median and 95% credibility intervals of equilibrium conceptual reference points for the Pacific Hake base assessment model. Equilibrium reference points were computed using 1975–2021 averages for mean weight-at-age and baseline selectivity-at-age (1966–1990; prior to time-varying deviations).

Quantity	2.5 th percentile	Median	97.5 th percentile
Unfished female spawning biomass (B_0 , thousand t)	1,140	1,813	3,131
Unfished recruitment (R_0 , millions)	1,343	2,535	5,657
Reference points (equilibrium) based on $F_{SPR=40\%}$			
Female spawning biomass at $F_{SPR=40\%}$ ($B_{SPR=40\%}$, thousand t)	370	645	1,111
SPR at $F_{SPR=40\%}$	–	40%	–
Exploitation fraction corresponding to $F_{SPR=40\%}$	16.1%	18.5%	21.3%
Yield associated with $F_{SPR=40\%}$ (thousand t)	167	309	599
Reference points (equilibrium) based on $B_{40\%}$ (40% of B_0)			
Female spawning biomass ($B_{40\%}$, thousand t)	456	725	1,253
SPR at $B_{40\%}$	40.7%	43.5%	51.5%
Exploitation fraction resulting in $B_{40\%}$	12.4%	16.4%	19.6%
Yield at $B_{40\%}$ (thousand t)	168	301	583
Reference points (equilibrium) based on estimated MSY			
Female spawning biomass (B_{MSY} , thousand t)	278	465	878
SPR at MSY	22.5%	29.8%	46.7%
Exploitation fraction corresponding to SPR at MSY	14.7%	26.0%	35.2%
MSY (thousand t)	175	326	638

REFERENCE POINTS

The term ‘reference points’ is used throughout this document to describe common conceptual summary metrics. The Agreement specifically identifies $F_{SPR=40\%}$ 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). Estimates of the 2022 base model reference points with posterior credibility intervals are in Table f. The medians of sustainable yields and biomass reference points are almost 10% higher than in the 2021 assessment. This is a result of incorporating the age-1 index to help refine estimates of recruitment. The probability that spawning biomass at the beginning of 2022 is below $B_{40\%}$ is $P(B_{2022} < B_{40\%}) = 9.5\%$, and of being below $B_{25\%}$ is $P(B_{2022} < B_{25\%}) = 0.8\%$. The probability that the relative fishing intensity was above its target of 1.0 at the end of 2021 is 0%.

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.

A more extensive examination of sensitivity results are provided for a model that excludes the age-1 index (see Appendix G).

The Pacific Hake stock displays high recruitment variability relative to other west coast groundfish stocks, resulting in large and rapid biomass changes. This leads to a dynamic fishery that potentially targets strong cohorts and results in time-varying fishery selectivity. This volatility results in a high level of uncertainty in estimates of current stock status and stock projections because, with limited data to estimate incoming recruitment, the cohorts are fished before the assessment can accurately determine how big they are (i.e., cohort strength is typically not well known until it is observed by the fishery and survey, typically at minimum age-3). 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. 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 2022 based on the default $F_{SPR=40\%}$ -40:10 harvest policy has a median of 715,643 t with a wide range of uncertainty, the 95% credibility interval being 300,110–1,882,776 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 have been reorganized this year to improve interpretation so that the projected outcome for each potential catch level and year (each row) can be more readily evaluated across the quantiles (columns) of the posterior distribution. Tables now show the result of a third year of catches on subsequent estimates of stock status and fishing intensity. Figure j shows the projected biomass for several 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 (2017–2021); and all other parameters as constant.

A relative fishing intensity above 1 (or 100% when shown as a percentage) indicates fishing greater than the $F_{SPR=40\%}$ default harvest rate catch target. This can happen for the median relative fishing intensity in projected years because the $F_{SPR=40\%}$ default harvest-rate catch limit is calculated using baseline selectivity from all years, 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 in excess of the default harvest policy. Alternative catch levels where median relative fishing intensity is 100% for three years of projections are provided for comparison (scenario m: FI=100%).

Management metrics that were identified as important to the Joint Management Committee and the Advisory Panel in 2012 are presented for 2023, 2024 and 2025 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 2022 (Table i and Figure k). However,

Table g. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year. Catch alternatives are based on: constant catches (rows a, b, c, d, f, g, i, k, l), including catch similar to 2021 (row f) and to the (unilaterally summed) TAC from 2021 (row l); and non-constant catches that result in annual 10% declines in catch (rows e, h, j), median relative fishing intensity of 100% (row m), median catch estimated via the default harvest policy ($F_{SPR=40\%}=40:10$, row n), and the fishing intensity that results in a 50% probability that the median projected catch will remain the same in 2022 and 2023 (row o).

Management Action			Biomass at start of year	Resulting relative spawning biomass		
				5%	50%	95%
	Catch year	Catch (t)	Start of 2022	0.35	0.65	1.19
a:	2022	0	Start of 2023	0.43	0.83	1.70
	2023	0	Start of 2024	0.44	0.87	1.96
	2024	0	Start of 2025	0.44	0.87	2.01
b:	2022	180,000	Start of 2023	0.39	0.78	1.64
	2023	180,000	Start of 2024	0.36	0.79	1.86
	2024	180,000	Start of 2025	0.32	0.74	1.86
c:	2022	225,000	Start of 2023	0.37	0.77	1.63
	2023	225,000	Start of 2024	0.34	0.76	1.84
	2024	225,000	Start of 2025	0.29	0.71	1.83
d:	2022	270,000	Start of 2023	0.37	0.76	1.62
	2023	270,000	Start of 2024	0.32	0.74	1.82
	2024	270,000	Start of 2025	0.26	0.68	1.79
e: 10% reduction	2022	320,000	Start of 2023	0.35	0.75	1.60
	2023	288,000	Start of 2024	0.31	0.73	1.80
	2024	259,200	Start of 2025	0.25	0.67	1.78
f: 2021 catch	2022	325,000	Start of 2023	0.35	0.74	1.60
	2023	325,000	Start of 2024	0.30	0.71	1.79
	2024	325,000	Start of 2025	0.23	0.64	1.75
g:	2022	350,000	Start of 2023	0.35	0.74	1.59
	2023	350,000	Start of 2024	0.29	0.70	1.77
	2024	350,000	Start of 2025	0.21	0.62	1.73
h: 10% reduction	2022	350,000	Start of 2023	0.35	0.74	1.59
	2023	315,000	Start of 2024	0.29	0.71	1.78
	2024	283,500	Start of 2025	0.24	0.65	1.76
i:	2022	380,000	Start of 2023	0.34	0.73	1.59
	2023	380,000	Start of 2024	0.27	0.69	1.75
	2024	380,000	Start of 2025	0.19	0.60	1.71
j: 10% reduction	2022	380,000	Start of 2023	0.34	0.73	1.59
	2023	342,000	Start of 2024	0.28	0.70	1.77
	2024	307,800	Start of 2025	0.22	0.63	1.74
k:	2022	430,000	Start of 2023	0.33	0.72	1.57
	2023	430,000	Start of 2024	0.25	0.66	1.73
	2024	430,000	Start of 2025	0.16	0.57	1.67
l: 2021 TAC	2022	473,880	Start of 2023	0.32	0.71	1.56
	2023	473,880	Start of 2024	0.23	0.64	1.70
	2024	473,880	Start of 2025	0.13	0.54	1.64
m: FI= 100%	2022	715,643	Start of 2023	0.26	0.64	1.49
	2023	581,743	Start of 2024	0.16	0.56	1.62
	2024	515,616	Start of 2025	0.09	0.46	1.55
n: default HR	2022	715,643	Start of 2023	0.26	0.64	1.49
	2023	586,146	Start of 2024	0.16	0.56	1.62
	2024	526,126	Start of 2025	0.09	0.45	1.54
o: C2022= C2023	2022	613,069	Start of 2023	0.29	0.67	1.52
	2023	613,030	Start of 2024	0.17	0.58	1.64
	2024	538,943	Start of 2025	0.09	0.46	1.56

Table h. Forecast quantiles of Pacific Hake relative fishing intensity $(1-SPR)/(1-SPR_{40\%})$, expressed as a proportion, for the 2022–2024 catch alternatives presented in Table g. Values greater than 1 indicate relative fishing intensities greater than the $F_{SPR=40\%}$ harvest policy calculated using baseline selectivity.

Management Action			Relative fishing intensity		
	Catch year	Catch (t)	5%	50%	95%
a:	2022	0	0.00	0.00	0.00
	2023	0	0.00	0.00	0.00
	2024	0	0.00	0.00	0.00
b:	2022	180,000	0.24	0.44	0.68
	2023	180,000	0.23	0.43	0.69
	2024	180,000	0.20	0.42	0.71
c:	2022	225,000	0.29	0.51	0.77
	2023	225,000	0.28	0.51	0.80
	2024	225,000	0.25	0.50	0.83
d:	2022	270,000	0.33	0.57	0.84
	2023	270,000	0.32	0.58	0.88
	2024	270,000	0.29	0.58	0.93
e: 10% reduction	2022	320,000	0.38	0.64	0.91
	2023	288,000	0.34	0.61	0.93
	2024	259,200	0.28	0.57	0.94
f: 2021 catch	2022	325,000	0.39	0.64	0.92
	2023	325,000	0.37	0.66	0.98
	2024	325,000	0.34	0.66	1.05
g:	2022	350,000	0.41	0.67	0.95
	2023	350,000	0.40	0.69	1.01
	2024	350,000	0.36	0.70	1.09
h: 10% reduction	2022	350,000	0.41	0.67	0.95
	2023	315,000	0.37	0.65	0.97
	2024	283,500	0.31	0.61	1.00
i:	2022	380,000	0.43	0.71	0.98
	2023	380,000	0.42	0.73	1.06
	2024	380,000	0.39	0.74	1.15
j: 10% reduction	2022	380,000	0.43	0.71	0.98
	2023	342,000	0.39	0.69	1.02
	2024	307,800	0.33	0.65	1.05
k:	2022	430,000	0.47	0.75	1.03
	2023	430,000	0.46	0.79	1.12
	2024	430,000	0.43	0.80	1.23
l: 2021 TAC	2022	473,880	0.51	0.79	1.07
	2023	473,880	0.50	0.83	1.18
	2024	473,880	0.47	0.86	1.29
m: FI= 100%	2022	715,643	0.65	0.96	1.24
	2023	581,743	0.59	0.96	1.32
	2024	515,616	0.51	0.95	1.34
n: default HR	2022	715,643	0.65	0.96	1.24
	2023	586,146	0.59	0.96	1.32
	2024	526,126	0.52	0.96	1.35
o: C2022= C2023	2022	613,069	0.60	0.90	1.18
	2023	613,030	0.60	0.96	1.31
	2024	538,943	0.52	0.96	1.34

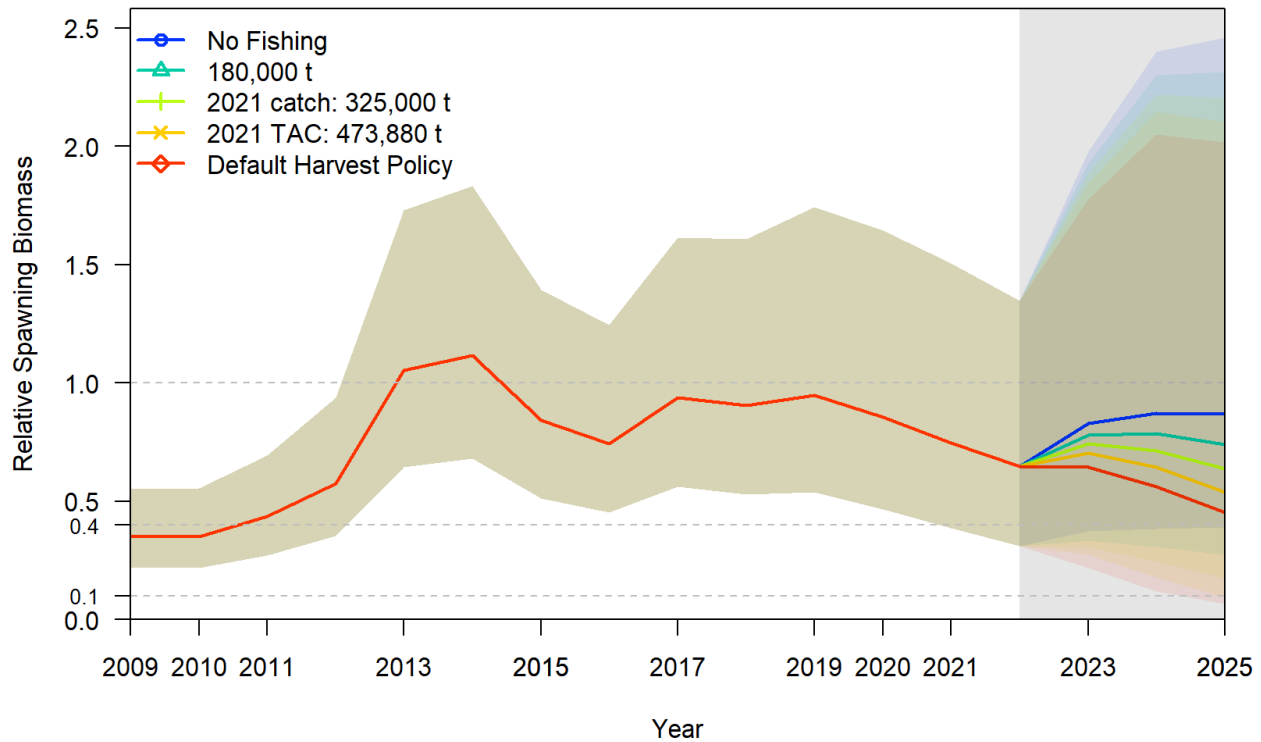


Figure j. Time series of estimated relative spawning biomass to 2022 from the base model, and forecast trajectories to 2025 (grey region) for several management actions defined in Table g, with 95% posterior credibility intervals.

interpolation is not appropriate for all catches in 2023 or 2024, because they are conditional on previous year(s) catch levels. This explains why a few probabilities decline (rather than rise) with increased 2023 and 2024 catch levels in Tables j and k and Figures l and m.

The predicted relative spawning biomass trajectory through 2025 is shown in Figure j for several of the management actions. With zero catch for the next three years, the biomass has a 8% probability of decreasing from 2022 to 2023 (Table i), a 47% probability of decreasing from 2023 to 2024 (Table j), and a 64% probability of decreasing from 2024 to 2025 (Table k).

The probability of the spawning biomass decreasing from 2022 to 2023 is under 57% for all catch levels (Table i and Figure k). It is 30% for the 2022 catch level similar to that for 2021 (catch alternative f). For all explored catches, the maximum probability of the spawning biomass dropping below $B_{10\%}$ at the start of 2023 is 0%, and of dropping below $B_{40\%}$ is 18% (Table i and Figure k). As the large 2010, 2014, and 2016 cohorts continue to age, their biomass is expected to decrease as losses from mortality outweigh increases from growth. The estimated above-average (yet still highly uncertain) 2020 cohort will play a large role in determining spawning stock biomass during the forecast years presented here.

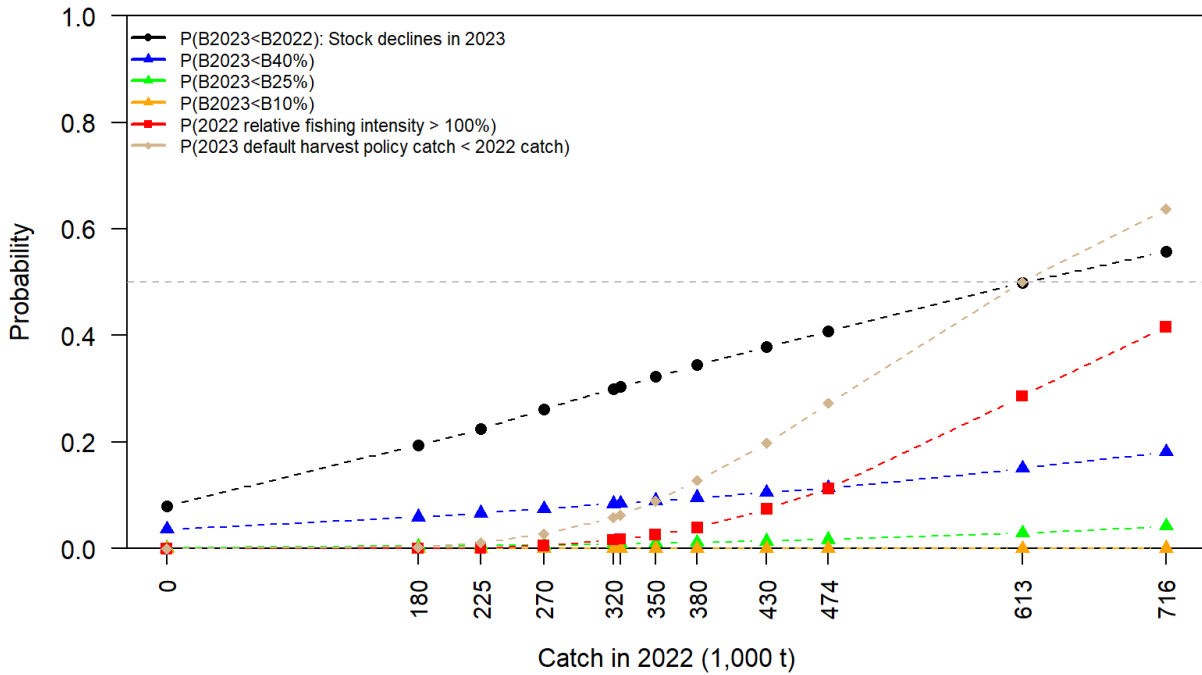


Figure k. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2023 default harvest policy catch for alternative 2022 catch options (explained in Table g) as listed in Table i. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table i. Probabilities related to spawning biomass, relative fishing intensity, and the 2023 default harvest policy catch for alternative 2022 catch options (explained in Table g).

Catch in 2022	Probability B ₂₀₂₃ < B ₂₀₂₂	Probability B ₂₀₂₃ < B _{40%}	Probability B ₂₀₂₃ < B _{25%}	Probability B ₂₀₂₃ < B _{10%}	Probability 2022 relative fishing intensity > 100%	Probability 2023 default harvest policy catch < 2022 catch
a: 0	8%	4%	0%	0%	0%	0%
b: 180,000	19%	6%	0%	0%	0%	0%
c: 225,000	23%	7%	1%	0%	0%	1%
d: 270,000	26%	7%	1%	0%	1%	3%
e: 320,000	30%	8%	1%	0%	2%	6%
f: 325,000	30%	8%	1%	0%	2%	6%
g: 350,000	32%	9%	1%	0%	3%	9%
h: 350,000	32%	9%	1%	0%	3%	9%
i: 380,000	34%	10%	1%	0%	4%	13%
j: 380,000	34%	10%	1%	0%	4%	13%
k: 430,000	38%	11%	1%	0%	7%	20%
l: 473,880	41%	11%	2%	0%	11%	27%
m: 715,643	56%	18%	4%	0%	42%	64%
n: 715,643	56%	18%	4%	0%	42%	64%
o: 613,069	50%	15%	3%	0%	29%	50%

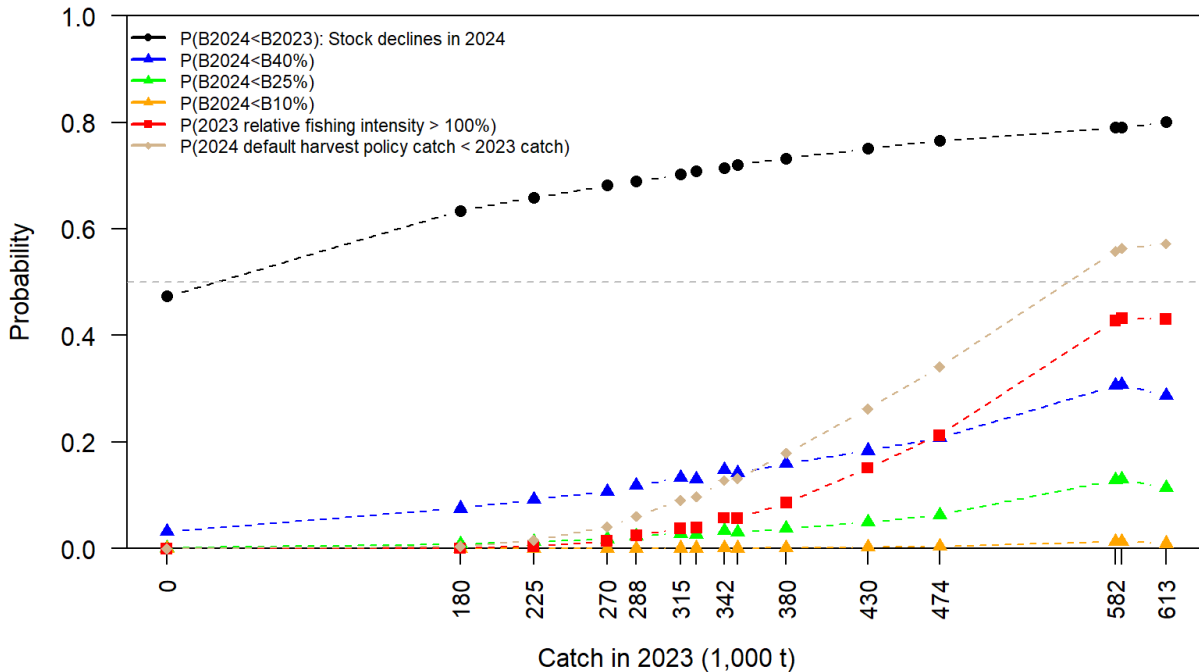


Figure 1. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2024 default harvest policy catch for alternative 2023 catch options (including associated 2022 catch; catch options explained in Table g) as listed in Table j. The symbols indicate 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 2024 default harvest policy catch for alternative 2023 catch options, given the 2022 catch shown in Table i (catch options explained in Table g).

Catch in 2023	Probability $B_{2024} < B_{2023}$	Probability $B_{2024} < B_{40\%}$	Probability $B_{2024} < B_{25\%}$	Probability $B_{2024} < B_{10\%}$	Probability 2023 relative fishing intensity > 100%	Probability 2024 default harvest policy catch < 2023 catch
a: 0	47%	3%	0%	0%	0%	0%
b: 180,000	63%	8%	1%	0%	0%	0%
c: 225,000	66%	9%	1%	0%	0%	2%
d: 270,000	68%	11%	2%	0%	1%	4%
e: 288,000	69%	12%	2%	0%	2%	6%
f: 325,000	71%	13%	3%	0%	4%	10%
g: 350,000	72%	14%	3%	0%	6%	13%
h: 315,000	70%	13%	3%	0%	4%	9%
i: 380,000	73%	16%	4%	0%	9%	18%
j: 342,000	71%	15%	3%	0%	6%	13%
k: 430,000	75%	18%	5%	0%	15%	26%
l: 473,880	77%	21%	6%	0%	21%	34%
m: 581,743	79%	31%	13%	1%	43%	56%
n: 586,146	79%	31%	13%	1%	43%	56%
o: 613,030	80%	29%	11%	1%	43%	57%

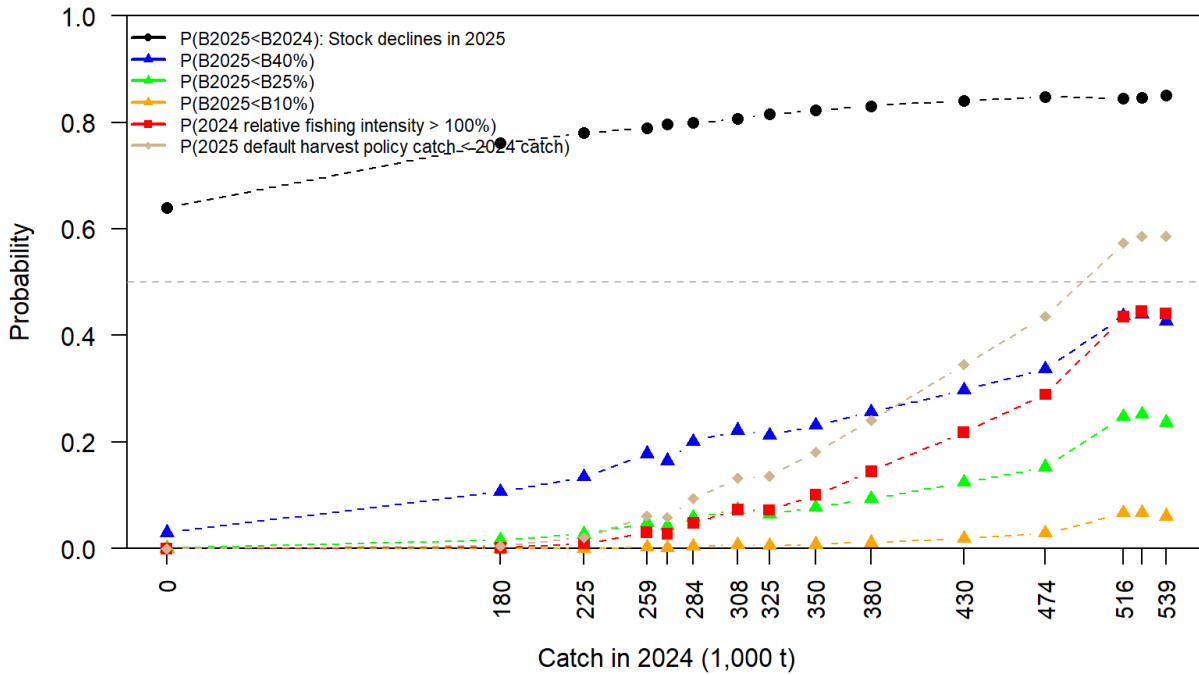


Figure m. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options (including associated 2022 and 2023 catches; catch options explained in Table g) as listed in Table k. The symbols 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 2025 default harvest policy catch for alternative 2024 catch options, given the 2022 and 2023 catches shown in Tables i and j (catch options explained in Table g).

Catch in 2024	Probability B ₂₀₂₅ < B ₂₀₂₄	Probability B ₂₀₂₅ < B _{40%}	Probability B ₂₀₂₅ < B _{25%}	Probability B ₂₀₂₅ < B _{10%}	Probability 2024 relative fishing intensity > 100%	Probability 2025 default harvest policy catch < 2024 catch
a: 0	64%	3%	0%	0%	0%	0%
b: 180,000	76%	11%	2%	0%	0%	0%
c: 225,000	78%	13%	3%	0%	1%	2%
d: 270,000	80%	16%	4%	0%	3%	6%
e: 259,200	79%	18%	5%	0%	3%	6%
f: 325,000	81%	21%	6%	1%	7%	14%
g: 350,000	82%	23%	8%	1%	10%	18%
h: 283,500	80%	20%	6%	0%	5%	9%
i: 380,000	83%	26%	9%	1%	15%	24%
j: 307,800	81%	22%	7%	1%	7%	13%
k: 430,000	84%	30%	12%	2%	22%	35%
l: 473,880	85%	34%	15%	3%	29%	44%
m: 515,616	84%	44%	25%	7%	43%	57%
n: 526,126	85%	44%	25%	7%	44%	59%
o: 538,943	85%	43%	24%	6%	44%	59%

RESEARCH AND DATA NEEDS

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

1. Conduct research to evaluate ways to improve recent, current, and future recruitment estimates for use in stock assessment. This could include the development of recruitment indices, time series of informative environmental or oceanographic variables, and models that have predictive skill. Explorations should also consider options for incorporating information on recruitment into the stock assessment model and the Pacific Hake management framework. For example, estimates could be included in the stock assessment as a standalone data source (similar to acoustic survey biomass estimates) or the estimation procedure itself could be integrated directly into the stock assessment model. Results from such work should be connected to ongoing research related to recruitment variability, σ_R , 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; ROMS) so that they are available stock-wide and can be used on a recurring basis as informative links in operational stock assessments.
2. Use and build upon the existing management strategy evaluation (MSE) framework to evaluate major sources of uncertainty relating to data, model structure, and the harvest policy for this fishery and compare potential methods to address them. In particular, utilize and adapt this simulation framework to address new and ongoing stock assessment research and data needs through the Pacific Hake MSE Working Group. For example, research investigating links between hake biomass, spatial distribution, growth, and recruitment and how these links vary with ocean conditions and ecosystem variables such as temperature, transport, and prey availability would be beneficial. These investigations have the potential to improve the scenarios considered in future MSE work and the basic understanding of drivers of hake population dynamics and availability to fisheries and surveys.
3. Document the existing survey methodologies, protocols, and adaptive survey-design decisions that lead to the development of Pacific Hake biomass and age-composition estimates and the age-1 index used in the stock assessment. Such documentation will ensure transparency, enable repeatability, and provide a record of changes in procedures over time. Also, continue to conduct research to improve the estimation of age composition and abundance from data collected during the acoustic survey. This includes, but is not limited to, research on species identification, target verification, target strength, implications of the south-to-north directionality of the survey, alternative technologies to assist in the survey, and efficient analysis methods. The latter should include bootstrapping of the acoustic survey time series or related methods that can incorporate relevant uncertainties into the calculations of survey variance. Relevant uncertainties include topics such as the target strength relationship, subjective scoring of echograms, thresholding methods, and methods to estimate the species-mix that are used to interpret the acoustic backscatter. Continue to work with acousticians and survey personnel from the Northwest Fisheries Science Center (and, more broadly, those involved with the U.S. Re-Envisioning West Coast Surveys Initiative) and Fisheries and Oceans Canada to determine optimal survey designs given constraints, in-

cluding designs that incorporate ecosystem-based factors and other potential target species (e.g., rockfish, euphausiids, and mesopelagics) for the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey.

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

This assessment is fully Bayesian, with the base model incorporating prior information on several key parameters (including natural mortality, M , and steepness of the stock-recruit relationship, h) and integrating over parameter uncertainty to provide results that can be probabilistically interpreted. From a range of alternate models investigated by the JTC, a subset of sensitivity analyses are also reported to provide a broad qualitative comparison of structural uncertainty with respect to the base model (Section 3.8). The structural assumptions of this 2022 base model, implemented using version 3.30.18 of the Stock Synthesis software (Methot and Wetzel, 2013), are largely the same as the 2021 base model (Grandin et al., 2020). The exception is that the 2022 base model includes an age-1 index from the acoustic survey. The Bayesian estimation continues to be computed using a new efficient approach that was successfully tested in 2020 assessment (Grandin et al., 2020). For the first time, all model runs reported in this stock assessment document are performed in a Bayesian context. Responses to 2021 SRG requests are in Section 3.3 and a Glossary of terms appears in Appendix C.

1.1 STOCK STRUCTURE AND LIFE HISTORY

Pacific Hake is a semi-pelagic schooling species distributed along the west coast of North America, generally ranging in latitude from 25°N to 55°N (see Figure 1 for an overview map). It is among 18 species of hake from four genera (being the majority of the family Merlucciidae), which are found in both hemispheres of the Atlantic and Pacific Oceans (Alheit and Pitcher, 1995; Lloris et al., 2005). The coastal stock of Pacific Hake is currently the most abundant groundfish population in the California Current system. Smaller populations of this species occur in the major inlets of the Northeast Pacific Ocean, including the Strait of Georgia, the Puget Sound, and the Gulf of California. Each of these smaller populations are genetically distinct from the coastal population

(Vrooman and Paloma, 1977; Iwamoto et al., 2004; King et al., 2012; García-De León et al., 2018). The coastal stock is also distinguished from the inshore populations by larger size-at-age and seasonal migratory behavior and from fish off the west of coast of Baja California by smaller size-at-age and later spawning (Zamora-García et al., 2020).

The coastal stock 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 (Hicks et al., 2013). 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 highest densities located over bottom depths of 200-300 m (Dorn and Methot, 1991, 1992).

Older Pacific Hake exhibit the greatest northern migration each season, with two- and three-year old fish rarely observed in Canadian waters north of southern Vancouver Island. During El Niño events (warm ocean conditions such as in 1998), a larger proportion of the stock 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) result in a southward shift in the stock's distribution, with a much smaller proportion of the population found in Canadian waters, as seen in the 2001 survey (Figure 2). In general, warmer than average thermal habitat conditions for mature Pacific Hake leads to higher biomass further north and lower biomass around the U.S.-Canadian border, while cooler than average conditions leads to higher biomass of immature Pacific Hake coast-wide (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). Recent research has developed an index of abundance for Humboldt Squid and suggested hake abundance decreased with increasing squid abundance (Stewart et al., 2014) and has evaluated hake distribution, recruitment, and growth patterns in relation to oceanographic conditions for assessment and management (Ressler et al., 2007; Hamel et al., 2015; Malick et al., 2020a,b). The 2015 Pacific Hake stock assessment document presented a sensitivity analysis where the mortality of Pacific Hake was linked to the Humboldt Squid index (Taylor et al., 2015), but further research on this topic is still needed. Ongoing research investigating abiotic (environmental conditions) and biotic (e.g., euphausiid distribution and abundance) drivers of the distribution, recruitment, and survival of Pacific Hake could provide insight into how the population is linked with broader ecosystem considerations. For example, Turley and Rykaczewski (2019) found decreased survival of larval Pacific Hake as storm events increased, contrary to many other species in the southern California Current Ecosystem. An analysis of drivers of recruitment across the maternal preconditioning, egg, and larval phases of Pacific Hake indicated recruitment is associated with eddy kinetic energy, the location of the North Pacific Current bifurcation, and upwelling during maternal preconditioning, as well as associated with northward long-shore transport and the number of days between storm events during larval stages (Vestfals et al., pers. comm.). In terms of an 'Ecosys-

tem Approach to Fisheries Management’ (a priority for DFO and NOAA), the use of empirical weight-at-age somewhat accounts for ecosystem effects (see Section 2.3.3).

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 between the U.S. and Canada 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 been adhered to since 2005. However, a bilateral agreement on the coast-wide TAC could not be reached in 2020 or 2021, and so catch targets were set unilaterally during these years for the first time since the inception of the Agreement.

Throughout the last decade, the total coast-wide catch has tracked harvest targets reasonably well. Since 1999, catch targets have been calculated using an $F_{SPR=40\%}$ default harvest rate with a 40:10 adjustment. This decreases the catch linearly from the catch target at a relative spawning biomass of 40% to zero catch at 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. In the last decade, total catch has never exceeded the coast-wide quota and harvest rates have not exceeded the $F_{SPR=40\%}$ target. Overall, management appears to be effective at maintaining a sustainable stock size, in spite of uncertain stock assessments and a highly dynamic population. However, management has been risk averse in years when very large quotas were suggested based upon the default harvest control rule and stock assessment outputs.

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 (3 inches). Regulations also restrict the area and season of fishing to reduce the bycatch of Chinook Salmon (*Oncorhynchus tshawytscha*), depleted rockfish stocks (though, all but Yelloweye Rockfish, *Sebastes ruberrimus*, have rebuilt in recent years), and other species as related to their specific harvest specifications. The at-sea fisheries begin on May 15, but processing and night fishing (midnight to one hour after official sunrise) are prohibited south of 42°N latitude (the Oregon-California border). Shore-based fishing is allowed after April 15 south of 40°30’N latitude, but only a small amount of the shore-based allocation is released prior to the opening of the main shore-based fishery (May 15). The current allocation agreement, effective since 1997, divides the U.S. harvest into tribal (17.5%) and non-tribal (82.5%, with a small amount set aside for research) components. Starting in 1996, the Makah Tribe has conducted a fishery with

a specified allocation in its “usual and accustomed fishing area”. The non-tribal harvest allocation is divided among catcher-processors (34%), motherships (24%), and the shore-based fleet (42%). Since 2011, the non-tribal U.S. fishery has been fully rationalized with allocations in the form of Individual Fishing Quotas (IFQs) to the shore-based sector and group shares to cooperatives in the at-sea mothership and catcher-processor 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 (CP) 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 (MS) 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. The shore-based fishery is managed with IFQs.

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 2021, Canadian hake fishermen were allocated a TAC of 104,480 t, including 10,390 t of uncaught carryover fish from 2020. Canadian priority lies with the domestic fishery, but when there is determined to be an excess of fish for which there is not enough domestic processing capacity, fisheries managers give consideration to a Joint-Venture fishery in which foreign processor vessels are allowed to accept codends from Canadian catcher vessels while at sea. The last year a Joint-Venture fishery was conducted was in 2018.

In 2021, all Canadian Pacific Hake trips were subject to 100% observer coverage, by electronic monitoring for the shoreside component of the domestic fishery or on-board observer for the freezer-trawler component. However, due to staffing issues, there were no observers available to board freezer-trawler vessels for the entirety of the fishing season. All shoreside landings are usually subject to 100% verification by the groundfish Dockside Monitoring Program, but because of staffing issues only four samples were taken in 2021.

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

1.4 FISHERIES

The fishery for the coastal population of Pacific Hake occurs along the coasts of northern California, Oregon, Washington, and British Columbia primarily during May-November (Hicks et al., 2013). The fishery is conducted with mid-water trawls and has met the Marine Stewardship Coun-

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

In the US, over US\$80 million in wages is estimated to have been paid to employees in 2019 (www.noaa.gov). This includes wages paid to crew and captains fishing on catcher vessels that deliver shoreside and at-sea to motherships, workers in shore-based processing facilities, crew, captains, and workers on catcher-processor vessels, and workers on mothership vessels. The exported value of Pacific Hake was US\$151 million in 2019, including to Ukraine, Nigeria, and Netherlands, which make up about 54% of the total (www.noaa.gov). The total economic impact of the Pacific Hake fishery on the U.S. West Coast in 2019 was US\$311 million in income and 4,200 jobs.

1.4.1 Overview of the fisheries in 2021

The coast-wide TAC of 473,880 t for 2021 was specified as the sum of unilateral TAC decisions due to the lack of a bilateral agreement in 2021. The U.S. catch target was set at 369,400 t and the Canadian catch target at 104,480 t. The historical catch of Pacific Hake for 1966–2021 by nation and fishery sector is shown in Figure 4 and Tables 1–3. Table 3 also shows recent catches in relation to targets (see Section 3.4.2). A review of the 2021 fishery now follows by nation.

United States

The U.S. specified catch target (i.e., adjusted for carryovers) of 369,400 t was further divided among the research, tribal, catcher-processor, mothership, and shore-based sectors. After the tribal allocation of 17.5% (64,645 t), and a 750 t allocation for research catch and bycatch in non-groundfish fisheries, the 2021 non-tribal U.S. catch limit of 304,005 t was allocated to the catcher-processor (34%), mothership (24%), and shore-based (42%) commercial sectors. Reallocation of 34,645 t of tribal quota to non-tribal sectors on September 15 resulted in final quotas for the catcher-processor, mothership, and shore-based sectors of 115,141 t, 81,276 t, and 142,233 t, respectively.

The midwater fishery for Pacific Hake began on May 15 for the shore-based and at-sea fisheries. In earlier years, the shore-based midwater fishery began on June 15 north of 42°N latitude, but could fish for hake between 40°30'N and 42°N latitudes starting on April 1. Beginning in 2015, the shore-based fishery has been allowed to fish north of 40°30'N latitude starting May 15 and could fish south of 40°30'N latitude starting on April 15. Regulations do not allow at-sea processing south of 42°N latitude at any time during the year.

The overall catch of Pacific Hake in U.S. waters was less than the past four years, but was the fifth highest value ever recorded (Table 1). Monthly catch rates in the at-sea sector were lower than last year in all months except October, which was only slightly higher than last year, and September, for which there was no fishing in September of last year (Figure 5). Tribal landings available at the time of the assessment were 3,638 t. The catcher-processor, mothership, and shore-based fleets caught 90.4%, 43.3%, and 89.1% of their final reallocated quotas, respectively. There was 27.0% of the total U.S. adjusted TAC that was not caught. For further details and specific impacts related to the COVID-19 pandemic see the report from the U.S. Advisory Panel (Appendix E).

In both U.S. at-sea sectors, age-5 and age-7 fish, associated with the 2016 and 2014 year classes, were the most common ages. Age-2 fish were again not seen in appreciable numbers in the catch this year. Age sampling was conducted on 279 catcher-processor hauls and 109 mothership hauls (Table 4). For the catcher-processor sector, the four most abundant age classes (by numbers) seen in 2021 were age-5 (36.9%), age-7 (23.6%), age-4 (14.4%), and age-11 (10.7%; Table 5). For the mothership sector, the four most abundant age classes for 2021 were age-5 (38.2%), age-7 (23.9%), age-11 (14.0%), and age-4 (11.1%; Table 6). Age-samples from 75 shoreside trips showed similar age compositions in the catch with the highest occurrences being for age-5 (35.3%), age-7 (23.9%), age-4 (13.1%), and age-11 (9.8%) in 2021 (Table 7).

The at-sea fishery maintained moderately high catch rates in the fall (Figure 5), but catch rates in the spring were lower than last year. The median fishing depth for the at-sea fleets was shallower than last year but near the average over the last five years (Figure 6). From mid-June to September/October, operators in the at-sea fishery moved to their usual summer fishing grounds off the coast of Alaska in search of Bering Sea Walleye Pollock. The shore-based fishery had the largest monthly catches during June, July, and August. The U.S. utilization rate (73.0%) continued to be maintained close to what it has been in recent years because of high catch rates (see Appendix E for more details).

Canada

The 2021 Canadian Pacific Hake domestic fishery removed 57,076 t from Canadian waters (Table 2), which was 54.6% of the Canadian TAC of 104,480 t. The attainment for Canada appears much lower than usual, due to the fishing vessels having a difficult time finding fish in Canadian waters. The Canadian report from the Advisory Panel explains this in more detail (Appendix D).

The shoreside component, made up of vessels landing fresh round product onshore, landed 16,953 t. The freezer-trawler component, which freezes headed and gutted product while at sea, landed 40,123 t. There was no Joint-Venture fishery this year.

Fishing started in early April and ended in mid-October. The general view from the Canadian fleet is that general abundance was down in 2021, especially in the shallower depths (Figure 7). Finding fish was difficult in 2021. The fish caught in Canada appeared to be mostly from one age class (approximately 800 grams body weight), with very few smaller fish (less than 500 grams) caught.

Usually the most abundant age classes found in the freezer-trawler catch are listed here. Unfortunately, no trips were observed due to staffing issues, leading to no age samples. Although there were four samples taken from the shoreside fleet, only one sample was received in time for ageing for this year's assessment.

The most abundant year classes in the Canadian shoreside catch were age-7 at 27.4%, age-5 at 24.0%, age-4 at 17.1%, and age-10 at 9.4%.

2 DATA

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

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

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

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

Some data sources were not included in the base model but have been explored, used for sensitivity analyses, or were included in previous stock assessments. Data sources not discussed at all 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). Some of these additional data sources are:

- Fishery and acoustic survey length compositions.

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- Fishery and acoustic survey age-at-length compositions.
 - Biomass index and age compositions from the following years of the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey 1977, 1980, 1983, 1986, 1989, and 1992.
 - Bottom trawl surveys in the U.S.A. and Canada (various years and spatial coverage from 1977–2021).
 - NWFSC/Southwest Fisheries Science Center/PWCC coast-wide juvenile Pacific Hake and rockfish surveys (2001–2021).
 - Bycatch of Pacific Hake in the trawl fishery for Pink Shrimp off the coast of Oregon (2004, 2005, 2007, and 2008).
 - Historical biological samples collected in Canada prior to 1990 but currently not available in electronic form.
 - Historical biological samples collected in the U.S.A. prior to 1975 but currently not available in electronic form or too incomplete to allow analysis with methods consistent with more current sampling programs.
 - California Cooperative Oceanic Fisheries Investigations (CalCOFI) larval Pacific Hake production index, 1951–2006. The data source was previously explored and rejected as a potential index of Pacific Hake spawning stock biomass.
 - NWFSC winter 2016 and 2017 acoustic research surveys of spawning Pacific Hake.

2.1 FISHERY-DEPENDENT DATA

2.1.1 Total catch

The catch of Pacific Hake for 1966–2021 is summarized by nation and fishery sector (Tables 1–3) and modeled as yearly coast-wide catches. Catches in U.S. waters prior to 1978 are available only by year from Bailey et al. (1982) and historical assessment documents. Canadian catches prior to 1989 are also unavailable in disaggregated form. The U.S. shore-based landings are from the Pacific Fishery Information Network (PacFIN). Foreign and Joint-Venture catches for 1981–1990 and U.S. domestic at-sea catches for 1991–2021 are calculated from the Alaska Fisheries Science Center (AFSC) North Pacific Groundfish and Halibut Observer (NORPAC) database, which also stores the NWFSC At-Sea Hake Observer Program data. Canadian Joint-Venture catches from 1989 are from the Groundfish Biological (GFBio) database. Canadian shore-based landings are from the Groundfish Catch (GFCatch) database (from 1989 to 1995), the Pacific Harvest Trawl (PacHarvTrawl) database (from 1996 to March 31 2007), and the Fisheries Operations System (FOS) database (from April 1 2007 to present).

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

was during 2020 and 2021 when there were no observers on Canadian freezer trawlers due to a suite of staffing issues. Canadian observers use volume/density methods to estimate total catch in each codend and this is used for catch reporting. Canadian shoreside landings are monitored using at-sea observers or electronic monitoring and catch is recorded by dockside monitors within the Groundfish Trawl Dockside Monitoring Program using total catch weights provided by processing plants. Discards are negligible relative to the total fishery catch for all sectors.

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

Minor updates to catches used in previous assessments were made based on the best available information extracted from the aforementioned databases. This included adjustments of less than 10 t to catch in several years over the period 2007–2018 and an increase in catches of 430 t and 1,128 t in 2019 and 2020, respectively. Tribal catches this year were available in PacFIN for the U.S. tribal fishery at the time the data were extracted and were cross-checked with numbers based on information provided by the Makah Tribe. The Makah Tribe is also working on providing historical catches such that shore-based catches can be summarized separately from tribal catches since the onset of the fishery.

2.1.2 Fishery biological data

Biological information from the U.S. at-sea fishery was extracted from the NORPAC database. This included sex, length, weight, and age information from the foreign and Joint-Venture fisheries from 1975–1990 and from the domestic at-sea fishery since 1990. Observers collect data by selecting fish randomly from each haul.

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

Observers aboard Canadian freezer-trawler vessels collect 50 otoliths and 300 lengths per sample, sampling once per day during trips that on average last approximately seven days. The sampled weight from which biological information is collected must be inferred from length-weight relationships.

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

When there is a Canadian Joint-Venture fishery, length samples are collected every second day of fishing operations, and otoliths are collected once a week. Length and age samples are taken

randomly from a given codend. The sampled weight from which biological information is collected must be inferred from length-weight relationships.

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

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

The aggregate fishery age-composition data (1975–2021) confirm the well-known pattern of very large cohorts born in 1980, 1984, 1999, 2010, and 2014 and above average cohorts born in 1973, 1977, 1987, 2008, and 2016 (Table 10 and Figure 9). Recent age-composition data still easily track the 2010 cohort, as well as the large cohorts born since then (Table 10 and Figure 9). Currently, the 2016 cohort is the largest observed cohort in all three U.S. fleets (Tables 5–7), whereas the 2014 cohort is slightly larger than the 2016 cohort in the Canadian shoreside fleet (Table 8). Canadian freezer trawlers have not collected ages since 2019. Age-1 fish were observed by the fishery this year (Table 10) in the U.S. catcher-processor and shore-based fleets. For the combined data in 2021, the 2016 cohort was the largest (36%), followed by the 2014 cohort (24%), then the 2017 cohort (14%). In 2020, the 2016 cohort was the largest (36%), followed by the 2014 cohort (31%), then the 2010 cohort (14%).

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

Both the weight- and length-at-age information suggest that growth of Pacific Hake has fluctuated markedly over time (Figure 15 and see Figure 7 in Stewart et al. 2011). This is particularly evident in the frequency of larger fish (> 55 cm) before 1990 and a shift to much more average-sized fish in more recent years. The treatment of weight- and length-at-age are described in more detail in Sections 2.3.3 and 2.3.4. Although length-composition data are not fit explicitly in the base assessment model presented here, the presence of the 2008 and 2010 year classes have been clearly observed in length data from both of the U.S. fishery sectors, and the 2014 year class has been apparent since 2016.

2.1.3 Catch per unit effort

Calculation of a reliable fishery catch-per-unit-effort (CPUE) metric is particularly problematic for Pacific Hake, and it has never been used as a tuning index for the assessment of this stock. There are many reasons that fishery CPUE would not index the abundance of Pacific Hake, which are discussed in the 2013 stock assessment (Hicks et al., 2013).

2.2 FISHERY-INDEPENDENT DATA

2.2.1 Acoustic survey

The Joint U.S. and Canadian Integrated Acoustic and Trawl Survey (Stewart et al., 2011) has been the primary fishery-independent tool used to assess the distribution, abundance, and biology of coastal age-2+ Pacific Hake along the west coasts of the U.S.A. and Canada. The acoustic surveys performed in 1995, 1998, 2001, 2003, 2005, 2007, 2009, 2011, 2012, 2013, 2015, 2017, 2019, and 2021 were used in this assessment (Table 12). The acoustic survey samples transects that represent all waters off the coasts of the U.S.A. and Canada thought to contain all portions of the age-2+ Pacific Hake stock. Observations of age-0 and age-1 Pacific Hake have been historically excluded from the main survey analysis, 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 an age-1 index.

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

Distributions of the backscatter of Pacific Hake plotted for each acoustic survey since 1995 illustrate the variable spatial patterns of age-2+ fish across years (Figure 2). This variability is due in part to changes in the composition of the age-2+ population because older Pacific Hake tend to migrate farther north and partly due to environmental and/or climatic factors. The 1998 acoustic survey is notable because it shows an extremely northward distribution that is thought to be related to the strong 1997-1998 El Niño. In contrast, distribution of Pacific Hake during the 2001 acoustic survey was compressed into the lower latitudes off the coast of Oregon and Northern California. There was a strong La Niña event in 2000. In 2003, 2005, and 2007 the distribution of Pacific Hake did not show an unusual coast-wide pattern despite 2003 and 2007 being characterized as El Niño years. In 2009, 2011, 2012, and 2013 the majority of the distribution of Pacific Hake was again found in U.S. waters, which is more likely due to age-composition than the environment, although 2013 showed some warmer than average sea-surface temperatures. In 2015, sea-surface temperatures were warmer again, resulting in a northern shift in the overall distribution. The distribution of Pacific Hake in 2017 was more latitudinally uniform than observed in 2015. This is likely a result of having large proportions of two cohorts (2010 and 2014 year-classes) in 2017 as opposed to many other years when a single cohort is dominant in the observed samples (Figure 2). Weak

2019 El Niño conditions decreased in their prevalence starting in March of that year, leading to neutral conditions by July. Consequently, the 2019 survey saw Pacific Hake on all survey transects from just north of Morro Bay, California to the northern end of Vancouver Island, with the greatest offshore extent found off of Cape Mendocino. The 2021 survey saw the majority of Pacific Hake in U.S. waters and a continuation of conditions moving towards higher productivity La Niña conditions in the California Current from 2020 to 2021. Ongoing research is looking into relationships between environmental conditions and Pacific Hake distribution and recruitment, that will help to inform the mechanisms behind observations (Malick et al., 2020b).

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

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

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

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

The 2021 stock assessment incorporated an updated estimate of 2019 survey biomass. A small double counting error was resolved that resulted in a less than 1% difference in biomass and had little influence on model results (see Figure 16). Additionally, the 2021 survey estimate was scaled by factor of 1.06 to convert EK 80 acoustic data (2021 survey only) to EK 60 acoustic data to

standardize the survey time series. The survey team will eventually be converting all pre-2021 EK 60 data to an equivalent EK 80 format. The survey team also provided estimates of the age-2+ survey biomass attributable to each country (Table 13).

Thus, a full time series of consistently analyzed survey biomass (Table 12 and Figure 10) and age compositions (Table 11 and Figure 9) since 1995 are used to fit the stock assessment model. These data contain many sources of variability (see Stewart et al. 2011) but results from research done in 2010 and 2014 on their representativeness show that trawl sampling and post-stratification is only a small source of variability. Specifically, repeated trawls at different depths and spatial locations on the same aggregation of Pacific Hake were similar and analyses regarding the method used to stratify the data led to similar overall conclusions.

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

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

The decision to include the age-1 index in the base model this year was based on multiple factors. While the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey was not originally designed to index recruitment, independent age-1 estimates from the survey have tracked recruitment estimates reasonably well when using assessment models that do not incorporate age-1 acoustic data (e.g., Figure 11 of Johnson et al. 2021). Incorporating the age-1 index results in estimates of recruitment strength (e.g., size of yearly deviations from the stock-recruitment relationship) that are informed on average one year earlier than models without the index (compare the retrospective Figures 54 and G.1 in Johnson et al. 2021 [updated as Figures G.1 and 55 here]). The suite of sensitivity models related to the age-1 index explored over the past decade indicate that its use typically provides the model with the correct direction of cohort strength (weak, strong, or neutral). The utility of an informed recruitment signal is far greater than an uninformed recruitment assumption, the latter of which (e.g., the mean over the time series, random samples from historical recruitment, or random samples from a distribution) have been used in Pacific Hake stock assessments, or the application of arbitrary positive and negative recruitment scalars. Finally, the Joint U.S. and

Canadian Integrated Acoustic and Trawl Survey team supports its use for stock assessment, and the team is committed to continually evaluating and refining approaches to improve survey estimates and related uncertainty.

In addition to the age-1 index, ongoing research is evaluating whether environmental drivers of recruitment can be used to accurately predict recruitment. Improving recent and current estimates of recruitment is a high priority because it should help increase the probability that realized levels of spawning stock biomass lie within the estimated prediction intervals and potentially reduce the prediction interval itself thereby increasing the robustness of management decisions. A model without the age-1 index was explored as a sensitivity (Appendix G).

2.2.2 Other fishery-independent data

Fishery-independent data from the AFSC bottom trawl survey, the NWFSC bottom trawl survey, the NWFSC and Pacific Whiting Conservation Cooperative (PWCC) pre-recruit survey, and DFO surveys not already mentioned were not used in this assessment. More information on these data sources is given in the 2013 stock assessment (Hicks et al., 2013).

2.3 EXTERNALLY ANALYZED DATA

2.3.1 Maturity and fecundity

Data related to the fecundity relationship were updated for the 2018 assessment (Edwards et al., 2018*b*). Previously, fecundity was based on the product of the maturity-at-length reported by Dorn and Saunders (1997) and the weight-at-length estimated in 2011. These values were converted to fecundity-at-age using a parametric growth curve estimated in 2011 from a model that included length data.

In 2018, a new age-based maturity ogive (Table 14 and Figure 12) was developed using histological estimates of functional maturity from 1,947 ovaries that were associated with age estimates. These samples were collected from the acoustic survey, winter and summer acoustic research trips, observers in the U.S. At-Sea Hake Observer Program aboard commercial catcher-processor vessels, and the U.S. West Coast bottom trawl survey (Table 15). Samples from south of Point Conception, California (34.44°N) were excluded from this analysis because they were thought to mature at earlier ages and smaller sizes (see Edwards et al. 2018*b* for more information). We retained the maturity ogive calculated for Edwards et al. (2018*b*), noting that additional samples are available (including samples collected from Canadian waters since 2018) but have yet to be analyzed.

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

Some fish at almost every age were found to be functionally immature based on histological criteria. Older, functionally immature fish are a combination of “skip spawners” that will not be spawning in the upcoming year and senescent fish that appear to no longer have viable ovaries.

Results from ongoing research investigating the impacts of functionally immature individuals on estimates of spawning stock biomass could help refine the fraction of fish mature at each age.

Tissue samples for genetic analyses have been collected from many of the same fish from which ovaries were sampled. It is the hope that these genetic samples may help determine whether the fish south of 34.44°N are from the same stock as the rest of the coastal population.

2.3.2 Ageing error

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

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

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

2.3.3 Weight-at-age

A matrix of empirically derived population weight-at-age means by year (Figures 13–15) is used in the current assessment model to translate numbers-at-age directly to biomass-at-age. Annual mean weight-at-age was calculated from year-specific samples pooled from all fisheries and the acoustic survey for the years 1975 to 2021 (Figures 13–15). Past investigations into calculating weight-at-age for the fishery and survey independently showed little impact on model results. New and historical samples were pulled from all relevant databases such that the derived matrices included the best available data. Samples from winter and research surveys are not included. Samples from the Canadian fishery are subset by area to exclude near-shore samples. Pre-1975 weight-at-age data available in the PacFIN database that were discovered during the 2018 assessment-review process were confirmed to be samples collected within Puget Sound and have not been included in any assessment. Weights from fish ages 15 and above for each year were pooled, and thus, ages 15–20 are assumed to have the same mean weight-at-age. Combinations of age and year with no observations were assumed to change linearly over time between observations at any given age. The number of samples (Figure 14) is generally proportional to the amount of catch, so the combinations of year and age with no samples should have relatively little importance in the overall estimates of the population dynamics.

The biomass at the start of a given year is based on the weight-at-age from the previous year; for example, the biomass at the start of 2022 is calculated using the empirical weight-at-age from 2021 (Figure 13). Prior to 1975, weight-at-age is assumed to be equal to the mean of all available information for each respective age (1975–2021), consistent with the 2021 base model (Figure 13). Both forecast weight-at-age data and forecast selectivity are based on the respective means from the most recent five years (2017–2021), for consistency (Figure 13).

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

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

2.3.4 Length-at-age

In the 2011 assessment model (Stewart et al., 2011) and in models used for management prior to the 2006 stock assessment, temporal variability in length-at-age was included in stock assessments via the calculation of empirical weight-at-age. In the 2006–2010 assessments that attempted to estimate the parameters describing a parametric growth curve, strong patterns were identified in the

observed data indicating sexually dimorphic and temporally variable growth. In aggregate, these patterns result in a greater amount of process error for length-at-age than is easily accommodated with parametric growth models, and attempts to explicitly model size-at-age dynamics (including use of both year-specific and cohort-specific growth) have not been very successful for Pacific Hake. The lack of success was particularly evident in the residuals of the length-frequency data from models prior to 2011. We have not revisited the potential avenues for explicitly modeling variability in length- and weight-at-age in this model, and retain the empirical approach to modeling weight-at-age used since 2011 and described above, which models this variability implicitly.

2.4 ESTIMATED PARAMETERS AND PRIOR PROBABILITY DISTRIBUTIONS

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

2.4.1 Natural Mortality

Since the 2011 assessment, a combination of the informative prior for natural mortality used in previous Canadian assessments and results from analyses using Hoenig's (1983) method support the use of a lognormal distribution with a median of 0.20 and a standard deviation (in log space) of 0.10. Sensitivity to this prior has been evaluated extensively in many previous assessments of Pacific Hake (see Hicks et al. 2013 for a discussion of the historical treatment of M and its prior) and is repeated here (see Section 3.8). Alternative prior distributions for M typically have a significant impact on the model results. But in the absence of new information on M there has been little option to update the prior.

2.4.2 Steepness

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

2.4.3 Variability on fishery selectivity deviations

Time-varying selectivity was introduced in the 2014 assessment (Taylor et al., 2014) and is modeled using yearly deviations since 1991 applied to the selectivity-at-age parameters for the fishery. A penalty function in the form of a normal distribution is applied to each deviation to keep it from straying far from zero, unless the data are overwhelming. The amount of deviation from zero is controlled by a fixed standard deviation, Φ (Edwards et al., 2018b).

For each age $a \geq 1$ there is an incremental selectivity parameter, p_a . The selectivity at age a is computed as

$$S_a = \exp(S'_a - S'_{\max}), \quad (1)$$

where

$$S'_a = \sum_{i=1}^a p_i \quad (2)$$

and

$$S'_{\max} = \max\{S'_a\}. \quad (3)$$

For $a = 0$ selectivity is fixed at $S_0 = 0$.

This formulation has the properties that the maximum selectivity equals 1, positive values of p_a are associated with increasing selectivity between ages $a - 1$ and a and negative values are associated with decreasing selectivity between those ages. Beyond the maximum age for which selectivity is estimated (age 6 in the base model for both the fishery and the survey), $p_a = 0$ gives constant selectivity beyond the last estimated value. The condition that maximum selectivity equals 1 results in one fewer degree of freedom than the number of estimated p_a . Therefore we can set $p_1 = 0$.

The implementation of time-varying selectivity uses a set of deviations to control annual changes to the fishery selectivity parameters. The standard deviation of the normal penalty function, Φ , associated with these deviations has been fixed at 1.4 since the 2018 assessment (see Edwards et al. 2018*b* for justification). The resulting changes in year-specific values controlling the changing selectivity from age $a - 1$ to a are

$$p_{ay} = p_a + \varepsilon_{ay}, \quad (4)$$

where ε_{ay} are the parameter deviations estimated in the model. For years with time-varying parameters, these deviations are included in an additional likelihood component with negative log-likelihood

$$-\log(L) \propto \frac{1}{2} \sum_{a=1}^6 \sum_{y=1991}^{2021} \frac{\varepsilon_{ay}^2}{\Phi^2}. \quad (5)$$

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. In response to the Pacific Hake population being comprised of several large cohorts over the past decade, alternative maximum ages for selectivity were once again investigated this year as a sensitivity analysis (see Section 3.8).

2.4.4 Age composition likelihood

Since 2018, the assessment has used a 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-composition data 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 D-M likelihood (see Equation 10 of Thorson et al. (2017)) is

$$L(\boldsymbol{\pi}, \theta | \tilde{\boldsymbol{\pi}}, n) = \frac{\Gamma(n+1)}{\prod_{a=1}^{A_{\max}} \Gamma(n\tilde{\pi}_a + 1)} \frac{\Gamma(\theta n)}{\Gamma(n + \theta n)} \prod_{a=1}^{A_{\max}} \frac{\Gamma(n\tilde{\pi}_a + \theta n\pi_a)}{\Gamma(\theta n\pi_a)}, \quad (6)$$

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 effective sample size associated with this likelihood is given by

$$n_{\text{eff}} = \frac{1}{1 + \theta} + \frac{n\theta}{1 + \theta}. \quad (7)$$

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

A uniform prior between -5 and 20 for θ_{fish} and θ_{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 θ_{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 McAllister-Ianelli method, is iterative, where the sample sizes are adjusted such that the fit of the expected mean age should be within the estimated uncertainty at a rate that is consistent with the variability expected

given the effective sample sizes. The Francis method is known to be sensitive to outliers and prone to convergence issues when selectivity is time-varying. 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 fit to fishery catch-at-age data and acoustic survey estimates of population biomass and age composition have been the primary assessment method.

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

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 AFSC/NWFSC triennial bottom trawl 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 identified as adding no appreciable contribution to model results (Helser et al., 2002, 2005; Stewart and Hamel, 2010). The process for generating fecundity-at-age from weight-at-age data changed in 2019 from using time-invariant to year-specific values. Even where data have been consistently used, the weighting of these data in the statistical likelihood has changed through the use of various emphasis factors (e.g., Dorn 1994; Dorn et al. 1999), a multinomial sample size on age compositions (e.g., Dorn et al. 1999; Helser et al. 2002, 2005; Stewart et al. 2011), internal estimations of effective sample size using the Dirichlet-multinomial distribution (Edwards et al., 2018*b*), 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 these stock assessments. Pacific Hake stock assessments have presented decision makers with constant F , variable F , and the following hybrid control rules: $F_{SPR=35\%}$, $F_{SPR=40\%}$, $F_{SPR=40\%-40:10}$, $F_{SPR=45\%}$, $F_{SPR=45\%-40:10}$, and $F_{SPR=50\%}$ (e.g., Dorn 1996; Hicks et al. 2013). Changes to policies such as the United States' National Standards Guidelines in 2002 and the $F_{SPR=40\%-40:10}$ harvest control rule in the Agreement (Appendix C) have required specific changes to control rules.

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

3.2 DESCRIPTION OF BASE MODEL

The 2022 base model has the same population dynamics structure as the 2021 stock assessment. The statistical-catch-at-age model assumes that the Pacific Hake population is a single coast-wide stock subject to one aggregated fleet with combined male and female population dynamics. Stock Synthesis (Methot and Wetzel, 2013) version 3.30.18 was the modeling platform used. The largest changes between the 2021 and 2022 stock assessments are the addition of another year of acoustic survey and fishery data and the incorporation of the age-1 index into the base model.

The 2022 base model includes a time series (1995 to 2021) of acoustic age-2+ biomass estimates and acoustic estimates of age-1 fish (see Section 2.2.1 for more details on the age-1 index). Maturity is assumed to be time-invariant and the maturity ogive updated in 2018 was retained (see Section 2.3.1). Fecundity is defined as weight-at-age multiplied by the maturity ogive and is time-varying across years with empirical weight-at-age data (1975–2021; see Section 2.3.3). The D-M likelihood approach (Thorson et al., 2017) is again used to estimate the weights associated with age-composition data, rather than iteratively tuning the sample size multiplier as in 2017 and

earlier assessments (see Section 2.4.4). Time-varying fishery selectivity is retained in the 2022 base model with the magnitude of the allowable deviations unchanged from the 2021 base model (see Section 2.4.3). The general parameterization of selectivity was retained, although additional parameters were required to estimate an additional year of deviations. The selectivity of the acoustic survey is assumed to be time invariant. Selectivity curves were modeled as non-parametric functions estimating age-specific values for each age beginning at age-2 for the index of age-2+ biomass and age-1 for the fishery until a maximum age of 6, after which all ages are assumed to have the same selectivity.

An age-1 index was included in the base model. It spans the same years as the acoustic survey, as it was part of the same survey, on the same vessels (but no value is available for 2001). Selectivity was set to one for age-1 for this index and zero for all other ages.

Prior probability distributions are used for a select few parameters and fixed values are used for several parameters. For the base model, the instantaneous rate of natural mortality (M) is estimated with a lognormal prior having a median of 0.20 and a standard deviation (in log-space) of 0.1 (see Section 2.4.1). The stock-recruitment function is a Beverton-Holt parameterization, with the log of the mean unexploited recruitment ($\log R_0$) freely estimated. This assessment uses the same beta-distributed prior for stock-recruit steepness (h), based on Myers et al. (1999), that has been applied since 2011 (Stewart et al., 2011). Year-specific recruitment deviations were estimated from 1966–2021 as well as the years 2022–2025 for purposes of forecasting. The standard deviation, σ_r , of recruitment variability serves as a recruitment deviation constraint and is fixed at 1.4 in this assessment. This value is based on consistency with the observed variability in the time series of recruitment deviation estimates and is the same as assumed in assessments from 2013 to 2021 (Table 17). Catchabilities associated with the biomass index (q_b) and with the age-1 index (q_1) were calculated analytically as per Ludwig and Walters (1981) for each sample of posterior parameters, resulting in a distribution of catchability for each.

Statistical likelihood functions used for data fitting are typical of many stock assessments. The biomass index was fit via a log-normal likelihood function, using the observed (and extra 2009) sampling variability, estimated via kriging, as year-specific weighting. The age-1 index was also specified as having lognormal error structure. An additional constant and additive standard deviation on the log-scale component is included for both the biomass index and the age-1 index, which were freely estimated to accommodate unaccounted-for sources of process and observation error. A D-M likelihood was applied to age-composition data, with input sample sizes equal to the sum of the number of trips and hauls sampled across all fishing fleets or the number of trawl sets in the research surveys (see Section 2.4.4).

Software and Hardware

The `adnuts` R package (Monnahan and Kristensen, 2018) was used to apply the NUTS algorithm producing 12,005 MCMC samples which describe posterior distributions for model parameters and derived quantities. This is nearly a ten-fold increase in samples from the 2020 assessment (Grandin et al., 2020) and earlier and a 33% increase in samples from last year's assessment (Johnson et al., 2021). The number of samples for the sensitivity analyses remained the same as last year's assess-

ment at 8,000 samples. 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.

The `adnuts` software goes through several steps including a pilot run using `rwMH` sampling with a few short chains in parallel to ensure the MCMC algorithm is converging. Once the pilot had been checked for convergence, low effective sample size, and for slow mixing parameters by comparing pairwise correlation plots, MLE was run to obtain the covariance matrix. The covariance matrix is then used as the mass matrix for a short run producing 500 samples using a warmup of 100 samples. The covariance matrix from this short run is used as the mass matrix for the main run, providing 12,005 samples from the posterior for inference. The `adapt_delta` value sets the target average acceptance probability and was set to 0.95 for the main NUTS run. The choice of `adapt_delta` of 0.95 was made based on less divergence of the posterior and higher effective sample size compared to 0.90, which was used for last year's assessment. 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).

Cloud computing was used for the first time for this assessment through Amazon Web Services' (AWS) Elastic Compute Cloud (EC2) instances. Use of these services allowed the JTC to run many models simultaneously and to acquire more samples from the posterior distribution than what was used for inference in the last assessment. Thus, the use of AWS left local computers available to continue work on the document and other analyses. AWS Simple Storage Service (S3), which can hold "any amount of data" privately, was used to share the model results between JTC members.

Calculations and figures from Stock Synthesis output were performed using R version 4.0.3 (2020-10-10) and many R (R Core Team, 2021) packages (in particular `r4ss`, `adnuts`, and `xtable`). The use of R, `knitr`, \LaTeX , and GitHub immensely facilitated the collaborative writing of this document. In particular, having most of the code under version control since the 2016 assessment (Grandin et al., 2016) allows for the completion of a full assessment in the limited time available. This successful workflow partly motivated a DFO workshop (Edwards et al., 2018a) and an e-book (Cuddington et al., 2021) to encourage wider uptake of such tools among biologists.

3.3 RESPONSE TO 2021 SCIENTIFIC REVIEW GROUP (SRG) REVIEW

The Scientific Review Group (SRG) meeting was held virtually from February 22-25, 2021.

The following are the 'SRG Recommendations and Conclusions for the Pacific Hake Stock Assessment' from the 2021 SRG report and associated responses from the JTC:

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

Response – Developing best practices for modeling equilibrium recruitment (R_0) and recruitment variability (σ_R) remain broad topics of contemporary research. Recent recommendations suggest that the next generation of stock assessment modeling frameworks should concomitantly treat re-

cruitment deviations as a random effect and estimate σ_R (Punt et al., 2020). The JTC continues to conduct, collaborate on, and monitor ongoing research projects concerning approaches for advancing recruitment estimation, as applied to Pacific Hake and in general. Many of these issues are widespread in stock assessment and scientific-based solutions are likely to be the result of medium to long-term research projects. We provide an update to our previous response, including specific advances in research endeavors.

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

The Management Strategy Evaluation (MSE) framework for Pacific Hake creates considerable advantages for examining recruitment. The stock assessment model in the MSE is written in Template Model Builder (TMB), which provides efficient estimation of random effects using the Laplace approximation, while being parameterized to mimic the pertinent features of Stock Synthesis used in this assessment. Thus, the performance of using restricted maximum likelihood to estimate σ_R (Thorson, 2019) can be investigated in terms of management as well as statistical performance. The MSE framework can also be used to evaluate the robustness of recruitment modeling assumptions and the advantages of including environmentally-driven recruitment indices on management performance and uncertainty. Research slated to be published by Dr. Cathleen Vestfals and colleagues at the Northwest Fisheries Science Center that identified specific climate drivers associated with Pacific Hake early life-history stages and recruitment is now being used to select which environmental variables to fit as an index of recruitment within the stock assessment model. The utility of fitting to a recruitment index will be investigated in terms of forecasting skill and management performance within the MSE by the MSE working group.

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

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

2. The SRG recommends exploring alternative methods to simulate recruitment in the projections, such as drawing from past observations or using a mixture distribution, to characterize a different process than the assumed lognormal distribution.

Response – The JTC has begun exploring approaches to make informed decisions about current and future recruitment in projections. The inclusion, and associated justification, of the age-1 index in the 2022 base model is one example of this (see Sections 2.2.1 and 3.2). Additionally, the JTC has been exploring the fit of oceanographic and environmental variables identified by Dr. Cathleen Vestfals as being informative about the early life history of Pacific Hake as indices of recruitment within Stock Synthesis. Originally, these variables were only available for the years 1980–2010. Recently, data through 2020 were kindly provided and future research will focus on how to best create a single time series from the two periods.

Stock synthesis currently does not have capacity to draw from past observations or use mixing distributions to simulate recruitment in the projection period. Available options for recruitment during the projection period are the stock-recruitment curve, the stock-recruitment curve with a multiplier, and the mean across a user-defined time period. The MSE tool could be used to consider alternative recruitment distributional assumptions as future research.

Appendix H presents some new ideas for visualising annual recruitment relative to the largest recent recruitment to avoid misunderstanding of how large some recruitment events might be. It also includes figures that further enhance understanding of the current method for projecting recruitment.

3. The SRG requests that the JTC consider developing a decision table in the next assessment with recruitment fixed at the median and mean levels to assess the resulting impact on stock depletion.

Response – Specifying projected recruitment as the median of a given year range is not currently an option in Stock Synthesis. To work around this, the JTC calculated the median of estimates of recruitment from the main time period (1970–2020) and scaled this value to the estimate of R_0 . Scaled median recruitment was then used as an input value to Stock Synthesis which does allow for scaling forecasted recruitment in terms of virgin recruitment. The standard suite of catch projections were then conducted using mean recruitment from the main time period and scaled virgin recruitment based on the median estimates of recruitment relative to R_0 . Results were presented during the 2022 SRG review meeting.

4. Pacific Hake dynamics are highly variable even without fishing mortality. The SRG encourages the JTC (and MSE technical team) to continue investigating the usefulness of dynamic reference points in the management of Pacific Hake.

Response – There has been no additional work investigating the usefulness of dynamic reference points over the past year. Instead, the JTC and MSE technical team have been working with Stock Synthesis developers to incorporate dynamic reference point capabilities into the stock assessment statistical (Bayesian) and MSE coding (full closed-loop simulation) frameworks. Posterior distributions associated with dynamic reference points are now possible within Stock Synthesis. Likewise, the MSE can now utilize dynamic reference points in management procedure scenarios. The JTC plans to continue engaging in research related to dynamic reference points broadly, as well as specifically for Pacific Hake.

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

Response – A project was initiated at the Northwest Fisheries Science Center just prior to the start of the COVID-19 pandemic that sought to refine Pacific Hake stock assessment assumptions through incorporation of physiological indices of fish reproductive and metabolic status. This novel biological information would bolster the current practice of using gonadal histology alone for surveyed Pacific Hake and provide important data to more accurately determine the reproductive cycle of females and the potential spawning stock biomass. Data generated so far indicate that two types of lipids, triacylglycerols and phospholipids, in the livers of Pacific Hake are inversely related and predictive of sexual maturity in females. Levels of these lipids are also considerably shifted when aborted/atretic ovarian follicles are observed, suggesting that lipid levels may be predictive of skipped spawning, which can reduce the effective spawning stock biomass. In 2021, over 20 novel gene expression assays were designed for validation in Pacific Hake that target factors involved in ovarian development and atresia. Gonadal histology and staging was also conducted for fish collected in summer 2018 and 2019, and additional physiological samples were collected during the 2021 Joint U.S. and Canadian Integrated Acoustic and Trawl Survey. To the extent that onsite laboratory work will be possible in 2022, the goal for the project is to conduct liver lipid-class and ovarian RNA analyses for Pacific Hake samples collected in 2018 and 2019. The addition of these samples will greatly expand the data set and will help determine the utility of physiological indicators of reproductive/metabolic status. New developments are expected to inform maturity in future Pacific Hake stock assessments.

Pacific Hake ovary samples continue to be collected (see Table 15) for future analyses. While laboratory work has been limited over the past year due to facility closures, plans remain to include any available Canadian samples in subsequent maturity analyses.

6. **The SRG strongly supports the ongoing genetic analyses to determine whether there are genetic differences between Pacific Hake from the area south of Point Conception and coastal regions to the north.**

Response – Genetic work headed by Gary Longo at the Northwest Fisheries Science Center using samples from throughout the United States west coast and British Columbian coast, including

the Strait of Georgia and Puget Sound, is ongoing. Across two rounds of sequencing, DNA were extracted from 2,311 individuals across a range of spatio-temporal grid locations from 2015–2019. A total of 2,008 were sequenced based on sufficient DNA concentrations, and 1,417 passed quality filters. Population genetic analyses generally corroborate the single-stock hypothesis with little to no differentiation among the spatio-temporal grids. A Principal Component Analysis grouped all ‘Coastal’ individuals across space and time together, while Salish Sea individuals fell out as clearly distinct. Likewise, a Bayesian clustering analysis found that the observed genetic variation is best explained by two distinct genetic clusters, the Salish Sea and Coastal populations. However, there was some evidence for weak differentiation among some spatio-temporal grid locations (across years and location), which may be due to weak differentiation among cohorts. This pattern was corroborated with weak, but statistically significant, pairwise fixation index comparisons. Overall, the genetic results corroborate the single-stock hypothesis and highlight the strong differentiation between the resident Salish Sea population and the migratory coastal population, similar to that found in García-De León et al. (2018).

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

Response – The JTC has conducted all of the requested sensitivities (and many others) and provides summaries in written (Section 3.8), tabular (beginning with Table 33), and graphical (beginning with Figure 41) formats in this document. Diagnostics of sensitivity models are produced in a separate document and are available upon request.

8. The SRG encourages the JTC to include a complete reproduction of the executive summary incorporating the age-1 index in the next assessment and, if time permits, the retrospective analyses.

Response – The age-1 index is incorporated into the 2022 base model. As a result, the JTC has produced a reproduction of the Executive Summary tables and figures for the results of the sensitivity model that excludes the age-1 index (see Appendix G).

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

Response – The JTC has extended this analysis in Figures 58–65 in response to this request, including a retrospective component given that all retrospective model runs are performed using MCMC. Analyses are also presented for the sensitivity to the base model that removes the age-1 index in Figures G.13 and G.14; all results are discussed in Section 3.10. Related, the JTC is continuing to explore options for improving recruitment estimation and predictions (see Responses 1–3, 5, and 8).

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

Response – An ageing error study in conjunction with CARE has commenced, including planned sample exchanges between United States and Canada ageing labs. However, a full exchange is on hold until there are staff to process the necessary aquatic animal health import permits to send age structures to Canada.

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

Response – Restrictions related to the COVID-19 pandemic have limited the availability to access historical data. Even if historical Pacific Hake age structures were found and were determined to be in a usable state, these new structures would need to be integrated into existing ageing laboratory work plans. The JTC has conducted analyses previously showing that small changes to historical data have little relevance to current management quantities of interest. So at this time, the JTC does not expect small amounts of historical weight-at-age data to significantly alter stock assessment results used for management decisions.

12. **If biological data cannot be collected by any fleet in 2021, the SRG encourages the JTC to explore model sensitivity to that absence. We commend the JTC for their foresight in investigating the impact of the lack of 2020 Canadian freezer-trawler age data in this year’s assessment.**

Response – In 2021, the JTC explored the absence of 2020 Canadian freezer-trawler age data and came to the conclusion that the loss of these data had little impact on overall results. This is, in part, because there were 2020 Canadian age data available from the shoreside fleet and the Canadian shoreside and freezer-trawler fleets tend to provide similar age-composition information.

In 2021, there were almost no biological data available for the Canadian fishery. Just a single shoreside trip was sampled, compared to a recent five-year average of 55 trips, and no freezer-trawlers provided age data. The single sample from the shoreside fishery represents 0.22% of the total number of samples collected in 2021 but because age-composition data are scaled by catch to create a single aggregated composition, the sample is weighted to represent 5% of the 2021 age composition. Fortunately, in 2021 the catches in the Canadian shoreside fishery were less than average, which has been around 15% over the last two decades, or else the single sample would have been given even more weight. The consequences of this loss of data is a disproportionate (relative to areal catch) reliance on age data sampled from U.S. waters as being representative of the coast-wide population for the 2021 fishing year. Whereas age-composition information

from U.S. fisheries typically includes fewer older fish relative to information from the Canadian fisheries.

The JTC is concerned about multi-year changes in sampling and, in particular, the ending of complete data series. As a result, the JTC conducted analyses to evaluate potential medium- to long-term impacts on the stock assessment due to the loss of Canadian age data. Starting with the most recent year and working back to 2008, we recalculated the age compositions used to fit the model assuming that samples were not available from the Canadian freezer-trawler fishery or any Canadian fishery (see Table 4 for sample sizes). The base model was refit to these contrived data sets similar to a retrospective analysis except only Canadian age data were removed. Estimates of recent spawning stock biomass decreased as years of information were removed because the data contained less information on older fish than the full data set.

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

Response – It is important to capture key, mechanistic and/or stochastic population processes in stock assessment projections to sufficiently characterize levels of prediction uncertainty that are consistent with available information to adequately contextualize metrics used to aid management decisions. Likewise, it is as important to evaluate the basic population-dynamics assumptions used in such projections. Recent, current, and future recruitment are perhaps the most influential sources of uncertainty in stock assessment projections. As a result, the JTC has prioritized research on recruitment, including supporting analyses and the justification for using the age-1 index in the 2022 base model and other related analyses mentioned in this section.

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

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

Response – Teamwork is an attribute of great interest and pride within the JTC, thank you.

Also, the final major conclusion of the SRG report was the following:

The SRG considered revisions to the decision tables in the stock assessment that depict fishing intensity for several catch streams and the associated impacts on the stock in terms of depletion (spawning biomass relative to B_0) for those catch streams. One main change was implemented: relative spawning biomass was projected forward for three years from 2021 instead of two years and the relative biomass values shown in each row now reflect the projected impact of the specified amount of harvest on stock status at the beginning of the following year. Additionally, the 25% and 75% intervals have been removed from both tables, leaving the median along with the 5% and 95% values from the distributions that define the 90% credible intervals. **The SRG believes that the resulting decision tables are clearer and easier to understand and recommends that the JMC review these tables along with the standard decision tables, and provide feedback to the SRG and JTC as to its preference during the March 15-17, 2021 JMC Meeting. These alternative decision tables are presented in Appendix B of the JTC Stock Assessment document.**

Response – Over the past year, the JTC engaged in discussions with the JMC about decision table formatting and alternative projection catch streams. As a result, the JTC will be using the the new format in the 2022 stock assessment, as discussed in Section 3.7.

3.4 MODELING RESULTS

3.4.1 Changes from 2021

A set of ‘bridging’ models was constructed to evaluate the component-specific effects of all changes from the 2021 base model to the 2022 base model.

In short, these included the following:

- Update to the latest version of Stock Synthesis, version 3.30.18;
- Update catch and age-composition data from years prior to 2021;
- Add new catch and age-composition data for 2021;
- Update acoustic survey biomass and age-composition data from years prior to 2021;
- Add the 2021 acoustic survey biomass and age-composition estimates;
- Add weight-at-age data for 2021 as well as update data for years prior; and
- Add the age-1 index time series.

The bridging steps can be grouped into three main sets of changes, with the majority of the steps being those that are performed routinely. The first step updated the Stock Synthesis framework to follow current best practices. The second step updated all information available from the fishery and acoustic survey. The third step implemented changes related to the addition of the age-1 index.

Stock Synthesis version 3.30.18 includes a number of changes since the version used by Johnson et al. (2021), mostly related to options not explicitly used in this assessment. Changes relevant

to the assessment of Pacific Hake include changes to how files are saved for MCMC samples and the timing of the calculation of key population processes such as growth and natural mortality. Adaptations within the Stock Synthesis modeling framework itself had little effect on parameter estimates compared to the 2021 base model and thus no effect on resulting time series.

The second set of bridging steps was conducted to update fishery-dependent and fishery-independent data. This primarily included minor adjustments in catch, fishery age compositions, the 2019 acoustic survey biomass estimate, and weight-at-age values as databases are continually updated. Samples that were recently aged but not available for the 2021 assessment were included. These changes to pre-2021 data were small enough that they had little impact on the model results (Figure 16).

The addition of 2021 catch and fishery age compositions extends the model to the start of 2022 but the estimates for 2022 are highly uncertain (Figure 16) in the absence of additional information about recent recruitment. These data had relatively little impact on the historical biomass estimates, indicating that the observed 2021 ages were consistent with the model estimates without those data (Figure 16). However, the addition of these data did slightly shift recent recruitment estimates, though overall uncertainty was still high. Recruitment estimates and stock trajectory were relatively unchanged with the addition of 2021 weight-at-age data. This bridging step also shifted the ending year of the deviations in the selectivity parameters from 2020 to 2021 because of the addition of fishery data in 2021.

Including the 2021 fishery-independent biomass estimate and age compositions led to a slightly more optimistic trajectory of the stock over the last couple of years (Figure 16), whereas updating the 2019 survey biomass estimate itself had negligible effect. The addition of 2021 survey data led to small shifts in expected recruitment, particularly for the 2016, 2017, and 2018 year classes. The 2018 year class is estimated to be higher in this assessment than in the 2021 assessment, but it still remains a below-average year class. This increase is largely driven by the addition of the 2021 acoustic-survey age compositions, because this was the first time the 2018 and 2019 cohorts were adequately sampled (age-2 or older) by the survey, which is why the uncertainty associated with these cohorts was reduced (though still quite uncertain; Figure 16).

The final bridging was adding the age-1 index time series (1995 to 2021) as an additional source of information to inform recent recruitment (Section 2.2.1). The age-1 index has been evaluated in many previous stock assessments as a sensitivity analysis and in recent years a close examination of the full suite of assessment results were produced to examine this key sensitivity. The age-1 index is fit in the assessment model through a lognormal contribution to the likelihood function. The addition of this data source resulted in a slight increase in estimated recent recruitment, most noticeably for the 2018 and 2020 year classes (Figure 17), and increase in virgin recruitment. In turn, this results in a slightly higher trajectory of spawning stock biomass from 2013–2022 and a change in 2022 median relative spawning stock biomass from 53.3% to 64.7%.

3.4.2 Assessment model results

Model Fit

Stationarity of the posterior distribution for model parameters was assessed via a suite of standard single-chain and multi-chain diagnostic tests via graphical summaries and interactive web applications (ShinySTAN; <https://mc-stan.org/users/interfaces/shinystan>). Key diagnostic figures are given in Appendix A and now discussed. All estimated parameters showed good mixing during sampling, no evidence for lack of convergence, and acceptable autocorrelation (results for some key parameters are shown in Figures A.1–A.3). Correlation-corrected effective sample sizes were sufficient to summarize the posterior distributions and neither the Geweke nor the Heidelberger and Welch statistics for these parameters exceeded critical values more frequently than expected via random chance (Figure A.4). The Gelman-Rubin multi-chain diagnostic test, which compares within-chain variance to among-chain variance, further indicated that convergence was adequately achieved (examined via ShinySTAN). Correlations among key parameters were generally low, with the exception of M and $\log R_0$ (Figure A.5). Estimates of recruitment in 2010 and 2014 were correlated with the derived quantity of catch from the default harvest rule in 2022, as to be expected given the dependencies among these quantities (Figure A.5). An examination of deviations in recruitment (log-scale differences between estimated and expected recruitment values) from recent years (Figure A.6) indicates the highest correlation (0.84) was between the 2014 and 2016 recruitment deviations. This continues to be likely caused by the relative proportion of these two cohorts being better informed by recent age-composition data.

The estimate (median and 95% credible interval) for $\log \theta_{\text{fish}}$ is -0.564 (-0.763, -0.346), giving an effective sample size multiplier $\theta_{\text{fish}}/(1 + \theta_{\text{fish}})$ of 0.363 (0.318, 0.414). The survey age-composition parameter is also well-sampled with $\log \theta_{\text{surv}}$ estimated as 2.591 (1.399, 4.787), and the resulting effective sample size multiplier $\theta_{\text{surv}}/(1 + \theta_{\text{surv}})$ of 0.930 (0.802, 0.992).

The base model fit to the acoustic survey biomass index (Figure 18) remains similar to the 2021 base model. The 2021 survey biomass estimate resulted in a slight upward shift in the fit to the 2019 survey data points, but the result of a relatively stable biomass trend from 2013–2019 is the same (Figure 18). The addition of 2021 fishery data was the main reason for this change in fit to the 2019 data point (Figure 16). The 2021 survey estimate was lower than in 2019 (second lowest since 2013), and the model fit indicates a decline in biomass compared to the relatively stable 2013–2019 period. The 2001 survey biomass index continues to be well below any model predictions that were evaluated, and no direct cause for this is known. The survey did begin earlier that year than all other surveys between 1995 and 2009 (Table 12), which may explain some portion of the anomaly, along with El Niño conditions and age structure. The underestimation of the 2009 biomass estimate is larger than the underestimation of any other year. The uncertainty of this point (both modeled and actual) is high because of the presence of large numbers of Humboldt Squid during the survey. Humboldt Squid have similar target strength to hake which could introduce bias in the biomass estimate for that year, and which also likely influenced hake population dynamics through predation in that year.

The median posterior density estimates were less than the 2015 survey index, greater than the 2017 and 2019 survey indices, and closely fit the 2021 index (Figure 18). This is likely due to slight differences in what the fishery composition data and survey composition data, when considered independently, would otherwise suggest as population trends. Additionally, the population has undergone recent high catch levels and produced a couple of above-average cohorts that are now mature.

The base model fit to the index of age-1 fish highlights an overall general confirmation of relative cohort strength (Figure 19). In particular, the 2008 and 2014 cohorts were estimated to be less than the index, while the 1994 and 2016 cohorts were estimated to be larger than indicated by the index. The age-1 fish in 2011 (the large 2010 cohort) was closely fit. Age-1 fish in 2021 (2020 cohort) were estimated slightly under the index value and, being so young, had the largest amount of uncertainty in the time series. The model indicates that the 2020 cohort may be similar in size to the 2016 cohort, based on information in the age-1 index and from age-1 fish caught in the fishery.

Fits to the age-composition data continue to show close correspondence to the dominant and small cohorts observed in the data when the data give a consistent signal (Figure 20). 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 2021 fishery, the 2016 cohort was the largest (36%), followed by the 2014 cohort (24%), then the 2017 cohort (14%). Age compositions from the 2021 acoustic survey suggest a similar age structure, i.e., the 2016 cohort was the largest (28%), followed by the 2014 cohort (21%), then the 2017 cohort (14%). Combined, the 2015–2021 fishery age-composition data and the 2017–2021 acoustic survey age-composition data suggest that 2014 was a strong recruitment year, and the model was able to adequately fit to these observations (Figure 20). The 2016 cohort, which has been observed twice by the survey, still appears to be smaller than the 2014 cohort. The 2021 survey was the first to sample the 2019 cohort, confirming that it was not extremely large (8.0% of the 2021 survey catch). Residual patterns to the fishery and survey age data do not show patterns that would indicate systematic bias in model predictions (Figure 21).

The median estimates for numbers, biomass, exploitation rate, and catch (in numbers and in biomass) for each age class in each year are given in Tables 18-22. For the major cohorts, the resulting estimated age-specific catch, natural mortality, and surviving biomasses are given in Table 23. For example, the catch weight of the 2014 cohort at age-5 was slightly less than that of the 2010 cohort at age-5 and the resulting surviving biomass of the 2014 cohort was approximately half of the surviving biomass of the 2010 cohort.

Posterior distributions for both steepness and natural mortality are strongly influenced by priors (Figure 22). The posterior for steepness is only slightly updated by the data, as expected given the low sensitivity to steepness values found in previous hake assessments. The natural mortality parameter, 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 sensi-

tivity runs (see Section 3.8). Other parameters showed updating from diffuse priors to posterior distributions, including θ_{fish} and θ_{surv} (as outlined in Section 2.4.4).

The 2022 base model specified the same level of variation (standard deviation of $\Phi = 1.4$) associated with time-varying fishery selectivity as the 2021 base model, effectively allowing the model flexibility (i.e., a lower penalty on the overall likelihood) to fit to data that suggests high variability among years for each age. This level of variation led to results that were consistent with the 2021 acoustic survey biomass estimate and gave reasonable fits to the fishery age-composition data, given that there is considerable uncertainty associated with spatial changes in fish availability (due to movement) and recent variability in oceanographic conditions. Estimated selectivity deviations for age-3 and age-4 fish are larger from 2010 to 2012 than in recent years until 2020 when the deviation for age-4 was large again (Figures 23 and 24). The median selectivity peaks at age-4 in 2010, 2012 and 2020 and at age-3 in 2011 suggesting targeting (or generally higher availability) of the younger cohorts in those years. This pattern is consistent with the 2008 cohort appearing strong in the fishery age compositions initially, but decreasing in prominence from 2013 onward (Figure 20). Fishery selectivity on age-2 fish was at its highest in 2016, followed by 2018. Fishery selectivity for the most recent year was characteristic of a logistic pattern, where selectivity increased smoothly from age-2 to a peak at age-5 and older ages (Figure 24). Even though the survey selectivity is time invariant, the posterior shows a broad band of uncertainty between ages 2 and 5 (Figure 25). The decline in survey selectivity between ages 3 and 4 may be an artifact of the interaction between large cohorts and the biennial timing of recent surveys, with the 2010, 2014, and 2016 cohorts occurring in the survey at ages 3 and 5 but not age-4. Fishery selectivity is likewise very uncertain (Figures 24 and 25), but in spite of this uncertainty, changes in year-to-year patterns in the estimates are still evident, particularly for 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 26 and 27 and Tables 24 and 25). The model estimates that it was below the unfished equilibrium in the 1960s, at the start of the assessment period, due to lower than average recruitment. The stock is estimated to have increased rapidly and was above unfished equilibrium in the mid-1970s and mid-1980s (after two large recruitments in the early 1980s). It then declined steadily to a low in 1999. This was followed by a brief increase to a peak in 2002 as the very large 1999 year class matured. The 1999 year class largely supported the fishery for several years due to relatively small recruitments between 2000 and 2007. With the aging 1999 year class, median female spawning biomass declined throughout the late 2000s, reaching a time-series low of 0.625 million t in 2010. The assessment model estimates that median spawning biomass then peaked again in 2013 and 2014 due to a very large 2010 year class and an above-average 2008 year class. The subsequent decline from 2014 to 2016 is primarily from the 2010 year class surpassing the age at which gains in weight from growth are greater than the loss in weight from mortality (growth-mortality transition). The 2014 year class is estimated to be large, though not as large as the 1999 and 2010 year classes, resulting in an increased biomass in 2017. The estimated biomass was relatively steady from 2017 to 2019,

and then declined in 2020 and 2021 due to the 2014 and 2016 year classes moving through the growth-mortality transition during a period of high catches.

The median estimate of the 2022 relative spawning biomass (spawning biomass at the start of 2022 divided by that at unfished equilibrium, B_0) is 65%. However, the uncertainty is large, with a 95% posterior credibility interval from 31% to 135% (Tables 24 and 25).

The median estimate of the 2022 spawning biomass is 1.171 million t (with a 95% posterior credibility interval from 0.584 to 2.585 million t). The estimate of the 2021 female spawning biomass is 1.347 (0.743–2.896) million t. This is a somewhat higher median and broader credibility interval than the 0.981 (0.404–2.388) million t estimated in the 2021 assessment, but there is considerable overlap of the credibility intervals. The increase appears to be due to the addition of survey data, namely the 2021 biomass index and age compositions, plus the full age-1 index (as outlined in Section 3.4.1).

Recruitment

The new data and addition of the age-1 index for this assessment do not significantly change the pattern of recruitment estimated in recent assessments. However, estimates of absolute recruitment for some recent years have increased. For example, this assessment's median estimate of the 2014 recruitment is 0.4 billion fish higher than in last year's assessment (a 5% increase). Similarly, estimates for the large 2016 and small 2018 recruitments have increased by 33% (1.6 billion fish) and 271% (0.5 billion fish), respectively, but the general notion remains that the 2016 cohort is above average and the 2018 cohort is below average.

Pacific Hake appear to have low average recruitment with occasional large year-classes (Figures 28 and 29, Tables 24 and 25). Very large year classes in 1980, 1984, and 1999 supported much of the commercial catch from the 1980s to the mid-2000s. From 2000 to 2007, estimated recruitment was at some of the lowest values in the time series, but this was followed by an above average 2008 year class. Current estimates continue to indicate a very strong 2010 year class comprising 64% of the coast-wide commercial catch in 2014, 33% of the 2016 catch, 23% of the 2018 catch (all unchanged from last year's assessment), and 14% of the 2020 catch. The decline from 2014 to 2016 was partly due to the large influx of the 2014 year class (50% of the 2016 catch was age-2 fish from the 2014 year class; this was larger than the proportion of age-2 fish, 41%, from the 2010 year class in 2012). The median estimate of the 2010 year class is very slightly below the highest ever (for 1980), with a 50% probability that the 2010 year class is larger than the 1980 year class (this probability was 46% for last year's assessment).

The current assessment also estimates a strong 2014 year class (Figure 30) comprising 50% of the 2016 catch, 38% of the 2017 catch, 27% of the 2018 catch, 32% of the 2019 catch, 31% of the 2020 catch, and 24% of the 2021 catch. The 2016 cohort also appears to be above average at 26% of the 2018 catch, 21% of the 2019 catch, 36% of the 2020 catch, and 36% of the 2021 catch. Although the absolute size of the 2014 year class remains uncertain, at least more so than cohorts that have been observed for more years, seven years of fishery data and four years of survey data show that it is a strong year class. The 2016 year class is estimated to be above average (similar

in size to the 2008 year class) from five years of fishery data and three years of survey data. The 2017 year class was first observed by the survey in 2019 and is estimated to be about average in size. With the addition of the age-1 index, there is information beyond just fishery encounters in the data to estimate the size of the 2020 year class. Collectively, these data indicate that the 2020 year class is above average, while the 2019 year class is informed by the 2021 biomass index and fishery data, but has no age-1 index.

The model currently estimates small 2011, 2013, 2015, 2018 and 2019 year classes (median recruitment well below the mean of all median recruitments) and near average 2012 and 2017 year class. The proportion of the fishery catch that was age-1 fish in 2019 (2018 year class) and 2020 (2019 year class) was well below that observed in 2018 (2017 year class) and 2017 (2016 year class; Table 10). There is no information in the data to estimate the sizes of the 2021 and 2022 year classes. Retrospective analyses of year class strength for young fish have shown the estimates of recent recruitment to be unreliable prior to at least model age-3 (observed at age-2) without a survey in the most recent year and age-2 (observed at age-1) with a survey.

The estimated recruitments with uncertainty for each year and the overall stock recruit relationship are provided in Figure 31. Extremely large variability about the expectation and about the joint uncertainty of individual recruitment and spawning biomass pairs are evident. High and low recruitments have been produced throughout the range of observed spawning biomass (Figure 31). The standard deviation of the time series of median recruitment deviation estimates for the years 1970-2020, which are informed by the age compositions and the age-1 index, is 1.71. This value is higher than, but consistent with, the base model value of 1.4.

Exploitation status

The median estimated relative fishing intensity on the stock is below the $SPR_{40\%}$ target for all years (Figure 32 and Tables 24 and 25). It was close to the target in 2008, 2010 and 2011, but harvest in those years did not exceed the catch limits that were specified, based on the best available science and harvest control rules in place at the time. Exploitation fraction (catch divided by biomass of fish of age-2 and above) has shown relatively similar patterns (Figure 33 and Tables 24 and 25). Although displaying similar patterns, the exploitation fraction does not necessarily correspond to fishing intensity because fishing intensity more directly accounts for the age-structure of both the population and the catch. Median relative fishing intensity is estimated to have declined from 90.5% in 2010 to 43.3% in 2015, and then it leveled off around 70% from 2016 to 2019 before dropping to 58.7% in 2020 and 52.8% in 2021. The median exploitation fraction has increased from a recent low of 0.05 in 2012 to 0.12 in 2017 and has remained relatively stable since then (dropping no further than 0.09). Although there is a considerable amount of imprecision around these recent estimates due to uncertainty in recruitment and spawning biomass, the 95% posterior credibility interval of relative fishing intensity was below the SPR management target from 2012 through 2016 and again from 2018 to 2021 (Figure 32). The median estimate for 2017 is below the management target, however the 95% posterior credibility interval does include the target level.

Management performance

Over the last decade (2012–2021), the mean coast-wide utilization rate (i.e., proportion of catch target removed) has been 69.4% and catches have been below coast-wide targets (Table 3). From 2017 to 2021, the mean utilization rates differed between the United States (73.0%) and Canada (63.9%). However, country-specific quotas (or catch targets) in 2020 and 2021 were specified unilaterally, due to the lack of an agreement on a coast-wide 2020 and 2021 TAC. In 2015, the utilization rate for the coast-wide fishery was the lowest of the previous decade (44.1%) due, in part, to difficulties locating aggregations of fish and possibly economic reasons. Before 2015, the underutilization in the United States was mostly a result of unrealized catch in the tribal apportionment, while reports from stakeholders in Canada suggested that hake were less aggregated in Canada and availability had declined. In 2016, the utilization rate increased but remained below pre-2015 levels, despite the total 2016 catch being one of the highest of the preceding years. This is in large part due to increasing catch targets as biomass continues to increase. The total utilization rate in recent years (2017–2021) has been relatively steady and close to the average over the last decade (68.9%). Total landings last exceeded the coast-wide quota in 2002 when utilization was 112%.

The median relative fishing intensity was below target in all years throughout the time series (Table 24 and Figures 32 and 34). The median relative spawning biomass was above the $B_{40\%}$ reference point in all years except 2007, 2009, and 2010 (Table 24 and Figure 27). These are also shown on a phase plot of the joint history of relative spawning biomass and relative fishing intensity (Figure 34). Relative spawning biomass increased from the lows in 2007–2010 with above average recruitment in 2008, 2010, 2014, and 2016. Correspondingly, relative fishing intensity has remained well below target despite recent increases in total catch. While there is large uncertainty in the 2021 estimates of relative fishing intensity and relative spawning biomass, the model estimates a 0% joint probability of being both above the target relative fishing intensity in 2021 and below the $B_{40\%}$ relative spawning biomass level at the start of 2022.

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 uncertainty portrayed by the posterior distribution is a better representation of uncertainty than asymptotic approximations about MLEs because it allows for asymmetry (Figure 22; also see Stewart et al. 2012 for further discussion and examples).

The medians of the key parameters from the posterior distribution are similar to those in last year's base model (Table 26). The largest change was a 12% increase in R_0 . Medians of some of the derived quantities also change somewhat; in particular, recruitment in 2010, 2014, and 2016 increased, and B_0 has increased from that estimated in the 2021 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. The addition of the age-1 index in this assessment will, in some cases, help to reduce this uncertainty. 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 a suite of other informative sensitivity analyses using full MCMC results (Section 3.8).

We also present an appendix showing results for the sensitivity model that excludes the age-1 survey index (Appendix G). The exclusion of the age-1 survey model was chosen because it matches the model structure of the 2021 base assessment model.

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 year, this will include evaluating the utility of incorporating environmentally-driven age-0 recruitment indices into the stock assessment.

3.6 REFERENCE POINTS

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

We report estimates of the base reference points (e.g., $F_{\text{SPR}=40\%}$, $B_{40\%}$, B_{MSY} , and MSY) with posterior credibility intervals in Table 27. The median of the female spawning biomass at $F_{\text{SPR}=40\%}$ (namely the median of $B_{\text{SPR}=40\%}$) and the median yield at $F_{\text{SPR}=40\%}$ are higher than the estimates in the 2021 assessment (Table 26).

As part of the DFO Sustainable Fisheries Framework, DFO (2009) defined a limit reference point as being a biomass below which serious harm is believed to be occurring to the stock, and an upper stock reference point above which the stock is considered to be healthy. These would equate to the Agreement reference points of $B_{10\%}$ and $B_{40\%}$ (the female spawning biomass being 10% and 40%, respectively, of the unfished equilibrium female spawning biomass). The probabilities of

the female spawning biomass at the start of 2022 being above each of these points are $P(B_{2022} > B_{10\%}) = 100\%$ and $P(B_{2022} > B_{40\%}) = 90.5\%$ [in last year's assessment the equivalent calculation was $P(B_{2021} > B_{40\%}) = 82.2\%$], such that the stock is estimated to be in the 'healthy zone' (above the upper stock reference point of $B_{40\%}$).

With respect to DFO's provisional limit reference point of $0.4B_{MSY}$ and provisional upper stock reference point of $0.8B_{MSY}$, the probabilities are $P(B_{2022} > 0.4B_{MSY}) = 100\%$ and $P(B_{2022} > 0.8B_{MSY}) = 99.7\%$ such that the stock is estimated to be in the provisional 'healthy zone'. For completeness, we note that $P(B_{2022} > B_{MSY}) = 98.7\%$

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 2022, the estimated posterior median relative spawning biomass is 65%, such that the spawning biomass is above $B_{40\%}$ and well above $B_{25\%}$. The probability that spawning biomass at the beginning of 2022 is above $B_{40\%}$ is $P(B_{2022} > B_{40\%}) = 90.5\%$ (as noted above), and of being above $B_{25\%}$ is $P(B_{2022} > B_{25\%}) = 99.2\%$.

3.7 MODEL PROJECTIONS

The median catch limit for 2022 based on the default $F_{SPR=40\%}$ -40:10 harvest policy is 715,643 t, but has a wide range of uncertainty (Figure 35), with the 95% credibility interval being 300,110–1,882,776 t.

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

The tables use the new format demonstrated by Johnson et al. (2021) arising from discussions at the 2021 SRG meeting. Enhancements include:

- showing current spawning biomass once in a single row at the top (*Start 2022*) rather than repeating it;
- showing values as proportions instead of percentages;
- removing the 25% and 75% columns;
- adding a new column, *Biomass year*, which emphasizes the timing of the biomass estimates;
- re-naming of the header for the relative biomass values from *Beginning of year relative spawning biomass* to *Resulting relative spawning biomass*;

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- the values shown in the *Resulting relative spawning biomass* columns now represent the biomass at the beginning of the year resulting from the catch taken in the previous year, as given in the *Catch year* column;
 - extending the projections of relative spawning biomass to the start of the *third* projection year (2025), rather than just the second year.

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 (2017–2021); 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 $F_{SPR=40\%}$ default harvest rate limit. This can happen for the median relative fishing intensity in 2022, 2023, 2024 and 2025 because the $F_{SPR=40\%}$ default harvest-rate catch limit is calculated using baseline selectivity from all years, whereas the forecasted catches are removed using selectivity averaged over the last five years. Recent changes in selectivity will thus be reflected in the projection of overfishing. An alternative catch level where median relative fishing intensity is 100% is provided for comparison (catch alternative m: FI=100%).

Key management metrics are presented for 2023, 2024 and 2025 projections (Tables 30–32 and Figures 36–39). These metrics summarize the probability of various outcomes from the base model given each potential management action. Although not linear, probabilities can be interpolated from this table for intermediate catch values in 2022 (Table 30 and Figure 37). However, interpolation is not appropriate for all catches in 2023 and 2024 because they are conditional on previous year(s) catch levels. This explains why a few probabilities decline (rather than rise) with increased 2023 and 2024 catch levels in Tables 31 and 32 and Figures 38 and 39.

Figure 36 shows the projected relative spawning biomass trajectory through 2025 for several of these management actions. With zero catch for the next three years, the biomass has a 8% probability of decreasing from 2022 to 2023 (Table 30 and Figure 37), a 47% probability of decreasing from 2023 to 2024 (Table 31 and Figure 38), and a 64% probability of decreasing from 2024 to 2025 (Table 32 and Figure 39).

The probability of the spawning biomass decreasing from 2022 to 2023 is under 57% for all catch levels (Table 30 and Figure 37). It is 30% for the 2022 catch level similar to that for 2021 (catch alternative f). For all explored catches, the maximum probability of the spawning biomass dropping below $B_{10\%}$ at the start of 2023 is 0%, at the start of 2024 is 1%, and at the start of 2025 is 7% (Tables 30–32 and Figures 37–39). The similar maximum probability of dropping below $B_{40\%}$ at the start of 2023 is 18%, at the start of 2024 is 31%, and at the start of 2025 is 44%. As the large 2010, 2014, and 2016 cohorts continue to age, their biomass is expected to decrease as losses from mortality continue to outweigh increases from growth. The estimated above-average 2020 cohort will play a large role in determining spawning stock biomass during the forecast years presented here.

It should be noted that forecasted biomass is not only influenced by catch levels. As the large 2010 and 2014 cohorts continue to age, their biomass is will continue to decrease (Table 23) as losses from mortality outweigh increases from growth. The smaller above-average 2016 cohort has also entered this growth-mortality transition period (Table 23). The below-average 2015 and 2018 cohorts will contribute much less to forecasted spawning biomass than the larger cohorts. The probability that the 2023 spawning biomass will be less than the 2022 spawning biomass ranges from 8% to 56% depending on the catch level (Table 30 and Figure 37).

The age composition (in numbers) of the catch in 2022 is projected to be (using MCMC medians) 24% age-6 fish from the 2016 cohort, 21% age-2 fish from the 2020 cohort, 16% age-8 fish from the 2014 cohort, 12% age-5 fish from the 2017 cohort, and only 7% age-12 fish from the large 2010 cohort (Figure 40). However, those estimates are highly uncertain with the 95% credibility interval for the age-6 fraction spanning 11%–38%, and for the very young and highly uncertain age-2 fraction spanning 4%–59%.

Due to the higher average weight at age-6 versus age-2, the median expected proportion of the 2022 catch by weight is 26% for the age-6 2016 cohort (compared to 24% by numbers) and 10% for the age-2 2020 cohort (compared to 21% by numbers; Figure 40).

With respect to the DFO reference points, with the largest 2022 catch of 715,643 t given in Table 30, at the start of 2023 the stock is expected to be above the critical zone with a probability of $P(B_{2023} > B_{10\%}) = 100\%$ and in the healthy zone with a probability of $P(B_{2023} > B_{40\%}) = 82\%$. 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 $P(B_{2023} > 0.4B_{MSY}) = 100\%$, in the healthy zone with a probability of $P(B_{2023} > 0.8B_{MSY}) = 98\%$, and above B_{MSY} with a probability of $P(B_{2023} > B_{MSY}) = 95\%$ for this catch.

With respect to PFMC stock size reference points, a level of 2022 catch consistent with the Agreement default harvest control rule (715,643 t) has an 18% estimated probability of resulting in the biomass going below $B_{40\%}$ at the start of 2023 (and 4% probability of going below $B_{25\%}$; Table 30). If catches in 2022 and 2023 are the same as in 2021 (325,000 t, catch scenario f) then the probability of the biomass going below $B_{40\%}$ is 8% for the start of 2023 and 13% for the start of 2024.

3.8 SENSITIVITY ANALYSES

Sensitivity analyses were conducted to investigate influence of data inputs and structural uncertainty of the base model by investigating how changes to the model affected the estimated values and derived quantities. All sensitivity analyses compared MCMC posteriors that were created using the `adnuts` R package (Monnahan and Kristensen, 2018; Monnahan et al., 2019) to implement the NUTS algorithm with a similar number of posterior samples as the base model. For a comparison of the parameter estimates for the sensitivity analyses with those from the base model see Tables 33–34. Many additional sensitivity runs were conducted when developing and testing the 2022 base model. Here we focus on the main sensitivities which include the following:

1. Consideration of higher standard deviations on the prior distribution for natural mortality;

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2. Consideration of alternative values for steepness;
 3. Assumption of higher/lower variation about the stock-recruitment curve (σ_r);
 4. Removal of the age-1 index as a data source;
 5. Downweighting fishery age-composition data;
 6. Consideration of alternative standard deviations for time-varying selectivity; and
 7. Consideration of an alternative maximum age for fishery and survey selectivity.

None of the sensitivities resulted in any substantial departure from the main population dynamics of the base model. All sensitivity models showed large estimated increases in spawning biomass in the early- to mid-2010s that continues to be driven by the 2010, 2014, and 2016 cohorts and a steady reduction in spawning biomass from high levels over the last few years. All sensitivity models indicate that 2022 relative spawning stock biomass is above $B_{40\%}$. The overall scale of the population was impacted by various alternative assumptions, and the highly uncertain size of the recent cohorts were more variable across sensitivity analyses than earlier cohorts which have been observed for more years.

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. Those identified here (as noted above) include the specification of natural mortality, the level of variation assumed about the stock-recruitment relationship (σ_r), and the resiliency of the stock in terms of recruitment (steepness).

The standard deviation of the prior distribution on natural mortality was increased from the base model value of 0.1 to 0.2 and 0.3. The median of the MCMC posteriors for natural mortality increased from 0.233 with a 95% credible interval of 0.193–0.280 for the base model (prior standard deviation of 0.1) to 0.309 with a 95% credible interval of 0.238–0.359 for the sensitivity run with the prior standard deviation set to 0.3 (Table 33). In addition to allowing a higher estimated value for natural mortality, the broader prior on M also increased the overall scale of the population, the estimated stock status relative to B_0 prior to 1990, the uncertainty in spawning biomass on both absolute and relative scales, halved estimated relative fishing intensity in 2021, and doubled equilibrium yield at $B_{SPR=40\%}$. (Table 33 and Figures 41 and 42).

The mean of the prior distribution on steepness was decreased from 0.777 (base) to 0.5 and, separately, steepness was fixed at 1.0. The decrease in the mean of the prior resulted in a decrease in the MCMC estimate of steepness from a median of 0.810 with a 95% credible interval of 0.567–0.958 to a median of 0.541 with a 95% credible interval of 0.344–0.757 (Table 33). However, neither steepness sensitivity analysis had an impact on the overall model results (Figures 41 and 42), because Pacific Hake spawning biomass has remained above levels where changes in steepness would appreciably influence stock-recruit dynamics (Figure 31).

The value of σ_r was changed from a value of 1.4 (base) to alternative high (1.6) and low (1.0) states. The low value, $\sigma_r = 1.0$, resulted in a model where the standard deviation of the MLEs of recruitment deviations in the period with the most informative data was 1.55, suggesting that the data were inconsistent with the lower value of σ_r . The high value, $\sigma_r = 1.6$, resulted in a model with a more consistent standard deviation for the estimated recruitment deviations, at 1.86. However, the high σ_r model had a larger difference between the spawning biomass at unfished equilibrium and the spawning biomass at the initial year of the model than the low σ_r model (Table 33 and Figures 41 and 42). Similar to previous assessments, estimates of unfished recruitment ($\log R_0$) and relative spawning biomass are sensitive to σ_r , whereas absolute estimates of spawning biomass are insensitive. The method of Methot and Taylor (2011) considers a combination of the variability among the estimated deviations and the uncertainty around the estimates using the formula

$$\sigma_r^2 = \text{Var}(\hat{r}) + \overline{\text{SE}(\hat{r}_y)^2}, \quad (8)$$

where $\text{Var}(\hat{r})$ is the variance among deviations and $\text{SE}(\hat{r}_y)$ is the standard error of each estimate. It produced a suggested σ_r of 1.77, which was slightly more similar to the base-model value of 1.4 than the 1.81 estimated in the 2021 assessment.

The sensitivity of the base model to the removal of the age-1 survey index provides a comparative evaluation of how the base model incorporates information about juvenile fish. Compared to the base model, estimates of spawning biomass throughout most of the time series are similar, but do diverge near the end of the time series (Table 33, Figures 43 and 44). The 2022 estimates of relative spawning biomass are 64.7% for the base model (95% credible interval of 31.1–134.7%) and 53.9% for the removal of the age-1 index model (95% credible interval of 24.7–119.5%). This change is likely due to the age-1 index suggesting slightly higher recruitment in 2014 (age-1 in 2015) and 2016 (age-1 in 2017) and moderately higher recruitment in 2018 (age-1 in 2019) and 2020 (age-1 in 2021) than the model without the index (Figures 11 and 45). The largest changes are for the most recent years where the model without the index has less information about recruitment size. Removing the age-1 index led to minor changes in fit to the acoustic survey estimates, with some years showing slight improvement and others a slight deterioration compared to the base model (Figure 46). For further details and results from the removal of the age-1 survey index sensitivity see Appendix G.

The high age-1 survey index from 2021 is largely in concurrence with oceanographic conditions, as summarized in NOAA's annual Ecosystem Status Report of the California Current. Recruitment is generally impacted by oceanographic conditions both during maternal preconditioning and during egg and larval stages. During maternal preconditioning (spring-fall, 2019) upwelling conditions were variable but near average (Harvey et al., 2020). Weaker upwelling conditions are associated with higher Pacific Hake recruitment during this phase (Vestfals et al., pers. comm.). During egg and larval phases (2020), ocean conditions were broadly associated with high productivity across many taxa (Harvey et al., 2021). These conditions were marked by strong winter upwelling which brings nutrients to coastal waters, cooler temperatures, an energy-rich copepod community, and high productivity of krill, a key food source for Pacific Hake (Buckley and Livingston, 1997; Harvey et al., 2021).

The base model includes a Dirichlet-multinomial likelihood component, which uses two estimated parameters to automatically weight each of the fishery and survey age compositions. The base model was compared to a sensitivity model that downweighted the fishery age compositions relative to the survey age compositions. The data weighting used in the sensitivity model was based on the McAllister-Ianelli method. This method requires manual iterative adjustments to the input sample sizes using a derived multiplier. The McAllister-Ianelli method, which was used in assessments prior to 2018, attempts to make the arithmetic mean of the input sample size approximately equal to the harmonic mean of the effective sample size. The McAllister-Ianelli method suggested a weighting factor of 0.14 and 0.46 (ratio of 0.30) for fishery and survey age compositions, respectively. The median estimate from Dirichlet-multinomial method used in the base model was 0.363 and 0.930 (ratio of 0.39). Downweighting fishery composition data using the McAllister-Ianelli method led to minor changes in relative spawning stock biomass and increased uncertainty in estimates of early recruitments compared to the base model (Figures 44 and 45).

The degree of flexibility of annual variation in the fishery selectivity was tested using three sensitivities which set alternative values of the Φ parameter (Figures 47-51). The consideration of alternative standard deviations (Φ) for time-varying selectivity is discussed earlier in Section 2.4.3. Changing the values of the parameter Φ controlling the flexibility in time-varying selectivity from the base model value of $\Phi = 1.40$ to alternative values of 0.21, 0.70, and 2.10, did not appreciably influence the estimates, or precision, associated with recruitment in 2014 (Figure 49). However, recruitment estimates for 2016 and 2017 are linked to the choice of Φ , where the model with the smallest Φ at 0.21 estimates the 2016 and 2017 recruitment deviation as the highest of the Φ sensitivity models (Figure 50), leading to a large increase in spawning biomass in recent years compared to the base model (Figure 47). It also provides the worst fit to the most recent survey biomass estimate (Figure 51).

The estimated population trends throughout the time series are similar, irrespective of maximum selectivity age (Figures 52-53). The largest differences are in the mid-1980s when age-composition data was sparse, and then again over the last few years of the model. The sensitivity run with maximum selectivity at age-5 resulted in the lowest estimate of the 2016 year class compared to the other model runs, while runs with higher maximum age produced similar levels of recruitment but at the cost of a considerable increase in the number of model parameters (Table 34). The choice of age-6 as the maximum was retained in the base model as it offered more flexibility than the choice of age-5.

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. With the addition of the age-1 index in this year's base model, the recruitment strength comes closer to the long-term stable estimate by age-2 in some cases (Figure 55). For example, the age-2 recruitment deviations for the 2016 cohort are almost the same as with the addition of further years of data. There is only a slight increase. However, some cohort recruitments are over-estimated at age-2. This can be seen most obviously with the 2014 cohort which reached a high deviation after two years, then even higher after three years only to drop 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 2017 cohort.

The stability of the recruitment estimates seen in this plot is also evident in the uncertainty estimates of each cohort. Uncertainty around the 2016 cohort has been substantially reduced compared with five years ago (Figure 54, bottom figure). 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 years of the retrospective model with the most years removed (Figure 54). In this assessment, there is very little retrospective bias other than a positive bias in spawning stock biomass five years previously when the 2014 year class was initially estimated too high. There is no indication from retrospective evaluations that the base model is displaying a systematic bias.

Cohort strength is usually not well estimated until the cohort reaches age-3 or more because at age-3 at least one year of biomass index (age-2+) age-composition data are available (Figure 55). Addition of the age-1 index can bring this down to age-2 but not without the caveat of possible over-estimation.

A comparison of the actual assessment models used in each year since 1991 is shown in Figure 57. There have been substantial differences in the structural assumptions of the models and, thus, results submitted each year. The variability between model results, especially early on in the time series, is larger than the uncertainty (95% credibility interval) reported from any single model in recent years. Prior to 2004, survey catchability was fixed at 1.0 and this assumption was heavily investigated between 2004 and 2007, leading to variability in model results because of the use of several different, but fixed, values of survey catchability. Since 2008, catchability has been freely estimated by the model. The fixing of survey catchability had the effect of driving the estimate of initial biomass upward, which in turn scaled the entire biomass trajectory up, leading to higher estimates of relative spawning biomass than in more recent assessments. The median estimates of spawning biomass for recent years have remained similar to the previous assessment but declined relative to the 2015-2017 assessments. The difference is most likely related to the recent under-fitting of the 2017 survey estimate of biomass despite the consistency in the structure of the assessment model in recent years. The uncertainty interval associated with the 2022 assessment brackets the majority of the historical estimates.

3.10 PERFORMANCE OF PAST PROJECTIONS

A comment from an industry representative in 2021 about the probabilities in the decision tables (such as Tables 30 and 31) changing from assessment to assessment led Johnson et al. (2021) to investigate the general question of how much confidence can we have in the probabilities in the decision tables.

As an example, the 2019 assessment (Berger et al., 2019) provides the estimated probability of the spawning stock biomass declining in the subsequent year, i.e., $P(B_{2020} < B_{2019})$, for several possible catches in 2019, such as 0 t, 180,000 t, 350,000 t, 410,000 t etc. Now, in 2022, we

‘know’ that the catch in 2019 was 411,574 t. Therefore, we can select the 410,000 t row (which is close enough to 411,574 t) in the table from the 2019 assessment to give that assessment’s $P(B_{2020} < B_{2019}) = 61\%$, given the catch that we now know occurred in 2019.

We can also calculate $P(B_{2020} < B_{2019})$ using the current assessment model, i.e., calculate our most up-to-date estimate of the probability that the stock declined from 2019 to 2020 using all available data. This implicitly includes the 411,574 t catch from 2019. From the current assessment model we get $P(B_{2020} < B_{2019}) = 98\%$. The 61% and 98% probabilities are shown for 2019 in Figure 58.

We extracted similar probabilities from past assessment documents going back to 2012 (Figure 58). For each assessment year t , we take the value of $P(B_{t+1} < B_t)$ from year t ’s stock assessment document, specifically the row in the decision table corresponding to the catch that we now know to have occurred in year t . This can require interpolation between catch levels if the exact catch in year t was not given in the decision tables in year t ’s assessment. We also calculate analogous probabilities, $P(B_{t+1} < B_t)$, from the current base model (Figure 58).

The historical probability of $P(B_{2013} < B_{2012}) = 43\%$ from the 2012 assessment is quite a lot higher than the 0% calculated using the current assessment model (Figure 58). But, this makes sense because the 2012 assessment model had no information that the 2010 recruitment was going to be very large (it did not include the age-1 index, which in 2011 did indicate a large 2010 recruitment, Figure 11). However, the current base model does have such information from many years of age data. Hence, the current model confidently ‘expects’ a large increase in spawning biomass from 2012 to 2013 as the individuals in the 2010 cohort grew in size. The 2013 assessment model had some information on the 2010 cohort, so the lower estimated probability that the stock would decline from 2013 to 2014 better concurs with the current base model than results from the 2012 assessment (Figure 58).

For later years, the probabilities vary, but for each year the probabilities either both lie above the 50% line or both lie below it (Figure 58), except for 2018. So, each assessment correctly predicts whether the stock will increase or decrease the following year, except for 2018. Also, for all years (except 2018 and 2021) the assessment year’s probabilities are closer to 50% than those from the current base model. Such behavior is desirable and sensible. These probabilities are for binary events that either happen or do not happen (the stock either declines or it does not decline, similar to a tossed coin only being a head or a tail). 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 document. 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 recruitments. The 2021 assessment’s estimate is very close to that of this year’s assessment.

Interestingly, in the last assessment (Figure B.3.1 of Johnson et al. 2021) we found that $P(B_{2019} < B_{2018})$ from the 2021 base model was above the 50% line (unlike for this year’s base model), agreeing with the 2018 assessment calculation (2018 was also the only year for which the probability from the 2021 assessment model was closer to 50% than that from that year’s assessment). The differing results to the current base model may be because there is no

definitive trend in biomass around that time (Figure 26), with the median spawning biomass slightly increasing from 2018 to 2019, whereas it was slightly decreasing in the equivalent figure in the 2021 assessment. Thus, probabilities of annual decline are expected to be sensitive to slight changes in results in such cases. Whether the stock declines or increases is not so important when such changes are small.

From this current 2022 assessment's projections, we show the probabilities for all catch alternatives in Figure 58 because we do not yet know which will correspond to the 2022 catch. Catching zero fish in 2022 (colored in pink) obviously gives the lowest probability that the stock will decline from 2022 to 2023. All probabilities except the highest catch lie below the 50% line, consistent with the expected large size of the 2020 cohort that will increase the spawning biomass as those fish grow and become mature.

We also provide similar calculations for the probability of the biomass falling below $B_{40\%}$ in the subsequent year (Figure 59), i.e., $P(B_{t+1} < B_{40\%})$. The 2012 assessment gave a $> 50\%$ chance of the biomass falling below $B_{40\%}$ in the subsequent year. This was the highest such probability from all assessments and also the poorest performing because the biomass did not fall below $B_{40\%}$, thanks again to the very large 2010 year class. The 2013-2017 assessments had information on the 2010 year class and estimated low probabilities of falling below $B_{40\%}$. Again, these estimates are closer to 50% than those from the current base model (blue dots), which is desirable behavior as mentioned above – the assessments gave low probabilities of an unlikely event occurring that we now believe to have been even more unlikely to have occurred. Since the 2018 assessment, the estimated probabilities of the biomass falling below $B_{40\%}$ were $> 10\%$ and continued to rise (Figure 59), until they fell in this year's assessment, for $P(B_{2023} < B_{40\%})$, presumably again due to the incoming 2020 cohort.

Probabilities from past assessments lie below those estimated from the current model (the blue line is below the red line). But, this won't necessarily always be the case. The probability from the 2021 assessment was the highest since 2012, yet probabilities from this 2022 assessment are much lower. If the incoming 2020 cohort is not as large it currently appears to be, then this would explain any future overlapping of the blue and red lines.

Note that the biomass has been relatively high in the time period shown, so 'correctly expecting' the biomass to remain $> B_{40\%}$ may not be a particular high bar to attain. Thus, we cannot simply conclude that the current assessment's probabilities will also turn out to be over-estimates of the probability of being $< B_{40\%}$ once we have more data, although it does appear from Figure 58 that the biomass is not expected to decline further next year.

Overall, these results suggest good confidence in the projected probabilities from the assessment model. Past projections of increases or decreases in the stock the following year have almost always been 'correct' (the most probable direction has agreed with the latest base model and data). And, except for the 2012 assessment incorrectly expecting the biomass to fall below $B_{40\%}$ (which did not happen thanks the large 2010 year class), projections 'correctly' estimated the biomass to not go below $B_{40\%}$.

Given we have Bayesian results for the retrospective analyses, we can calculate retrospective versions of Figures 58 and 59. By using data only up to 2011, the current base model estimates a very low probability of biomass decline from 2012 to 2013, $P(B_{2013} < B_{2012})$, similar to that from the base model with data from all years (top panel of Figure 60). However, the 2012 assessment estimated a much higher probability of 43%. This difference is presumably due to changes in modelling framework since 2012 (Table 17).

An obvious relevant change is the inclusion of the age-1 index in this year's base model. The equivalent retrospective calculation for the sensitivity run that excludes the age-1 index (and hence excludes the 2011 age-1 index that gives strong evidence for the large 2010 cohort), gives $P(B_{2013} < B_{2012}) > 20\%$ (grey square in Figure G.13). This suggests that the age-1 index accounts for some of the reduction of $P(B_{2013} < B_{2012})$ from the 2012 assessment's calculation (red circle in top panel of Figure 60) to the retrospective calculation using the current base model but data only up to 2011 (grey square in top panel of Figure 60). However, there is still a difference between the grey square and red circle at 2012 in Figure G.13 (excluding the age-1 index), which is caused by changes in model structure (and any updates in data) since 2012 beyond the inclusion of the age-1 index (else the square and circle would overlap).

For 2013 onwards (Figures 60–64), the retrospective probabilities (colored squares) are generally close to the probabilities currently estimated using all available data (blue triangles), with 2018 again being an exception. All retrospectives are shown together in Figure 64 for ease of comparison.

Of note is that $P(B_{2016} < B_{2015})$ is close to the current base model's value when using data up to 2014 (the dark grey square and blue squares at 2015 are close together in the top panel of Figure 61). Yet, when the 2015 data are included, the probability falls noticeably (the gold square at 2014 in the middle panel of Figure 61). It falls further when the 2016 data are included (the orange square at 2014 in the bottom panel of Figure 61), finally agreeing with the current base model when the 2017 data are included (the pink square at 2014 in the top panel of Figure 62). This is presumably explained by the retrospective analysis of recruitment deviations of the large 2014 cohort. The 2014 cohort is overestimated (compared to current estimates) when including data up to 2015 and 2016 (the highest two green points for the 2014 cohort in Figure 55), but then is more consistently estimated once the 2017 data are included (note that 2017 was a survey year). The same behaviour is seen when excluding the age-1 index (Figure G.13).

The equivalent retrospective figure to Figure 59 for $P(B_{t+1} < B_{40\%})$, Figure 65, shows, in particular, that $P(B_{2013} < B_{40\%})$ when using data up to 2011 (first grey square, though hidden by other squares) is very low, compared to the 2012 assessment's estimate of $> 50\%$. This is also the case (though not quite as low) when including the age-1 index (Figure G.14), again suggesting that changes in model framework (Table 17) beyond recent inclusion of the age-1 index are improving understanding of stock dynamics.

4 RESEARCH AND DATA NEEDS

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

1. Conduct research to evaluate ways to improve recent, current, and future recruitment estimates for use in stock assessment. This could include the development of recruitment indices, time series of informative environmental or oceanographic variables, and models that have predictive skill. Explorations should also consider options for incorporating information on recruitment into the stock assessment model and the Pacific Hake management framework. For example, estimates could be included in the stock assessment as a standalone data source (similar to acoustic survey biomass estimates) or the estimation procedure itself could be integrated directly into the stock assessment model. Results from such work should be connected to ongoing research related to recruitment variability, σ_R , as discussed in Section 3.3. Related, there is a need to streamline and broaden the availability of products from oceanographic models (e.g., ROMS) so that they are available stock-wide and can be used on a recurring basis as informative links in operational stock assessments.
2. Use and build upon the existing MSE framework to evaluate major sources of uncertainty relating to data, model structure, and the harvest policy for this fishery and compare potential methods to address them. In particular, utilize and adapt this simulation framework to address new and ongoing stock assessment research and data needs through the Pacific Hake MSE Working Group. For example, research investigating links between hake biomass, spatial distribution, growth, and recruitment and how these links vary with ocean conditions and ecosystem variables such as temperature, transport, and prey availability would be beneficial. These investigations have the potential to improve the scenarios considered in future MSE work and the basic understanding of drivers of hake population dynamics and availability to fisheries and surveys.
3. Document the existing survey methodologies, protocols, and adaptive survey-design decisions that lead to the development of Pacific Hake biomass and age-composition estimates and the age-1 index used in the stock assessment. Such documentation will ensure transparency, enable repeatability, and provide a record of changes in procedures over time. Also, continue to conduct research to improve the estimation of age composition and abundance from data collected during the acoustic survey. This includes, but is not limited to, research on species identification, target verification, target strength, implications of the south-to-north directionality of the survey, alternative technologies to assist in the survey, and efficient analysis methods. The latter should include bootstrapping of the acoustic survey time series or related methods that can incorporate relevant uncertainties into the calculations of survey variance. Relevant uncertainties include topics such as the target strength relationship, subjective scoring of echograms, thresholding methods, and methods to estimate the species-mix that are used to interpret the acoustic backscatter. Continue to work with acousticians and survey personnel from the Northwest Fisheries Science Center (and, more broadly, those involved with the U.S. Re-Envisioning West Coast Surveys Initiative) and Fisheries and Oceans Canada to determine optimal survey designs given constraints, in-

cluding designs that incorporate ecosystem-based factors and other potential target species (e.g., rockfish, euphausiids, and mesopelagics) for the Joint U.S. and Canadian Integrated Acoustic and Trawl Survey.

4. Develop a set of candidate ecosystem indicators that are potentially associated with Pacific Hake biology and ecology (e.g., recruitment, distribution, predator, and prey). Such information can broaden the context within which a single species stock assessment is interpreted, be used to support model development, and provide non-assessment indicators to management.
5. Conduct an inter-laboratory otolith exchange and use the results to update estimates of ageing error used in the stock assessment. This would include updated information about ageing imprecision and the effects of large cohorts as understood given simulation analyses and blind-source age reads of samples with differing underlying age distributions – with and without dominant year classes. The last inter-laboratory comparison was done in 2010 (“CARE” exchanges).
6. Continue to collect and analyze life-history data, including weight, maturity, and fecundity for Pacific Hake. Explore possible relationships among these life-history traits and correlations with time, empirical growth, and population density. Improve understanding of links between fecundity and size, age, weight, and batch spawning, as well as spatio-temporal variability in the timing of spawning, skip spawning, batch fecundity, and size and age at maturity. Continue to explore the possibility of using additional data types such as length data within the stock assessment. Additionally, a more spatially comprehensive maturity analysis that incorporates information from Canadian samples would be advantageous.
7. Explore the operational use of eDNA data for characterizing aspects of Pacific Hake population dynamics, such as changes in species distribution or perhaps density, and the incorporation of these data into stock assessments.
8. Maintain the flexibility to undertake additional acoustic surveys for Pacific Hake in non-survey years when uncertainty in the results of the stock assessment presents a potential risk to or underutilization of the stock.
9. 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.
10. Consider alternative methods for refining existing prior distributions for natural mortality (M), including the use of meta-analytic methods. Evaluate feasibility of estimating age-specific natural mortality for Pacific Hake.
11. Explore the potential to use acoustic data collected from commercial fishing vessels to study hake distributions, schooling patterns, and other questions of interest. This could be simi-

lar to the “acoustic vessels of opportunity” program on fishing vessels targeting Pollock in Alaska (Stienessen et al., 2019).

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6 REFERENCES

- Agostini, V.N., Francis, R.C., Hollowed, A., Pierce, S.D., Wilson, C.D. 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., eds. 1995. *Hake: Biology, fisheries and markets*. Springer, Netherlands. xxii+478 p.
- 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. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fishery Service and Fisheries and Oceans Canada. 249 p. Available at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/hake-assessment-2019-final.pdf.
- 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. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fishery Service and Fisheries and Oceans Canada. 203 p. Available at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/2017-hake-assessment.pdf.
- Buckley, T.W. and Livingston, P.A. 1997. Geographic variation in the diet of Pacific hake, with a note on cannibalism. *California Cooperative Oceanic Fisheries Investigations Report* 53–62.
- Cuddington, K., Edwards, A.M. and Ingalls, B. 2021. *Building Skills in Quantitative Biology*. Available at <https://www.quantitative-biology.ca>.
- DFO. 2009. A fishery decision-making framework incorporating the Precautionary Approach. Available at <http://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm>.
- DFO. 2021. DFO Groundfish Pacific Region 2021 Integrated Fisheries Management Plan, 326 p. Available at <https://waves-vagues.dfo-mpo.gc.ca/Library/4093732x.pdf>.
- Dorn, M.W. and Saunders, M. 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. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- Dorn, M.W. 1994. Status of the coastal Pacific whiting resource in 1994. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- Dorn, M.W. 1996. Status of the coastal Pacific whiting resource in 1996. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.

-
- Dorn, M.W. 1997. Mesoscale fishing patterns of factory trawlers in the Pacific hake (*Merluccius productus*) fishery. *CalCOFI Reports* **38**: 77–89.
- Dorn, M.W. and Methot, R.D. 1991. Status of the Pacific whiting resource in 1991. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- Dorn, M.W. and Methot, R.D. 1992. Status of the coastal Pacific whiting resource in 1992. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- 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. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- Dorn, M. 1995. The effects of age composition and oceanographic conditions on the annual migration of Pacific whiting, *Merluccius productus*. *CalCOFI Reports* **36**: 97–105.
- Edwards, A.M., Duplisea, D.E., Grinnell, M.H., Anderson, S.C., Grandin, C.J., Ricard, D., Keppel, E.A., Anderson, E.D., Baker, K.D., Benoît, H.P., Cleary, J.S., Connors, B.M., Desgagnés, M., English, P.A., Fishman, D.J., Freshwater, C., Hedges, K.J., Holt, C.A., Holt, K.R., Kronlund, A.R., Mariscak, A., Obradovich, S.G., Patten, B.A., Rogers, B., Rooper, C.N., Simpson, M.R., Surette, T.J., Tallman, R.F., Wheeland, L.J., Wor, C., and Zhu, X. 2018a. Proceedings of the Technical Expertise in Stock Assessment (TESA) national workshop on ‘Tools for transparent, traceable, and transferable assessments,’ 27–30 November 2018 in Nanaimo, British Columbia. Available at <https://waves-vagues.dfo-mpo.gc.ca/Library/40750152.pdf>. Canadian Technical Report of Fisheries and Aquatic Sciences **3290**: v + 10 p.
- Edwards, A.M., Taylor, I.G., Grandin, C.J. and Berger, A.M. 2018b. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2018. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fishery Service and Fisheries and Oceans Canada. 222 p. Available at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/hake-assessment-2018.pdf.
- Francis, R.C., Swartzman, G.L., Getz, W.M., Haar, R. and Rose, K. 1982. A management analysis of the Pacific whiting fishery. US Department of Commerce, NWAFC Processed Report **82-06**: 48 p.
- Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* **68**(6): 1124–1138.
- 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**: 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. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fishery Service and Fisheries and Oceans Canada. 165 p. Avail-

able at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/pacific_whiting_status_2016-final.pdf.

- 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. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fishery Service and Fisheries and Oceans Canada. 273 p. Available at <https://www.fisheries.noaa.gov/resource/document/2020-pacific-hake-whiting-stock-assessment>.
- 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 H. Arancibia, ed., Hakes: biology and exploitation, chap. 9, 234–262. Wiley Blackwell.
- 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. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- Harvey, C., Garfield, N.T., Williams, G., Tolimieri, N., Andrews, K., Barnas, K., Bjorkstedt, E., Bograd, S., Borchert, J., Braby, C., Brodeur, R., Burke, B., Cope, J., Coyne, A., Demer, D., deWitt, L., Field, J., Fisher, J., Frey, P., Good, T., Grant, C., Greene, C., Hazen, E., Holland, D., Hunter, M., Jacobson, K., Jacox, M., Jahncke, J., Juhasz, C., Kaplan, I., Kasperski, S., Kim, S., Lawson, D., Leising, A., Manderson, A., Mantua, N., Melin, S., Miller, R., Moore, S., Morgan, C., Muhling, B., Munsch, S., Norman, K., Parrish, J., Phillips, A., Robertson, R., Rudnick, D., Sakuma, K., Samhoury, J., Santora, J., Schroeder, I., Siedlecki, S., Somers, K., Stanton, B., Stierhoff, K., Sydeman, W., Thompson, A., Trong, D., Warzybok, P., Whitmire, C., Wells, B., Williams, M., Williams, T., Zamon, J., Zeman, S., Zubkousky-White, V. and Zwolinski, J. 2020. Ecosystem Status Report of the California Current for 2019-20: A Summary of Ecosystem Indicators Compiled by the California Current Integrated Ecosystem Assessment Team (CCIEA) doi:10.25923/e5rb-9f55. Available from <https://repository.library.noaa.gov/view/noaa/27303>.
- Harvey, C.J., Garfield, N.T., 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) doi: 10.25923/x4ge-hn11. Available from <https://repository.library.noaa.gov/view/noaa/32902>.
- Helser, T.E., Fleischer, G.W., Martell, S.J.D. and Taylor, N. 2005. Stock assessment of Pacific hake (whiting) in U.S. and Canadian waters in 2004. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- Helser, T.E. and Martell, S.J.D. 2007. Stock assessment of Pacific hake (Whiting) in U.S. and Canadian waters in 2007. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- 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. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.

-
- Helser, T.E., Stewart, I.J., Fleischer, G.W. and Martell, S.J.D. 2006. Stock Assessment of Pacific Hake (Whiting) in U.S. and Canadian Waters in 2006. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- 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. 190 p. Available at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/hakeassessment2013_final.pdf.
- Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. *Fishery Bulletin* **82**: 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. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- 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. Department of Commerce, NOAA Technical Memorandum, NMFS-NWFSC-168. Available at <https://repository.library.noaa.gov/view/noaa/30919>.
- 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. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fishery Service and Fisheries and Oceans Canada. 269 p. Available at <https://www.fisheries.noaa.gov/resource/document/2021-pacific-hake-whiting-stock-assessment>.
- 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.
- 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. 69 p.
- 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**: 711–720.

-
- Malick, M., Hunsicker, M., Haltuch, M., Parker-Stetter, S., Berger, A. and Marshall, K. 2020a. Relationships between temperature and Pacific hake distribution vary across latitude and life-history stage. *Marine Ecology Progress Series* **639**: 185–197. doi:10.3354/meps13286.
- Malick, M., Siedlecki, S., Norton, E., Kaplan, I., Haltuch, M., Hunsicker, M., Parker-Stetter, S., Marshall, K., Berger, A., Hermann, A., Bond, N. and Gauthier, S. 2020b. Environmentally driven seasonal forecasts of Pacific hake distribution. *Frontiers in Marine Science* **7**: 578,490. doi:10.3389/fmars.2020.578490.
- Martell, S.J.D. 2010. Assessment and management advice for Pacific hake in U.S. and Canadian waters in 2010. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- 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**: 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**: 659–670.
- 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**: 1744–1760.
- Methot, 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.
- 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 admuts and tmbstan R packages. *PLoS ONE* **13**(5).
- 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**: 2404–2419.
- Nielsen, A. and Berg, C.W. 2014. Estimation of time-varying selectivity in stock assessments using state-space models. *Fisheries Research* **158**: 96–101.
- Petitgas, P. 1993. Geostatistics for fish stock assessments: a review and an acoustic application. *ICES Journal of Marine Science* **50**: 285–298.
- Punt, A.E., Dunn, A., Elvarsson, B., Hampton, J., Hoyle, S.D., Maunder, M.N., Methot, R.D. and Nielsen, A. 2020. Essential features of the next-generation integrated fisheries stock assessment package: A perspective. *Fisheries Research* **229**. doi:10.1016/j.fishres.2020.105617.
- R Core Team. 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available from <http://www.R-project.org>.

-
- 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. 206 p.
- 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.J., 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. In: *Status of the Pacific Coast Groundfish Fishery through 2011, Stock Assessment and Fishery Evaluation: Stock Assessments, STAR Panel Reports, and rebuilding analyses*. Pacific Fishery Management Council, Portland, Oregon. 217 p. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- 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. 194 p. Available at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/2012-stock-assess.pdf.
- 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, 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. Available at <http://www.pcouncil.org/groundfish/stock-assessments/by-species/pacific-whiting-hake>.
- 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**: 1832–1843.
- Stienessen, S., Honkalehto, T., Lauffenburger, N., Ressler, P. and Lauth, R. 2019. Acoustic Vessel-of-Opportunity (AVO) index for midwater Bering Sea walleye pollock, 2016-2017. AFSC Processed Rep. 2019-01, AFSC, NOAA, NMFS, Seattle, Washington. 24 p. Available at <https://repository.library.noaa.gov/view/noaa/19594>.
- Stock, B.C. and Miller, T.J. 2021. The Woods Hole Assessment Model WHAM: A general state-space assessment framework that incorporates time- and age-varying processes via random effects and links to environmental covariates. *Fisheries Research* **240**: 105,967.
- 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. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement; National Marine Fishery Service; Canada Department of Fisheries and Oceans. 159 p. Available at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/hakeassessment2015_final.pdf.

-
- 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. 194 p. Available at https://archive.fisheries.noaa.gov/wcr/publications/fishery_management/groundfish/whiting/2014-stock-assess.pdf.
- Thorson, J.T. 2019. Perspective: Let's simplify stock assessment by replacing tuning algorithms with statistics. *Fisheries Research* **217**: 133–139.
- Thorson, J.T., Hicks, A.C. and Methot, R.D. 2015. Random effect estimation of time-varying factors in Stock Synthesis. *ICES Journal of Marine Science* **72**: 178–185.
- 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. and Rykaczewski, 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**: 2418–2432.
- Vrooman, A. and Paloma, P. 1977. Dwarf hake off the coast of Baja California. *California Cooperative Oceanic Fisheries Investigations Reports* **19**: 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**: 268–285.
- Zamora-García, O.G., Márquez-Farás, J.F. and Stavrinsky-Suárez, A. 2020. Catch rate, length, and sex ratio of Pacific hake (*Merluccius productus*) in the northern Gulf of California. *Fishery Bulletin* **118**: 365–379.

7 TABLES

Table 1. Annual catches of Pacific Hake (t) in U.S. waters by sector, 1966-2021. Tribal catches are included in the sector totals. Research catch includes landed catch associated with research-related activities. Catch associated with surveys and discarded bycatch in fisheries not targeting hake is not currently included in the table or model.

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

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Year	Foreign	JV	Mothership	Catcher-Processor	Shore-based	Research	Total
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	150,841	0	354,229
2018	0	0	67,121	116,073	135,112	0	318,306
2019	0	0	52,646	116,146	148,210	0	317,002
2020	0	0	37,978	111,147	138,688	95	287,908
2021	0	0	35,219	104,030	130,304	0	269,553

Table 2. Annual catches of Pacific Hake (t) in Canadian waters by sector, 1966-2021.

Year	Foreign	JV	Shoreside	Freezer-Trawler	Total
1966	700	0	0	0	700
1967	36,710	0	0	0	36,710
1968	61,360	0	0	0	61,360
1969	93,850	0	0	0	93,850
1970	75,010	0	0	0	75,010
1971	26,700	0	0	0	26,700
1972	43,410	0	0	0	43,410
1973	15,130	0	0	0	15,130
1974	17,150	0	0	0	17,150
1975	15,700	0	0	0	15,700
1976	5,970	0	0	0	5,970
1977	5,190	0	0	0	5,190
1978	3,450	1,810	0	0	5,260
1979	7,900	4,230	300	0	12,430
1980	5,270	12,210	100	0	17,580
1981	3,920	17,160	3,280	0	24,360
1982	12,480	19,680	0	0	32,160
1983	13,120	27,660	0	0	40,780
1984	13,200	28,910	0	0	42,110
1985	10,530	13,240	1,190	0	24,960
1986	23,740	30,140	1,770	0	55,650
1987	21,450	48,080	4,170	0	73,700
1988	38,080	49,240	830	0	88,150
1989	29,750	62,718	2,562	0	95,029
1990	3,810	68,314	4,021	0	76,144
1991	5,610	68,133	16,174	0	89,917
1992	0	68,779	20,043	0	88,822
1993	0	46,422	12,352	0	58,773
1994	0	85,154	23,776	0	108,930
1995	0	26,191	46,181	0	72,372
1996	0	66,779	26,360	0	93,139
1997	0	42,544	49,227	0	91,771
1998	0	39,728	48,074	0	87,802
1999	0	17,201	70,121	0	87,322
2000	0	15,625	6,382	0	22,007
2001	0	21,650	31,935	0	53,585
2002	0	0	50,244	0	50,244
2003	0	0	63,217	0	63,217
2004	0	58,892	66,175	0	125,067
2005	0	15,695	77,335	9,985	103,014
2006	0	14,319	65,289	15,136	94,744
2007	0	6,820	52,624	14,122	73,566
2008	0	3,592	57,799	13,214	74,605
2009	0	0	44,136	13,223	57,359
2010	0	8,081	35,362	13,573	57,016
2011	0	9,717	31,760	14,596	56,073
2012	0	0	32,147	14,912	47,059
2013	0	0	33,665	18,584	52,249
2014	0	0	13,326	21,792	35,118

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Year	Foreign	JV	Shoreside	Freezer-Trawler	Total
2015	0	0	16,775	22,909	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	50,621	43,950	94,571
2020	0	0	51,551	39,812	91,362
2021	0	0	16,953	40,123	57,076

Table 3. Pacific Hake landings and management decisions. A dash (–) indicates the management decision was either not specified or was unknown to the authors at the time of this assessment. Catch targets in 2020 and 2021 were specified unilaterally.

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

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Year	U.S. landings (t)	Canada landings (t)	Total landings (t)	U.S. proportion of total catch	Canada proportion of total catch	U.S. catch target (t)	Canada catch target (t)	Coast-wide catch target (t)	U.S. proportion of catch target removed	Canada proportion of catch target removed	Total proportion of catch target removed
2003	141,945	63,217	205,162	69.2%	30.8%	148,200	–	228,000	95.8%	–	90.0%
2004	217,240	125,067	342,307	63.5%	36.5%	250,000	–	514,441	86.9%	–	66.5%
2005	260,120	103,014	363,135	71.6%	28.4%	269,069	95,128	364,197	96.7%	108.3%	99.7%
2006	266,955	94,744	361,699	73.8%	26.2%	269,545	95,297	364,842	99.0%	99.4%	99.1%
2007	217,682	73,566	291,247	74.7%	25.3%	242,591	85,767	328,358	89.7%	85.8%	88.7%
2008	248,496	74,605	323,101	76.9%	23.1%	269,545	95,297	364,842	92.2%	78.3%	88.6%
2009	121,324	57,359	178,683	67.9%	32.1%	135,939	48,061	184,000	89.2%	119.3%	97.1%
2010	171,043	57,016	228,059	75.0%	25.0%	193,935	68,565	262,500	88.2%	83.2%	86.9%
2011	231,261	56,073	287,334	80.5%	19.5%	290,903	102,848	393,751	79.5%	54.5%	73.0%
2012	160,144	47,059	207,203	77.3%	22.7%	186,036	65,773	251,809	86.1%	71.5%	82.3%
2013	233,578	52,249	285,828	81.7%	18.3%	269,745	95,367	365,112	86.6%	54.8%	78.3%
2014	264,141	35,118	299,259	88.3%	11.7%	316,206	111,794	428,000	83.5%	31.4%	69.9%
2015	154,160	39,684	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	354,229	86,721	440,950	80.3%	19.7%	441,433	156,067	597,500	80.2%	55.6%	73.8%
2018	318,306	95,413	413,719	76.9%	23.1%	441,433	156,067	597,500	72.1%	61.1%	69.2%
2019	317,002	94,571	411,574	77.0%	23.0%	441,433	156,067	597,500	71.8%	60.6%	68.9%
2020	287,908	91,362	379,271	75.9%	24.1%	424,810	104,480	529,290	67.8%	87.4%	71.7%
2021	269,553	57,076	326,629	82.5%	17.5%	369,400	104,480	473,880	73.0%	54.6%	68.9%

Table 4. Annual summary of U.S. and Canadian fishery sampling included in this stock assessment. Canadian, foreign, joint-venture and at-sea sectors are in number of hauls sampled for age-composition, the shore-based sector is in number of trips. A dash (–) indicates there was no sampled catch. A number indicates how many samples from the catch were taken. The number of fish with otoliths sampled per haul has varied over time but is typically small (current protocols for the U.S. At-Sea sectors is three fish every third haul).

Year	U.S.						Canada			
	Foreign (hauls)	Joint-Venture (hauls)	Mother-ship (hauls)	Combined Mother-ship Catcher-processor (hauls)	Catcher-processor (hauls)	Shore-based (trips)	Foreign (hauls)	Joint-Venture (hauls)	Shoreside (trips)	Freezer Trawlers (hauls)
1975	13	–	–	–	–	–	–	–	–	–
1976	142	–	–	–	–	–	–	–	–	–
1977	320	–	–	–	–	–	–	–	–	–
1978	336	5	–	–	–	–	–	–	–	–
1979	99	17	–	–	–	–	–	–	–	–
1980	191	30	–	–	–	–	–	–	–	–
1981	113	41	–	–	–	–	–	–	–	–
1982	52	118	–	–	–	–	–	–	–	–
1983	–	117	–	–	–	–	–	–	–	–
1984	49	74	–	–	–	–	–	–	–	–
1985	37	19	–	–	–	–	–	–	–	–
1986	88	32	–	–	–	–	–	–	–	–
1987	22	34	–	–	–	–	–	–	–	–
1988	39	42	–	–	–	–	–	3	–	–
1989	–	77	–	–	–	–	–	3	–	–
1990	–	143	–	–	–	15	–	5	–	–
1991	–	–	–	116	–	26	–	18	–	–
1992	–	–	–	164	–	46	–	33	–	–
1993	–	–	–	108	–	36	–	25	3	–
1994	–	–	–	143	–	50	–	41	1	–
1995	–	–	–	61	–	51	–	35	3	–
1996	–	–	–	123	–	35	–	28	1	–
1997	–	–	–	127	–	65	–	27	1	–
1998	–	–	–	149	–	64	–	21	9	–
1999	–	–	–	389	–	80	–	14	26	–
2000	–	–	–	413	–	91	–	25	1	–
2001	–	–	–	429	–	82	–	28	1	–
2002	–	–	–	342	–	71	–	–	36	–
2003	–	–	–	358	–	78	–	–	20	–
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	–	–	26	79
2015	–	–	203	–	431	84	–	–	6	74
2016	–	–	502	–	671	76	–	–	75	116
2017	–	–	353	–	684	112	–	–	75	76
2018	–	–	403	–	549	92	–	–	47	83
2019	–	–	286	–	494	92	–	–	48	81
2020	–	–	186	–	389	97	–	–	32	–
2021	–	–	109	–	279	75	–	–	1	–

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+
2012	981	332	0.00	50.41	9.94	23.82	2.95	5.30	2.72	1.64	0.79	0.28	0.47	0.49	0.56	0.33	0.31
2013	1,402	474	0.10	0.51	72.04	7.12	13.80	1.50	1.19	1.44	0.84	0.36	0.24	0.10	0.07	0.44	0.24
2014	1,652	557	0.00	4.13	5.17	71.41	5.98	8.89	0.89	2.03	0.89	0.44	0.09	0.00	0.00	0.09	0.00
2015	1,263	431	3.49	1.66	7.55	3.45	76.45	3.20	2.16	0.33	0.77	0.52	0.00	0.12	0.12	0.00	0.15
2016	1,995	671	0.40	52.87	2.37	5.57	2.23	31.31	1.56	2.06	0.73	0.20	0.44	0.20	0.00	0.04	0.00
2017	2,026	684	1.75	0.87	50.75	2.36	4.99	3.08	28.79	3.01	2.11	1.17	0.25	0.58	0.17	0.00	0.12
2018	1,162	549	5.42	35.76	1.05	26.03	2.14	2.65	2.69	19.36	2.50	1.25	0.28	0.40	0.29	0.10	0.07
2019	1,190	494	0.00	6.84	25.00	1.35	39.00	1.48	4.09	1.81	17.40	1.15	0.84	0.45	0.05	0.16	0.38
2020	909	389	0.00	0.19	7.90	40.75	1.16	31.65	1.85	1.61	1.80	11.14	0.68	1.08	0.00	0.05	0.13
2021	806	279	2.26	0.63	2.17	14.41	36.95	0.94	23.58	2.61	1.98	1.75	10.74	1.44	0.40	0.12	0.00

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+
2012	884	299	0.70	76.44	5.88	13.09	1.34	0.84	0.87	0.32	0.07	0.00	0.09	0.04	0.10	0.07	0.12
2013	1,215	409	0.00	1.19	83.16	4.52	7.51	0.25	0.96	1.18	0.13	0.19	0.15	0.05	0.23	0.35	0.14
2014	1,252	423	0.00	5.01	3.50	74.63	4.75	7.51	1.01	1.28	1.00	0.52	0.11	0.08	0.00	0.14	0.47
2015	601	203	1.81	0.65	10.41	4.77	71.42	4.00	4.13	1.07	0.63	0.83	0.29	0.00	0.00	0.00	0.00
2016	1,495	502	0.53	59.25	1.45	5.10	2.44	26.82	1.54	1.92	0.38	0.32	0.09	0.15	0.00	0.00	0.00
2017	1,054	353	7.78	0.77	51.20	2.21	3.41	1.28	27.73	1.88	1.96	0.49	0.08	0.81	0.19	0.16	0.06
2018	818	403	17.23	26.16	1.93	27.24	0.69	2.31	1.75	16.91	3.32	1.00	0.52	0.33	0.20	0.34	0.06
2019	824	286	0.00	15.17	20.36	0.94	36.52	1.24	4.01	1.61	16.51	1.46	1.08	0.44	0.50	0.15	0.01
2020	509	186	0.00	0.00	8.81	40.36	2.56	28.39	1.59	2.20	2.18	11.30	1.34	0.85	0.42	0.00	0.00
2021	320	109	0.00	0.00	1.31	11.08	38.20	2.30	23.89	0.54	1.85	3.50	14.05	2.47	0.00	0.00	0.82

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+
2012	1,522	76	0.00	23.04	18.86	51.02	1.53	2.39	1.18	0.66	0.29	0.07	0.00	0.34	0.23	0.20	0.22
2013	1,915	96	0.00	0.36	79.28	5.93	9.79	0.67	1.38	1.01	0.36	0.37	0.13	0.04	0.09	0.31	0.27
2014	1,355	68	0.00	2.14	3.38	63.99	8.26	15.10	1.30	2.40	1.67	0.63	0.23	0.00	0.20	0.20	0.50
2015	1,680	84	6.12	1.34	7.42	4.91	67.24	4.05	5.06	0.78	1.05	1.28	0.24	0.17	0.00	0.00	0.32
2016	1,518	76	0.11	65.44	1.41	3.25	1.55	22.03	1.60	2.70	0.72	0.29	0.31	0.26	0.14	0.10	0.08
2017	2,235	112	3.68	0.71	35.37	2.63	3.66	2.50	43.03	2.89	2.12	1.66	0.64	0.53	0.27	0.11	0.20
2018	1,834	92	7.72	27.85	1.75	31.45	1.24	2.40	2.61	19.08	2.65	1.32	0.86	0.49	0.40	0.15	0.05
2019	1,826	92	0.00	17.23	21.94	0.90	30.78	1.85	3.36	1.87	16.75	1.54	1.77	0.80	0.57	0.32	0.33
2020	1,934	97	0.00	0.03	8.58	34.62	1.42	31.54	1.27	2.70	1.74	15.27	1.08	0.81	0.48	0.07	0.40
2021	1,500	75	0.35	0.37	2.30	13.10	35.28	3.29	23.92	1.72	3.53	2.20	9.75	2.37	0.86	0.22	0.73

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+
2012	441	43	0.00	0.84	11.29	54.02	5.30	13.07	5.41	2.21	1.56	0.81	1.09	0.21	2.52	0.29	1.38
2013	226	10	0.00	0.00	1.36	4.70	4.33	2.26	26.17	7.99	4.57	14.15	0.51	2.90	4.36	24.83	1.87
2014	279	26	0.00	0.00	0.19	14.91	12.60	23.94	8.97	14.68	8.90	1.88	4.40	0.56	0.46	0.90	7.62
2015	296	6	2.79	0.00	1.12	2.64	63.49	8.13	11.52	1.31	5.61	1.85	0.00	0.53	0.00	0.34	0.68
2016	554	75	0.00	5.00	0.25	2.77	2.54	69.91	9.18	8.57	0.72	0.44	0.10	0.20	0.14	0.02	0.14
2017	750	75	6.93	0.33	7.81	1.72	3.00	7.30	48.05	13.30	6.94	1.33	1.25	1.19	0.14	0.15	0.55
2018	476	47	0.48	5.12	1.94	22.24	1.20	4.50	5.94	35.73	12.37	4.42	2.53	1.17	0.92	1.17	0.26
2019	327	48	0.00	14.30	11.60	2.62	28.74	2.26	4.33	2.51	25.84	2.91	3.15	1.23	0.51	0.00	0.00
2020	1,438	32	0.00	0.04	9.59	19.80	1.37	30.16	2.71	3.49	2.56	24.07	2.86	2.12	0.22	0.48	0.54
2021	100	1	0.00	0.00	0.00	17.11	24.00	6.89	27.45	2.85	2.85	9.41	5.45	1.15	0.00	2.85	0.00

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+
2012	1,114	101	0.00	0.05	2.90	25.18	6.26	29.03	13.78	3.49	3.85	1.05	1.31	1.80	8.24	1.95	1.09
2013	1,332	105	0.00	0.00	2.77	5.84	18.09	5.89	18.86	13.11	5.48	5.57	2.06	2.73	4.15	11.67	3.77
2014	1,056	79	0.00	0.00	0.97	13.25	10.05	24.60	5.36	14.17	7.62	4.77	3.18	1.44	1.93	2.08	10.56
2015	755	74	0.00	0.28	2.59	2.67	58.75	12.33	11.62	3.20	3.84	2.24	0.81	0.64	0.15	0.25	0.62
2016	886	116	0.16	4.84	1.96	4.29	6.93	57.54	9.06	8.25	2.07	2.37	1.29	0.53	0.14	0.12	0.44
2017	760	76	0.00	0.58	7.30	2.42	5.47	5.07	49.97	12.28	9.77	2.37	2.50	1.37	0.21	0.19	0.50
2018	1,225	83	0.10	4.67	0.54	17.73	2.61	3.91	5.07	45.54	9.42	5.37	2.52	0.97	0.71	0.61	0.23
2019	902	81	0.05	17.09	15.62	4.11	19.02	2.36	3.96	5.20	23.39	5.31	2.47	0.61	0.36	0.46	0.00

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 sector are weighted by the catch in that sector. Sample sizes are sum of hauls and trips from individual sectors (shown in preceding tables) as described in Section 2.1.2. Age 15 is an accumulator group for comparing observed and expected proportions.

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

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Year	Number of samples	Age (% of total for each year)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15+
2008	794	0.76	9.82	30.53	2.40	14.42	1.03	3.63	3.17	28.07	3.05	1.15	0.73	0.49	0.31	0.43
2009	685	0.64	0.56	31.03	27.20	3.36	10.67	1.30	2.27	2.27	16.14	2.49	0.87	0.60	0.28	0.34
2010	874	0.03	25.23	3.37	35.38	21.43	2.29	2.94	0.43	0.58	0.98	5.86	0.93	0.29	0.10	0.15
2011	1,081	2.67	8.73	70.84	2.63	6.34	4.38	1.12	0.80	0.29	0.37	0.12	1.33	0.17	0.11	0.11
2012	851	0.18	40.93	11.54	32.99	2.49	5.10	2.52	1.13	0.66	0.23	0.33	0.35	0.87	0.28	0.38
2013	1,094	0.03	0.54	70.31	5.90	10.47	1.12	3.41	2.06	0.91	1.37	0.26	0.33	0.53	2.28	0.46
2014	1,153	0.00	3.28	3.81	64.42	6.93	12.06	1.58	3.11	1.83	0.81	0.46	0.12	0.19	0.28	1.12
2015	798	3.64	1.14	6.88	3.94	69.99	4.94	5.09	0.96	1.55	1.09	0.20	0.21	0.06	0.05	0.27
2016	1,440	0.29	50.22	1.69	4.47	2.48	32.85	2.77	3.23	0.76	0.44	0.37	0.23	0.06	0.05	0.07
2017	1,300	3.76	0.73	38.38	2.37	4.12	3.11	36.85	4.41	3.10	1.33	0.61	0.72	0.21	0.09	0.20
2018	1,174	7.35	25.53	1.49	26.98	1.52	2.80	3.04	22.75	4.31	1.91	0.94	0.55	0.41	0.31	0.10
2019	1,001	0.01	13.72	20.72	1.57	32.31	1.77	3.82	2.25	18.66	1.99	1.65	0.69	0.38	0.23	0.23
2020	704	0.00	0.08	8.49	35.70	1.46	31.05	1.67	2.36	1.91	14.39	1.18	1.06	0.28	0.10	0.27
2021	464	1.00	0.40	2.00	13.58	35.60	2.51	24.00	1.97	2.71	2.61	10.39	1.97	0.54	0.31	0.43

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

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

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

Year	Start date	End date	Vessels	Age-2+ biomass index (million t)	Sampling CV age-2+	Number of hauls with age samples	Age-1 index (billions of fish)	Sampling CV age-1
1995	1-Jul	1-Sep	Miller Freeman Ricker	1.318	0.086	69	0.232	0.5
1998	6-Jul	27-Aug	Miller Freeman Ricker	1.569	0.046	105	0.107	0.5
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	0.5
2005	20-Jun	19-Aug	Miller Freeman	1.376	0.062	47	0.009	0.5
2007	20-Jun	21-Aug	Miller Freeman	0.943	0.074	69	1.029	0.5
2009	30-Jun	7-Sep	Miller Freeman Ricker	1.502	0.096	72	3.396	0.5
2011	26-Jun	10-Sep	Bell Shimada Ricker	0.675	0.113	46	5.949	0.5
2012	23-Jun	7-Sep	Bell Shimada Ricker	1.279	0.065	94	0.064	0.5
2013	13-Jun	11-Sep	F/V Forum Star Bell Shimada Ricker	1.929	0.062	67	0.422	0.5
2015	15-Jun	14-Sep	Bell Shimada Ricker	2.156	0.081	78	4.665	0.5
2017	22-Jun	13-Sep	Bell Shimada Nordic Pearl	1.418	0.063	58	1.238	0.5
2019	13-Jun	15-Sep	Bell Shimada Nordic Pearl	1.718	0.062	75	0.734	0.5
2021	27-Jun	24-Sep	Bell Shimada Nordic Pearl	1.525	0.122	65	2.147	0.5

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

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

Table 14. Information on maturity and fecundity used in this assessment as shown in Figure 12. The sample sizes refer to the subset of samples in Table 15 for which age readings and histological estimates of maturity have been completed. The mean weight (kg) is based on a much larger set of samples. Mean fecundity is the product of maturity and mean weight, but note that year-specific fecundities from 1975–2021 were used in the stock assessment. The values reported for ages 15 and above represent the average across all samples in this range.

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

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

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

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

Parameter	Number of parameters	Bounds (low, high)	Prior (Mean, SD) single value = fixed
Stock Dynamics			
Log (R_0)	1	(13, 17)	Uniform
Steepness (h)	1	(0.2, 1)	Beta (0.78, 0.11)
Recruitment variability (σ_r)	–	–	1.4
Log recruitment deviations: 1946–2021	76	(-6, 6)	Lognormal (0, σ_r)
Natural mortality (M)	1	(0.05, 0.4)	Lognormal (-1.61, 0.10)
Data Source			
Acoustic Survey			
Additional variance for survey log (SE)	1	(0.05, 1.2)	Uniform
Non-parametric age-based selectivity: ages 3–6	4	(-5, 9)	Uniform
Age-1 Survey			
Additional variance for age-1 index log (SE)	1	(0.05, 1.2)	Uniform
Fishery			
Non-parametric age-based selectivity: ages 2–6	5	(-5, 9)	Uniform
Selectivity deviations (1991–2021, ages 2–6)	155	(-10, 10)	Normal (0, 1.4)
Data weighting			
Dirichlet-Multinomial likelihood (log θ)	2	(-5, 9)	Normal (-1, 0.01)

Table 17. Annual changes in the modeling framework used to assess Pacific Hake since 2011. The bias adjustment is reported as the maximum used for each assessment. Methods used to weight the age-composition data (Comp Method), i.e., McAllister-Ianelli (MI) and Dirichlet-multinomial (D-M) approaches, are explained in the main text.

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

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

Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	1,560	1,436	866	467	293	181	135	106	85	74	61	51	43	35	29	24	20	16	13	10	34
1967	4,558	1,241	1,140	674	357	219	134	95	75	60	52	43	36	30	25	20	17	14	11	9	41
1968	2,909	3,636	981	883	500	256	154	87	62	49	39	34	28	23	19	16	13	11	9	7	42
1969	681	2,324	2,887	768	675	373	190	108	62	44	34	28	24	20	16	14	11	9	8	7	42
1970	8,843	543	1,847	2,253	578	494	269	128	74	42	30	23	19	16	13	11	9	8	6	5	37
1971	812	7,017	429	1,431	1,679	417	348	177	85	48	27	20	15	12	11	9	7	6	5	4	32
1972	517	646	5,559	335	1,093	1,260	309	247	125	60	34	19	14	11	9	8	6	5	4	4	29
1973	5,869	412	513	4,365	258	836	956	227	181	91	44	25	14	10	8	6	6	5	4	3	27
1974	339	4,655	327	403	3,357	195	629	694	164	131	66	32	18	10	7	6	5	4	3	3	24
1975	1,798	269	3,682	257	308	2,520	145	447	493	117	93	47	23	13	7	5	4	3	3	2	21
1976	195	1,426	213	2,886	198	233	1,891	105	324	357	85	68	34	16	9	5	4	3	2	2	19
1977	6,526	155	1,132	168	2,231	151	177	1,394	77	239	263	62	50	25	12	7	4	3	2	2	17
1978	130	5,163	123	892	131	1,727	117	134	1,054	58	180	199	47	38	19	9	5	3	2	2	15
1979	1,352	103	4,095	97	698	102	1,334	89	101	800	44	137	151	36	28	14	7	4	2	2	14
1980	17,202	1,071	81	3,223	76	539	78	1,006	67	76	603	33	103	113	27	21	11	5	3	2	12
1981	254	13,629	848	64	2,520	59	418	60	767	51	58	460	25	79	86	20	16	8	4	2	11
1982	298	202	10,786	667	50	1,935	45	310	44	571	38	43	342	19	58	64	15	12	6	3	11
1983	524	237	160	8,490	520	39	1,488	34	234	33	430	28	32	257	14	44	48	11	9	5	12
1984	13,897	417	188	126	6,634	403	30	1,130	26	177	25	327	22	25	195	11	33	37	9	7	14
1985	127	11,018	330	148	98	5,127	310	23	854	19	134	19	247	16	19	148	8	25	28	7	17
1986	173	101	8,727	261	116	76	3,963	236	17	651	15	102	14	188	12	14	112	6	19	21	20
1987	6,587	137	80	6,860	203	89	58	2,956	176	13	485	11	76	11	140	9	11	84	5	14	31
1988	2,105	5,224	109	63	5,301	155	67	43	2,175	129	9	357	8	56	8	103	7	8	62	3	34
1989	110	1,669	4,140	85	48	4,033	117	49	31	1,593	95	7	262	6	41	6	75	5	6	45	28
1990	4,316	87	1,325	3,234	65	36	2,987	83	35	22	1,128	67	5	185	4	29	4	53	4	4	52
1991	1,256	3,420	69	1,038	2,492	50	27	2,177	60	25	16	822	49	4	135	3	21	3	39	3	41
1992	124	1,000	2,710	52	715	1,853	35	19	1,562	43	18	12	590	35	3	97	2	15	2	28	31
1993	3,231	99	792	2,121	36	503	1,367	25	14	1,083	30	13	8	410	24	2	67	2	11	1	41
1994	3,312	2,558	78	623	1,588	25	358	984	18	10	779	22	9	6	295	17	1	48	1	8	31
1995	1,264	2,625	2,025	61	481	1,121	17	227	622	11	6	493	14	6	4	186	11	1	31	1	24
1996	1,897	1,001	2,079	1,596	47	366	780	11	150	412	7	4	327	9	4	2	123	7	1	20	17
1997	1,015	1,503	792	1,562	1,168	33	266	491	7	94	259	5	3	205	6	2	2	78	5	0	23
1998	2,049	805	1,192	620	1,089	790	22	166	307	4	59	162	3	2	128	4	2	1	49	3	15
1999	13,374	1,625	639	922	390	750	469	14	104	193	3	37	102	2	1	80	2	1	1	30	11
2000	323	10,597	1,286	464	608	223	475	287	9	63	118	2	23	62	1	1	49	1	1	0	25
2001	1,275	256	8,396	1,009	337	436	152	299	181	5	40	74	1	14	39	1	0	31	1	0	16
2002	46	1,010	203	6,600	745	225	293	100	198	119	4	26	49	1	9	26	0	0	20	1	11
2003	1,789	36	800	160	5,098	545	158	208	71	140	85	3	19	35	0	7	18	0	0	15	8
2004	45	1,417	29	633	125	3,829	393	113	148	50	100	60	2	13	25	0	5	13	0	0	16
2005	2,916	35	1,120	22	470	76	2,668	263	75	99	34	67	40	1	9	17	0	3	9	0	11
2006	2,123	2,310	28	884	17	329	46	1,719	169	49	64	22	43	26	1	6	11	0	2	6	7

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Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
2007	25	1,683	1,829	20	629	11	202	28	1,042	103	29	39	13	26	16	0	3	6	0	1	8
2008	5,816	20	1,332	1,391	13	415	7	120	17	621	61	17	23	8	16	9	0	2	4	0	5
2009	1,552	4,611	15	1,011	930	8	252	4	67	9	348	34	10	13	4	9	5	0	1	2	3
2010	17,156	1,230	3,645	12	713	647	6	161	2	43	6	223	22	6	8	3	6	3	0	1	3
2011	418	13,594	976	2,779	8	398	415	4	109	2	29	4	151	15	4	6	2	4	2	0	3
2012	1,716	331	10,742	754	1,661	5	272	291	3	77	1	20	3	106	10	3	4	1	3	2	2
2013	381	1,360	262	8,317	553	1,126	4	194	208	2	55	1	15	2	76	7	2	3	1	2	3
2014	9,312	302	1,078	206	6,162	408	820	2	131	141	1	37	1	10	1	51	5	1	2	1	3
2015	42	7,377	239	836	148	4,546	298	567	2	91	97	1	26	0	7	1	35	3	1	1	3
2016	6,418	34	5,824	187	634	109	3,340	222	423	1	68	73	1	19	0	5	1	26	3	1	3
2017	2,576	5,085	26	4,203	137	459	77	2,374	158	300	1	48	52	0	14	0	4	0	19	2	3
2018	665	2,041	3,992	19	3,014	95	323	51	1,568	104	198	1	32	34	0	9	0	2	0	12	3
2019	1,002	527	1,578	2,941	13	2,180	69	216	34	1,050	69	133	0	21	23	0	6	0	2	0	10
2020	5,224	794	417	1,172	2,172	9	1,500	45	142	22	694	46	87	0	14	15	0	4	0	1	7
2021	934	4,131	630	329	903	1,481	6	993	30	94	15	460	30	58	0	9	10	0	3	0	5
2022	924	740	3,261	496	255	667	994	4	664	20	63	10	308	20	39	0	6	7	0	2	4

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

Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	21	138	223	179	143	97	79	69	60	57	52	46	41	37	29	25	21	16	13	11	35
1967	62	119	294	259	174	118	78	62	53	47	44	39	34	32	25	21	18	15	12	9	43
1968	39	349	253	339	244	137	89	57	44	38	33	31	27	25	20	17	14	11	10	7	43
1969	9	223	744	295	329	200	111	71	44	34	29	25	23	21	16	14	12	10	8	7	43
1970	119	52	476	865	282	264	157	84	52	32	25	21	18	17	13	12	10	8	7	5	39
1971	11	674	111	549	818	223	203	116	60	37	23	18	15	13	11	9	8	6	5	4	33
1972	7	62	1,433	129	533	675	180	162	89	46	29	18	13	12	9	8	6	5	4	4	30
1973	79	40	132	1,676	126	448	557	148	129	71	37	23	14	11	8	7	6	5	4	3	28
1974	5	447	84	155	1,636	105	366	454	117	102	56	29	17	11	7	6	5	4	3	3	25
1975	99	42	1,100	94	189	1,589	114	391	477	106	91	80	34	25	14	14	11	9	8	6	58
1976	11	141	50	1,440	103	162	1,520	96	391	475	123	112	62	30	18	15	10	8	6	6	51
1977	359	13	454	83	1,331	102	134	1,165	75	260	315	79	67	41	24	15	8	6	5	4	35
1978	7	374	16	419	69	1,041	75	99	888	57	198	247	63	56	33	21	12	7	5	4	35
1979	65	8	987	25	406	70	1,024	79	92	830	53	171	231	55	51	29	14	8	4	3	27
1980	778	86	17	1,460	30	265	40	660	48	67	641	39	133	147	34	30	15	7	4	2	17
1981	11	1,464	181	22	1,327	23	219	33	573	37	48	479	28	106	129	25	20	10	5	3	14
1982	12	24	2,659	223	16	1,079	18	166	25	439	26	37	362	18	60	75	18	14	7	3	13
1983	18	31	22	2,895	192	13	774	17	144	23	379	26	34	265	19	65	72	17	14	7	17
1984	446	55	31	31	2,908	166	13	664	15	120	18	311	24	25	250	20	63	69	16	13	26
1985	4	1,917	73	37	40	2,796	167	13	598	12	90	16	186	15	13	127	7	22	24	6	15
1986	4	16	2,426	76	35	28	2,150	135	11	534	14	121	17	258	21	23	181	10	31	34	32
1987	146	20	11	2,600	56	26	21	1,707	105	8	371	11	70	13	168	13	15	118	6	20	43
1988	40	731	20	20	2,497	57	25	22	1,408	89	7	329	9	57	12	150	10	11	90	5	49
1989	2	232	1,133	27	14	2,080	51	20	16	1,037	64	4	238	4	34	7	88	6	7	53	33
1990	67	12	323	1,138	26	19	1,669	53	23	12	877	55	11	220	4	42	6	77	5	6	75
1991	20	468	19	384	1,146	25	15	1,286	44	22	18	591	31	4	163	7	50	7	93	6	98
1992	2	136	628	18	339	989	21	12	1,000	28	12	8	434	30	2	100	2	16	2	29	32
1993	50	13	197	718	14	228	675	12	7	595	15	16	8	251	15	1	46	1	7	1	28
1994	51	305	23	226	709	11	189	561	11	5	494	10	6	4	207	13	1	36	1	6	23
1995	19	291	543	21	235	601	11	142	410	8	4	367	11	5	2	149	9	1	24	1	19
1996	29	102	598	636	22	195	441	7	89	262	4	3	221	7	6	2	93	5	0	15	13
1997	16	140	281	675	576	18	145	286	4	57	163	4	2	146	4	2	1	67	4	0	20
1998	31	67	250	223	550	409	12	105	187	3	46	115	2	1	96	3	1	1	39	2	12
1999	203	222	160	319	166	395	261	8	64	135	2	29	77	2	1	66	2	1	0	25	9
2000	5	2,012	495	220	351	147	341	209	6	53	96	1	19	58	1	1	46	1	1	0	24
2001	19	13	2,407	488	220	290	113	258	155	5	38	73	1	15	39	1	0	30	1	0	16
2002	1	76	73	3,012	434	168	212	78	181	102	3	24	41	1	10	27	0	0	21	1	12
2003	27	4	204	70	2,664	321	119	144	53	116	65	2	17	27	0	7	18	0	0	15	8
2004	1	153	6	276	60	2,036	255	80	97	36	80	52	1	13	21	0	4	12	0	0	15
2005	43	4	292	10	239	41	1,516	166	49	70	27	54	33	1	10	16	0	3	8	0	11
2006	31	306	11	404	9	189	27	1,028	111	34	46	16	33	17	0	5	10	0	2	5	7

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Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
2007	0	75	418	9	338	6	123	18	675	72	23	30	11	23	13	0	3	6	0	1	7
2008	83	3	325	568	7	264	5	82	12	447	46	14	20	6	14	8	0	2	3	0	4
2009	21	302	4	344	430	5	165	3	50	8	264	28	10	11	4	9	5	0	1	2	3
2010	221	134	848	3	309	343	4	135	3	44	6	196	19	7	6	3	5	3	0	1	3
2011	5	1,147	240	895	3	204	247	3	93	2	28	4	160	15	4	5	2	3	2	0	3
2012	20	43	2,304	266	680	3	179	201	2	69	1	20	3	105	10	3	4	1	2	1	2
2013	4	176	75	2,990	260	575	2	139	152	2	55	1	18	2	81	8	2	3	1	2	3
2014	97	31	440	97	2,956	219	470	1	87	101	1	43	1	9	1	54	5	2	2	1	3
2015	0	560	59	327	66	2,140	165	337	1	62	70	1	24	0	7	1	44	4	1	2	3
2016	59	6	1,421	72	264	48	1,556	114	219	1	45	52	0	18	0	7	1	38	4	1	4
2017	22	713	8	1,688	67	242	43	1,315	92	197	1	35	41	0	11	0	3	0	17	2	2
2018	10	382	1,415	9	1,516	51	178	31	925	66	127	0	22	25	0	10	0	3	0	13	3
2019	20	36	453	1,311	7	1,178	42	135	23	717	50	102	0	18	20	0	6	0	1	0	10
2020	104	79	144	558	1,102	5	854	27	85	14	449	32	55	0	12	14	0	4	0	1	6
2021	19	539	185	170	549	897	4	647	20	73	11	329	21	44	0	8	9	0	2	0	5
2022	15	92	1,038	229	136	370	591	2	412	13	43	7	218	16	32	0	6	6	0	2	3

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Year	Age																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+		
2006	0.00	0.10	2.52	6.96	11.75	18.89	21.18	21.98	22.33	21.59	21.31	24.59	23.20	30.54	33.61	21.65	21.65	21.65	21.65	21.65	21.65	21.65	
2007	0.00	0.26	4.25	11.04	12.22	11.62	20.70	21.31	21.66	22.24	21.49	23.82	21.57	24.70	42.21	35.36	35.36	35.36	35.36	35.36	35.36	35.36	35.36
2008	0.00	0.16	4.11	14.34	10.50	17.45	21.63	23.54	23.31	24.82	25.54	28.17	25.99	30.59	26.20	31.95	31.95	31.95	31.95	31.95	31.95	31.95	31.95
2009	0.00	0.08	1.21	11.52	12.06	7.95	14.46	15.99	15.09	14.91	17.07	17.20	14.68	17.38	17.33	17.64	17.64	17.64	17.64	17.64	17.64	17.64	17.64
2010	0.00	0.04	3.73	10.89	28.25	18.49	11.83	9.63	8.10	9.57	10.31	11.99	13.89	10.04	16.73	15.42	15.42	15.42	15.42	15.42	15.42	15.42	15.42
2011	0.00	0.19	2.32	27.80	15.23	12.68	9.94	10.02	8.45	8.12	8.44	7.98	9.05	10.24	8.70	11.58	11.58	11.58	11.58	11.58	11.58	11.58	11.58
2012	0.00	0.08	2.56	7.27	16.11	8.73	8.04	8.14	8.47	7.89	8.24	7.95	7.91	8.90	9.24	9.86	9.86	9.86	9.86	9.86	9.86	9.86	9.86
2013	0.00	0.03	0.61	5.93	5.60	7.82	12.02	11.40	11.97	11.77	9.65	9.84	8.78	10.01	11.76	12.45	12.45	12.45	12.45	12.45	12.45	12.45	12.45
2014	0.00	0.08	1.01	6.66	5.67	6.18	11.36	10.67	10.71	11.03	12.07	9.08	10.66	9.89	10.29	10.51	10.51	10.51	10.51	10.51	10.51	10.51	10.51
2015	0.00	0.29	1.23	3.72	6.03	6.66	5.15	5.36	4.81	5.00	5.04	5.06	4.43	4.48	4.25	4.09	4.09	4.09	4.09	4.09	4.09	4.09	4.09
2016	0.00	0.36	8.35	5.26	8.88	9.73	11.91	11.34	12.54	12.94	10.35	11.00	13.57	9.29	6.10	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38
2017	0.00	0.61	5.31	8.25	9.68	9.43	15.12	16.56	16.44	16.10	18.60	17.68	15.19	18.93	27.29	20.98	20.98	20.98	20.98	20.98	20.98	20.98	20.98
2018	0.00	1.05	4.87	6.13	7.38	5.71	13.95	13.87	15.07	15.05	15.93	17.94	16.92	17.83	14.01	13.67	13.67	13.67	13.67	13.67	13.67	13.67	13.67
2019	0.00	0.20	4.08	5.44	7.13	11.32	13.43	14.93	14.71	15.62	15.67	15.99	18.67	15.70	17.05	17.25	17.25	17.25	17.25	17.25	17.25	17.25	17.25
2020	0.00	0.01	0.22	1.61	11.08	8.97	15.18	15.06	16.32	17.21	17.19	16.81	20.96	15.14	15.59	16.72	16.72	16.72	16.72	16.72	16.72	16.72	16.72
2021	0.00	0.05	0.45	1.29	4.38	12.40	12.19	14.54	15.48	13.57	15.08	16.78	19.16	19.22	17.98	16.43	16.43	16.43	16.43	16.43	16.43	16.43	16.43

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

Age	1999 cohort				2010 cohort				2014 cohort				2016 cohort			
	Start Biomass 000s t	Catch Weight 000s t	M 000s t	Surviving Biomass 000s t	Start Biomass 000s t	Catch Weight 000s t	M 000s t	Surviving Biomass 000s t	Start Biomass 000s t	Catch Weight 000s t	M 000s t	Surviving Biomass 000s t	Start Biomass 000s t	Catch Weight 000s t	M 000s t	Surviving Biomass 000s t
0	203.3	0.0	42.2	161.1	221.3	0.0	45.9	175.4	96.8	0.0	20.1	76.7	59.0	0.0	12.3	46.8
1	2,012.4	0.3	417.8	1,594.3	1,147.3	2.2	238.5	906.6	559.9	1.7	116.2	442.1	713.4	4.5	148.9	560.1
2	2,407.0	15.0	499.8	1,892.2	2,304.1	60.2	460.0	1,783.9	1,420.6	119.2	276.1	1,025.2	1,414.8	75.8	296.6	1,042.4
3	3,011.6	55.9	629.3	2,326.4	2,989.8	168.9	605.8	2,215.2	1,688.1	142.4	335.1	1,210.5	1,311.5	72.2	270.9	968.3
4	2,663.9	111.3	552.2	2,000.4	2,955.8	175.5	599.6	2,180.7	1,515.9	118.0	301.3	1,096.5	1,102.3	127.5	223.1	751.7
5	2,036.4	209.8	407.7	1,418.9	2,140.3	150.5	417.1	1,572.7	1,177.9	138.5	229.3	810.1	897.3	111.3	183.6	602.5
6	1,515.7	253.3	285.6	976.9	1,555.6	178.4	271.5	1,105.8	854.3	132.9	155.8	565.6	591.2			
7	1,027.9	223.7	181.4	622.9	1,314.7	213.1	233.3	868.3	646.7	93.4	120.6	432.8				
8	674.7	146.6	126.2	401.8	924.6	133.6	172.1	618.9	412.3							
9	447.5	108.8	88.0	250.6	716.8	109.0	134.0	473.8								
10	264.2	44.3	50.2	169.7	448.6	73.5	78.0	297.2								
11	195.6	23.3	40.1	132.1	329.4	54.6	54.4	220.4								
12	159.6	14.3	33.2	112.2	218.3											
13	104.8	9.4	20.5	74.9												
14	80.8	9.6	16.7	54.6												
15	54.1	5.7	10.9	37.5												
16	44.2	1.8	9.5	32.9												
17	38.3	2.4	8.6	27.2												
18	17.5	3.8	2.2	11.5												
19	13.2	1.8	0.5	10.9												
20	9.6															

Table 24. Time series of median posterior population estimates from the base model. Relative spawning biomass is spawning biomass relative to the unfished equilibrium (B_0). Total biomass includes females and males of ages 0 and above. Age-2+ biomass includes females and males ages 2 and above. Exploitation fraction is total catch divided by total age-2+ biomass. Relative fishing intensity is $(1-SPR)/(1-SPR_{40\%})$. A dash (–) indicates a quantity requiring 2022 catch which has not taken place yet.

Year	Female spawning biomass (thousand t)	Relative spawning biomass	Total biomass (thousand t)	Age-2+ biomass (thousand t)	Age-0 recruits (millions)	Relative fishing intensity	Exploitation fraction
1966	862	47.8%	2,279	2,084	1,560	49.0%	6.6%
1967	863	48.0%	2,362	2,133	4,558	67.1%	10.0%
1968	859	48.0%	2,517	2,116	2,909	48.6%	5.8%
1969	953	53.7%	2,868	2,615	681	59.9%	6.9%
1970	1,132	63.7%	3,045	2,851	8,843	65.9%	8.2%
1971	1,170	65.9%	3,330	2,645	812	48.7%	5.8%
1972	1,237	69.9%	3,761	3,685	517	37.2%	3.2%
1973	1,592	89.9%	3,800	3,681	5,869	41.0%	4.4%
1974	1,569	88.4%	3,850	3,392	339	46.9%	6.2%
1975	1,807	101.6%	4,824	4,673	1,798	51.9%	4.7%
1976	2,225	125.1%	5,087	4,935	195	45.1%	4.8%
1977	1,918	107.6%	4,768	4,389	6,526	29.5%	3.0%
1978	1,619	90.7%	3,875	3,492	130	29.7%	3.0%
1979	1,686	94.4%	4,363	4,286	1,352	32.2%	3.2%
1980	1,690	94.8%	4,615	3,748	17,202	24.9%	2.4%
1981	1,535	86.0%	4,834	3,349	254	36.3%	4.2%
1982	1,582	88.5%	5,356	5,315	298	30.4%	2.0%
1983	2,224	124.3%	5,099	5,050	524	29.3%	2.3%
1984	2,285	127.7%	5,343	4,833	13,897	33.7%	2.9%
1985	1,968	109.8%	6,217	4,290	127	22.7%	2.6%
1986	2,062	114.9%	6,202	6,178	173	40.2%	3.4%
1987	2,406	134.3%	5,586	5,416	6,587	45.2%	4.3%
1988	2,329	129.9%	5,675	4,901	2,105	45.4%	5.1%
1989	1,923	107.1%	5,180	4,943	110	52.6%	6.0%
1990	2,034	113.1%	4,753	4,671	4,316	46.3%	5.6%
1991	1,876	104.4%	4,527	4,036	1,256	70.5%	7.9%
1992	1,546	86.0%	3,861	3,720	124	60.4%	8.1%
1993	1,232	68.5%	2,916	2,849	3,231	51.5%	7.0%
1994	1,190	66.2%	2,908	2,552	3,312	62.2%	14.2%
1995	1,024	56.9%	2,887	2,579	1,264	54.4%	9.7%
1996	1,002	55.6%	2,762	2,630	1,897	69.1%	11.6%
1997	1,035	57.5%	2,622	2,468	1,015	70.8%	13.2%
1998	878	48.8%	2,164	2,063	2,049	85.3%	15.5%
1999	739	41.0%	2,155	1,728	13,374	95.2%	18.0%
2000	799	44.4%	4,100	2,080	323	66.7%	11.0%
2001	1,112	61.8%	4,191	4,158	1,275	67.5%	5.5%
2002	1,897	105.5%	4,487	4,408	46	47.6%	4.1%
2003	1,764	98.1%	3,888	3,858	1,789	43.2%	5.3%
2004	1,398	77.7%	3,203	3,049	45	71.3%	11.2%
2005	1,092	60.7%	2,597	2,549	2,916	68.4%	14.2%
2006	891	49.6%	2,299	1,961	2,123	80.3%	18.4%
2007	702	39.1%	1,852	1,776	25	83.6%	16.4%
2008	720	40.3%	1,918	1,831	5,816	87.9%	17.6%
2009	626	35.0%	1,676	1,351	1,552	76.1%	13.2%
2010	625	35.0%	2,295	1,939	17,156	90.5%	11.8%
2011	776	43.5%	3,070	1,913	418	84.8%	15.0%
2012	1,025	57.6%	3,931	3,864	1,716	63.9%	5.4%
2013	1,878	105.3%	4,560	4,376	381	61.4%	6.5%
2014	1,987	111.6%	4,629	4,501	9,312	58.7%	6.6%
2015	1,502	84.1%	3,880	3,321	42	43.3%	5.8%
2016	1,328	74.5%	3,940	3,873	6,418	69.4%	8.6%
2017	1,676	93.9%	4,514	3,771	2,576	73.5%	11.7%

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Year	Female spawning biomass (thousand t)	Relative spawning biomass	Total biomass (thousand t)	Age-2+ biomass (thousand t)	Age-0 recruits (millions)	Relative fishing intensity	Exploitation fraction
2018	1,615	90.4%	4,818	4,413	665	68.3%	9.4%
2019	1,697	94.7%	4,173	4,110	1,002	68.1%	10.0%
2020	1,538	85.7%	3,633	3,410	5,224	58.7%	11.2%
2021	1,347	74.8%	3,770	3,039	934	52.8%	10.7%
2022	1,171	64.7%	3,667	3,347	924	–	–

Table 25. Time-series of 95% posterior credibility intervals for the quantities shown in Table 24. A dash (–) indicates a quantity requiring 2022 catch which has not taken place yet.

Year	Female spawning biomass (thousand t)	Relative spawning biomass	Total biomass (thousand t)	Age-2+ biomass (thousand t)	Age-0 recruits (millions)	(1-SPR) / (1-SPR _{40%})	Exploitation fraction
1966	505 - 1,691	27.0 - 85.2%	1,450 - 4,449	1,236 - 4,098	58 - 9,541	25.6 - 74.3%	3.4 - 11.1%
1967	520 - 1,708	27.3 - 86.4%	1,536 - 4,686	1,319 - 4,242	247 - 14,452	37.6 - 93.5%	5.1 - 16.3%
1968	528 - 1,744	27.1 - 87.4%	1,620 - 5,166	1,305 - 4,414	230 - 9,877	24.3 - 73.6%	2.8 - 9.4%
1969	605 - 1,963	30.4 - 96.4%	1,841 - 5,917	1,655 - 5,401	42 - 3,876	31.1 - 85.2%	3.3 - 10.9%
1970	712 - 2,343	35.8 - 115.2%	1,929 - 6,368	1,815 - 5,931	4,471 - 22,241	34.9 - 92.4%	4.0 - 12.9%
1971	727 - 2,452	36.7 - 121.6%	2,042 - 7,173	1,645 - 5,565	79 - 2,919	23.2 - 74.6%	2.8 - 9.4%
1972	761 - 2,613	38.4 - 128.3%	2,285 - 8,100	2,239 - 7,941	63 - 1,875	16.8 - 60.4%	1.5 - 5.2%
1973	979 - 3,350	49.0 - 165.9%	2,326 - 8,056	2,259 - 7,767	3,037 - 14,296	19.0 - 65.2%	2.1 - 7.2%
1974	965 - 3,256	48.4 - 162.0%	2,340 - 8,077	2,089 - 7,057	36 - 1,302	22.4 - 73.2%	3.0 - 10.1%
1975	1,101 - 3,732	55.5 - 184.8%	2,909 - 10,085	2,828 - 9,774	868 - 4,358	24.5 - 81.0%	2.3 - 7.8%
1976	1,343 - 4,572	67.8 - 227.2%	3,071 - 10,466	2,978 - 10,139	22 - 865	21.0 - 72.8%	2.3 - 8.0%
1977	1,156 - 3,884	58.5 - 194.3%	2,859 - 9,743	2,633 - 8,904	3,561 - 14,395	13.1 - 51.4%	1.5 - 5.0%
1978	984 - 3,209	49.7 - 161.7%	2,364 - 7,712	2,127 - 6,913	17 - 647	13.2 - 51.4%	1.5 - 4.9%
1979	1,043 - 3,246	52.4 - 166.7%	2,716 - 8,452	2,663 - 8,303	527 - 3,361	15.2 - 53.7%	1.7 - 5.1%
1980	1,062 - 3,188	53.0 - 164.5%	2,898 - 8,771	2,353 - 7,069	10,031 - 34,775	11.7 - 42.7%	1.3 - 3.8%
1981	986 - 2,823	48.8 - 147.1%	3,103 - 8,927	2,156 - 6,163	30 - 1,040	18.2 - 58.1%	2.3 - 6.5%
1982	1,035 - 2,831	50.6 - 149.4%	3,513 - 9,655	3,481 - 9,581	49 - 965	15.1 - 49.7%	1.1 - 3.1%
1983	1,494 - 3,863	72.0 - 206.8%	3,428 - 8,864	3,389 - 8,770	97 - 1,488	14.9 - 47.4%	1.3 - 3.4%
1984	1,570 - 3,835	75.0 - 209.0%	3,671 - 8,998	3,321 - 8,112	8,886 - 25,273	17.6 - 53.5%	1.7 - 4.2%
1985	1,386 - 3,205	65.5 - 177.7%	4,356 - 10,236	3,020 - 6,972	17 - 522	12.1 - 36.2%	1.6 - 3.7%
1986	1,489 - 3,247	69.6 - 182.8%	4,470 - 9,873	4,455 - 9,821	22 - 649	23.1 - 59.2%	2.1 - 4.7%
1987	1,776 - 3,704	82.1 - 213.4%	4,115 - 8,627	3,995 - 8,357	4,227 - 11,523	26.7 - 64.9%	2.8 - 5.9%
1988	1,754 - 3,489	80.4 - 205.1%	4,247 - 8,598	3,691 - 7,346	1,131 - 3,845	27.3 - 64.7%	3.4 - 6.7%
1989	1,472 - 2,817	66.5 - 167.9%	3,946 - 7,653	3,766 - 7,308	16 - 409	33.0 - 72.4%	4.1 - 7.9%
1990	1,578 - 2,936	70.7 - 177.2%	3,682 - 8,860	3,624 - 6,735	2,870 - 7,235	29.0 - 64.2%	3.9 - 7.2%
1991	1,485 - 2,638	65.3 - 162.4%	3,559 - 6,401	3,195 - 5,680	588 - 2,473	45.9 - 99.7%	5.6 - 10.0%
1992	1,240 - 2,135	53.9 - 133.5%	3,075 - 5,382	2,971 - 5,163	16 - 474	39.2 - 92.3%	5.8 - 10.1%
1993	997 - 1,686	43.0 - 106.4%	2,349 - 4,025	2,302 - 3,922	2,200 - 5,242	32.8 - 80.5%	5.1 - 8.6%
1994	979 - 1,609	41.7 - 102.6%	2,365 - 3,972	2,095 - 3,455	2,257 - 5,385	42.5 - 84.3%	10.5 - 17.3%
1995	839 - 1,391	35.8 - 88.2%	2,338 - 3,990	2,096 - 3,520	761 - 2,185	37.0 - 72.2%	7.1 - 11.9%
1996	822 - 1,357	35.1 - 86.4%	2,245 - 3,808	2,142 - 3,608	1,239 - 3,195	48.7 - 91.4%	8.5 - 14.3%
1997	847 - 1,411	36.3 - 89.2%	2,128 - 3,613	2,009 - 3,376	569 - 1,889	50.5 - 90.4%	9.6 - 16.2%
1998	717 - 1,203	30.7 - 76.0%	1,755 - 2,997	1,680 - 2,844	1,307 - 3,563	63.8 - 103.2%	11.3 - 19.1%
1999	597 - 1,028	25.9 - 64.0%	1,703 - 3,099	1,391 - 2,417	9,243 - 22,446	72.3 - 113.4%	12.9 - 22.4%
2000	629 - 1,143	27.8 - 69.3%	3,108 - 6,195	1,631 - 3,007	105 - 736	46.3 - 85.5%	7.6 - 14.0%
2001	867 - 1,617	38.9 - 96.8%	3,230 - 6,228	3,204 - 6,183	852 - 2,174	46.4 - 86.2%	3.7 - 7.1%
2002	1,493 - 2,748	66.2 - 164.9%	3,524 - 6,499	3,465 - 6,378	14 - 130	30.3 - 64.8%	2.8 - 5.2%
2003	1,425 - 2,482	62.1 - 152.4%	3,135 - 5,489	3,112 - 5,437	1,231 - 3,072	27.4 - 59.3%	3.8 - 6.6%
2004	1,156 - 1,916	49.3 - 120.3%	2,635 - 4,434	2,520 - 4,182	12 - 153	47.9 - 96.7%	8.2 - 13.6%
2005	910 - 1,490	38.5 - 93.8%	2,146 - 3,604	2,110 - 3,521	1,983 - 5,129	46.2 - 92.0%	10.3 - 17.2%
2006	737 - 1,239	31.5 - 76.9%	1,871 - 3,292	1,619 - 2,736	1,442 - 3,695	54.9 - 111.4%	13.2 - 22.3%
2007	570 - 1,011	24.8 - 60.8%	1,487 - 2,717	1,428 - 2,599	6 - 97	57.0 - 116.5%	11.2 - 20.4%
2008	569 - 1,082	25.5 - 62.8%	1,505 - 2,904	1,443 - 2,762	4,077 - 10,245	62.1 - 111.4%	11.7 - 22.4%
2009	480 - 975	21.9 - 55.3%	1,280 - 2,631	1,036 - 2,105	883 - 3,173	50.1 - 99.2%	8.5 - 17.2%
2010	477 - 986	21.8 - 55.5%	1,725 - 3,740	1,483 - 3,082	11,201 - 32,818	61.5 - 120.3%	7.4 - 15.4%
2011	588 - 1,251	27.0 - 69.5%	2,242 - 5,220	1,443 - 3,102	166 - 1,011	54.9 - 115.6%	9.3 - 19.9%
2012	747 - 1,741	35.3 - 93.9%	2,824 - 6,780	2,783 - 6,671	1,049 - 3,473	38.3 - 91.6%	3.1 - 7.4%
2013	1,365 - 3,207	64.4 - 172.9%	3,301 - 7,825	3,178 - 7,480	123 - 1,003	37.4 - 82.6%	3.8 - 9.0%
2014	1,451 - 3,391	68.0 - 183.2%	3,359 - 7,950	3,276 - 7,684	6,019 - 18,582	34.4 - 82.0%	3.9 - 9.1%
2015	1,096 - 2,570	51.2 - 139.3%	2,799 - 6,779	2,418 - 5,708	9 - 177	23.4 - 65.4%	3.4 - 8.0%
2016	965 - 2,300	45.2 - 124.5%	2,823 - 6,988	2,782 - 6,844	3,791 - 13,869	40.8 - 95.0%	4.9 - 11.9%
2017	1,182 - 3,028	56.3 - 161.4%	3,136 - 8,265	2,654 - 6,841	1,198 - 6,598	44.0 - 107.2%	6.4 - 16.6%
2018	1,089 - 3,049	52.9 - 160.7%	3,191 - 9,252	2,954 - 8,323	171 - 2,100	38.9 - 99.9%	5.0 - 14.0%
2019	1,093 - 3,323	54.0 - 174.2%	2,664 - 8,243	2,629 - 8,110	235 - 3,516	38.7 - 96.9%	5.1 - 15.7%
2020	929 - 3,155	46.7 - 164.3%	2,164 - 7,417	2,050 - 7,022	935 - 24,333	31.7 - 84.0%	5.4 - 18.6%
2021	743 - 2,896	38.6 - 150.5%	2,030 - 8,141	1,667 - 6,572	45 - 20,814	27.6 - 78.6%	5.0 - 19.6%
2022	584 - 2,585	31.1 - 134.7%	1,707 - 9,309	1,561 - 8,367	44 - 19,595	–	–

Table 26. Select parameters, derived quantities, and reference point posterior median estimates for the (2022) base model compared to the previous assessment’s (2021) base model.

	2022 Base model	2021 Base model
Parameters		
Natural mortality (M)	0.233	0.230
Unfished recruitment (R_0 , millions)	2,535	2,264
Steepness (h)	0.810	0.807
Additional biomass index SD	0.292	0.302
Catchability: biomass index (q_b)	0.824	0.864
Additional age-1 index SD	0.373	–
Catchability: age-1 index (q_1)	0.422	–
Dirichlet-Multinomial fishery ($\log \theta_{\text{fish}}$)	-0.564	-0.569
Dirichlet-Multinomial survey ($\log \theta_{\text{surv}}$)	2.591	2.324
Derived Quantities		
2010 recruitment (millions)	17,156	16,149
2014 recruitment (millions)	9,312	8,908
2016 recruitment (millions)	6,418	4,828
Unfished female spawning biomass (B_0 , thousand t)	1,813	1,658
2009 relative spawning biomass	35.0%	37.3%
2022 relative spawning biomass	64.7%	–
Reference Points based on $F_{\text{SPR}=40\%}$		
2021 rel. fishing intensity: $(1-\text{SPR})/(1-\text{SPR}_{40\%})$	52.8%	–
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	645	584
SPR at $F_{\text{SPR}=40\%}$	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.5%	18.3%
Yield at $B_{\text{SPR}=40\%}$ (thousand t)	309	275

Table 27. Summary of median and 95% credibility intervals of equilibrium conceptual reference points for the base assessment model. Equilibrium reference points were computed using 2017–2021 averages for mean weight-at-age and baseline selectivity (1966–1990; prior to time-varying deviations.)

Quantity	2.5 th percentile	Median	97.5 th percentile
Unfished female spawning biomass (B_0 , thousand t)	1,140	1,813	3,131
Unfished recruitment (R_0 , millions)	1,343	2,535	5,657
Reference points (equilibrium) based on $F_{SPR=40\%}$			
Female spawning biomass at $F_{SPR=40\%}$ ($B_{SPR=40\%}$, thousand t)	370	645	1,111
SPR at $F_{SPR=40\%}$	–	40%	–
Exploitation fraction corresponding to $F_{SPR=40\%}$	16.1%	18.5%	21.3%
Yield associated with $F_{SPR=40\%}$ (thousand t)	167	309	599
Reference points (equilibrium) based on $B_{40\%}$ (40% of B_0)			
Female spawning biomass ($B_{40\%}$, thousand t)	456	725	1,253
SPR at $B_{40\%}$	40.7%	43.5%	51.5%
Exploitation fraction resulting in $B_{40\%}$	12.4%	16.4%	19.6%
Yield at $B_{40\%}$ (thousand t)	168	301	583
Reference points (equilibrium) based on estimated MSY			
Female spawning biomass (B_{MSY} , thousand t)	278	465	878
SPR at MSY	22.5%	29.8%	46.7%
Exploitation fraction corresponding to SPR at MSY	14.7%	26.0%	35.2%
MSY (thousand t)	175	326	638

Table 28. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year. Catch alternatives are based on: constant catches (rows a, b, c, d, f, g, i, k, l), including catch similar to 2021 (row f) and to the (unilaterally summed) TAC from 2021 (row l); and non-constant catches that result in annual 10% declines in catch (rows e, h, j), median relative fishing intensity of 100% (row m), median catch estimated via the default harvest policy ($F_{SPR=40\%}=40:10$, row n), and the fishing intensity that results in a 50% probability that the median projected catch will remain the same in 2022 and 2023 (row o).

Management Action			Biomass at start of year	Resulting relative spawning biomass		
				5%	50%	95%
Catch year	Catch (t)		Start of 2022	0.35	0.65	1.19
a:	2022	0	Start of 2023	0.43	0.83	1.70
	2023	0	Start of 2024	0.44	0.87	1.96
	2024	0	Start of 2025	0.44	0.87	2.01
b:	2022	180,000	Start of 2023	0.39	0.78	1.64
	2023	180,000	Start of 2024	0.36	0.79	1.86
	2024	180,000	Start of 2025	0.32	0.74	1.86
c:	2022	225,000	Start of 2023	0.37	0.77	1.63
	2023	225,000	Start of 2024	0.34	0.76	1.84
	2024	225,000	Start of 2025	0.29	0.71	1.83
d:	2022	270,000	Start of 2023	0.37	0.76	1.62
	2023	270,000	Start of 2024	0.32	0.74	1.82
	2024	270,000	Start of 2025	0.26	0.68	1.79
e: 10% reduction	2022	320,000	Start of 2023	0.35	0.75	1.60
	2023	288,000	Start of 2024	0.31	0.73	1.80
	2024	259,200	Start of 2025	0.25	0.67	1.78
f: 2021 catch	2022	325,000	Start of 2023	0.35	0.74	1.60
	2023	325,000	Start of 2024	0.30	0.71	1.79
	2024	325,000	Start of 2025	0.23	0.64	1.75
g:	2022	350,000	Start of 2023	0.35	0.74	1.59
	2023	350,000	Start of 2024	0.29	0.70	1.77
	2024	350,000	Start of 2025	0.21	0.62	1.73
h: 10% reduction	2022	350,000	Start of 2023	0.35	0.74	1.59
	2023	315,000	Start of 2024	0.29	0.71	1.78
	2024	283,500	Start of 2025	0.24	0.65	1.76
i:	2022	380,000	Start of 2023	0.34	0.73	1.59
	2023	380,000	Start of 2024	0.27	0.69	1.75
	2024	380,000	Start of 2025	0.19	0.60	1.71
j: 10% reduction	2022	380,000	Start of 2023	0.34	0.73	1.59
	2023	342,000	Start of 2024	0.28	0.70	1.77
	2024	307,800	Start of 2025	0.22	0.63	1.74
k:	2022	430,000	Start of 2023	0.33	0.72	1.57
	2023	430,000	Start of 2024	0.25	0.66	1.73
	2024	430,000	Start of 2025	0.16	0.57	1.67
l: 2021 TAC	2022	473,880	Start of 2023	0.32	0.71	1.56
	2023	473,880	Start of 2024	0.23	0.64	1.70
	2024	473,880	Start of 2025	0.13	0.54	1.64
m: FI= 100%	2022	715,643	Start of 2023	0.26	0.64	1.49
	2023	581,743	Start of 2024	0.16	0.56	1.62
	2024	515,616	Start of 2025	0.09	0.46	1.55
n: default HR	2022	715,643	Start of 2023	0.26	0.64	1.49
	2023	586,146	Start of 2024	0.16	0.56	1.62
	2024	526,126	Start of 2025	0.09	0.45	1.54
o: C2022= C2023	2022	613,069	Start of 2023	0.29	0.67	1.52
	2023	613,030	Start of 2024	0.17	0.58	1.64
	2024	538,943	Start of 2025	0.09	0.46	1.56

Table 29. Forecast quantiles of Pacific Hake relative fishing intensity $(1-SPR)/(1-SPR_{40\%})$, expressed as a proportion, for the 2022–2024 catch alternatives presented in Table g. Values greater than 1 indicate relative fishing intensities greater than the $F_{SPR=40\%}$ harvest policy calculated using baseline selectivity.

Management Action			Relative fishing intensity		
Catch year	Catch (t)		5%	50%	95%
a:	2022	0	0.00	0.00	0.00
	2023	0	0.00	0.00	0.00
	2024	0	0.00	0.00	0.00
b:	2022	180,000	0.24	0.44	0.68
	2023	180,000	0.23	0.43	0.69
	2024	180,000	0.20	0.42	0.71
c:	2022	225,000	0.29	0.51	0.77
	2023	225,000	0.28	0.51	0.80
	2024	225,000	0.25	0.50	0.83
d:	2022	270,000	0.33	0.57	0.84
	2023	270,000	0.32	0.58	0.88
	2024	270,000	0.29	0.58	0.93
e: 10% reduction	2022	320,000	0.38	0.64	0.91
	2023	288,000	0.34	0.61	0.93
	2024	259,200	0.28	0.57	0.94
f: 2021 catch	2022	325,000	0.39	0.64	0.92
	2023	325,000	0.37	0.66	0.98
	2024	325,000	0.34	0.66	1.05
g:	2022	350,000	0.41	0.67	0.95
	2023	350,000	0.40	0.69	1.01
	2024	350,000	0.36	0.70	1.09
h: 10% reduction	2022	350,000	0.41	0.67	0.95
	2023	315,000	0.37	0.65	0.97
	2024	283,500	0.31	0.61	1.00
i:	2022	380,000	0.43	0.71	0.98
	2023	380,000	0.42	0.73	1.06
	2024	380,000	0.39	0.74	1.15
j: 10% reduction	2022	380,000	0.43	0.71	0.98
	2023	342,000	0.39	0.69	1.02
	2024	307,800	0.33	0.65	1.05
k:	2022	430,000	0.47	0.75	1.03
	2023	430,000	0.46	0.79	1.12
	2024	430,000	0.43	0.80	1.23
l: 2021 TAC	2022	473,880	0.51	0.79	1.07
	2023	473,880	0.50	0.83	1.18
	2024	473,880	0.47	0.86	1.29
m: FI= 100%	2022	715,643	0.65	0.96	1.24
	2023	581,743	0.59	0.96	1.32
	2024	515,616	0.51	0.95	1.34
n: default HR	2022	715,643	0.65	0.96	1.24
	2023	586,146	0.59	0.96	1.32
	2024	526,126	0.52	0.96	1.35
o: C2022= C2023	2022	613,069	0.60	0.90	1.18
	2023	613,030	0.60	0.96	1.31
	2024	538,943	0.52	0.96	1.34

Table 30. Probabilities related to spawning biomass, relative fishing intensity, and the 2023 default harvest policy catch for alternative 2022 catch options (catch options explained in Table 28).

Catch in 2022	Probability $B_{2023} < B_{2022}$	Probability $B_{2023} < B_{40\%}$	Probability $B_{2023} < B_{25\%}$	Probability $B_{2023} < B_{10\%}$	Probability 2022 relative fishing intensity > 100%	Probability 2023 default harvest policy catch < 2022 catch
a: 0	8%	4%	0%	0%	0%	0%
b: 180,000	19%	6%	0%	0%	0%	0%
c: 225,000	23%	7%	1%	0%	0%	1%
d: 270,000	26%	7%	1%	0%	1%	3%
e: 320,000	30%	8%	1%	0%	2%	6%
f: 325,000	30%	8%	1%	0%	2%	6%
g: 350,000	32%	9%	1%	0%	3%	9%
h: 350,000	32%	9%	1%	0%	3%	9%
i: 380,000	34%	10%	1%	0%	4%	13%
j: 380,000	34%	10%	1%	0%	4%	13%
k: 430,000	38%	11%	1%	0%	7%	20%
l: 473,880	41%	11%	2%	0%	11%	27%
m: 715,643	56%	18%	4%	0%	42%	64%
n: 715,643	56%	18%	4%	0%	42%	64%
o: 613,069	50%	15%	3%	0%	29%	50%

Table 31. Probabilities related to spawning biomass, relative fishing intensity, and the 2024 default harvest policy catch for alternative 2023 catch options, given the 2022 catch level shown in Table 30 (catch options explained in Table 28).

Catch in 2023	Probability $B_{2024} < B_{2023}$	Probability $B_{2024} < B_{40\%}$	Probability $B_{2024} < B_{25\%}$	Probability $B_{2024} < B_{10\%}$	Probability 2023 relative fishing intensity > 100%	Probability 2024 default harvest policy catch < 2023 catch
a: 0	47%	3%	0%	0%	0%	0%
b: 180,000	63%	8%	1%	0%	0%	0%
c: 225,000	66%	9%	1%	0%	0%	2%
d: 270,000	68%	11%	2%	0%	1%	4%
e: 288,000	69%	12%	2%	0%	2%	6%
f: 325,000	71%	13%	3%	0%	4%	10%
g: 350,000	72%	14%	3%	0%	6%	13%
h: 315,000	70%	13%	3%	0%	4%	9%
i: 380,000	73%	16%	4%	0%	9%	18%
j: 342,000	71%	15%	3%	0%	6%	13%
k: 430,000	75%	18%	5%	0%	15%	26%
l: 473,880	77%	21%	6%	0%	21%	34%
m: 581,743	79%	31%	13%	1%	43%	56%
n: 586,146	79%	31%	13%	1%	43%	56%
o: 613,030	80%	29%	11%	1%	43%	57%

Table 32. Probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options, given the 2022 and 2023 catch levels shown in Tables 30 and 31 (catch options explained in Table 28).

Catch in 2024	Probability B₂₀₂₅ < B₂₀₂₄	Probability B₂₀₂₅ < B_{40%}	Probability B₂₀₂₅ < B_{25%}	Probability B₂₀₂₅ < B_{10%}	Probability 2024 relative fishing intensity > 100%	Probability 2025 default harvest policy catch < 2024 catch
a: 0	64%	3%	0%	0%	0%	0%
b: 180,000	76%	11%	2%	0%	0%	0%
c: 225,000	78%	13%	3%	0%	1%	2%
d: 270,000	80%	16%	4%	0%	3%	6%
e: 259,200	79%	18%	5%	0%	3%	6%
f: 325,000	81%	21%	6%	1%	7%	14%
g: 350,000	82%	23%	8%	1%	10%	18%
h: 283,500	80%	20%	6%	0%	5%	9%
i: 380,000	83%	26%	9%	1%	15%	24%
j: 307,800	81%	22%	7%	1%	7%	13%
k: 430,000	84%	30%	12%	2%	22%	35%
l: 473,880	85%	34%	15%	3%	29%	44%
m: 515,616	84%	44%	25%	7%	43%	57%
n: 526,126	85%	44%	25%	7%	44%	59%
o: 538,943	85%	43%	24%	6%	44%	59%

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

	Base model	Steepness		Sigma R	Sigma R	Natural Mortality (SD=0.2)	Natural Mortality (SD=0.3)	Remove Age 1 Index	Downweight Fishery Comps
		Mean Prior Low (0.5)	Steepness Fix 1.0						
Parameters									
Natural mortality (M)	0.233	0.236	0.231	0.229	0.234	0.289	0.309	0.231	0.234
Unfished recruitment (R_0 , millions)	2,535	2,660	2,463	1,870	3,112	5,520	7,666	2,364	2,741
Steepness (h)	0.810	0.541	–	0.813	0.811	0.797	0.795	0.809	0.807
Additional biomass index SD	0.292	0.294	0.290	0.289	0.294	0.306	0.310	0.285	0.292
Catchability: biomass index (q_b)	0.824	0.806	0.832	0.831	0.818	0.552	0.454	0.859	0.843
Additional age-1 index SD	0.373	0.372	0.378	0.377	0.389	0.353	0.350	–	0.331
Catchability: age-1 index (q_1)	0.422	0.411	0.429	0.404	0.427	0.249	0.194	–	0.399
Dirichlet-Multinomial fishery (log θ_{fish})	-0.564	-0.563	-0.564	-0.619	-0.548	-0.563	-0.562	-0.562	–
Dirichlet-Multinomial survey (log θ_{surv})	2.591	2.582	2.591	2.548	2.593	2.584	2.585	2.619	–
Derived Quantities									
2010 recruitment (millions)	17,156	17,759	16,821	16,607	17,438	33,419	45,050	16,100	17,107
2014 recruitment (millions)	9,312	9,571	9,143	9,040	9,425	16,859	22,155	8,492	9,352
2016 recruitment (millions)	6,418	6,637	6,308	6,205	6,501	11,473	15,032	5,776	6,604
Unfished female spawning biomass (B_0 , thousand t)	1,813	1,861	1,783	1,372	2,198	2,615	3,148	1,708	1,933
2009 relative spawning biomass	35.0%	35.0%	35.1%	45.6%	29.1%	38.6%	40.1%	35.8%	31.5%
2022 relative spawning biomass	64.7%	65.0%	64.8%	82.2%	54.4%	70.7%	71.6%	53.9%	61.5%
Reference Points based on $F_{SPR=40\%}$									
2021 rel. fishing intensity: $(1-SPR)/(1-SPR_{40\%})$	52.8%	51.4%	53.6%	53.7%	52.4%	31.9%	25.1%	59.0%	52.7%
Female spawning biomass at $F_{SPR=40\%}$ ($B_{SPR=40\%}$, thousand t)	645	424	713	489	779	915	1,086	604	681
SPR at $F_{SPR=40\%}$	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.5%	18.7%	18.4%	18.3%	18.6%	21.8%	22.9%	18.4%	18.6%
Yield at $B_{SPR=40\%}$ (thousand t)	309	204	340	232	376	543	699	288	328
Negative log likelihoods									
Total	2,091.89	2,093.48	2,101.57	2,094.63	2,094.28	2,091.89	2,091.89	2,087.56	198.47
Survey	-6.26	-6.28	-6.25	-5.48	-6.35	-6.26	-6.26	-8.88	-7.83
Survey age compositions	1,730.49	1,730.54	1,730.46	1,737.02	1,728.75	1,730.48	1,730.47	1,729.36	106.51
Fishery age compositions	289.28	289.26	289.29	289.96	289.11	289.27	289.26	289.02	37.57
Recruitment	61.59	62.74	61.27	55.50	66.16	61.61	61.63	61.07	53.81
Parameter priors	0.94	1.37	10.96	0.92	0.97	0.95	0.95	0.96	-0.03
Parameter deviations	15.84	15.85	15.84	16.70	15.65	15.83	15.83	16.02	8.44

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).

	Base model	Phi t.v. selectivity (0.21)	Phi t.v. selectivity (0.70)	Phi t.v. selectivity (2.10)	Max. age selectivity 5	Max. age selectivity 7	Max. age selectivity 8
Parameters							
Natural mortality (M)	0.233	0.220	0.228	0.236	0.233	0.234	0.232
Unfished recruitment (R_0 , millions)	2,535	2,417	2,427	2,640	2,630	2,537	2,506
Steepness (h)	0.810	0.809	0.809	0.808	0.809	0.809	0.807
Additional biomass index SD	0.292	0.319	0.291	0.296	0.294	0.295	0.280
Catchability: biomass index (q_b)	0.824	0.859	0.858	0.802	0.751	0.949	1.060
Additional age-1 index SD	0.373	0.441	0.421	0.345	0.377	0.377	0.378
Catchability: age-1 index (q_1)	0.422	0.421	0.437	0.411	0.423	0.431	0.433
Dirichlet-Multinomial fishery ($\log \theta_{\text{fish}}$)	-0.564	-0.858	-0.615	-0.547	-0.574	-0.556	-0.556
Dirichlet-Multinomial survey ($\log \theta_{\text{surv}}$)	2.591	2.699	2.605	2.554	2.610	2.632	2.593
Derived Quantities							
2010 recruitment (millions)	17,156	15,820	16,165	17,838	17,268	16,558	16,531
2014 recruitment (millions)	9,312	9,584	8,895	9,675	9,131	8,862	9,032
2016 recruitment (millions)	6,418	8,687	6,421	6,667	5,926	6,234	6,311
Unfished female spawning biomass (B_0 , thousand t)	1,813	1,920	1,810	1,840	1,872	1,804	1,795
2009 relative spawning biomass	35.0%	30.0%	33.6%	35.6%	34.8%	34.9%	34.3%
2022 relative spawning biomass	64.7%	76.2%	64.8%	66.3%	60.6%	61.9%	62.6%
Reference Points based on $F_{\text{SPR}=40\%}$							
2021 rel. fishing intensity: $(1-\text{SPR})/(1-\text{SPR}_{40\%})$	52.8%	51.3%	54.9%	51.0%	53.8%	54.9%	54.2%
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	645	683	642	651	662	636	633
SPR at $F_{\text{SPR}=40\%}$	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.5%	17.7%	18.3%	18.7%	18.5%	18.6%	18.5%
Yield at $B_{\text{SPR}=40\%}$ (thousand t)	309	309	302	315	318	306	303
Negative log likelihoods							
Total	2,091.89	2,213.16	2,120.39	2,080.33	2,094.52	2,087.25	2,085.07
Survey	-6.26	-3.93	-5.50	-6.38	-6.13	-6.17	-6.78
Survey age compositions	1,730.49	1,817.78	1,747.43	1,722.74	1,730.69	1,730.30	1,730.61
Fishery age compositions	289.28	288.46	289.21	289.56	291.46	284.80	283.08
Recruitment	61.59	60.65	62.06	60.93	61.50	61.48	61.46
Parameter priors	0.94	1.17	0.98	0.93	0.94	0.99	0.98
Parameter deviations	15.84	49.04	26.21	12.54	16.05	15.84	15.72

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.

	2022 Base model	-1 year	-2 years	-3 years	-4 years	-5 years
Parameters						
Natural mortality (M)	0.233	0.231	0.231	0.230	0.229	0.229
Unfished recruitment (R_0 , millions)	2,535	2,454	2,427	2,402	2,326	2,458
Steepness (h)	0.810	0.806	0.806	0.809	0.809	0.808
Additional biomass index SD	0.292	0.315	0.311	0.326	0.325	0.313
Catchability: biomass index (q_b)	0.824	–	–	–	–	–
Additional age-1 index SD	0.373	0.312	0.290	0.306	0.313	0.321
Catchability: age-1 index (q_1)	0.422	–	–	–	–	–
Dirichlet-Multinomial fishery ($\log \theta_{\text{fish}}$)	-0.564	-0.575	-0.552	-0.538	-0.549	-0.579
Dirichlet-Multinomial survey ($\log \theta_{\text{surv}}$)	2.591	2.398	2.408	2.159	2.159	1.717
Derived Quantities						
2010 recruitment (millions)	17,156	17,166	16,021	15,046	14,498	16,725
2014 recruitment (millions)	9,312	9,990	10,239	10,188	10,373	18,494
2016 recruitment (millions)	6,418	5,431	4,879	4,573	4,579	944
Unfished female spawning biomass (B_0 , thousand t)	1,813	1,784	1,759	1,760	1,716	1,814
2009 relative spawning biomass	35.0%	35.7%	35.0%	34.1%	34.3%	34.7%
2022 relative spawning biomass	64.7%	66.4%	67.4%	79.9%	70.6%	94.2%
Reference Points based on $F_{\text{SPR}=40\%}$						
2021 rel. fishing intensity: $(1-\text{SPR})/(1-\text{SPR}_{40\%})$	52.8%	56.7%	57.9%	53.4%	57.5%	42.7%
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	645	632	623	623	608	644
SPR at $F_{\text{SPR}=40\%}$	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Exploitation fraction corresponding to SPR	18.5%	18.4%	18.4%	18.3%	18.3%	18.3%
Yield at $B_{\text{SPR}=40\%}$ (thousand t)	309	300	294	294	285	301

8 FIGURES

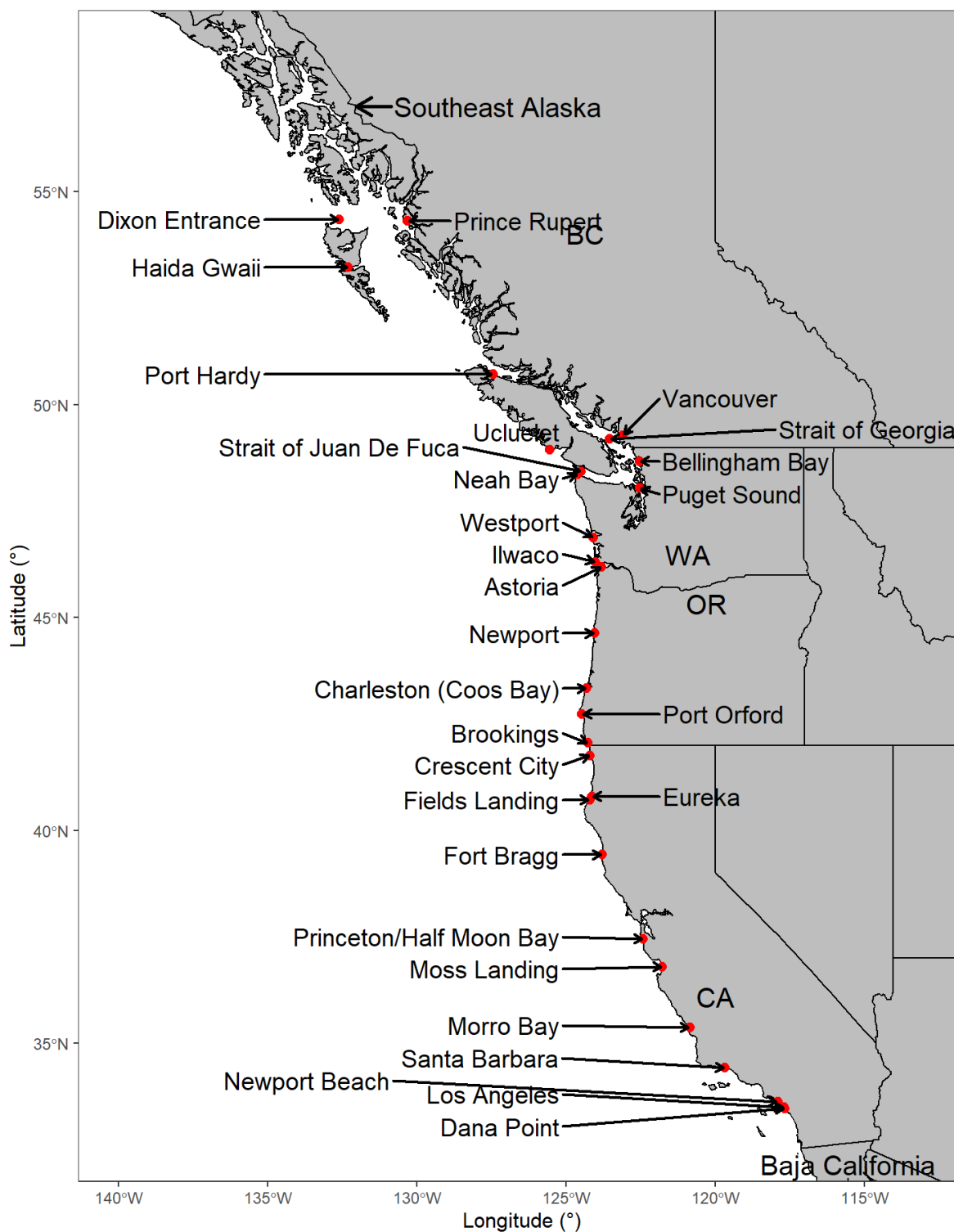


Figure 1. Overview map of the area in the Northeast Pacific Ocean occupied by Pacific Hake. Common areas referred to in this document are shown.

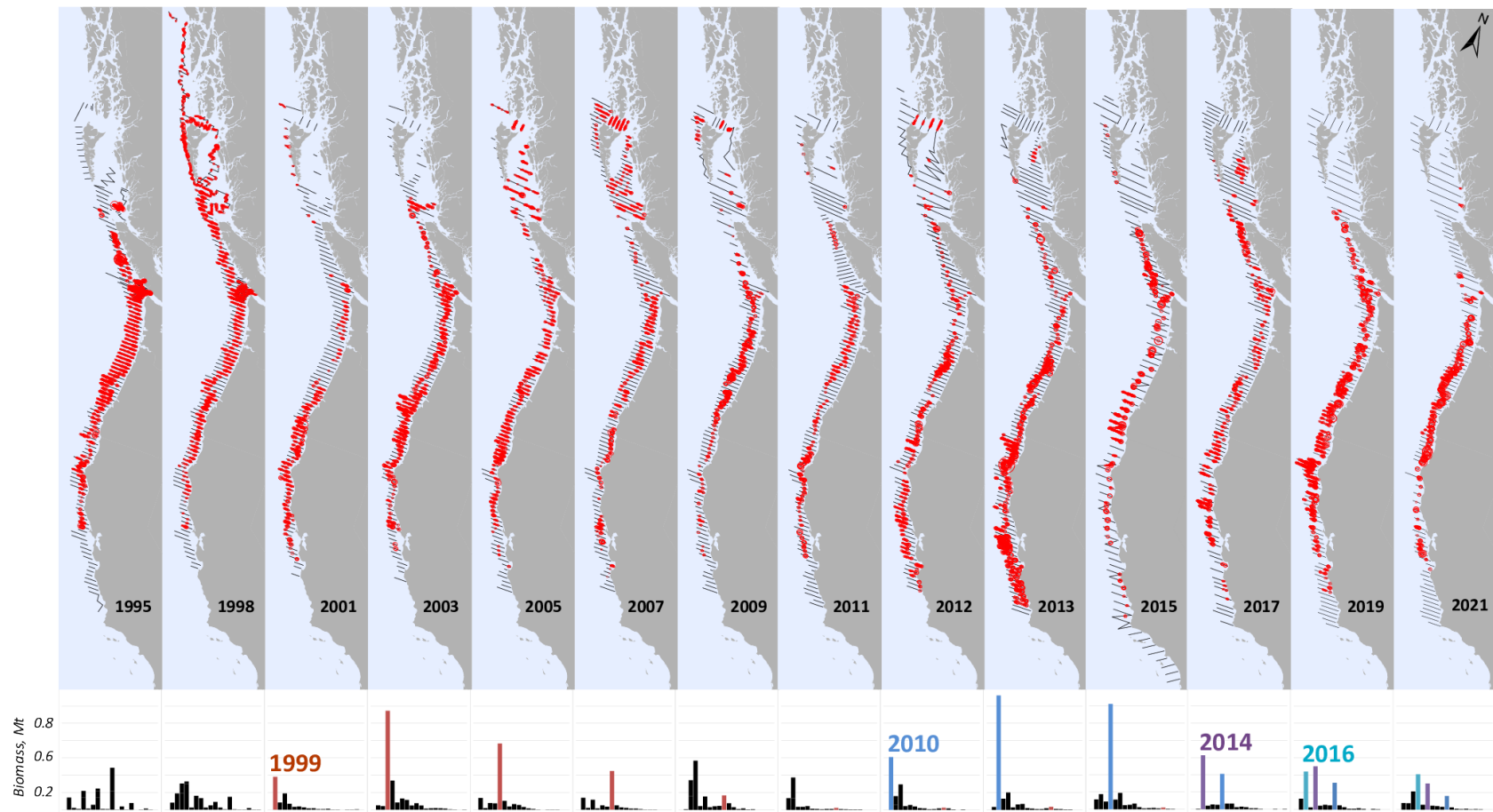


Figure 2. Spatial distribution of acoustic backscatter attributable to age-2 and older Pacific Hake from the Joint U.S. and Canada acoustic surveys 1995–2021. Area of the circle is roughly proportional to observed backscatter. Barplots show survey-estimated biomass for ages 2 to 20, with major cohorts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

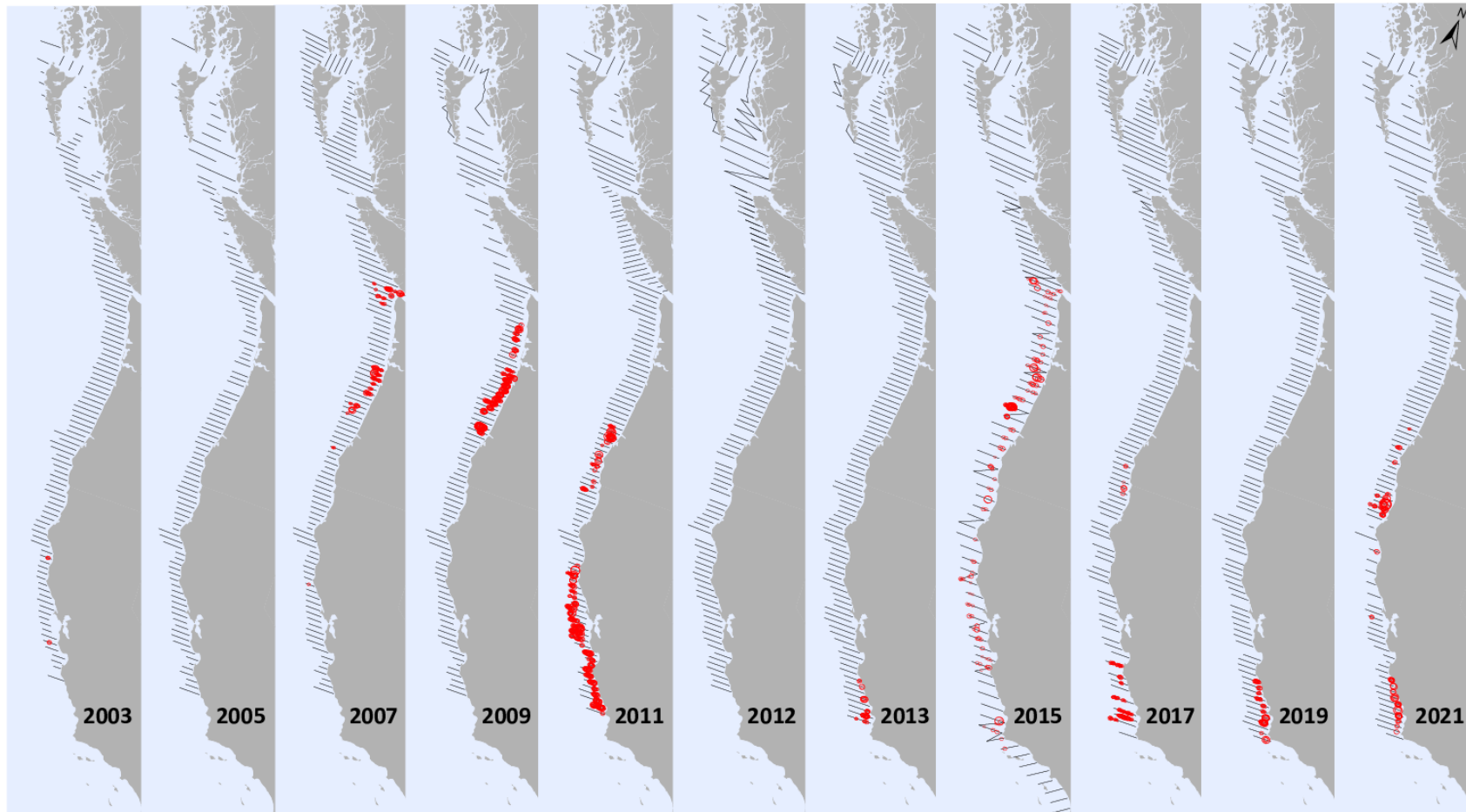


Figure 3. Spatial distribution of acoustic backscatter attributable to age-1 Pacific Hake from the Joint U.S. and Canada acoustic surveys 2003–2021. Age-1 Pacific Hake are not fully sampled during the acoustic survey and were not explicitly considered during establishment of the survey sampling design.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

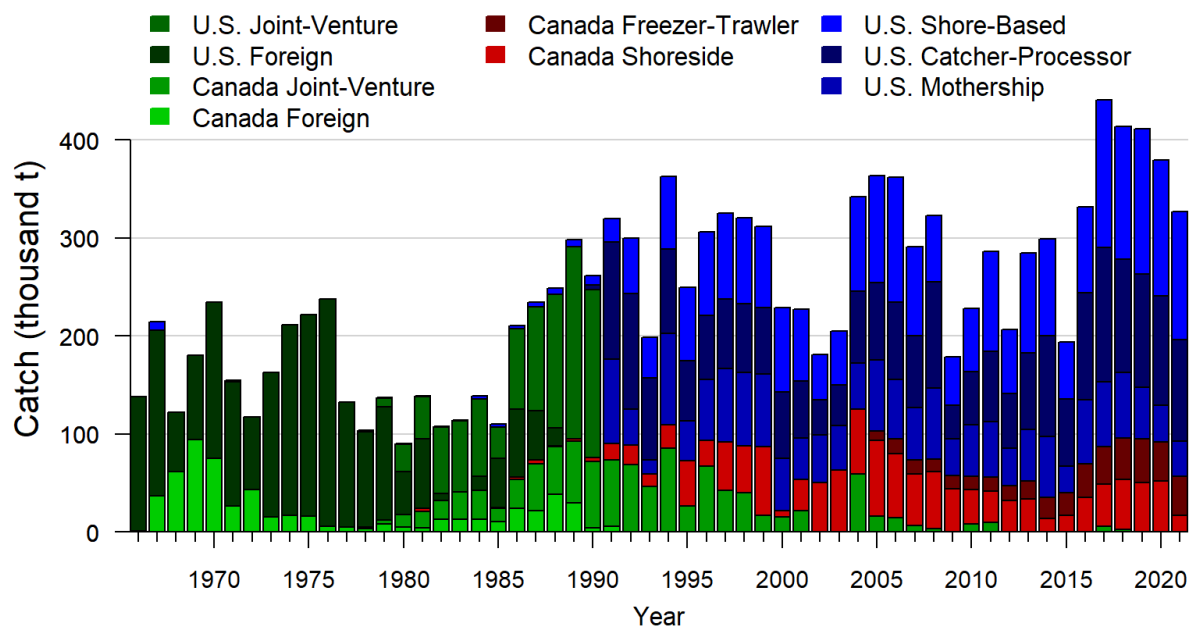


Figure 4. Total Pacific Hake catch used in the assessment by sector, 1966–2021. U.S. tribal catches are included in the appropriate sector.

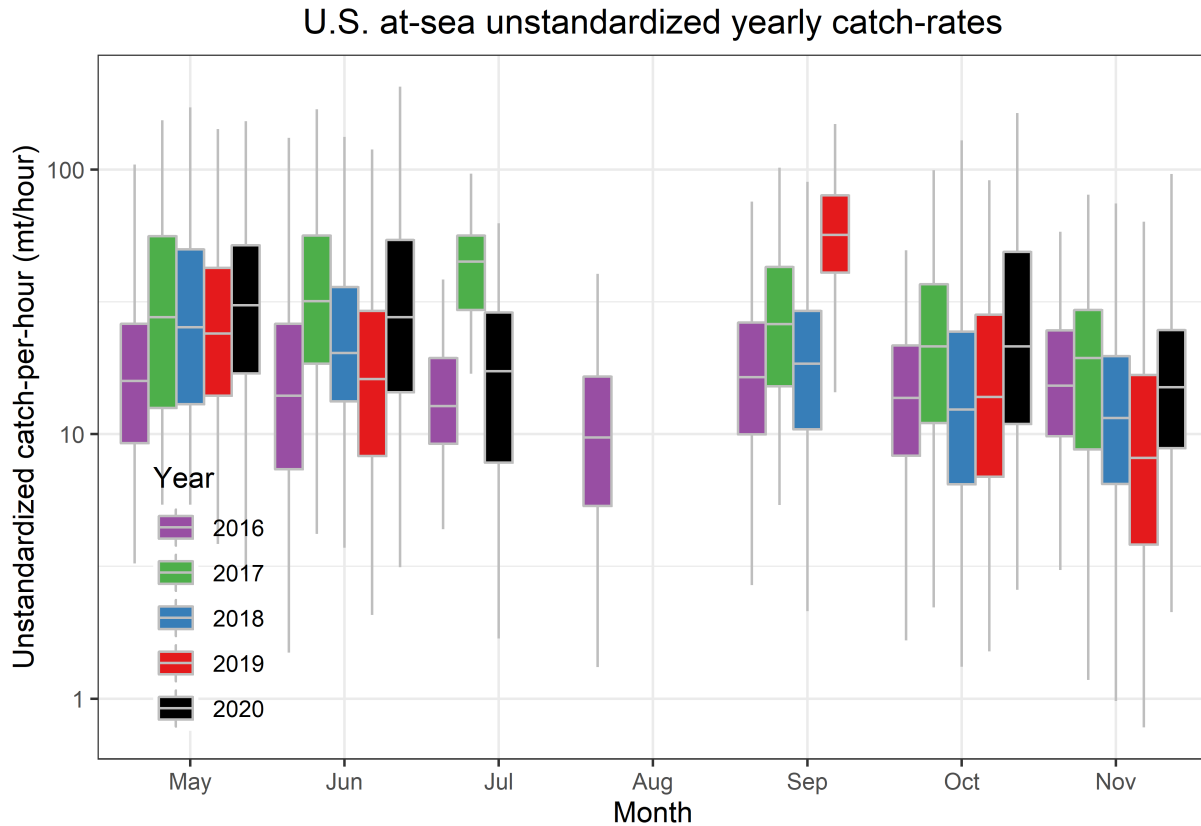


Figure 5. Unstandardized (raw) catch-rates (t/hr) of Pacific Hake catches by tow in the U.S. at-sea fleet from 2017–2021.

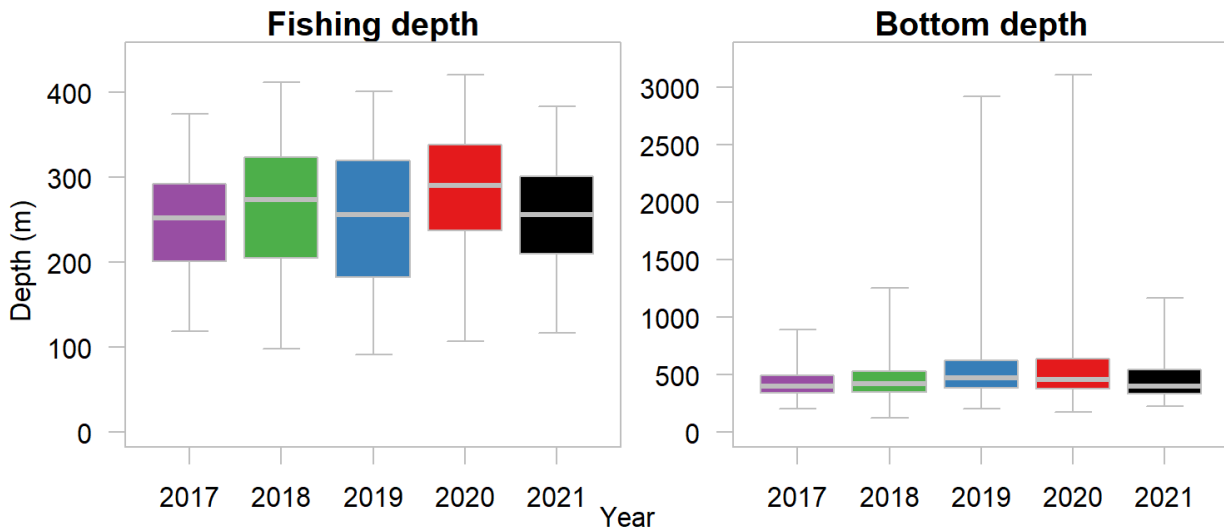


Figure 6. Distribution of fishing depths (left) and bottom depths (right), in meters, of hauls targeting Pacific Hake in the U.S. Catcher-Processor and Mothership sectors from 2017–2021. Horizontal lines in each box represent the median depth and boxes encompass the middle 50% of the data. Whiskers encompass the 95% quantiles.

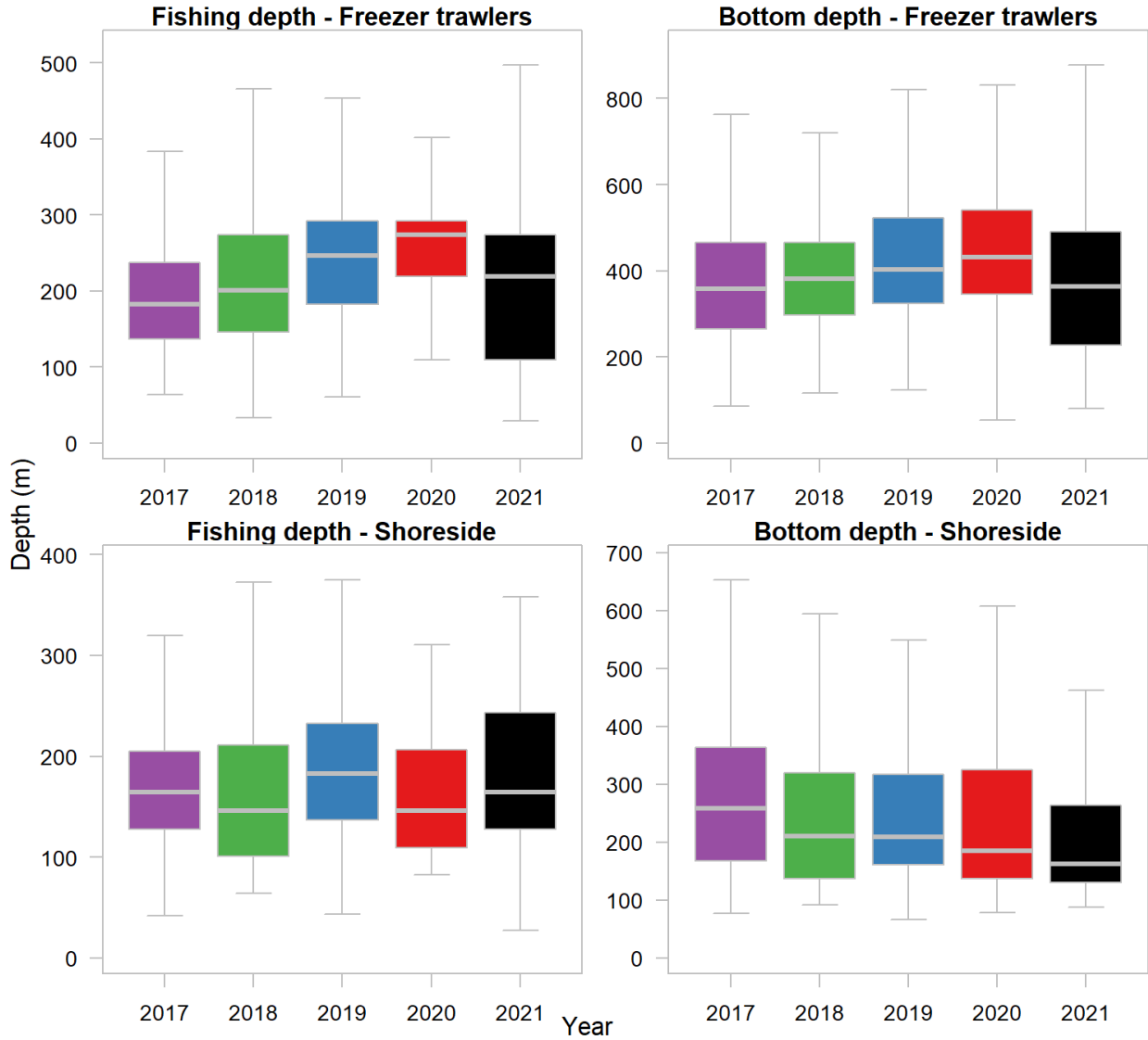


Figure 7. Distribution of fishing depths (left) and bottom depths (right), in meters, of hauls targeting Pacific Hake in the Canadian fleets from 2017–2021. Horizontal lines in each box represent the median depth and boxes encompass the middle 50% of the data. Whiskers encompass the 95% quantiles.

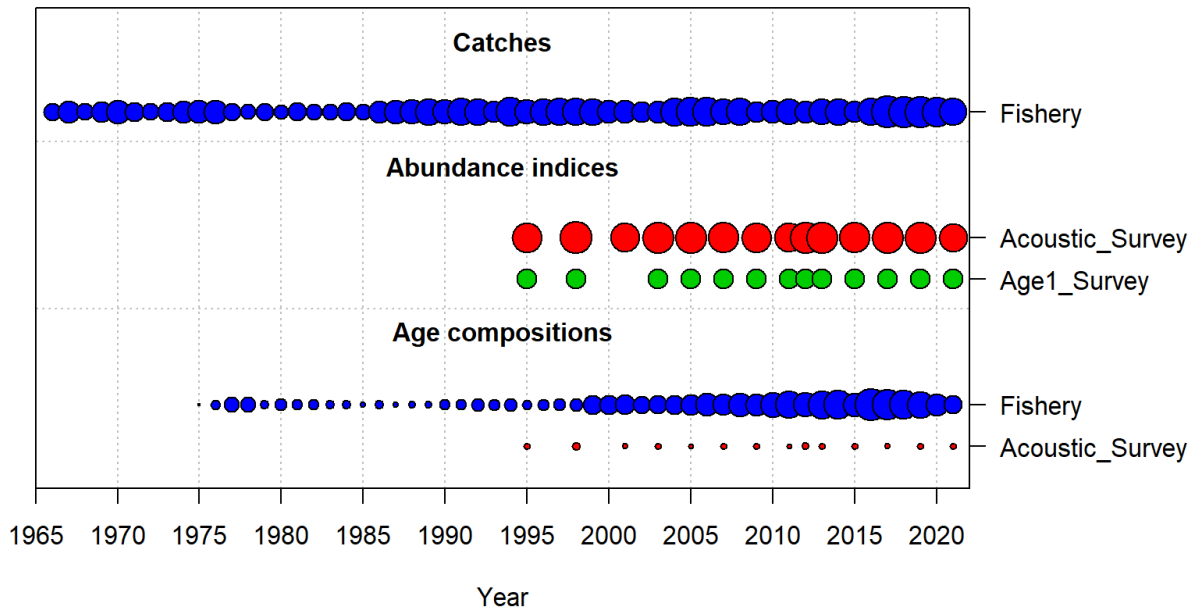


Figure 8. Overview of data used in this assessment. Circle areas are proportional to: total catch for the fishery data, precision for the indices, and total sample size for the age compositions (and cannot be compared across data types).

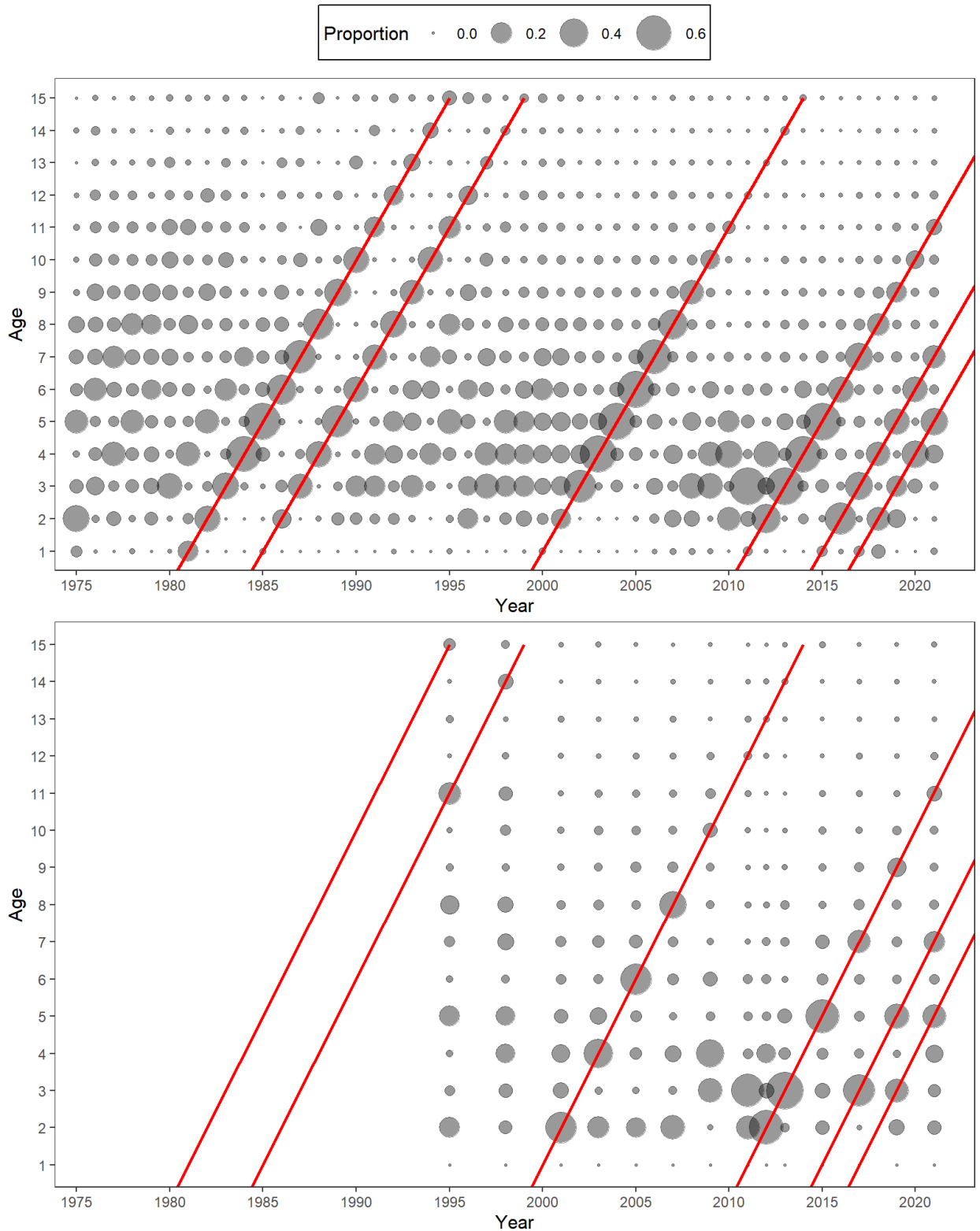


Figure 9. Age compositions for the aggregate fishery (top, all sectors combined) and acoustic survey (bottom) for the years 1975–2021. Proportions in each year sum to 1.0 and area of the bubbles are proportional to the proportion and consistent in both panels (see key at top). The largest bubble in the fishery data is 0.71 for age 3 in 2011 and in the survey data is 0.75 for age 3 in 2013. Red lines track cohorts from years of large recruitment events.

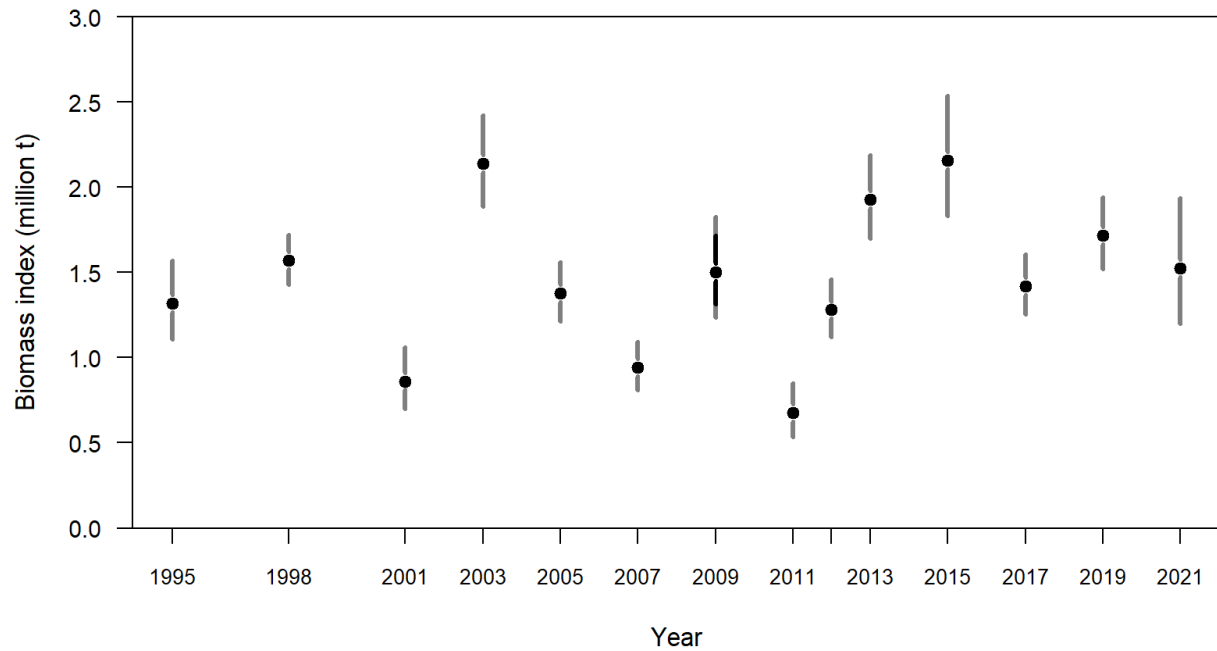


Figure 10. Acoustic survey biomass index of age-2+ fish (millions of tons, Table 12). Approximate 95% confidence intervals are based on sampling variability (intervals without squid/hake apportionment uncertainty in 2009 are displayed in black).

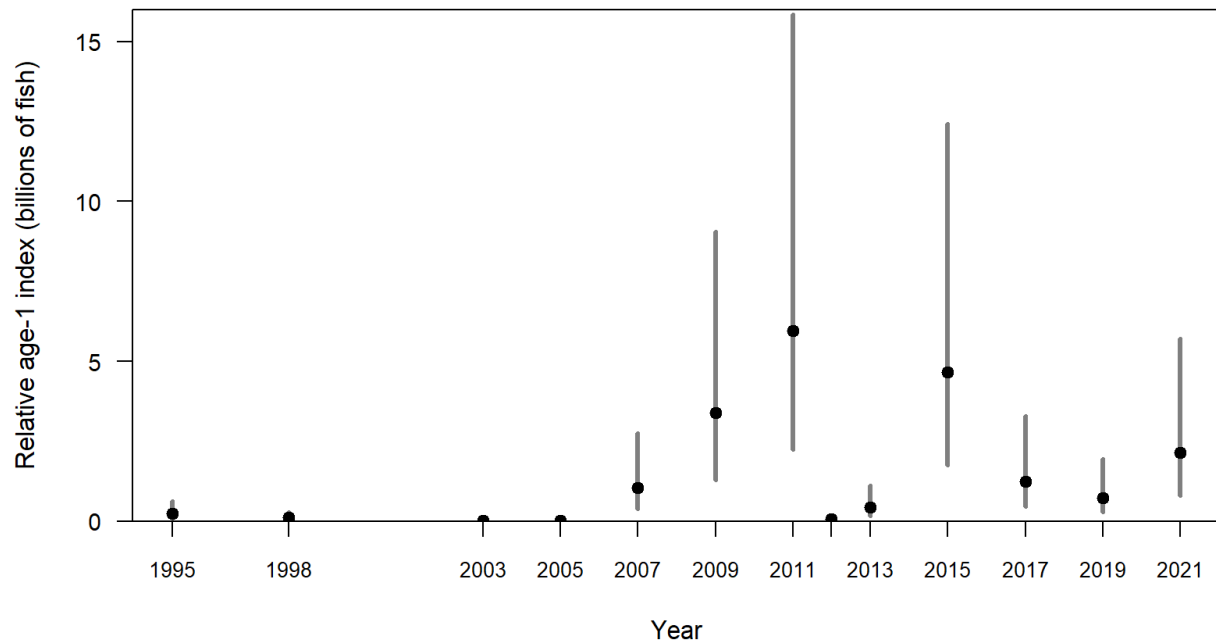


Figure 11. Relative age-1 index (numbers of fish, Table 12) and approximate 95% confidence intervals based on sampling variability. The index is relative because the survey does not attempt to catch all available age-1 fish and the analysis does not include kriging unlike estimates of age-2+ biomass.

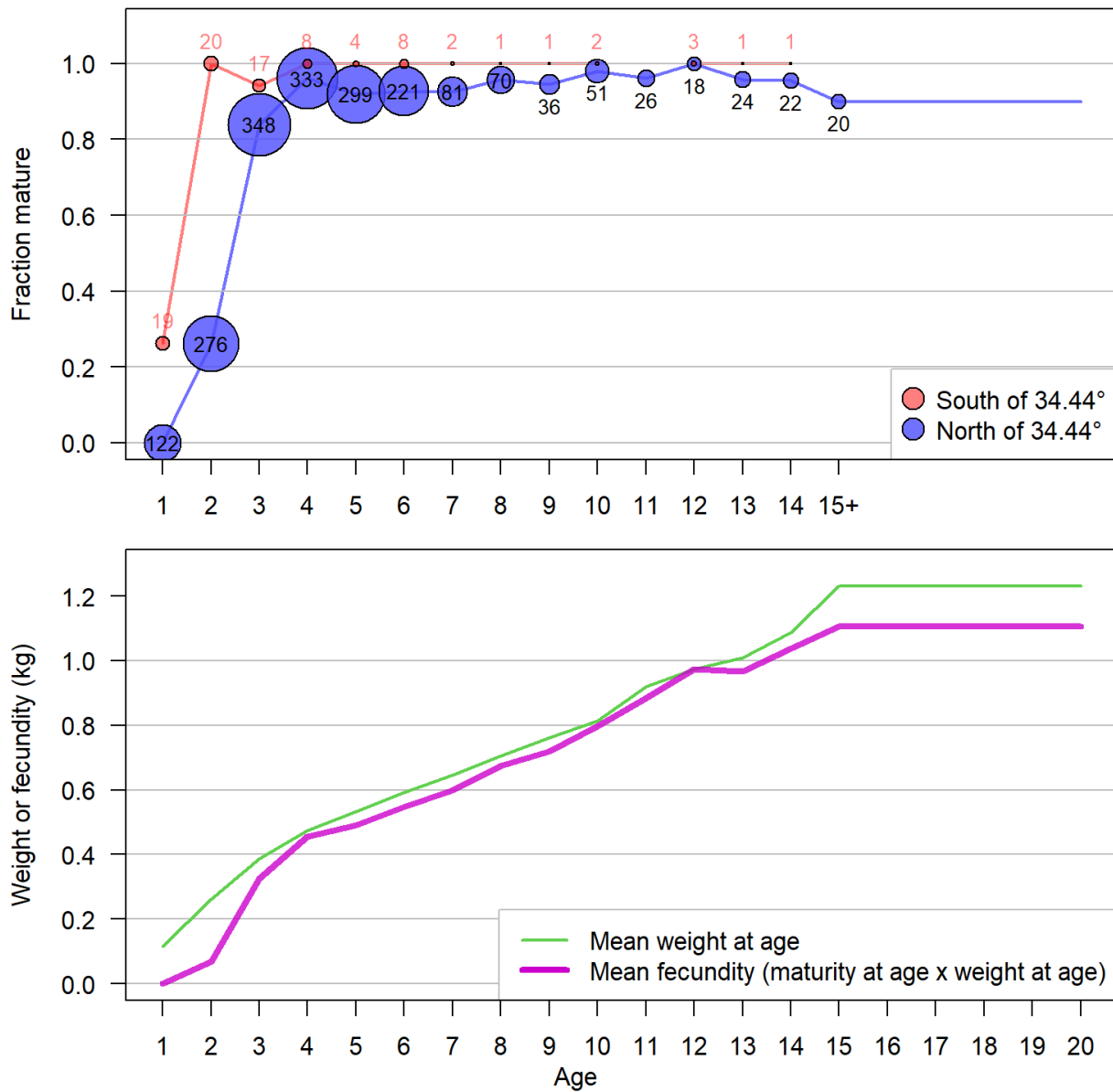


Figure 12. Fraction of fish that are mature at each age north and south of 34.44°N (upper panel) and the fecundity relationship (lower panel). The fecundity relationship (purple line) is the product of the weight-at-age and the maturity-at-age for the samples collected from North of 34.44°N (blue line in upper plot) averaged across 1975 to 2021.

2024	0.02	0.12	0.32	0.46	0.53	0.55	0.59	0.61	0.62	0.68	0.68	0.72	0.71	0.79	0.84	0.96
2023	0.02	0.12	0.32	0.46	0.53	0.55	0.59	0.61	0.62	0.68	0.68	0.72	0.71	0.79	0.84	0.96
2022	0.02	0.12	0.32	0.46	0.53	0.55	0.59	0.61	0.62	0.68	0.68	0.72	0.71	0.79	0.84	0.96
2021	0.02	0.13	0.29	0.52	0.61	0.61	0.68	0.65	0.66	0.78	0.77	0.72	0.71	0.76	0.71	0.91
2020	0.02	0.10	0.34	0.48	0.51	0.56	0.57	0.59	0.60	0.64	0.65	0.70	0.63	0.84	0.87	0.94
2019	0.02	0.07	0.29	0.45	0.55	0.54	0.61	0.63	0.67	0.68	0.73	0.77	0.71	0.83	0.89	0.94
2018	0.01	0.19	0.35	0.46	0.50	0.54	0.55	0.62	0.59	0.64	0.64	0.68	0.69	0.72	0.90	1.07
2017	0.01	0.14	0.31	0.40	0.49	0.53	0.56	0.55	0.58	0.66	0.61	0.72	0.80	0.78	0.81	0.93
2016	0.01	0.17	0.24	0.38	0.42	0.44	0.47	0.51	0.52	0.51	0.66	0.72	0.59	0.96	1.45	1.45
2015	0.01	0.08	0.25	0.39	0.44	0.47	0.55	0.59	0.67	0.69	0.72	0.83	0.95	1.02	1.09	1.25
2014	0.01	0.10	0.41	0.47	0.48	0.54	0.57	0.62	0.66	0.72	0.69	1.16	1.01	0.95	0.97	1.06
2013	0.01	0.13	0.29	0.36	0.47	0.51	0.63	0.72	0.73	0.83	1.00	1.08	1.23	1.12	1.07	1.05
2012	0.01	0.13	0.21	0.35	0.41	0.49	0.66	0.69	0.78	0.91	0.96	0.96	0.96	0.99	0.99	0.94
2011	0.01	0.08	0.25	0.32	0.39	0.51	0.59	0.67	0.85	0.93	0.98	1.07	1.06	1.03	1.06	0.92
2010	0.01	0.11	0.23	0.29	0.43	0.53	0.66	0.83	1.08	1.03	0.96	0.88	0.85	1.13	0.72	0.90
2009	0.01	0.07	0.25	0.34	0.46	0.63	0.66	0.67	0.75	0.81	0.76	0.81	1.03	0.84	0.98	1.03
2008	0.01	0.13	0.24	0.41	0.56	0.64	0.69	0.68	0.71	0.72	0.75	0.81	0.85	0.78	0.88	0.83
2007	0.01	0.04	0.23	0.42	0.54	0.56	0.61	0.63	0.65	0.71	0.77	0.76	0.81	0.87	0.80	0.87
2006	0.01	0.13	0.38	0.46	0.53	0.57	0.59	0.60	0.66	0.70	0.73	0.72	0.78	0.66	0.64	0.95
2005	0.01	0.12	0.26	0.43	0.51	0.54	0.57	0.63	0.66	0.70	0.80	0.81	0.81	0.76	1.14	0.97
2004	0.01	0.11	0.20	0.44	0.48	0.53	0.65	0.71	0.66	0.71	0.80	0.86	0.77	0.97	0.86	0.90
2003	0.01	0.10	0.26	0.44	0.52	0.59	0.76	0.69	0.75	0.82	0.77	0.89	0.93	0.79	0.84	1.00
2002	0.01	0.08	0.36	0.46	0.58	0.74	0.72	0.78	0.91	0.86	0.88	0.90	0.84	0.84	1.08	1.05
2001	0.02	0.05	0.29	0.48	0.65	0.66	0.75	0.86	0.86	0.88	0.96	0.98	1.01	1.05	0.99	0.98
2000	0.02	0.19	0.39	0.47	0.58	0.66	0.72	0.73	0.75	0.84	0.82	0.88	0.86	0.94	0.87	0.93
1999	0.02	0.14	0.25	0.35	0.43	0.53	0.56	0.57	0.61	0.70	0.66	0.80	0.76	0.88	0.73	0.82

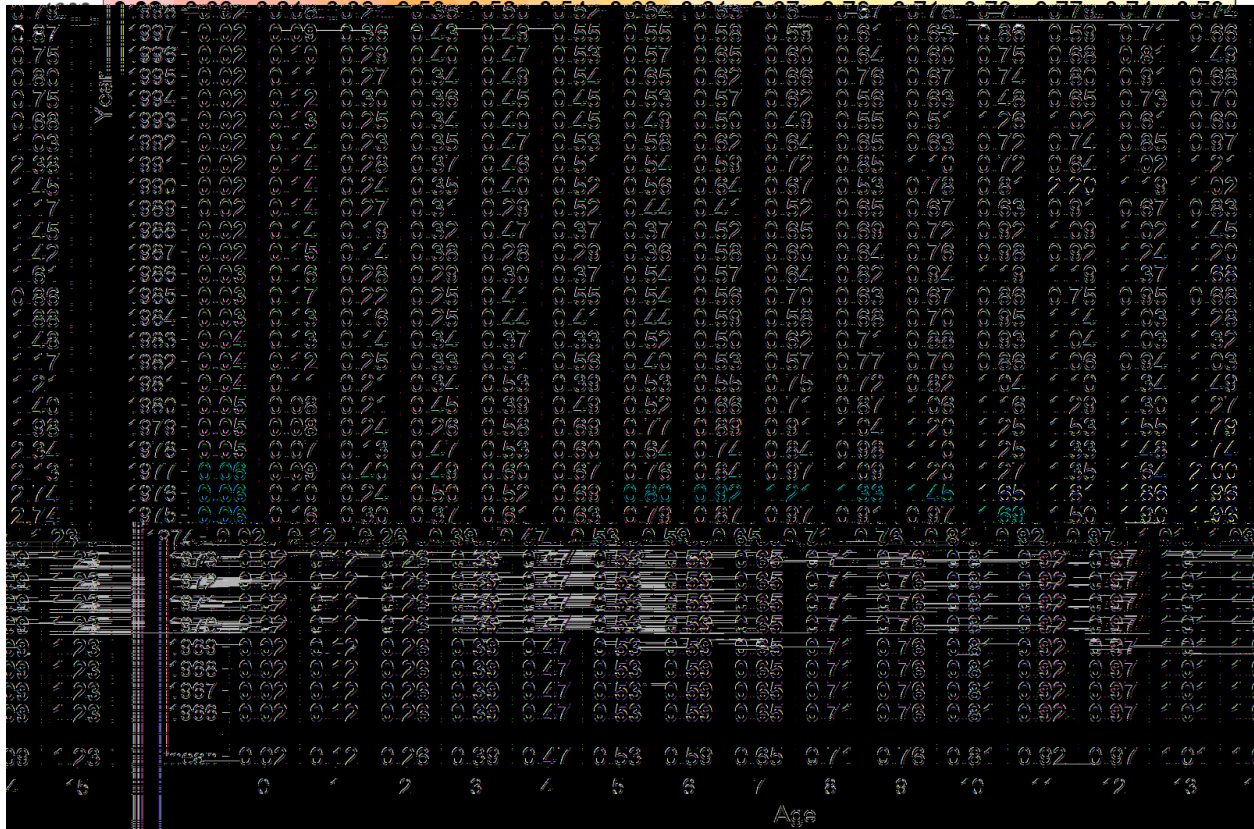


Figure 13. Empirical weight-at-age (kg) values used for the base model. Colors correspond to the values, with red being the lightest fish (across all years and ages) and blue being the heaviest fish. For each age, the most transparent cells indicate the lightest fish of that age. Data are only available from 1975–2021. Values based on assumptions for the pre-1975 and forecast years are shown outside the blue lines. Bold values between 1975–2021 represent unavailable data such that weights were interpolated or extrapolated from adjacent ages or years. The bottom row (mean) is the sample-weighted mean weight-at-age.

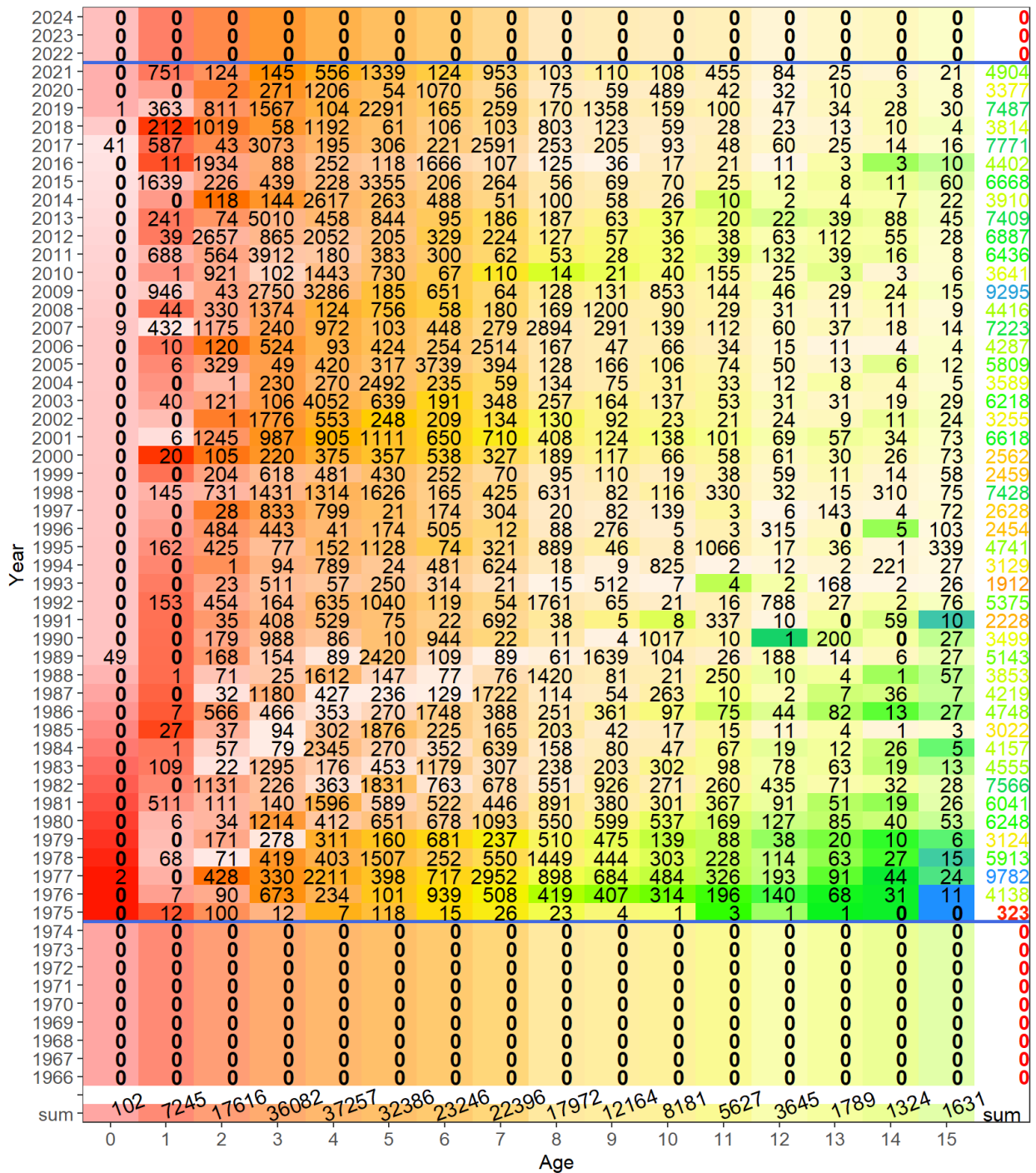


Figure 14. Sample sizes of empirical weight-at-age measurements used to calculate mean weight-at-age fit in the base model. Colors and transparency are identical to Figure 13 and based on mean values. Sample sizes of zero highlight years for which data are not available, i.e., pre 1975 and post 2021. The total sample sizes for each age used in the mean over all years are shown at the bottom and year-specific sample sizes are shown to the right using the same color scale with red indicating small sample sizes and blue indicating the large sample sizes.

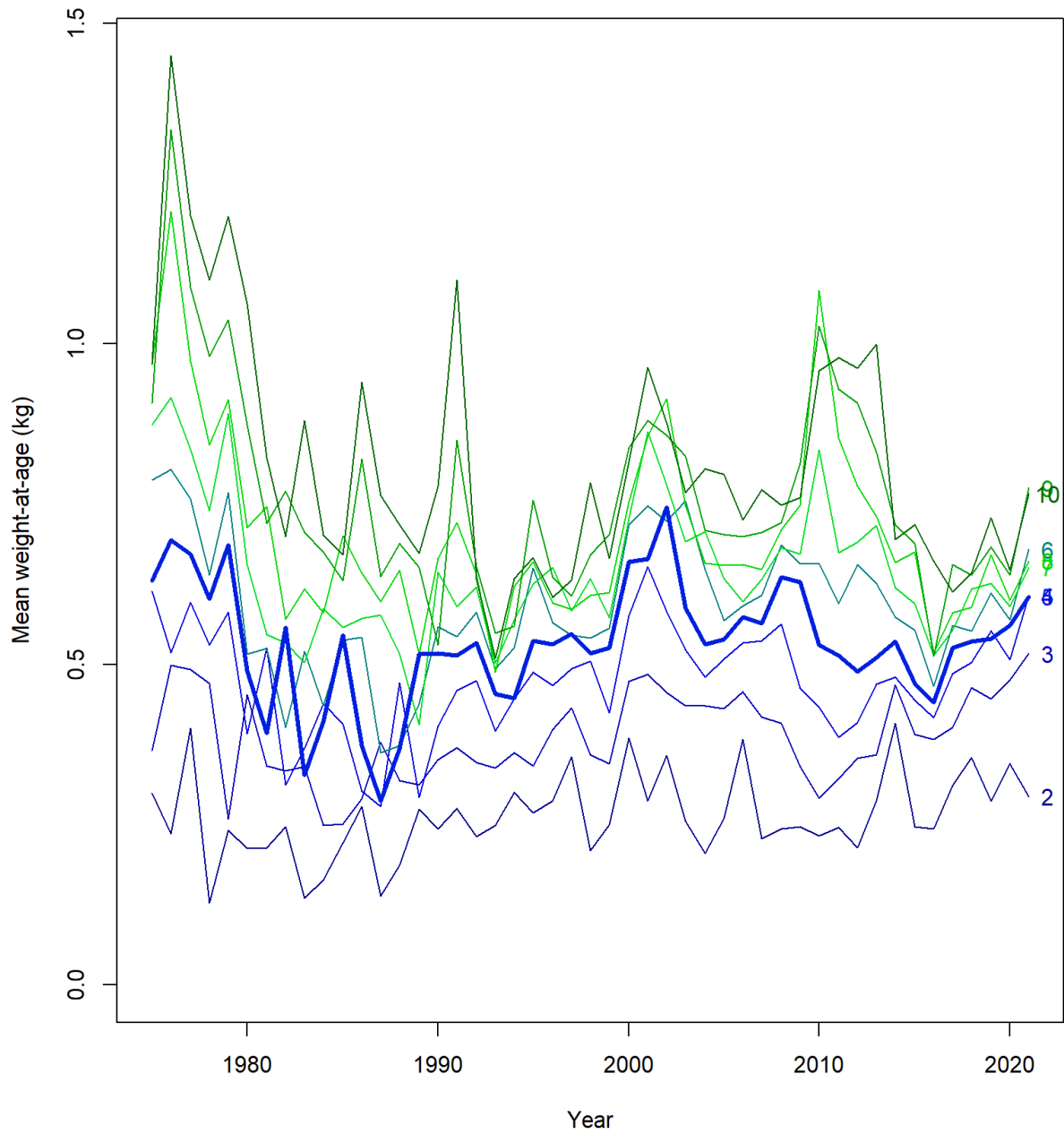


Figure 15. Empirical mean weight-at-age (kg) values for ages 2–10 used for the base model, as in Figure 13 but shown as time series. Blue lines are for the youngest ages and green lines are for the oldest ages shown, with age-5 highlighted in bold as a visual aid.

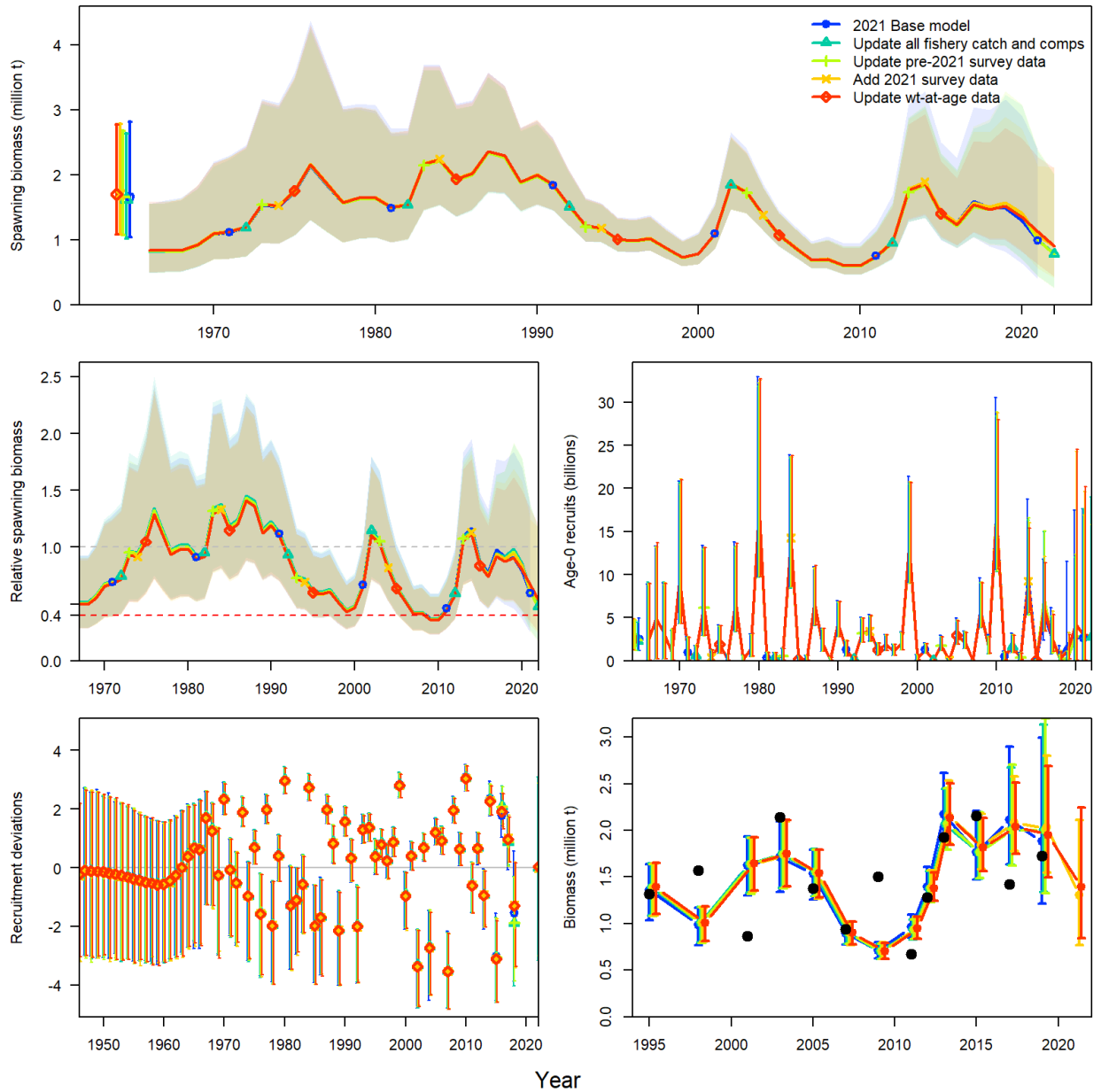


Figure 16. Bridging models showing the sequential addition of updating pre-2021 fishery data, pre-2021 survey data, adding 2021 survey data, and adding 2021 weight-at-age information. Panels are spawning biomass (upper panel), relative spawning biomass (spawning biomass in each year relative to the unfished equilibrium spawning biomass, middle left), absolute recruitment (middle right), recruitment deviations (lower left), and survey biomass index (lower right).

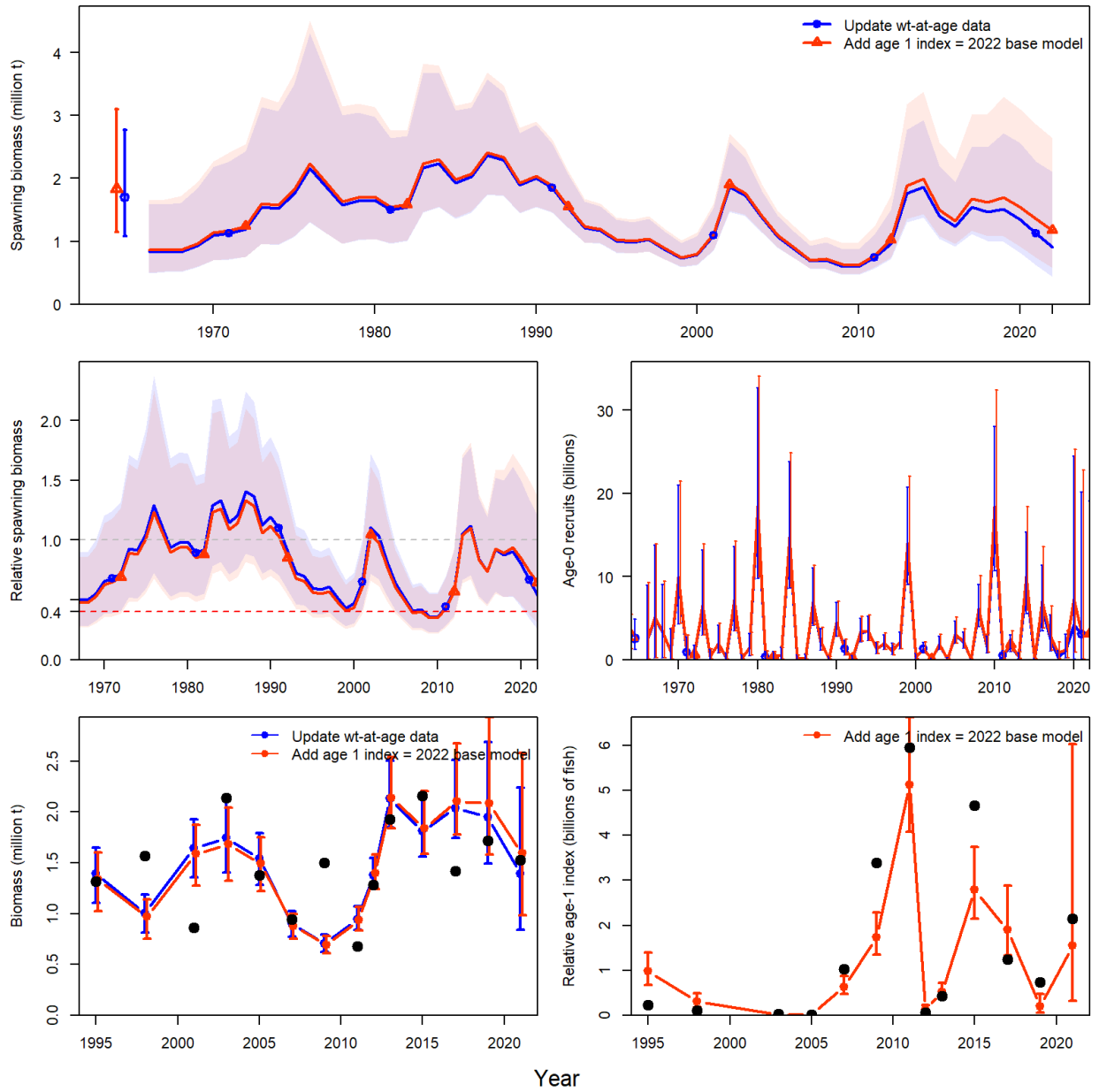


Figure 17. Bridging models showing the addition of the age-1 index to the final bridging model (update weight-at-age data) from Figure 16. Panels are spawning biomass (upper panel), relative spawning biomass (spawning biomass in each year relative to the unfished equilibrium spawning biomass, middle left), absolute recruitment (middle right), survey biomass index (lower left), and age-1 index (lower right).

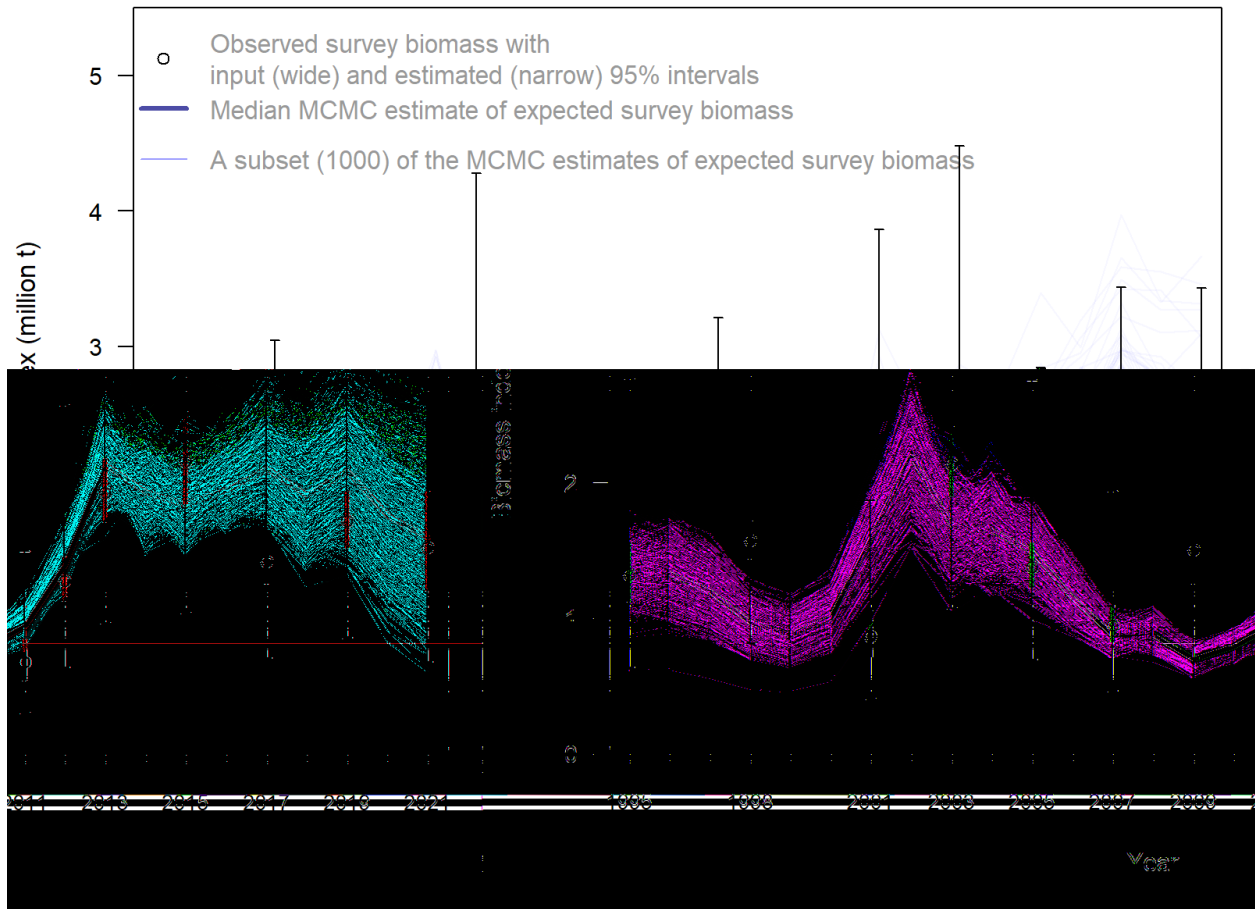


Figure 18. Fits (colored lines) to the acoustic survey (points) with input 95% intervals around the observations. The thin blue lines are the results of a random subset of individual MCMC samples. Thicker uncertainty intervals around observed survey points indicate 95% log-normal uncertainty intervals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

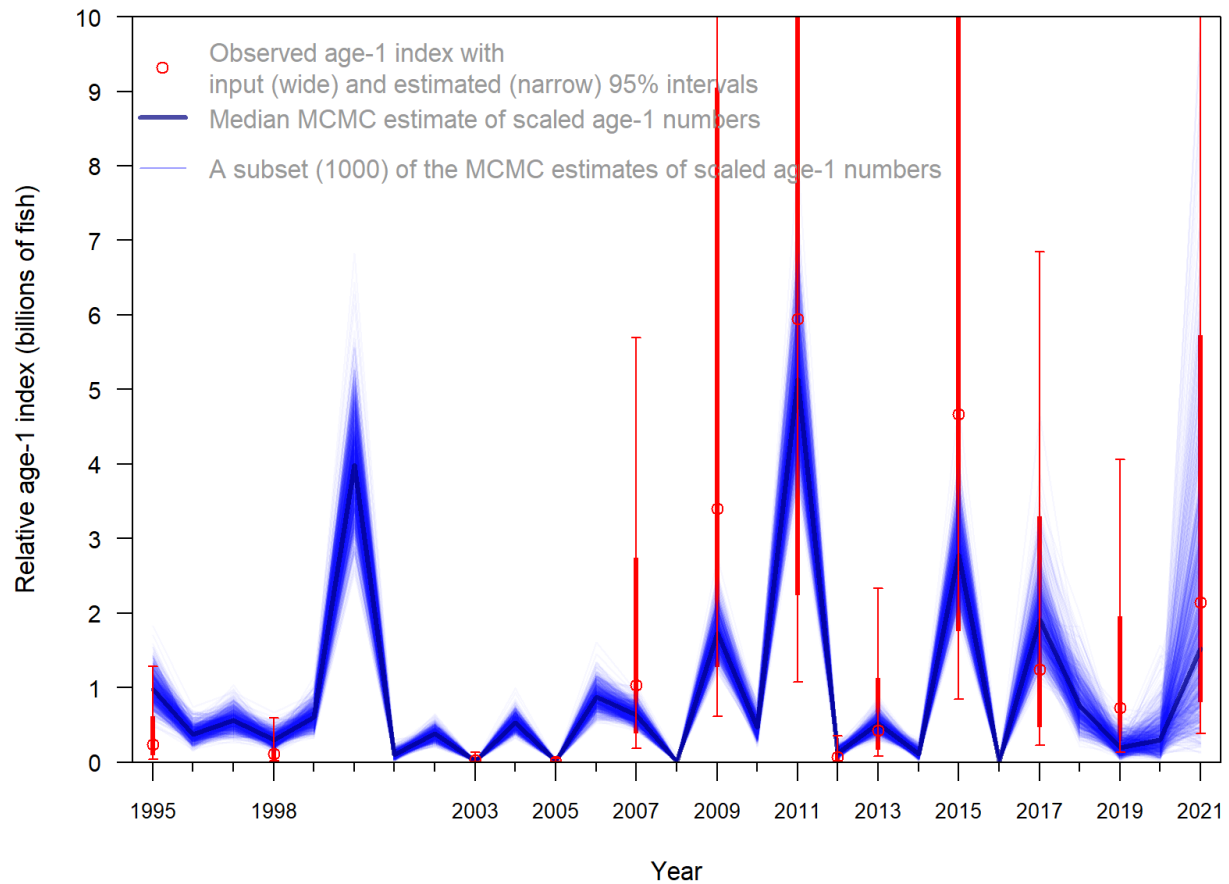


Figure 19. Fits (colored lines) to the relative age-1 index estimated from the acoustic survey (points) with input 95% intervals around the observations. The thin blue lines are the results of a random subset of individual MCMC samples. Thicker uncertainty intervals around observed survey points indicate 95% log-normal uncertainty intervals based on sampling variability and are used as input to the assessment model. Thinner uncertainty intervals indicate estimated 95% uncertainty intervals that account for the model estimate of additional uncertainty.

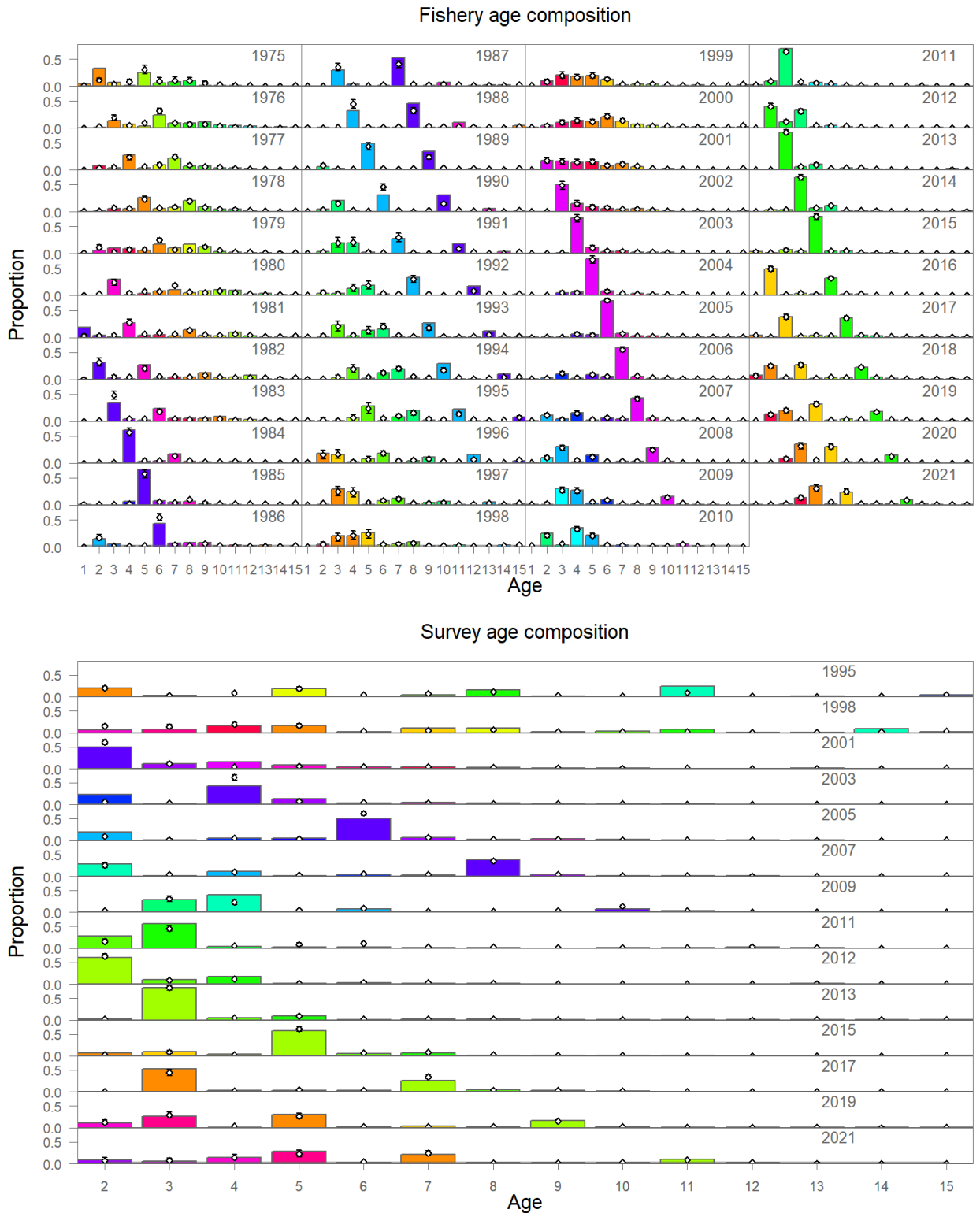


Figure 20. Base model fits to the observed fishery (top) and acoustic survey (bottom) age-composition data. Colored bars show observed proportions with colors following each cohort across years. Points with intervals indicate median expected proportions and 95% credibility intervals from the MCMC calculations.

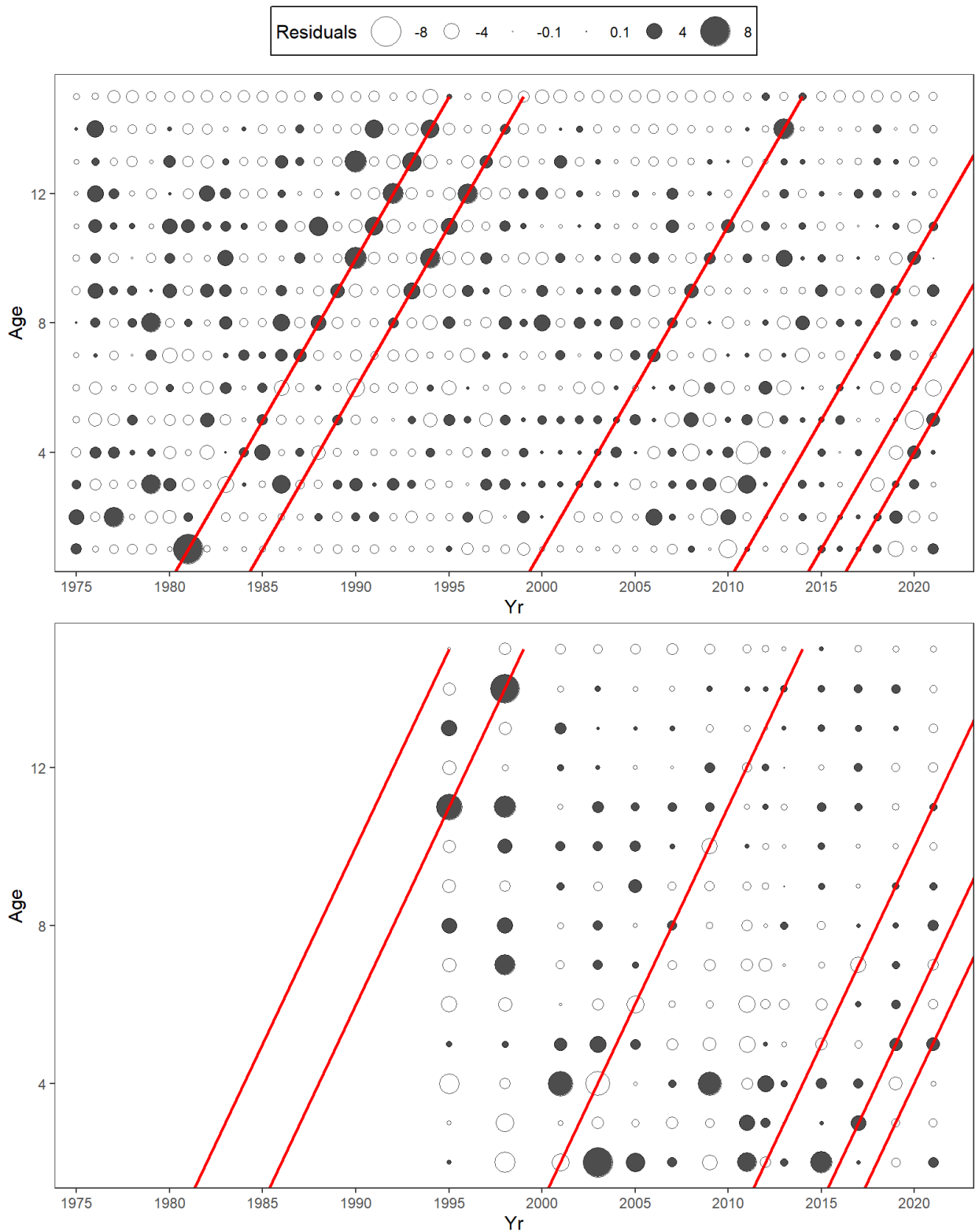


Figure 21. Pearson residuals for base model fits to the age-composition data for the medians of the MCMC posteriors. Closed bubbles are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected). Red lines track cohorts from years of large recruitment events.

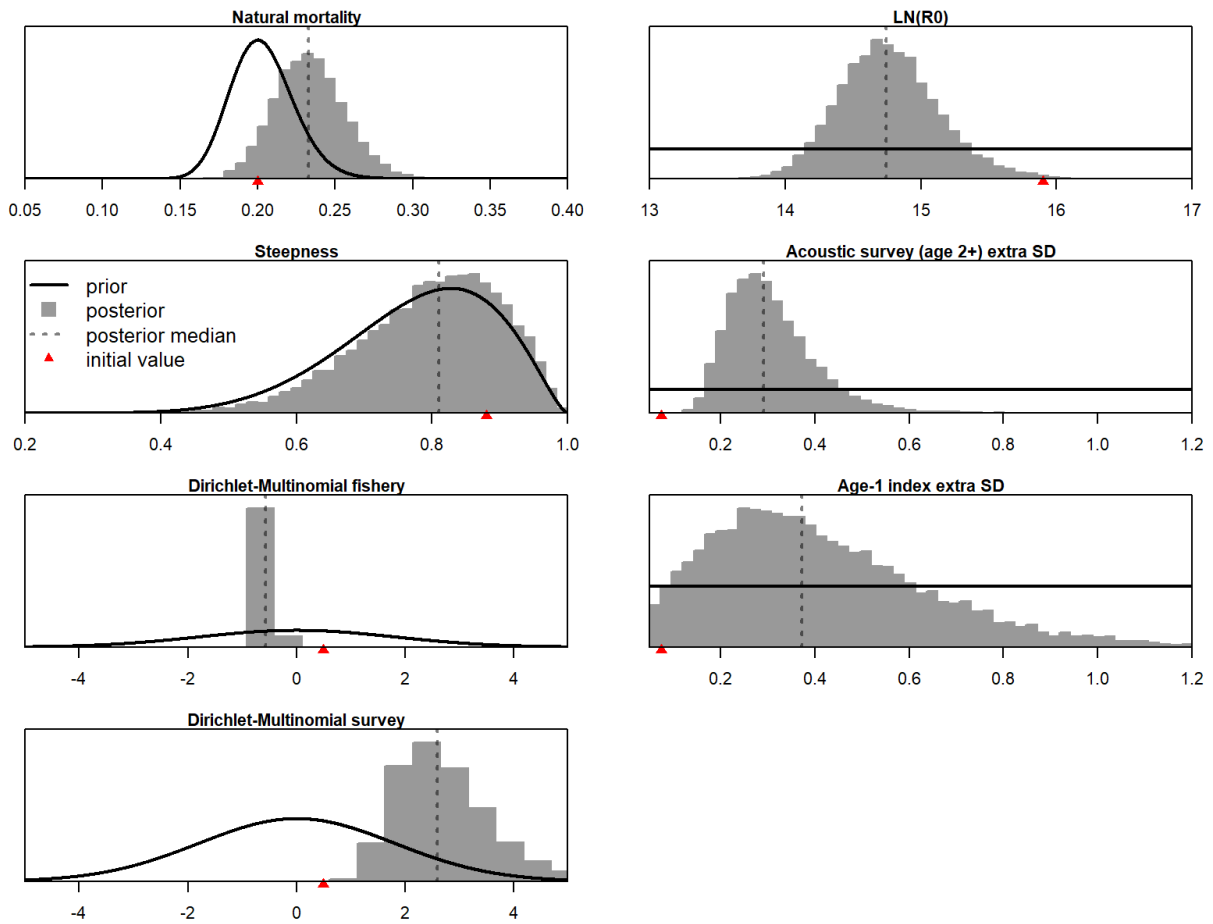


Figure 22. Prior (black lines) and posterior (gray histograms) distributions for key parameters in the base model. The parameters are: natural mortality (M), equilibrium log recruitment ($\log R_0$), steepness (h), the additional process-error standard deviation for the acoustic survey and the age-1 biomass index, and the Dirichlet-multinomial parameters for the fishery (θ_{fish}) and the survey (θ_{surv}).

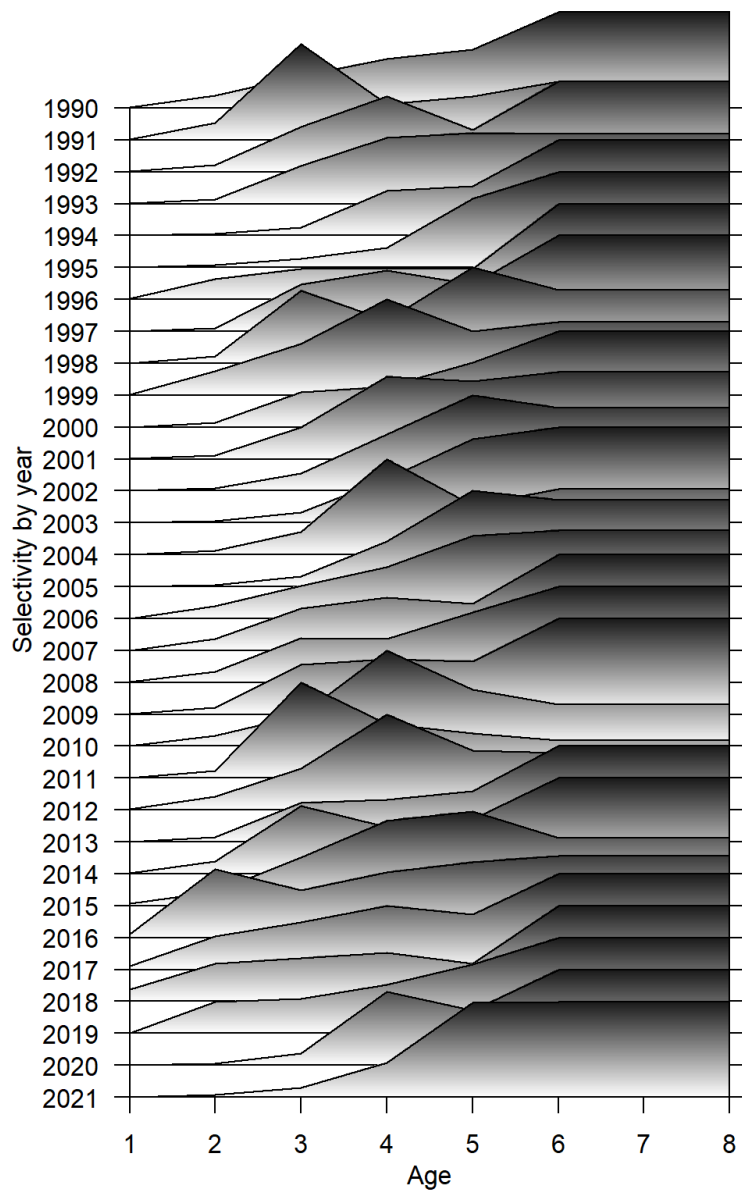


Figure 23. Mountains plot of median fishery selectivity in each year for the base model. Range of selectivity is 0 to 1 in each year.

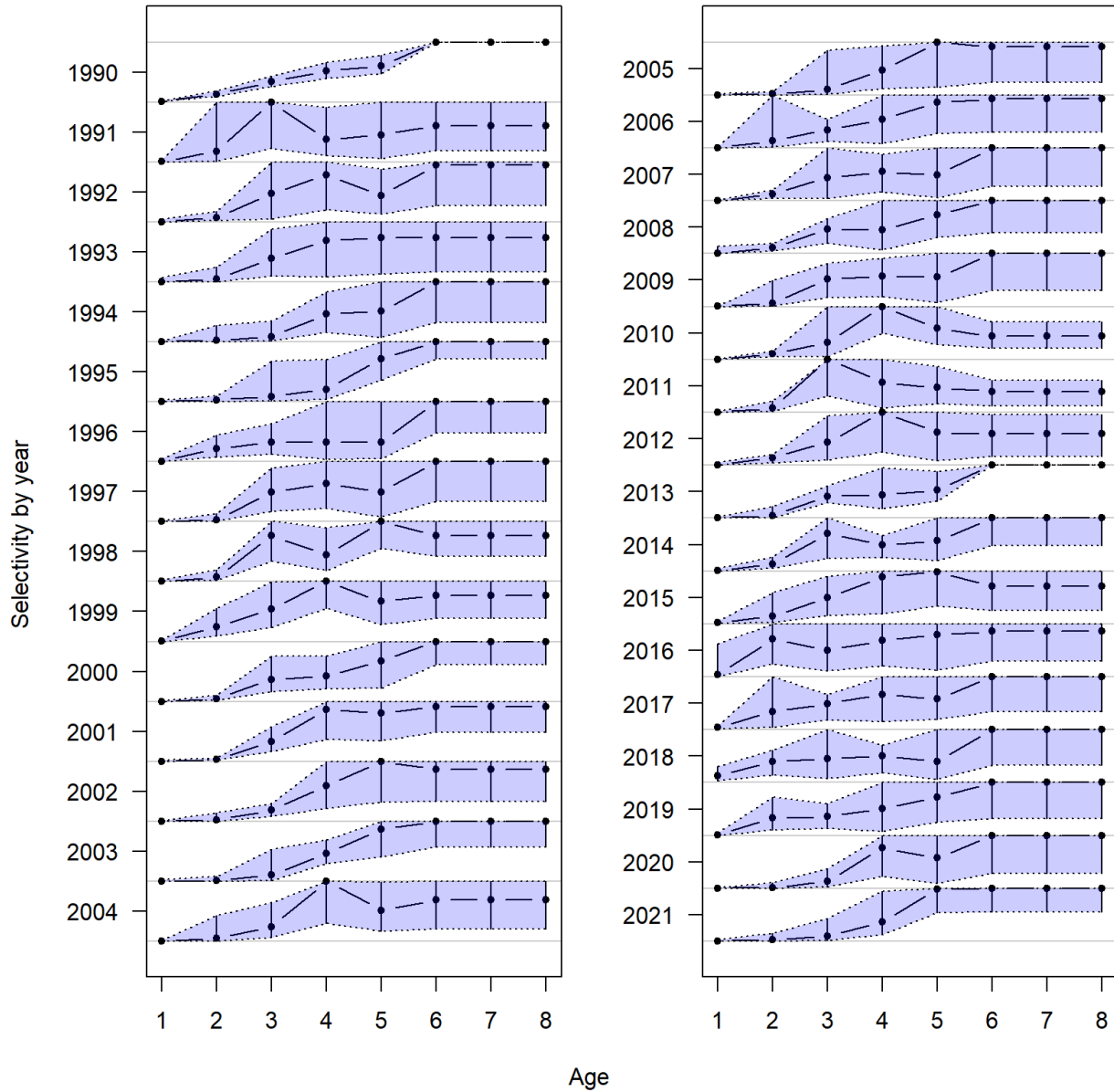


Figure 24. Fishery selectivity sampled from posterior probability distribution by year for the base model. Black dots and bars indicate the median and 95% credibility interval, respectively. The shaded polygon also shows the 95% credibility interval. Range is from 0 to 1 within each year. Selectivity for 1990 is shared for all years from 1966 to 1990.

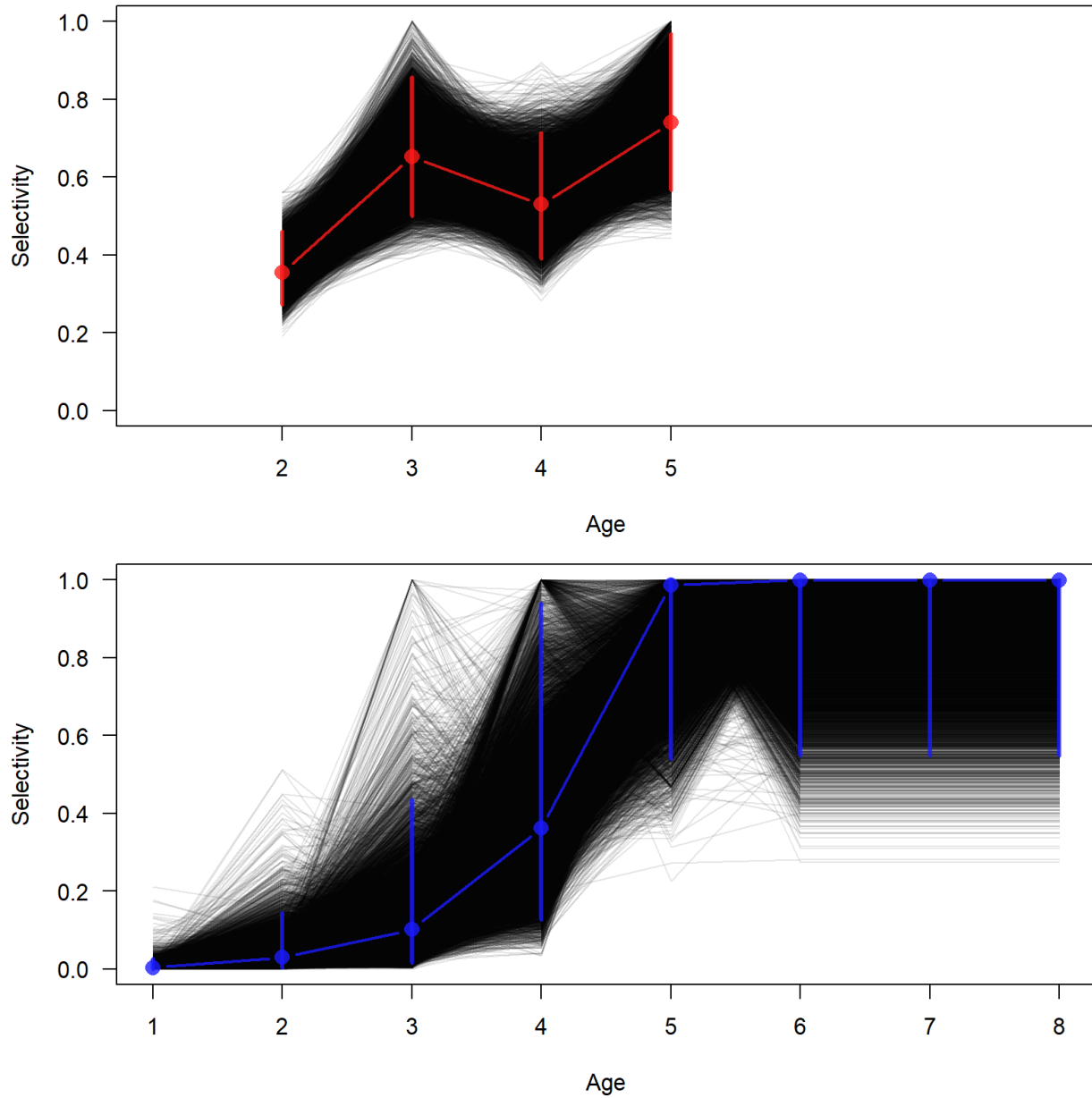


Figure 25. Estimated selectivities for the biomass index (top – for all years) and fishery (bottom – for 2021 only) from the posterior distribution for the base model. Selectivity for the biomass index is 0 at age-1 and constant from age-6 onwards.

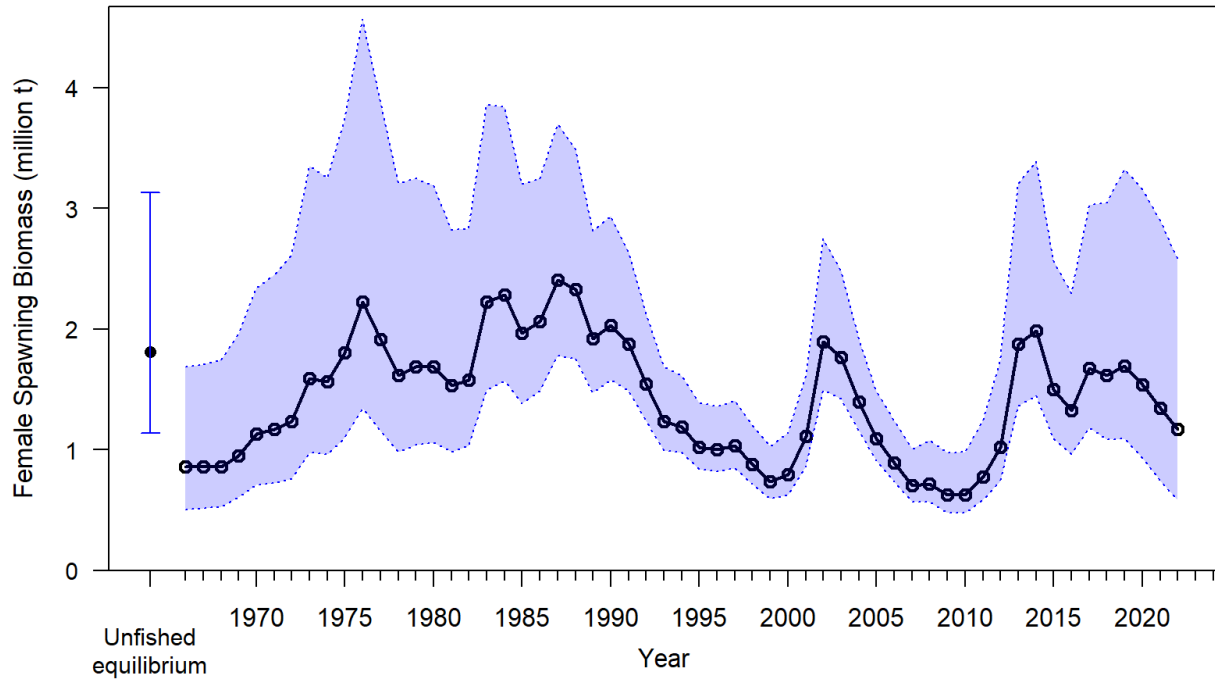


Figure 26. Median of the posterior distribution for female spawning biomass at the start of each year (B_t) for the base model up to 2022 (solid line) with 95% posterior credibility intervals (shaded area).

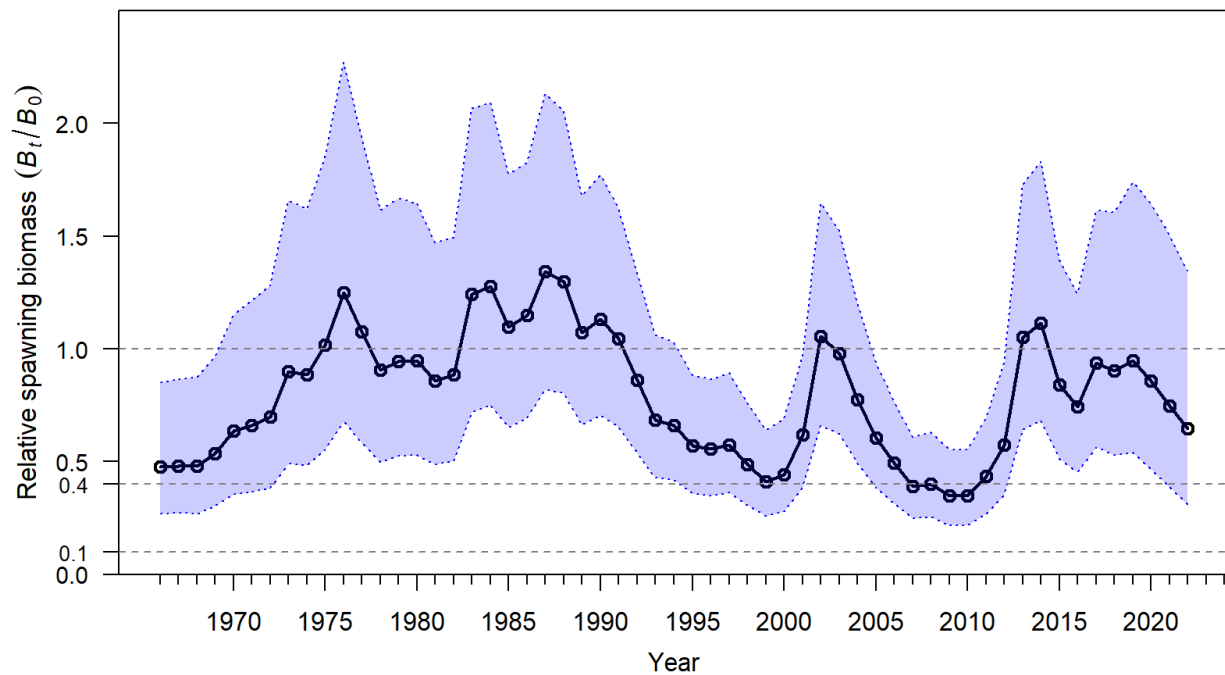


Figure 27. Median (solid line) of the posterior distribution for relative spawning biomass (B_t/B_0) for the base model through 2022 with 95% posterior credibility intervals (shaded area). Dashed horizontal lines show 10%, 40% and 100% levels.

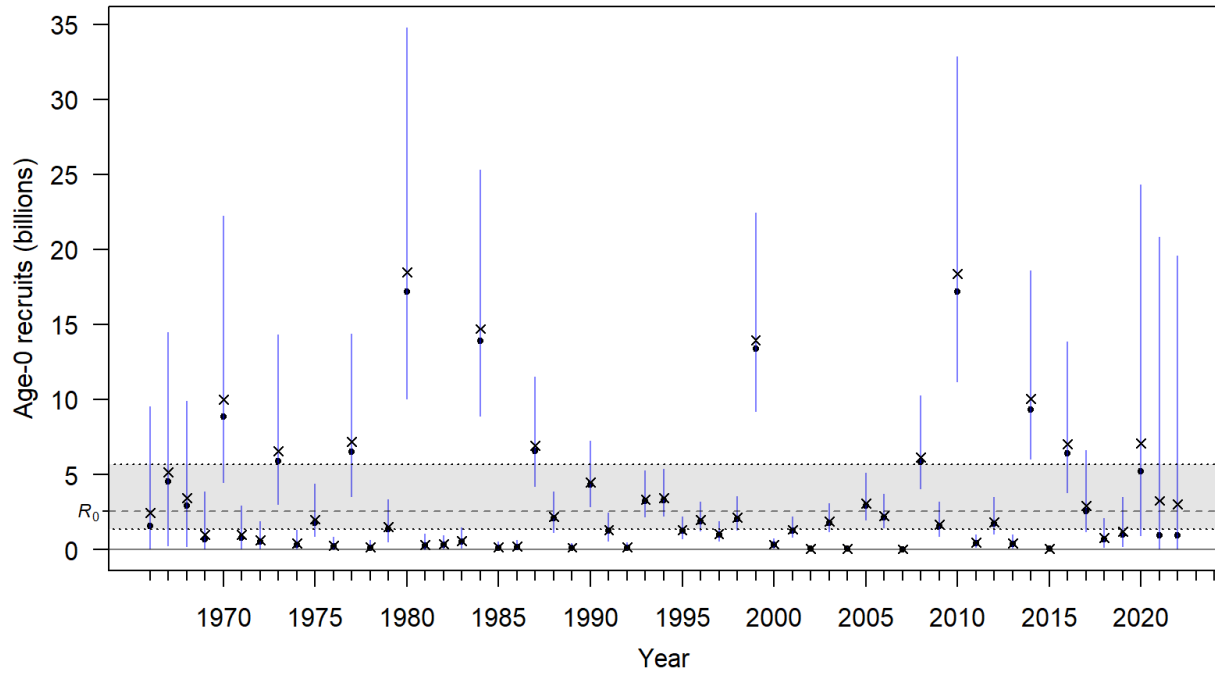


Figure 28. Medians (solid circles) and means (\times) of the posterior distribution for recruitment (billions of age-0 fish) with 95% posterior credibility intervals (blue lines). The median of the posterior distribution for mean unfish equilibrium recruitment (R_0) is shown as the horizontal dashed line with a 95% posterior credibility interval shaded between the dotted lines.

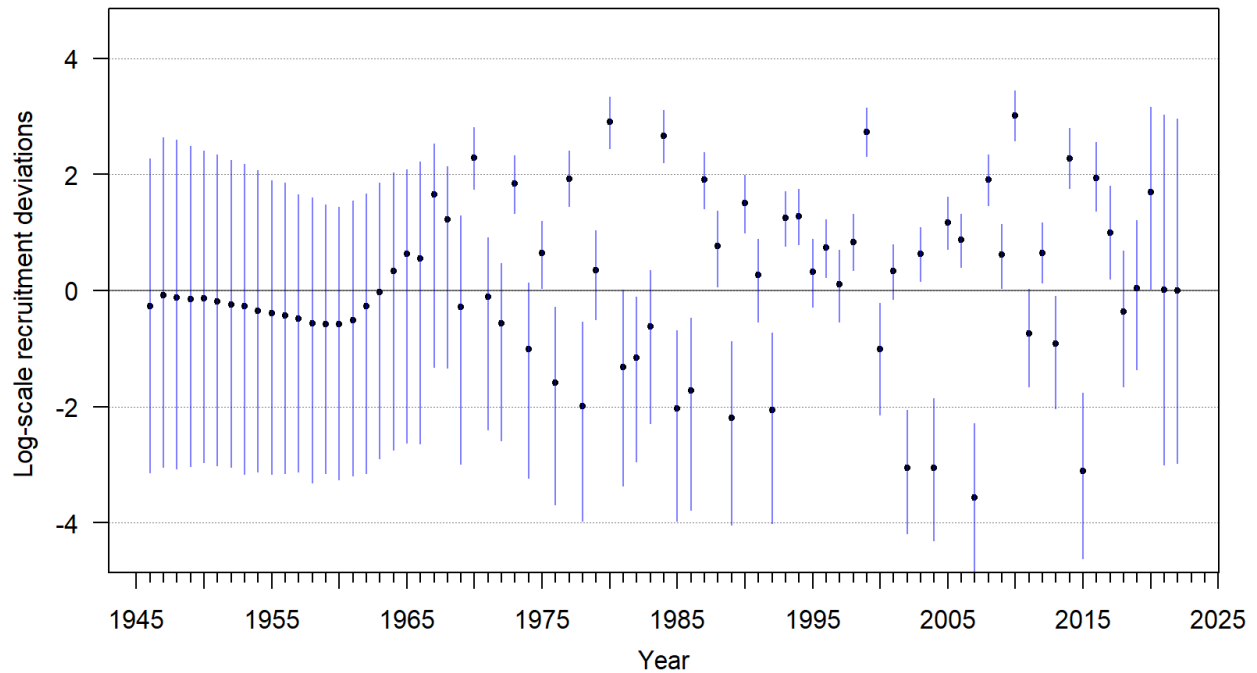


Figure 29. Medians (solid circles) of the posterior distribution for log-scale recruitment deviations with 95% posterior credibility intervals (blue lines). Recruitment deviations for the years 1946–1965 are used to calculate the numbers at age in 1966, the initial year of the model.

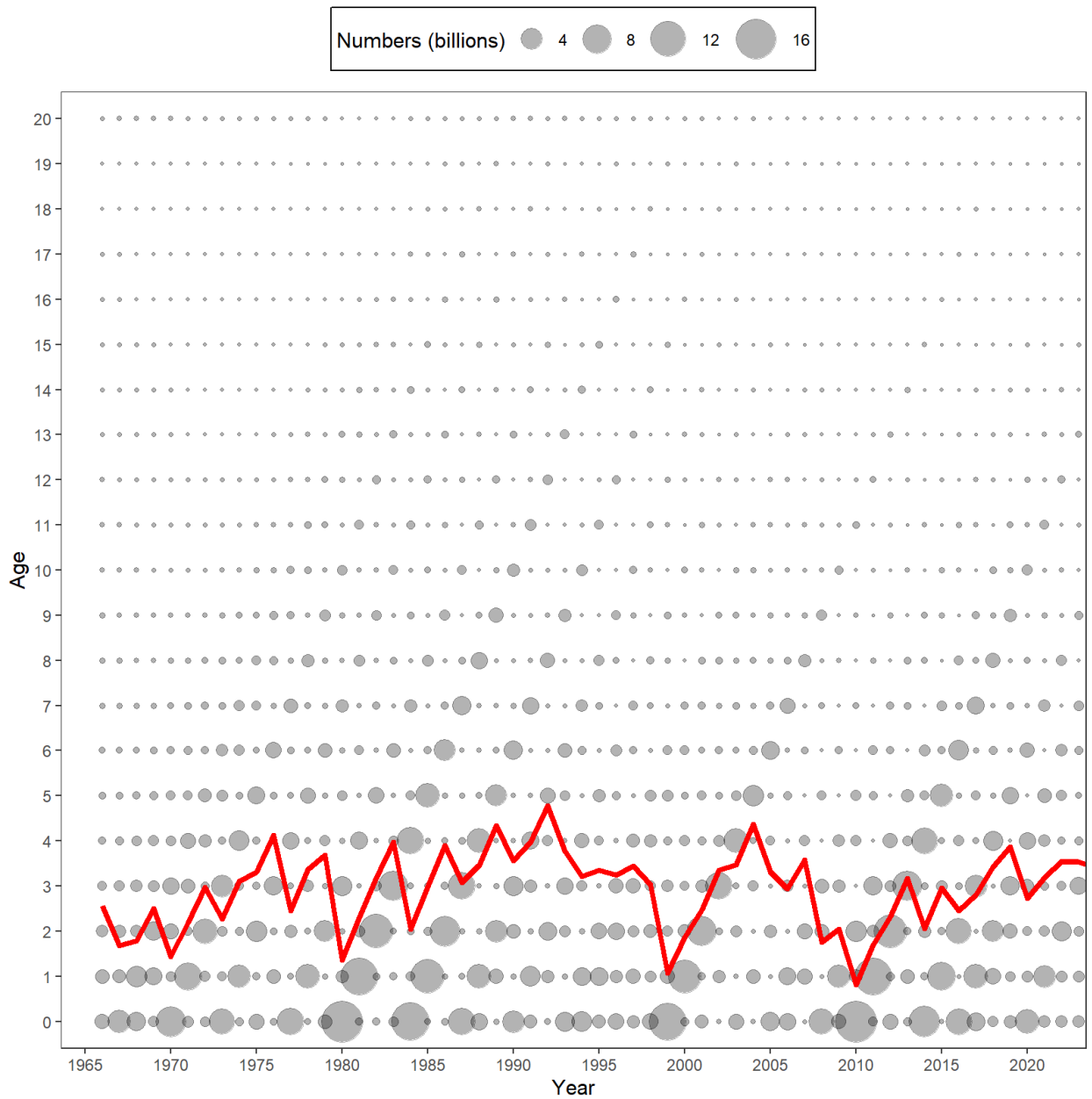


Figure 30. Bubble plot of the medians of the posterior distributions of population numbers at age at the beginning of each year, where diagonals follow each year-class through time. The red line represents the mean age. The scale of the bubbles is represented in the key where the units are billions of fish; the largest overall bubble represents the 17.2 billion age-0 recruits in 1980. See Table 18 for values.

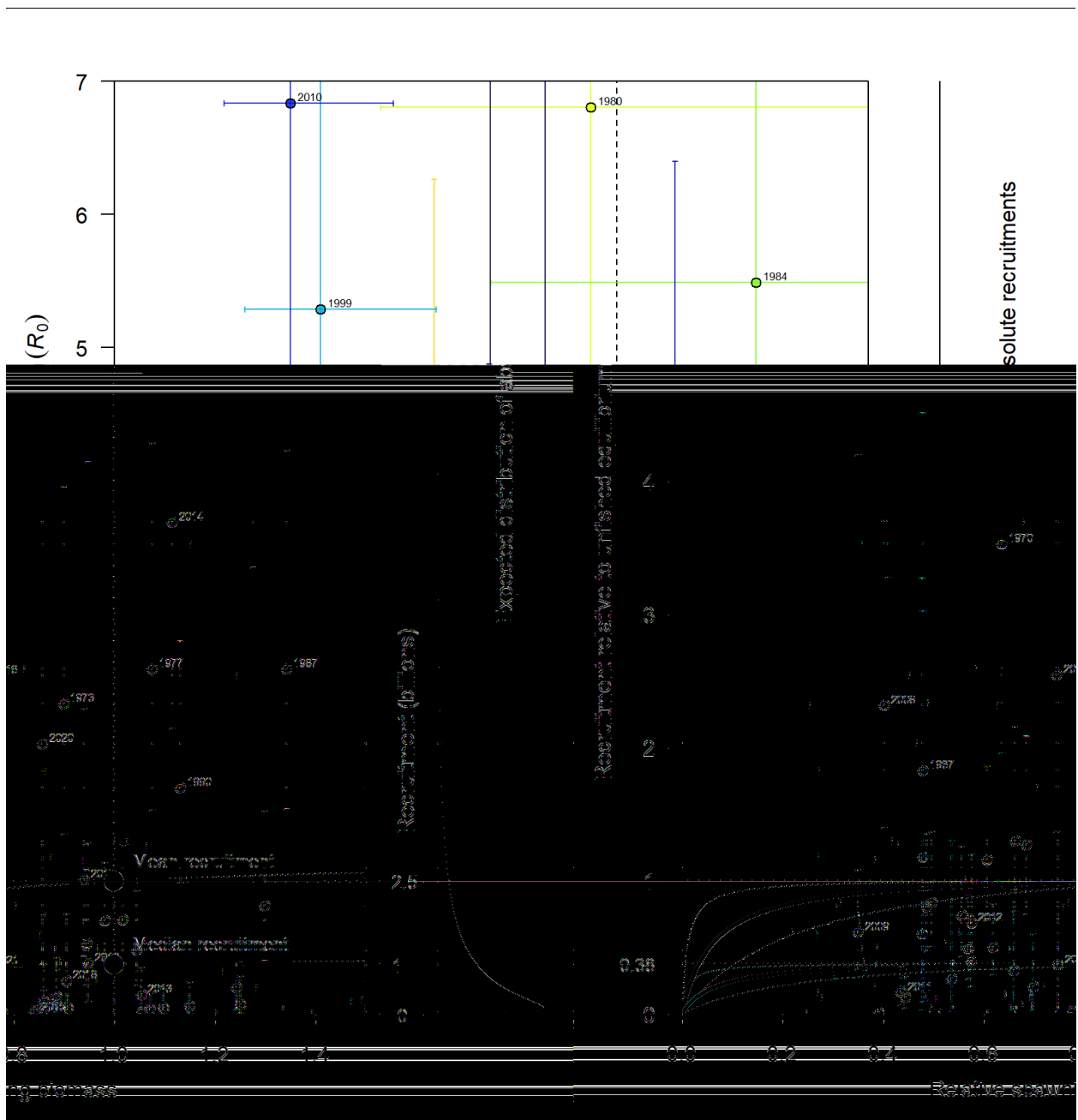


Figure 31. Estimated stock-recruit relationship for the base model with median predicted recruitments and 95% posterior credibility intervals. Colors indicate time-period, with yellow colors in the early years and blue colors in the recent years. The thick solid black line indicates the central tendency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

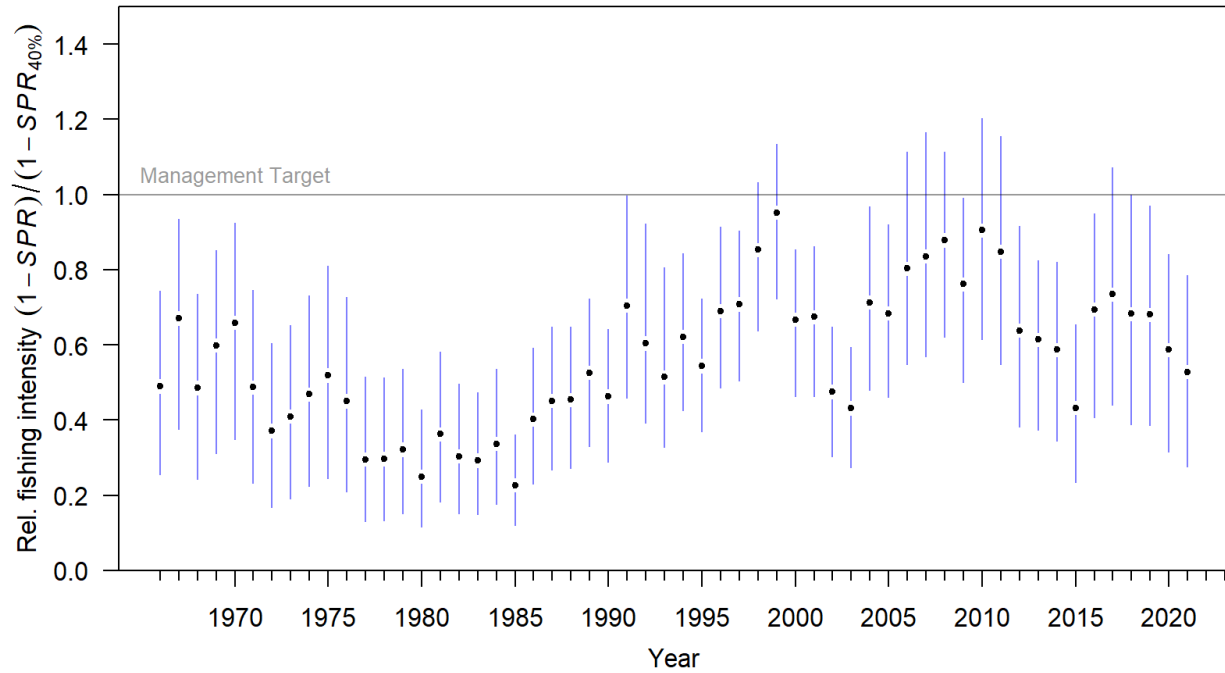


Figure 32. Trend in median fishing intensity (relative to the SPR management target) through 2021 with 95% posterior credibility intervals. The management target defined in the Agreement is shown as a horizontal line at 1.0.

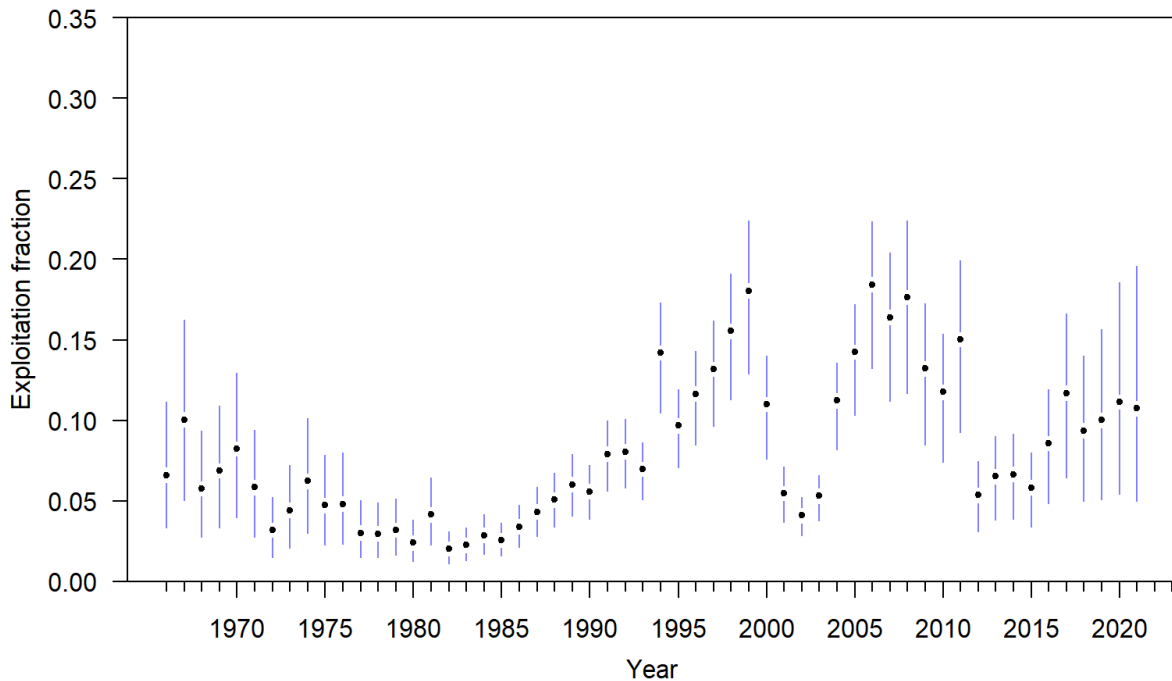


Figure 33. Trend in median exploitation fraction (catch divided by biomass of fish of age-2 and above) through 2021 with 95% posterior credibility intervals.

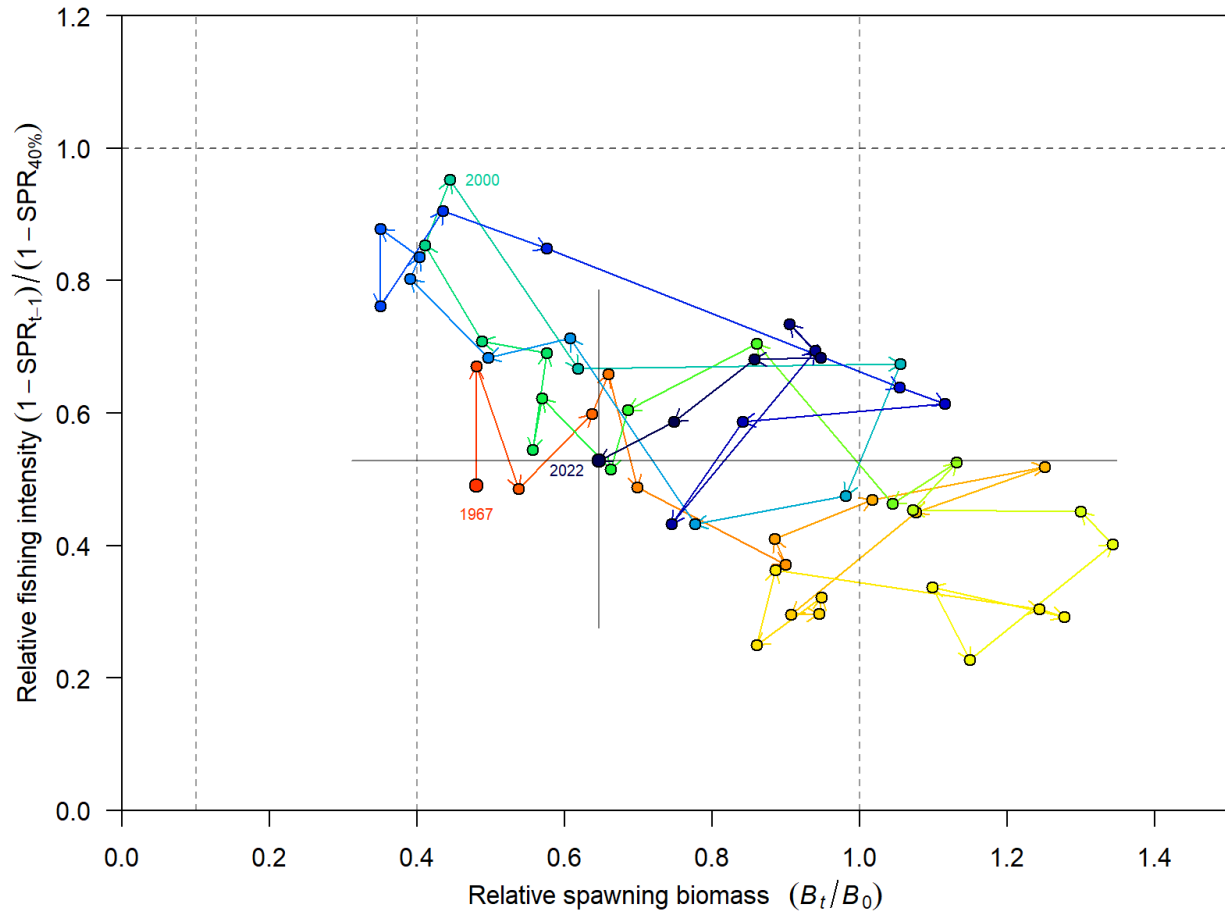


Figure 34. Estimated historical path of median relative spawning biomass in year t and corresponding median relative fishing intensity in year $t - 1$. Labels show the start year, end year and year of highest relative fishing intensity; labels correspond to year t (i.e., year of the relative spawning biomass). Gray bars span the 95% credibility intervals for 2022 relative spawning biomass (horizontal) and 2021 relative fishing intensity (vertical).

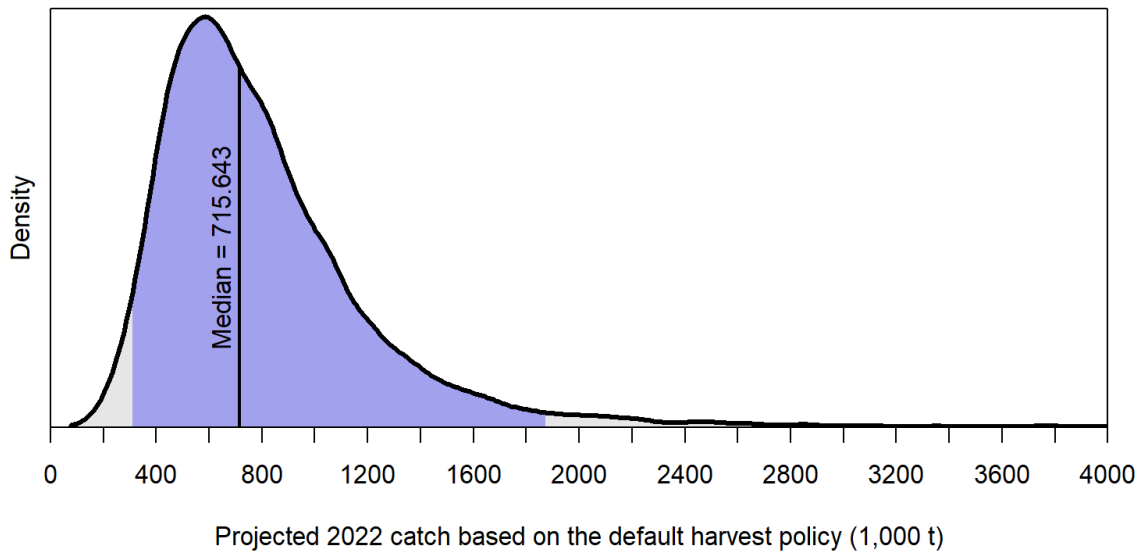


Figure 35. The posterior distribution of the default 2022 catch limit calculated using the default harvest policy ($F_{SPR=40\%}-40:10$). The median is 715,643 t (vertical line), with the dark shaded area ranging from the 2.5% quantile to the 97.5% quantile, covering the range 300,110–1,882,776 t.

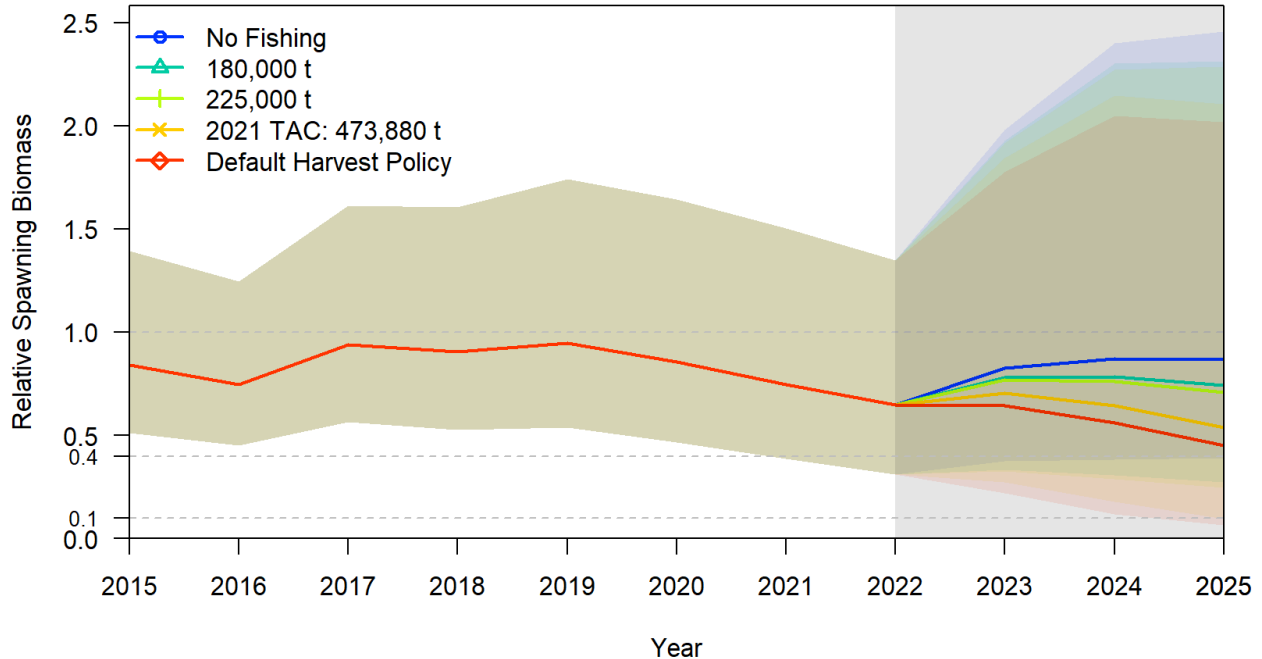


Figure 36. Time series of relative spawning biomass at the start of each year until 2022 as estimated from the base model, and forecast trajectories to the start of 2025 for several management options from the decision table (grey region), with 95% posterior credibility intervals. The default harvest policy catches are 715,643 t in 2022, 586,146 t in 2023, and 526,126 t in 2024.

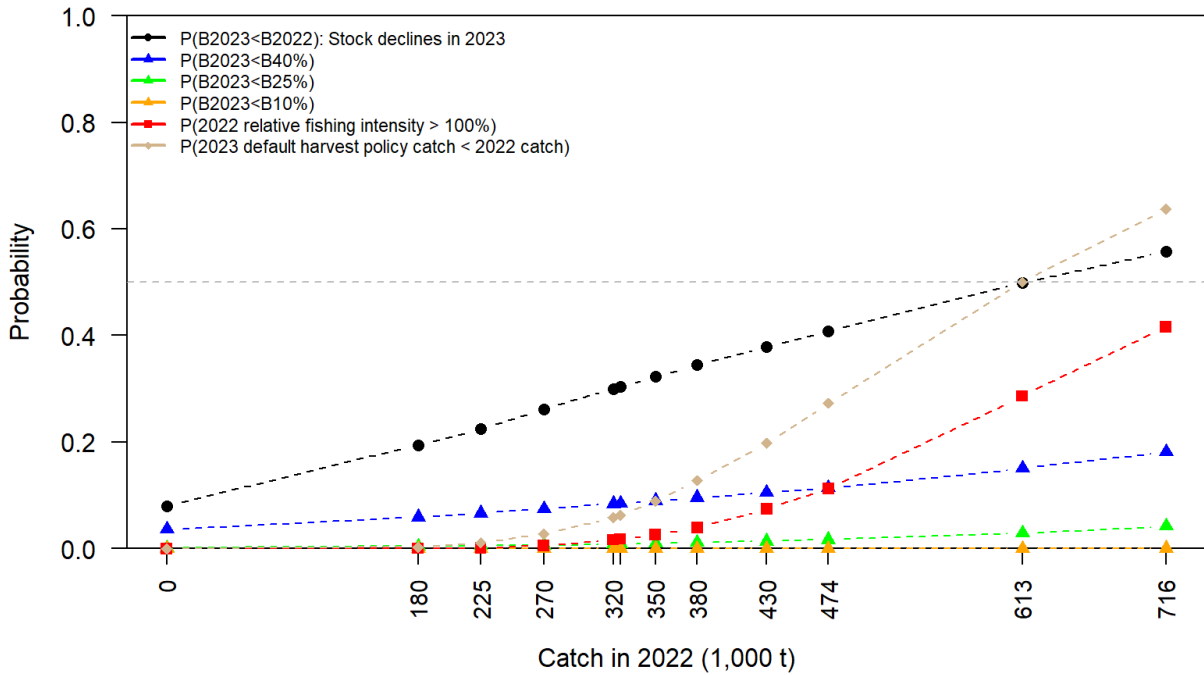


Figure 37. Graphical representation of the base model results presented in Table 30 for various catches in 2022. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

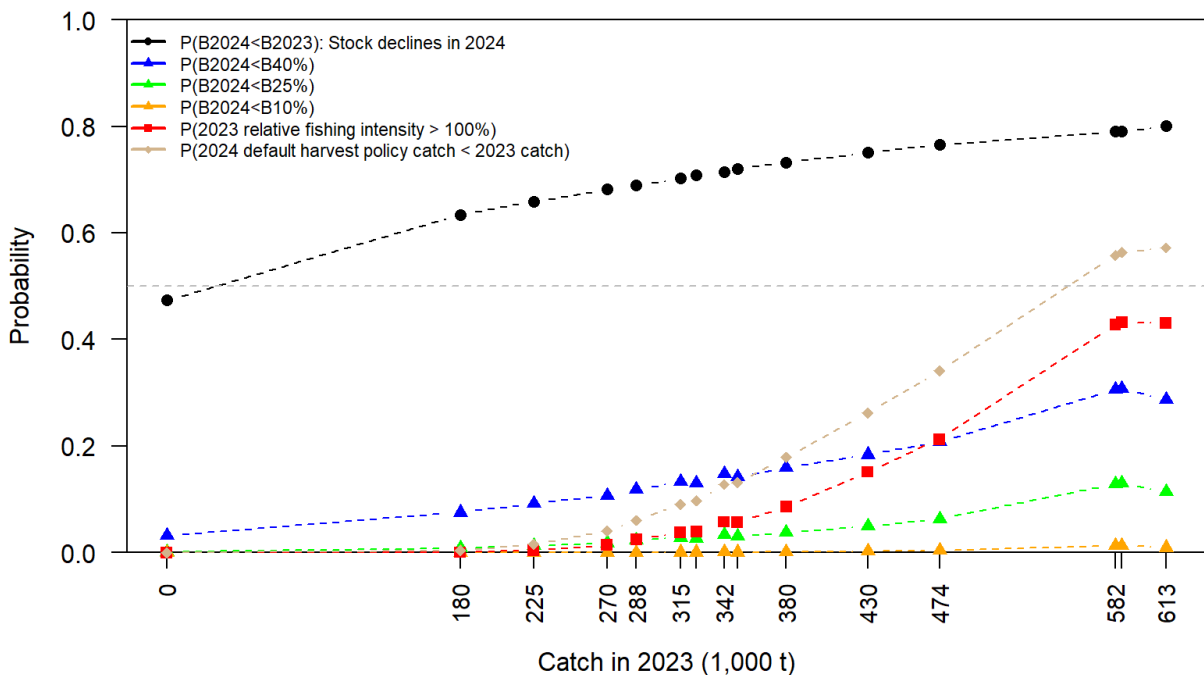


Figure 38. Graphical representation of the base model results presented in Table 31 for catch in 2023, given the 2022 catch level shown in Table 30. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

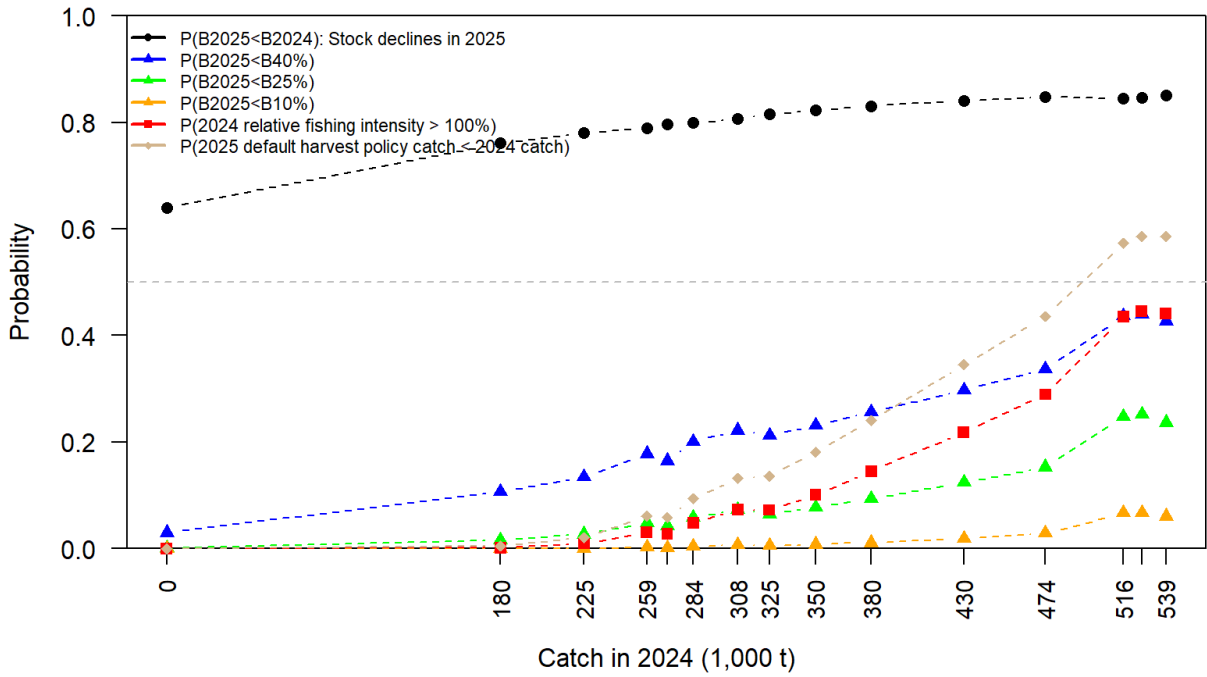


Figure 39. Graphical representation of the base model results presented in Table 32 for catch in 2024, given the 2022 and 2023 catch levels shown in Tables 30 and 31. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

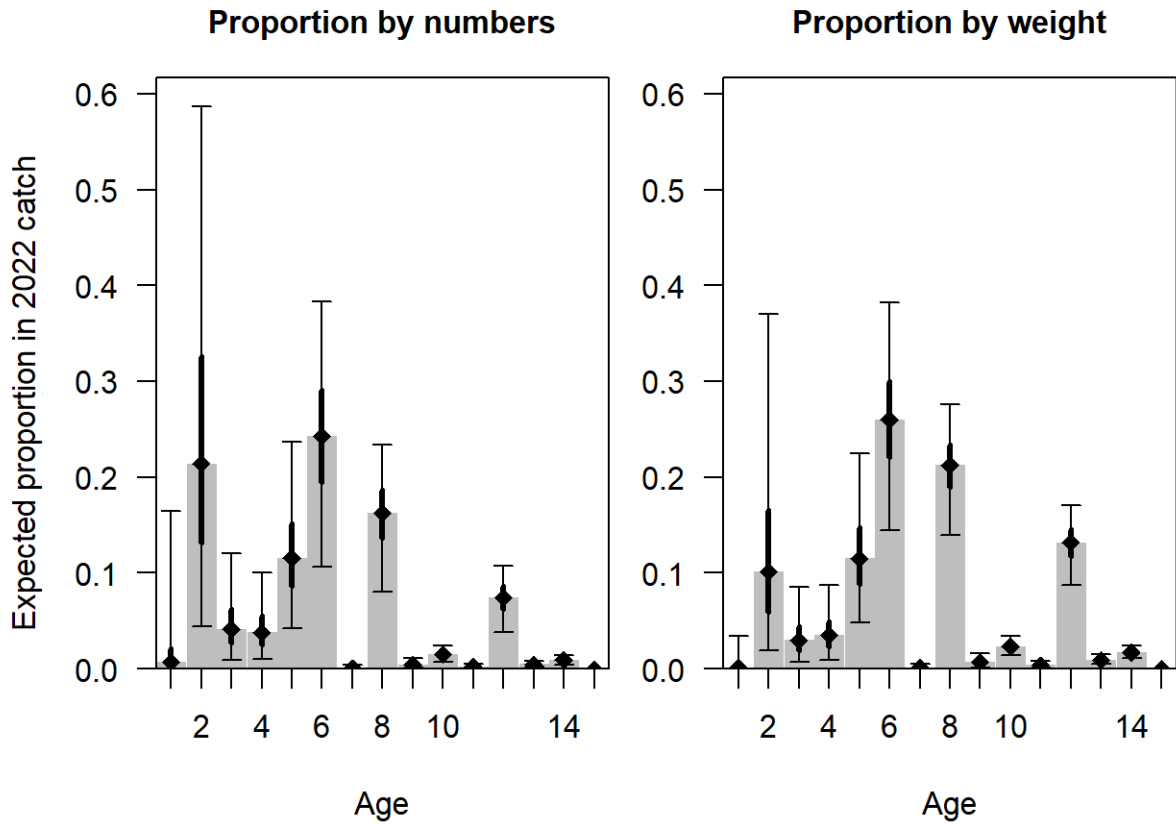


Figure 40. Forecast age compositions in numbers and in weight for the 2022 fishery catch (combined across all sectors in both countries). Gray bars show median estimates. Thick black lines show 50% credibility intervals and thin black lines show 95% credibility intervals. These estimates are based on the posterior distribution for selectivity averaged across the most recent five years, weight-at-age data averaged across the most recent five years, and the distribution for expected numbers at age at the start of 2022 (see Table 18 for the MCMC medians of numbers-at-age for all years). The panel on the right is scaled based on the weight at each age averaged across the last five years.

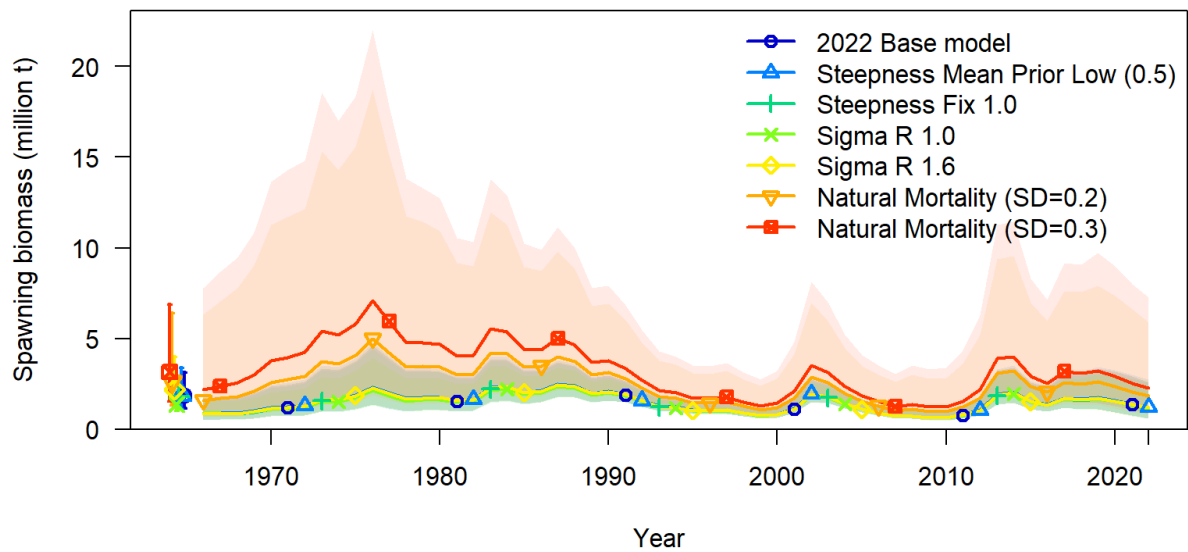


Figure 41. MCMC estimates of spawning biomass for the base model and alternative sensitivity runs representing changing the mean of the prior for steepness from 1.0 to 0.5, fixing steepness at 1.0, lower (1.0) and higher (1.6) levels of variation assumed about the stock-recruitment relationship (σ_r), and changing the standard deviation of the prior for natural mortality from 0.1 to 0.2 or 0.3.

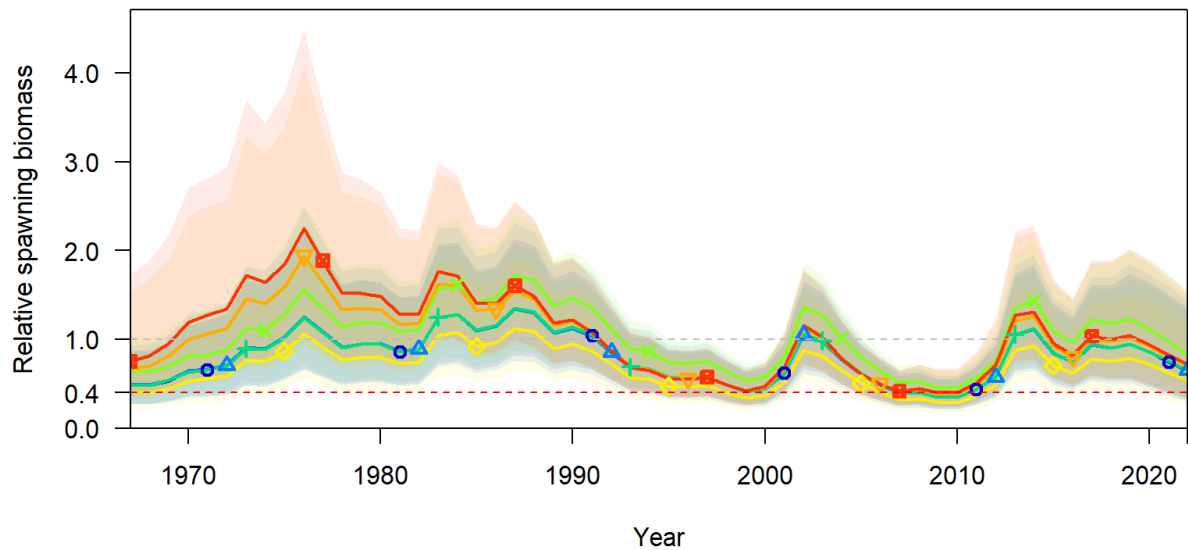


Figure 42. MCMC estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity runs representing changing key parameters. See Figure 41 for sensitivity descriptions.

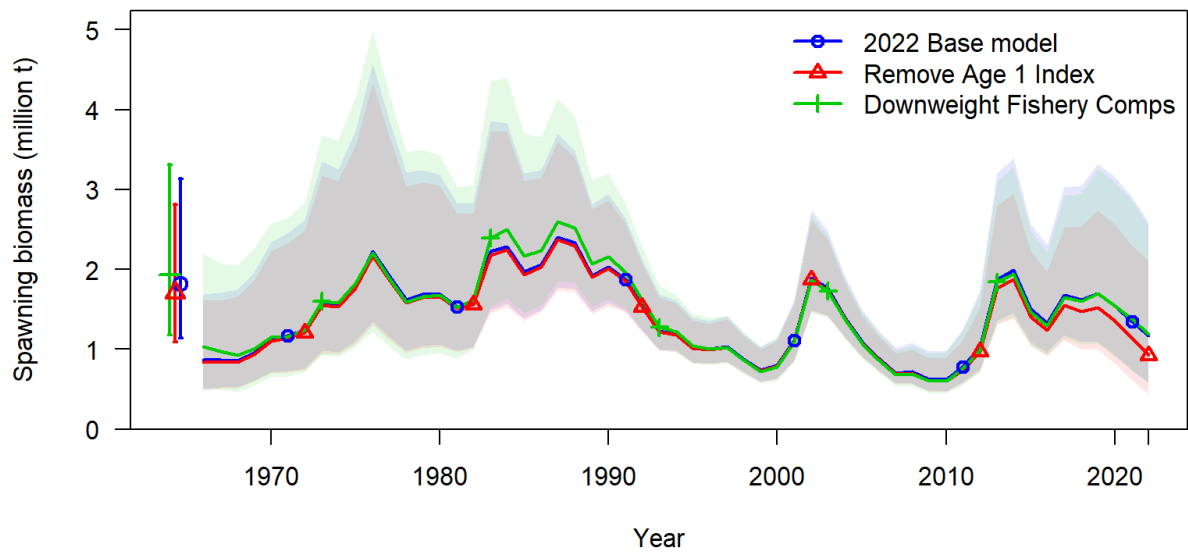


Figure 43. MCMC estimates of spawning biomass for the base model and alternative sensitivity runs that represent the following changes in data: removing the index of age-1 fish and downweighting fishery composition data using the McAllister-Ianelli method.

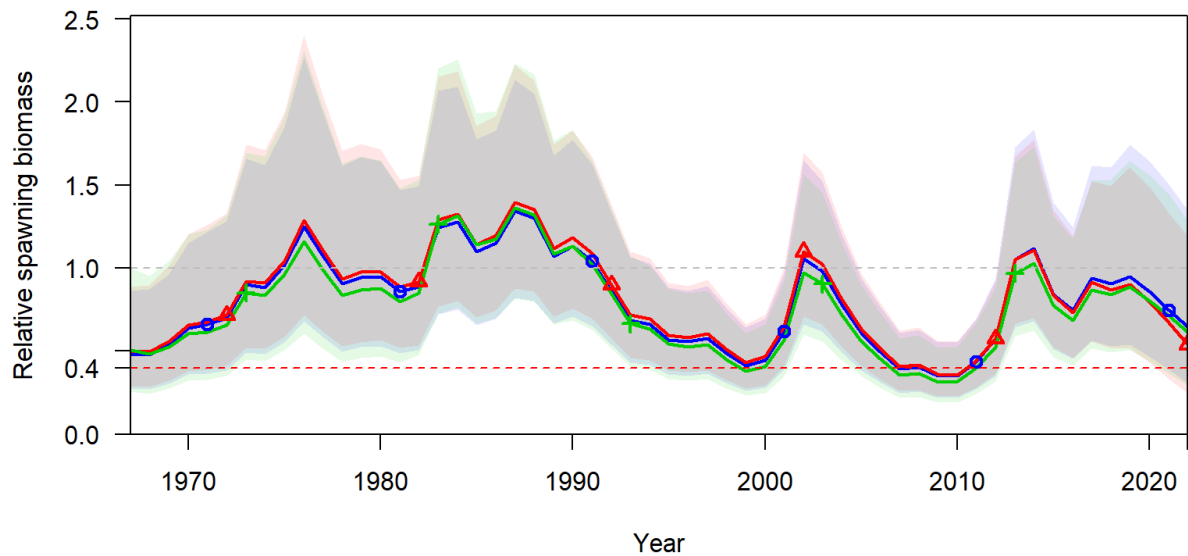


Figure 44. MCMC estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity runs that represent changes in data. See Figure 43 for sensitivity descriptions.

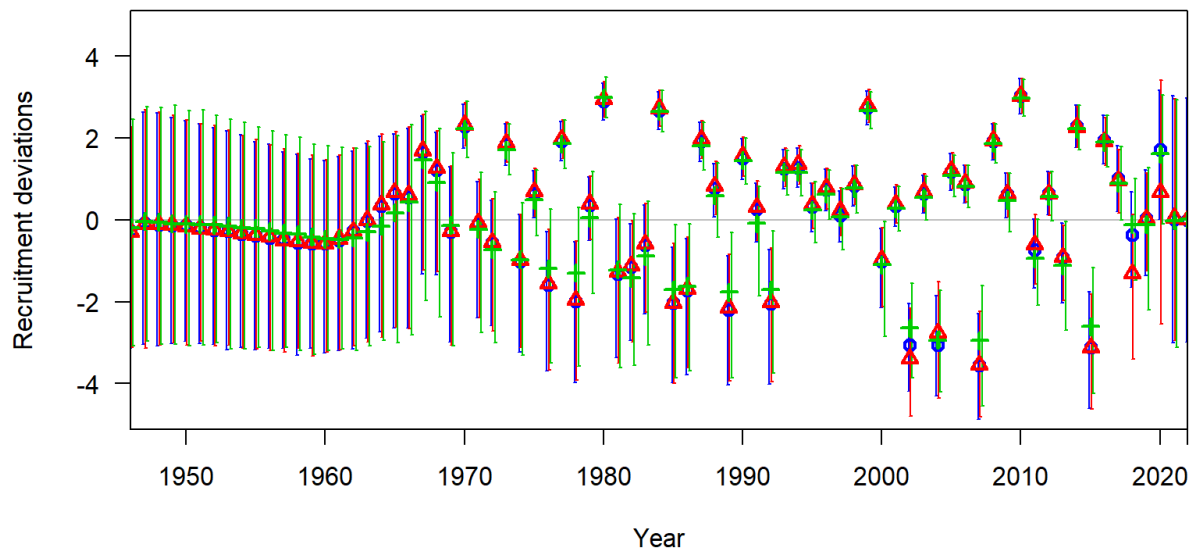


Figure 45. MCMC estimates of recruitment deviations for the base model and alternative sensitivity runs that represent changes in data. See Figure 43 for sensitivity descriptions.

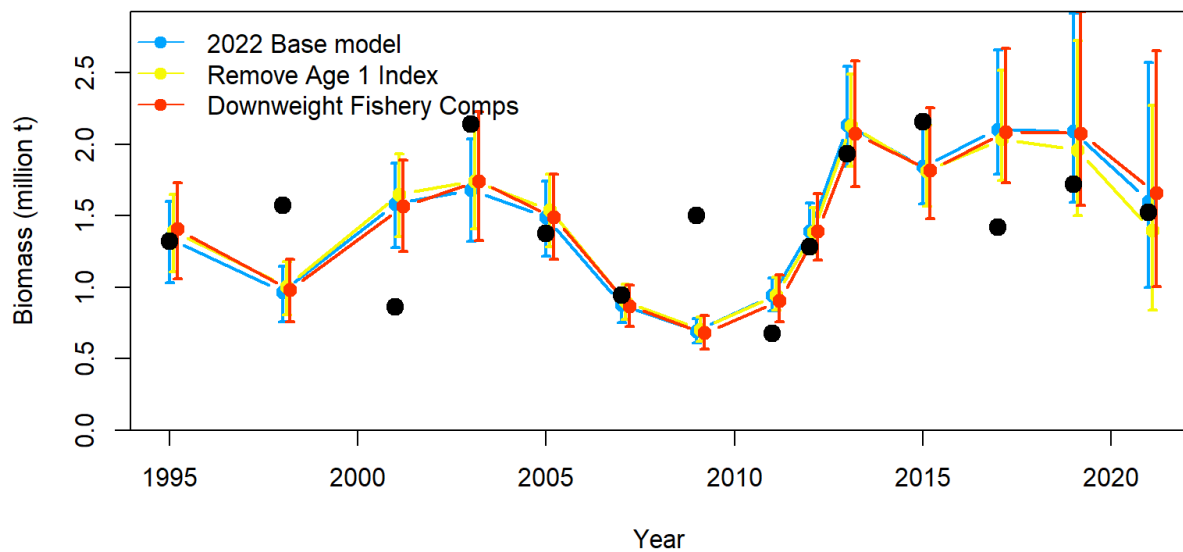


Figure 46. MCMC estimates of the fit to the biomass index for the base model and alternative sensitivity runs that represent changes in data. See Figure 43 for sensitivity descriptions.

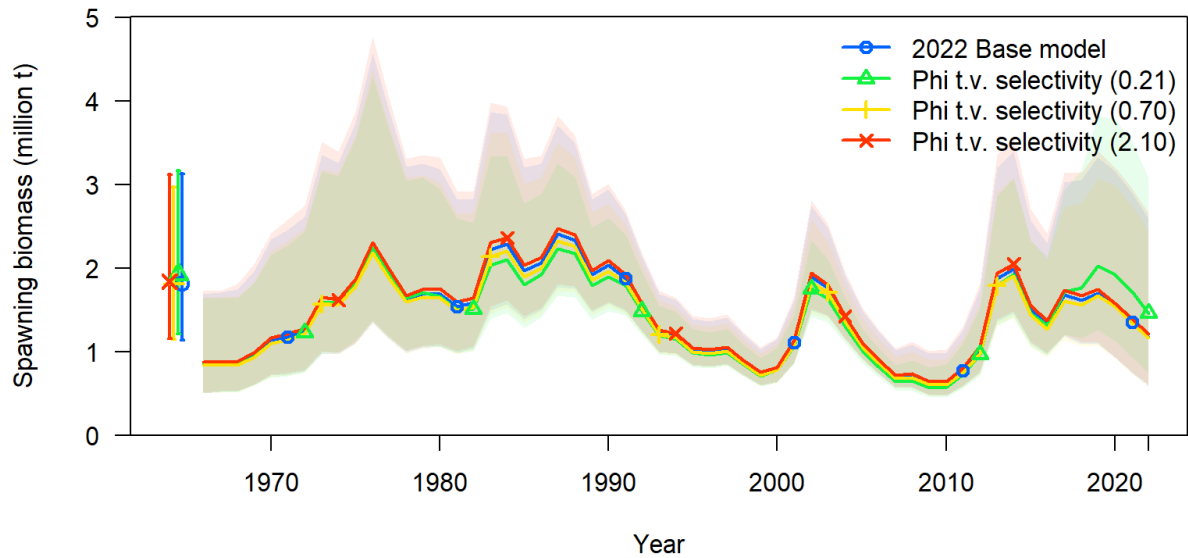


Figure 47. MCMC estimates of spawning biomass for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity.

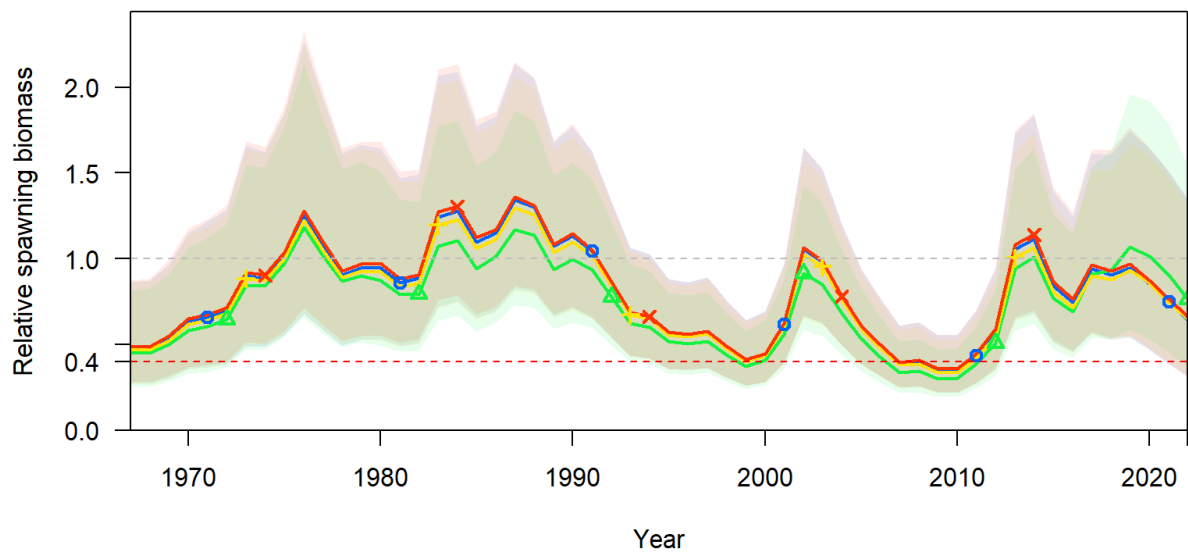


Figure 48. MCMC estimates of stock status (relative spawning biomass) for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

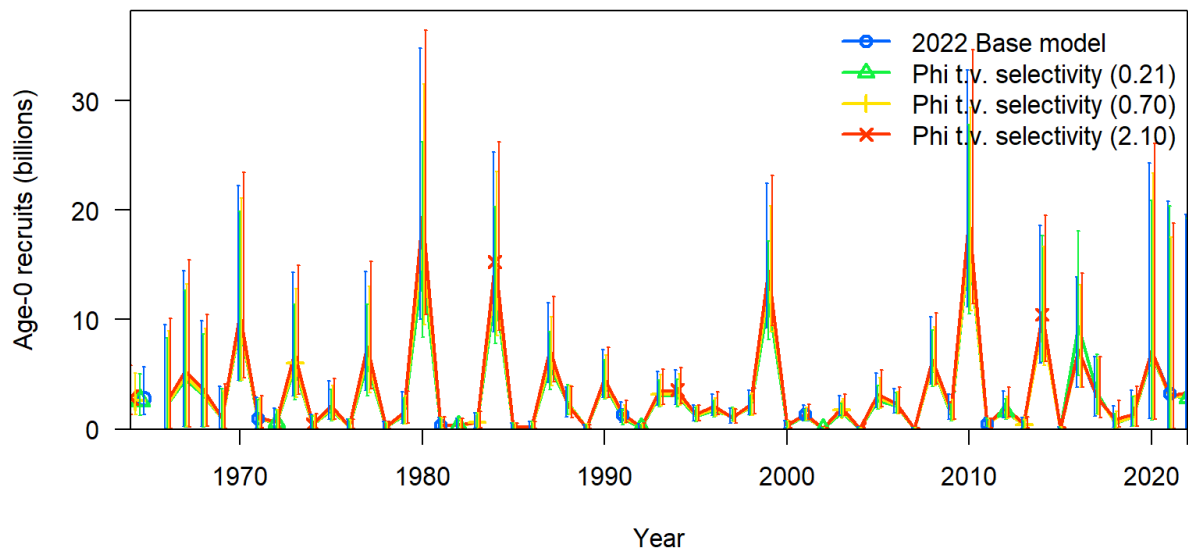


Figure 49. MCMC estimates of recruitment for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

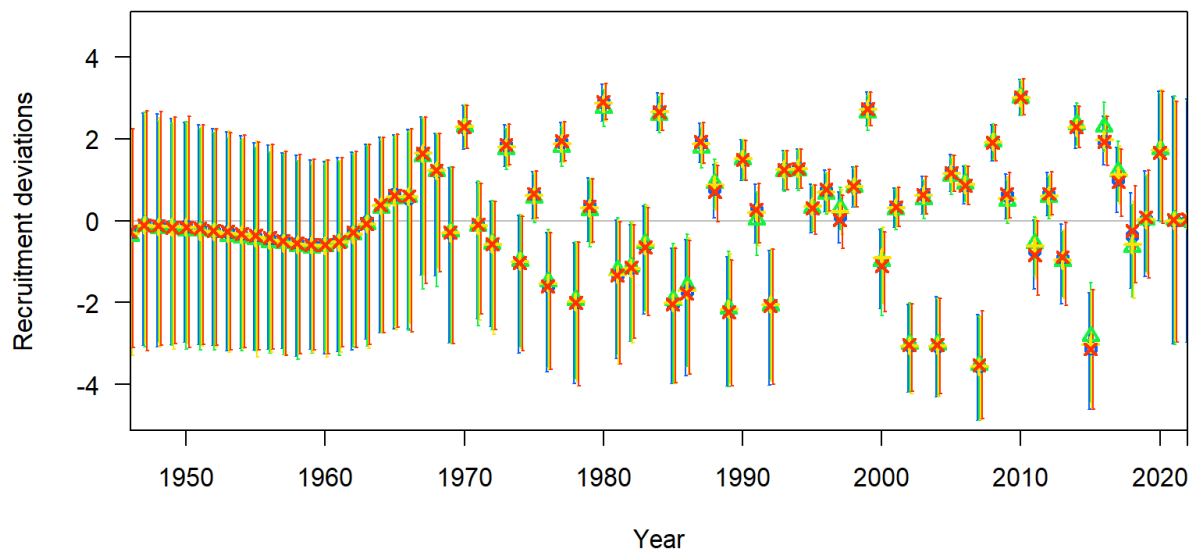


Figure 50. MCMC estimates of recruitment deviations for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

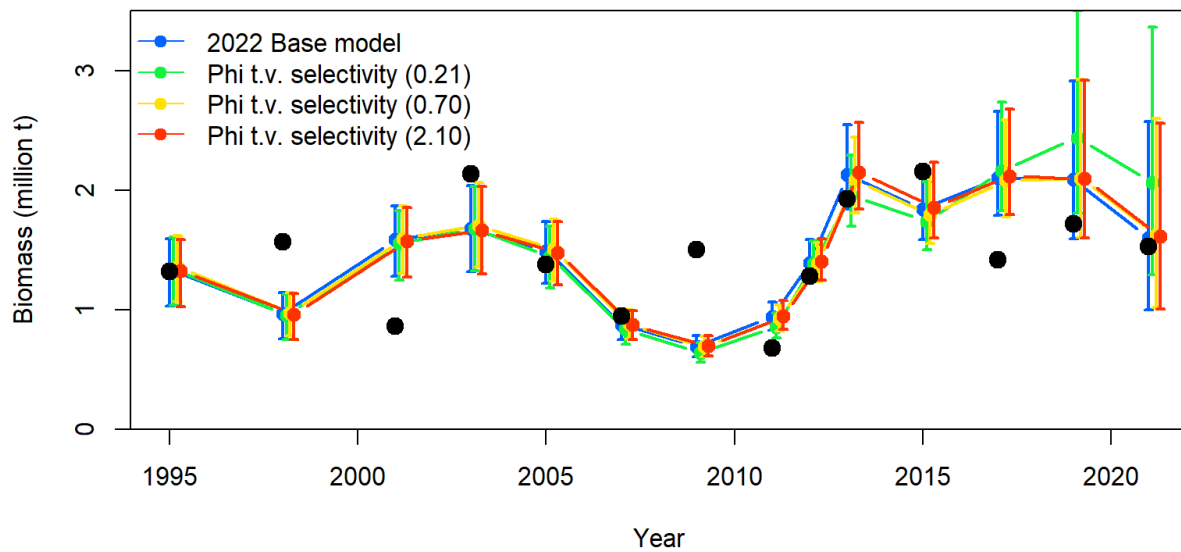


Figure 51. MCMC estimates of the fit to the survey index of age-2+ biomass for the base model and alternative sensitivity runs representing different standard deviations (Φ) associated with time-varying selectivity. See Figure 47 for sensitivity descriptions.

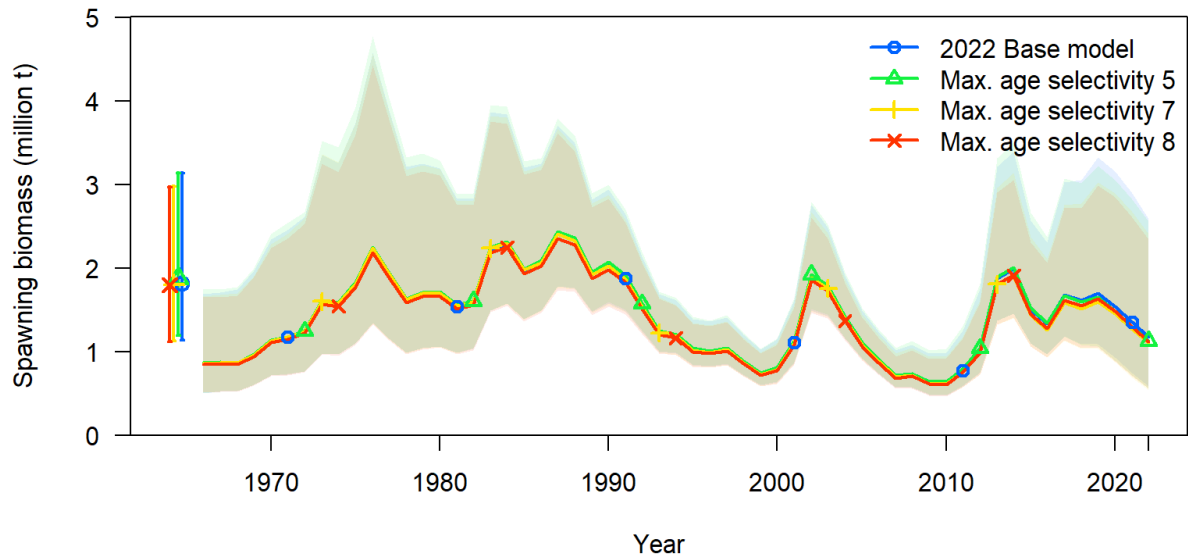


Figure 52. MCMC estimates of spawning biomass for the base model and alternative sensitivity runs with maximum age-based selectivity decreased (age-5) or increased (age-7 and age-8) relative to the base model (age-6).

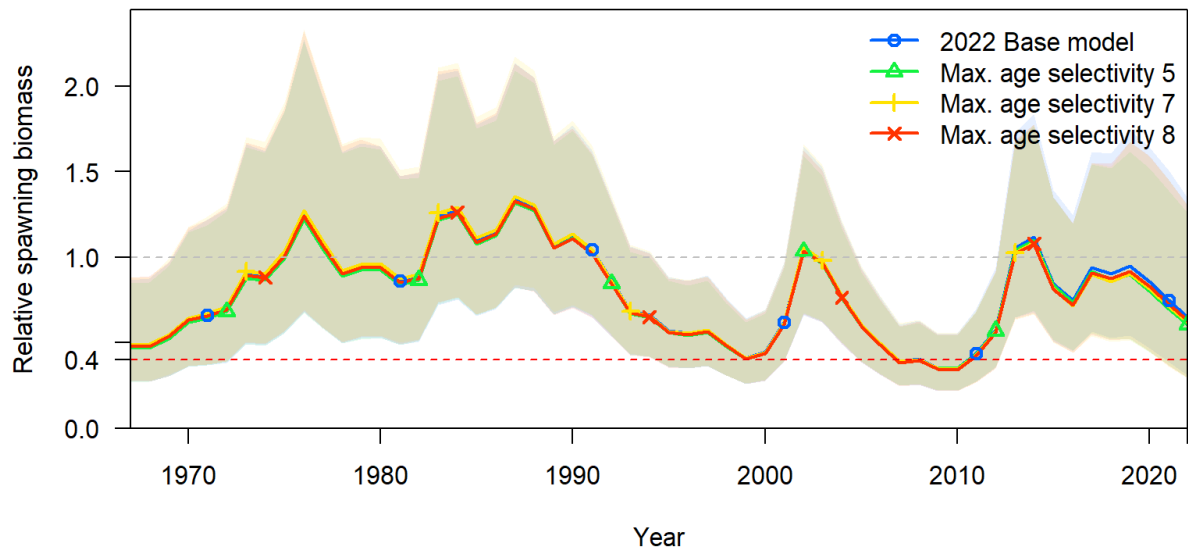


Figure 53. MCMC estimates of stock status for the base model and alternative sensitivity runs with maximum age-based selectivity decreased (age-5) or increased (age-7 and age-8) relative to the base model (age-6).

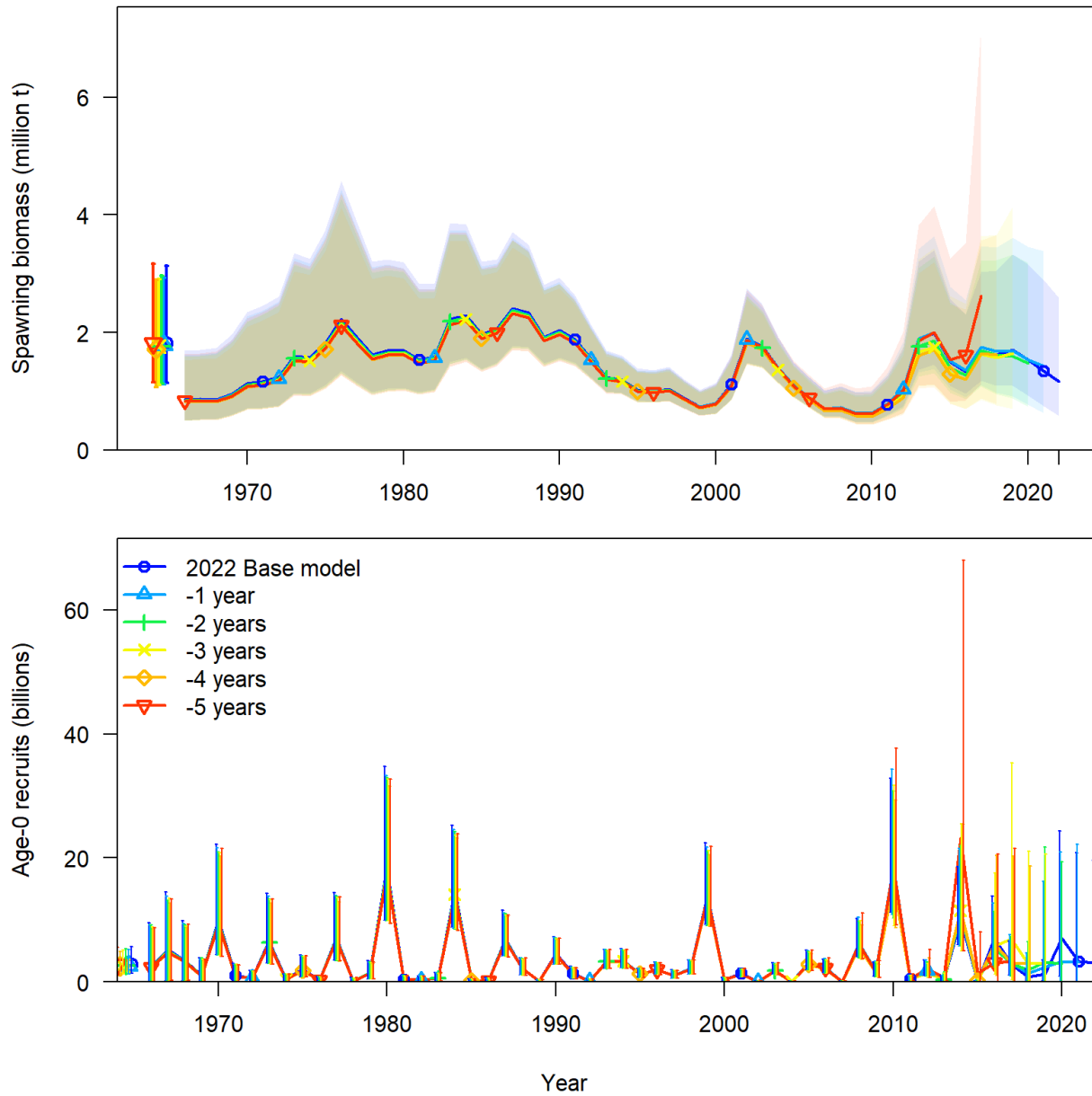


Figure 54. Estimates of spawning biomass at the start of each year (top) and recruitment (bottom) for the base model and retrospective runs (based on MCMC model runs).

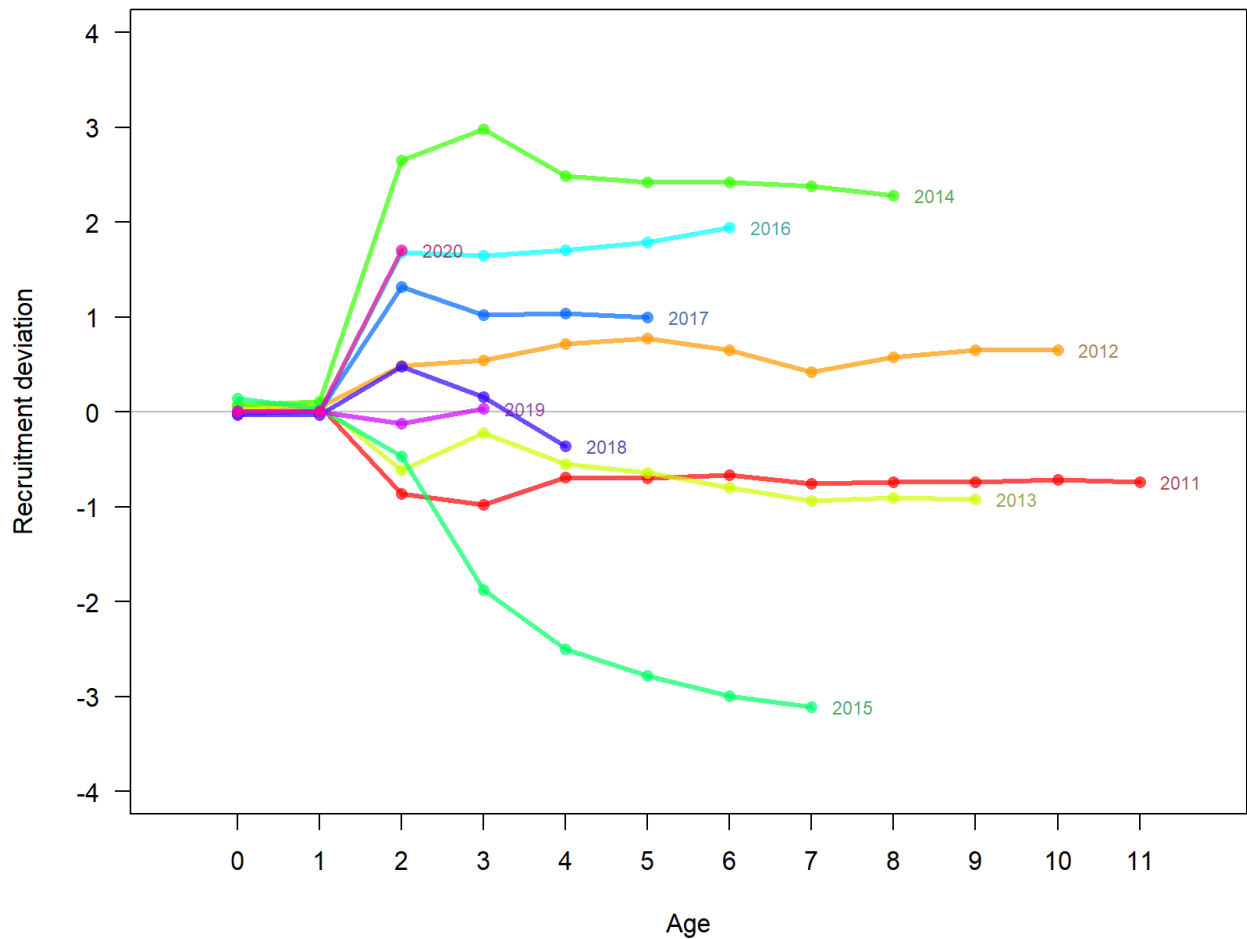


Figure 55. Retrospective analysis of recruitment deviations from MCMC models over the last 11 years. Recruitment deviations are the median log-scale differences between recruitment estimated by the model and expected recruitment from the spawner-recruit relationship. Age-0 recruitment deviations are non-zero because MCMC allows for sampling from the full log-normal distribution. Lines represent estimated recruitment deviations for cohorts born from 2011 to 2020, with cohort birth year marked at the right of each color-coded line. For example, the right-most point for the 2014 cohort shows the cohort at age-8 (i.e., at the start of 2022, which represents the base model and includes data to 2021 because data collection ends December 31). The next point to the left is the 2014 cohort at age-7, calculated by removing one year of data (so includes data up to 2020). 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.

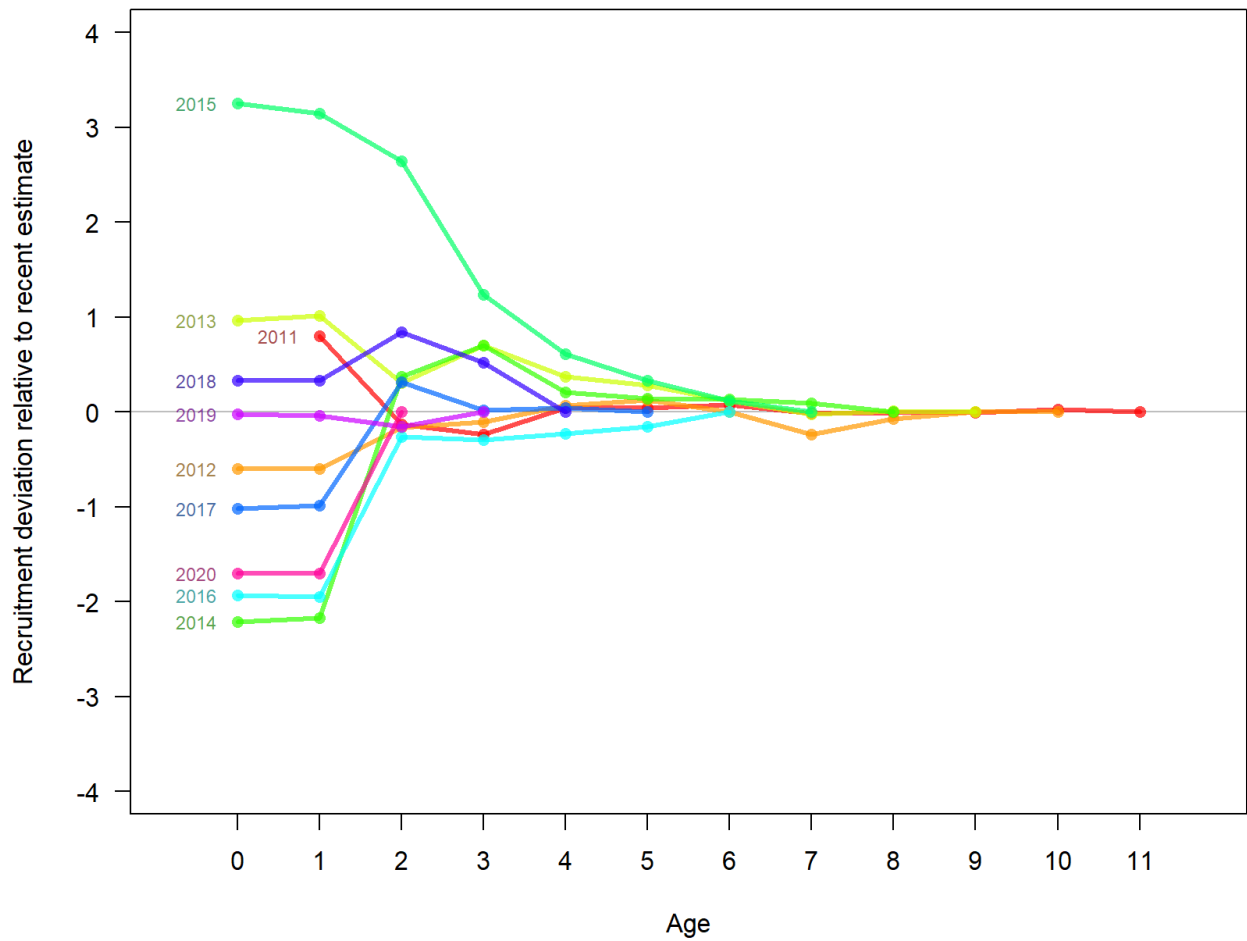


Figure 56. Retrospective recruitment estimates shown in Figure 55 scaled relative to the most recent estimate of the strength of each cohort.

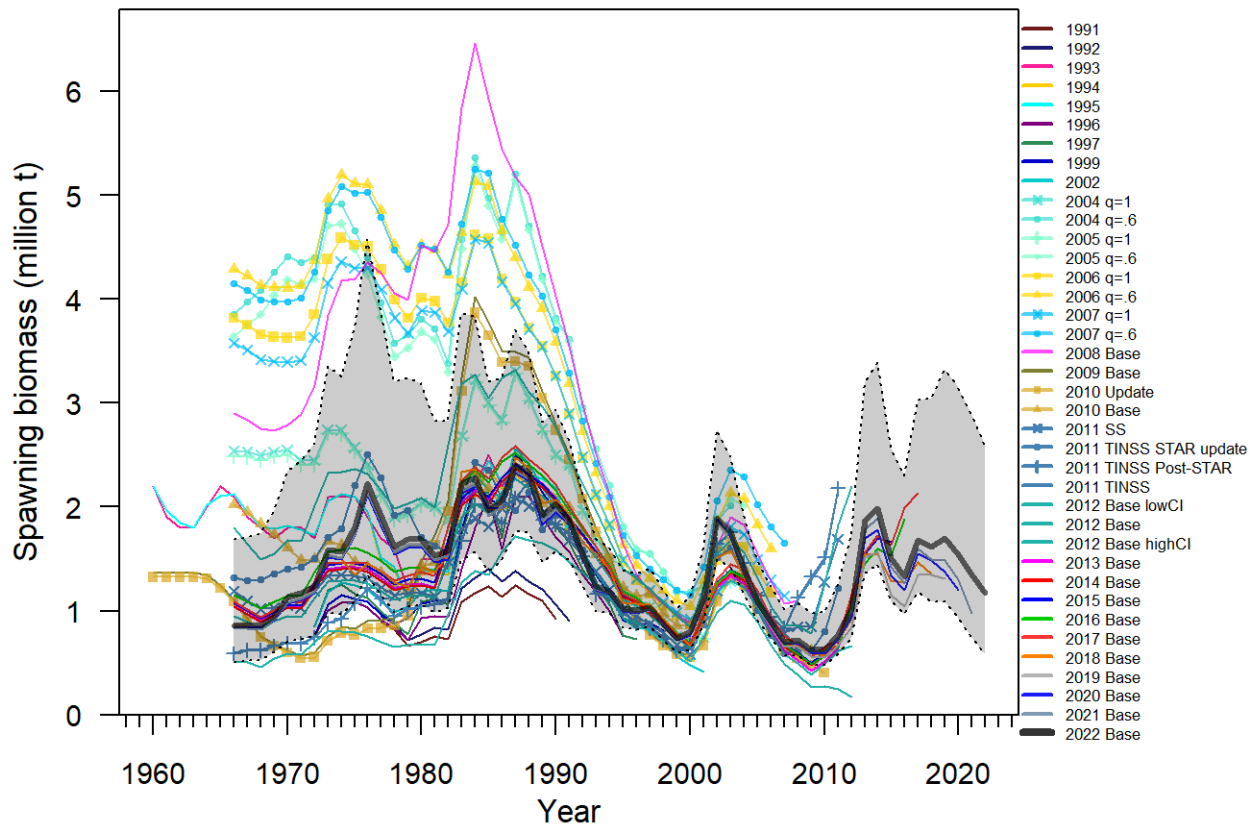


Figure 57. Summary of historical Pacific Hake assessment estimates of spawning biomass. Estimates are MLEs or MCMC medians depending on the model structure. Shading represents the 95% credible interval from the 2022 base model.

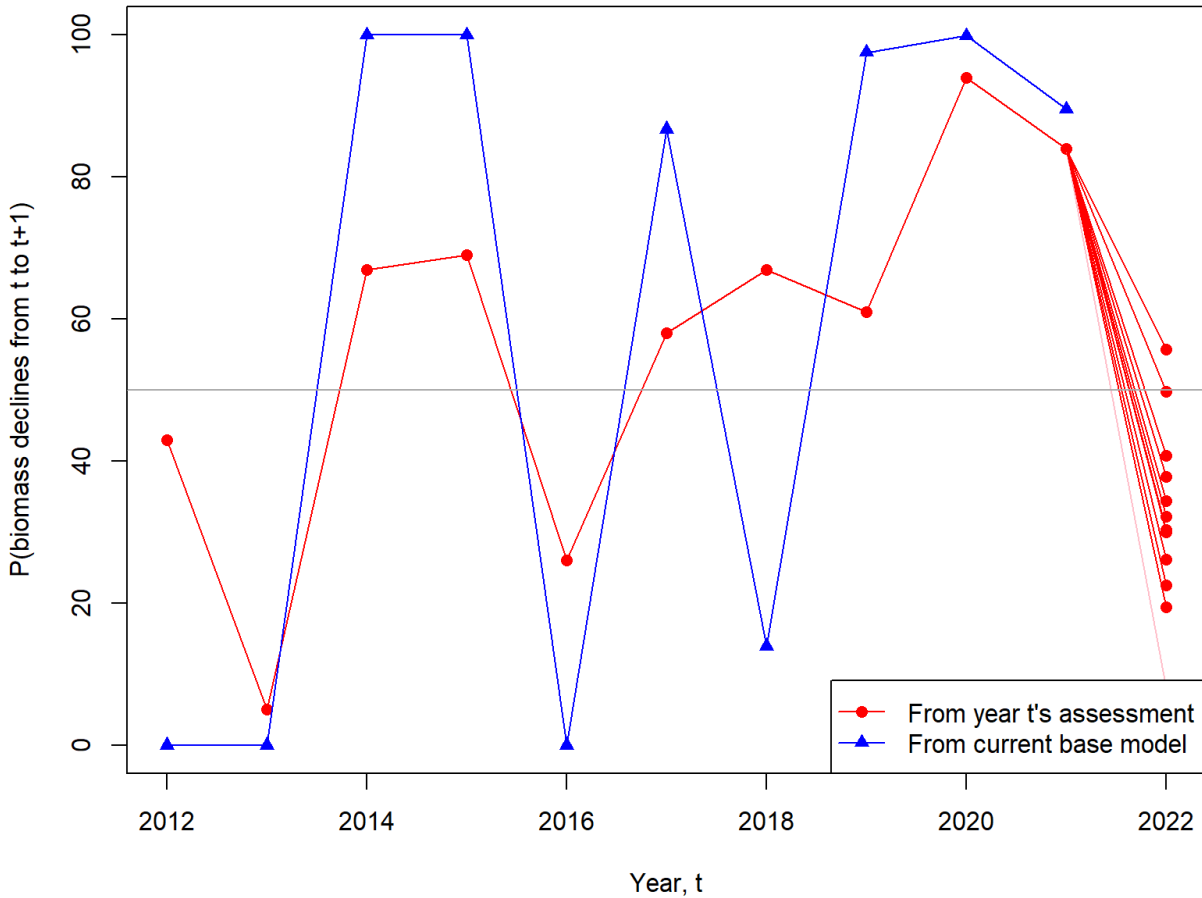


Figure 58. For each year t , $P(B_{t+1} < B_t)$ is the probability that the spawning biomass at the start of $t + 1$ is below that at the start of t . It is calculated in two ways. Red: the probability is taken from year t 's stock assessment document, from the row in the decision table corresponding to the consequent catch in year t (with interpolation if necessary). Blue: the probability is calculated using the current 2022 base model. The grey horizontal line is the 50% value. For each year except 2018, 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 2022 assessment the probabilities are shown for all catch alternatives for 2022, as described in Table 28, with 0 t shown in pink.

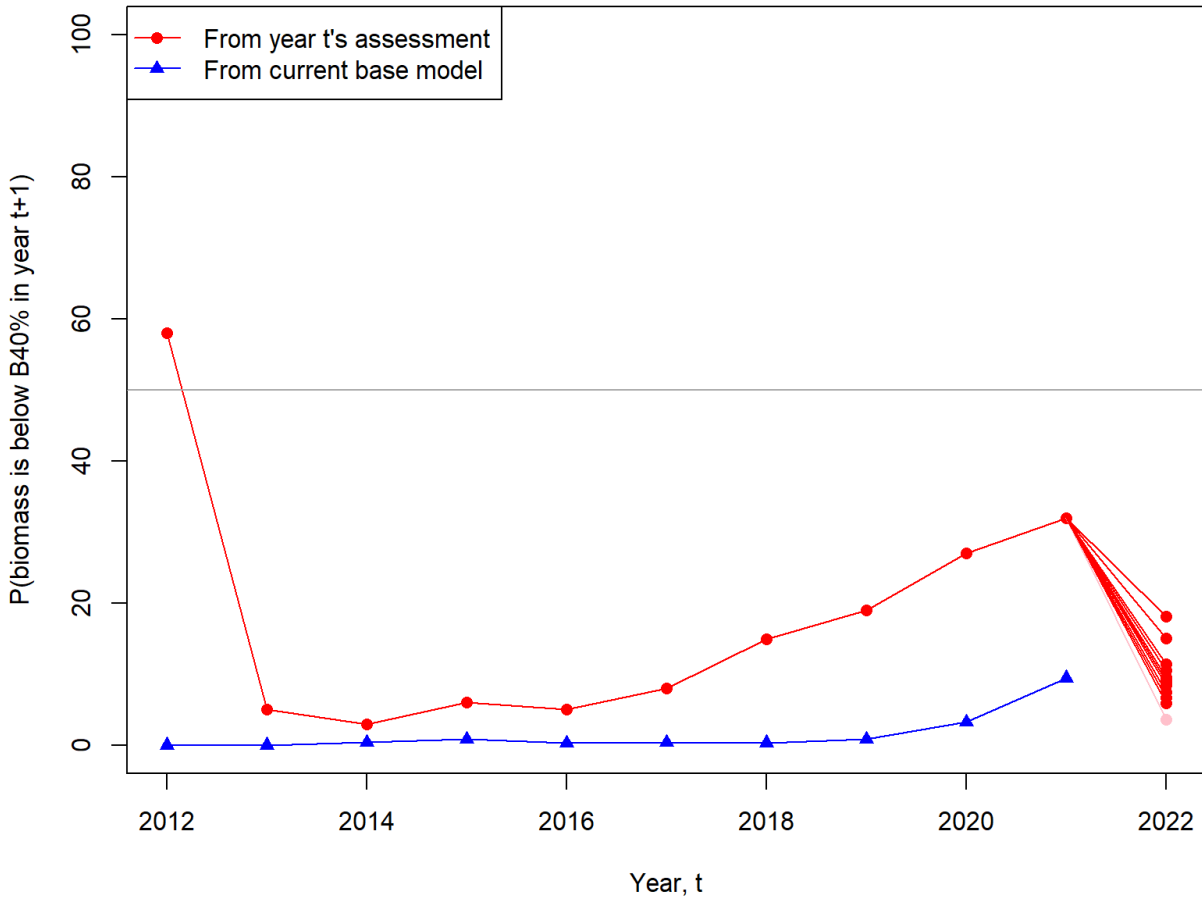


Figure 59. For each year t , $P(B_{t+1} < B_{40\%})$ is the probability that the spawning biomass at the start of $t + 1$ is below $B_{40\%}$. It is calculated in two ways (as for Figure 58). Red: the probability is taken from year t 's stock assessment document, from the row in the decision table corresponding to the consequent catch in year t (with interpolation if necessary). Blue: the probability is calculated using the current 2022 base model. 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 2022 assessment the probabilities are shown for all catch alternatives for 2022, as described in Table 28, with 0 t shown in pink.

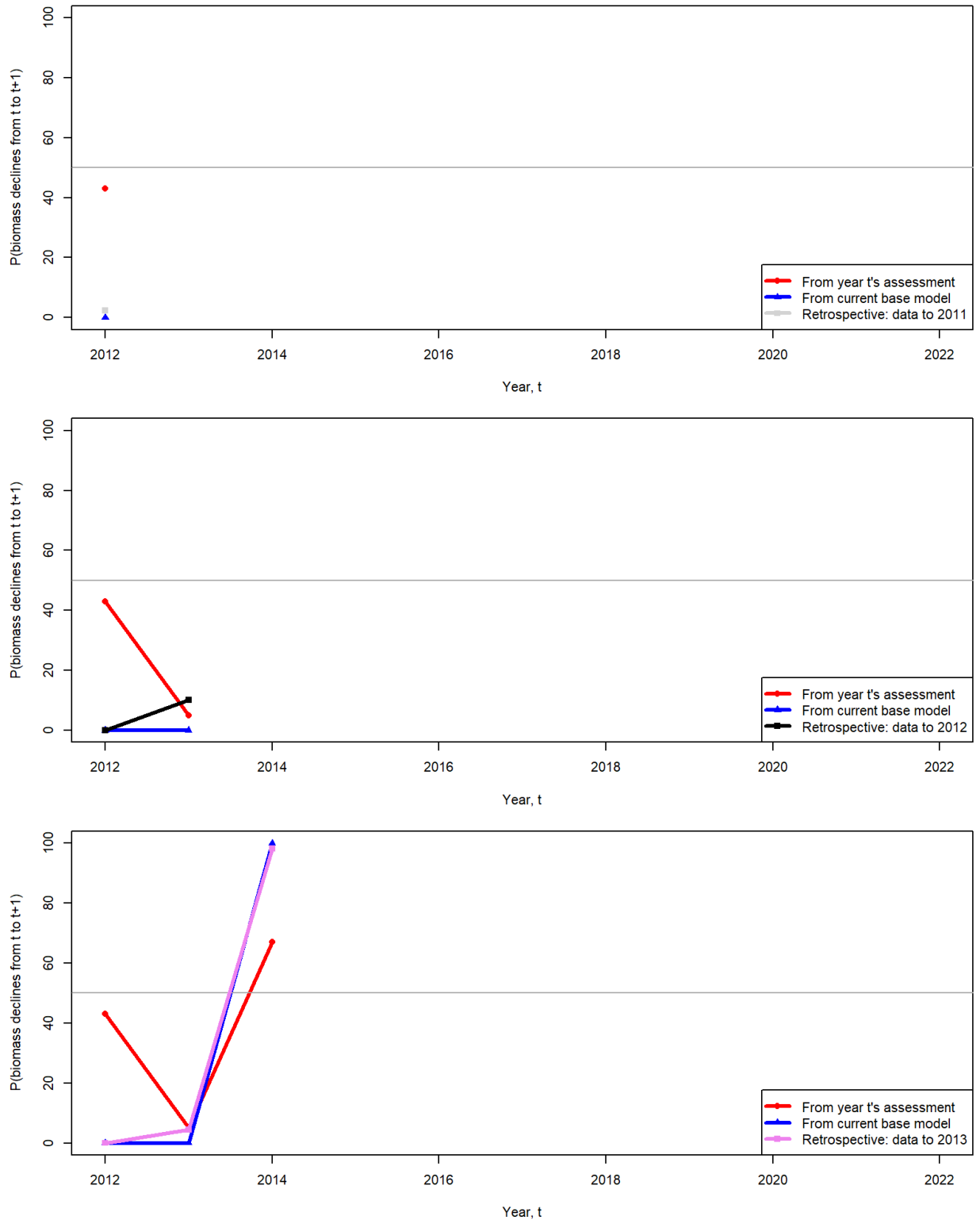


Figure 60. Retrospective versions of Figure 58. For each panel, the current base model is run using only data up to (and including) the year shown (i.e. a retrospective analysis) – ‘data to 2011’ would equate to doing an assessment at the start of 2012. Results are shown for further retrospective years in Figures 61, 62 and 63, and in a single panel in Figure 64.

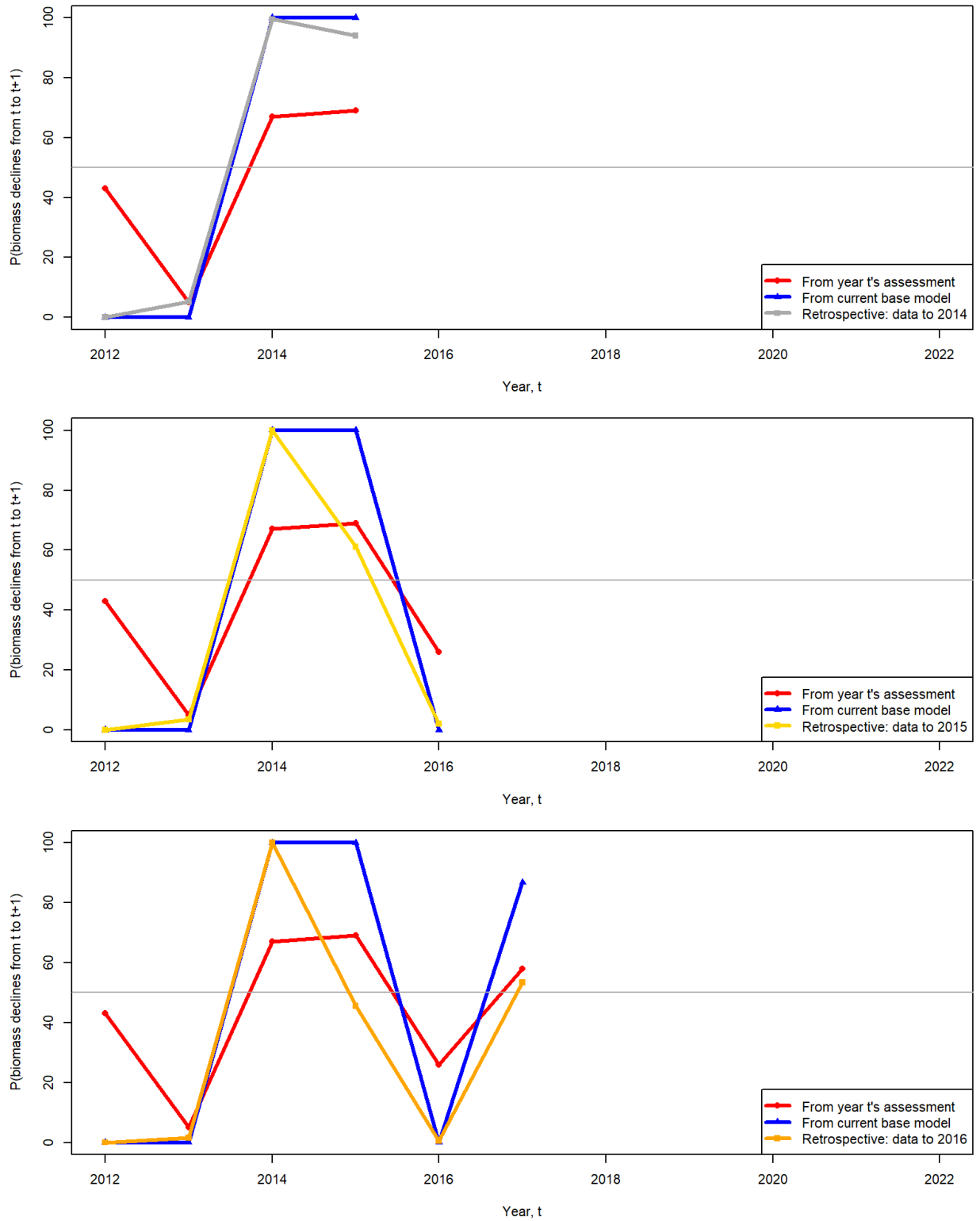


Figure 61. As for Figure 60 for further retrospective years.

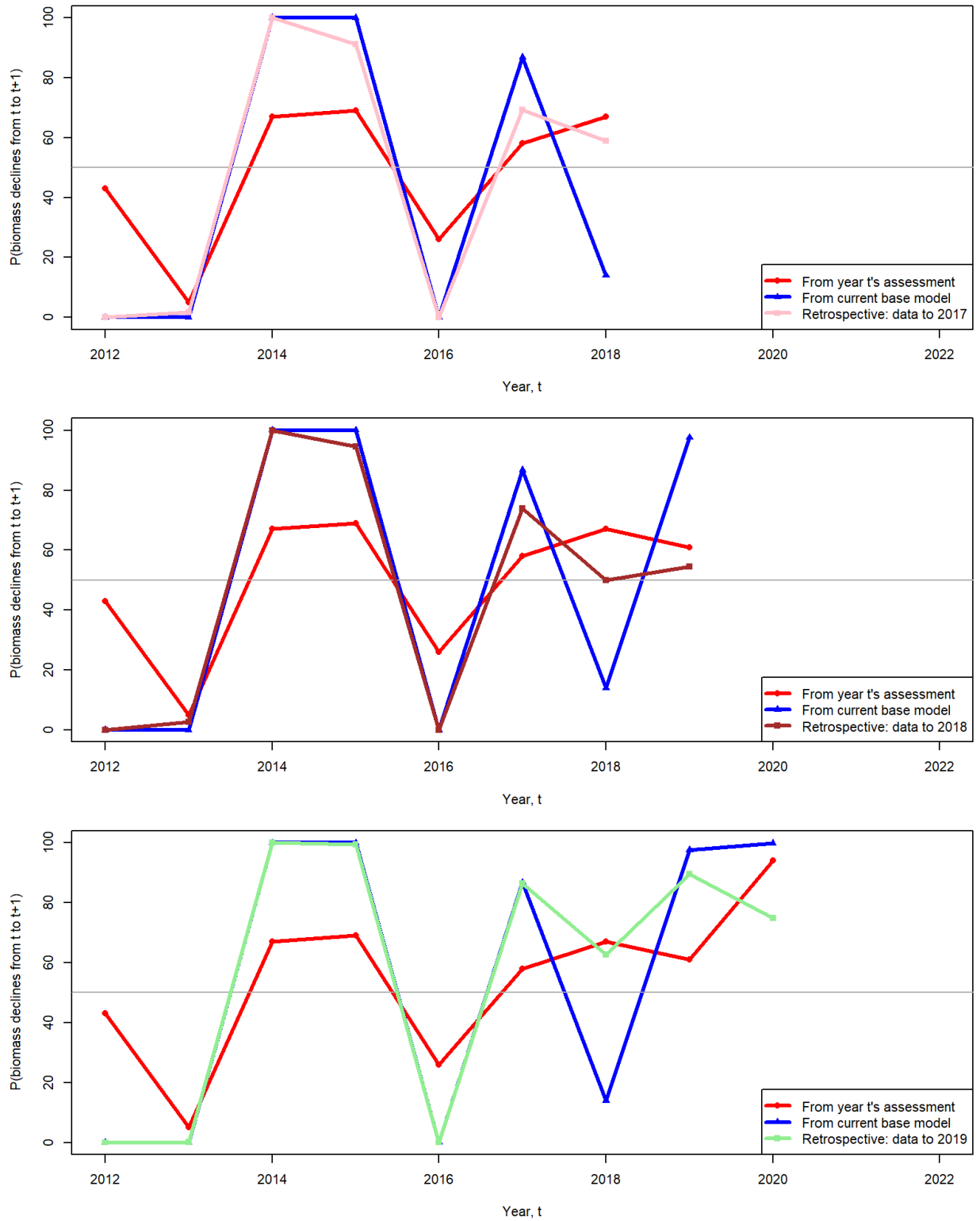


Figure 62. As for Figure 60 for further retrospective years.

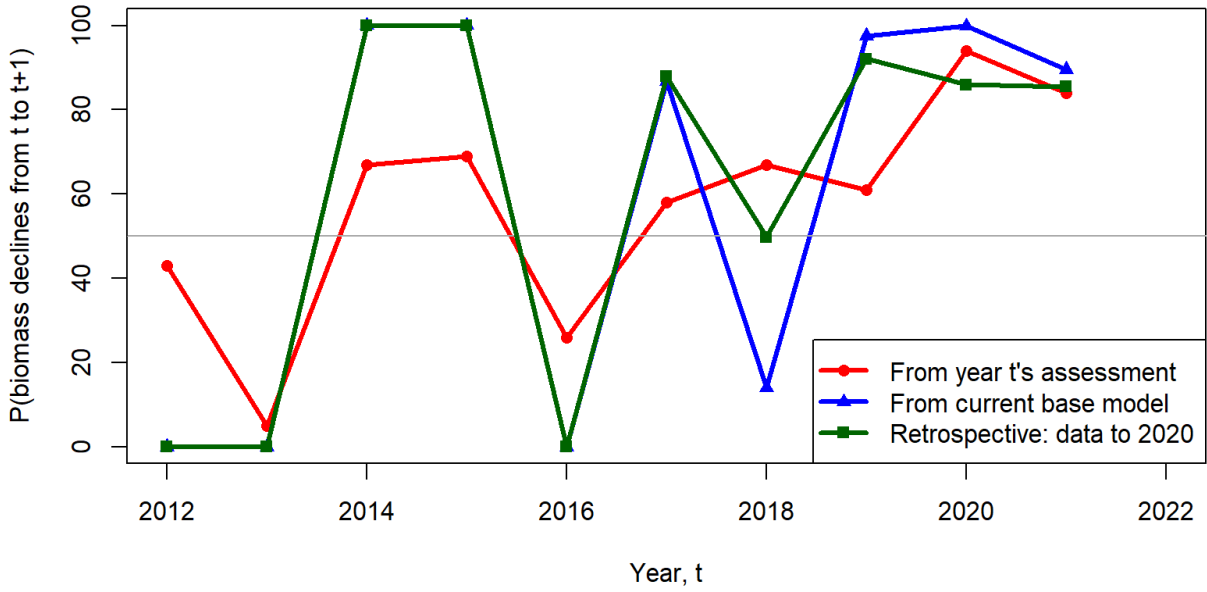


Figure 63. As for Figure 60 for the final retrospective year.

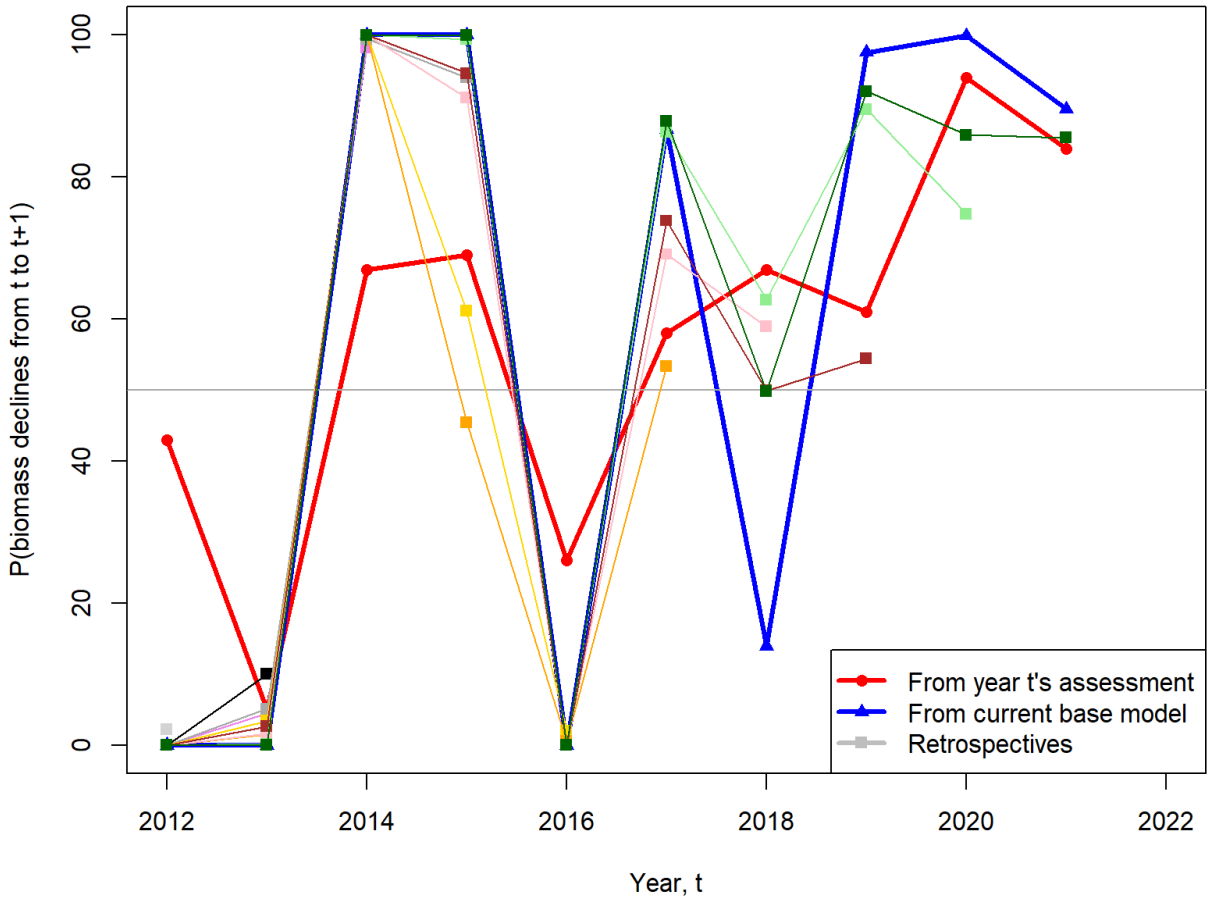


Figure 64. Retrospective results of Figures 60–63 shown in a single panel.

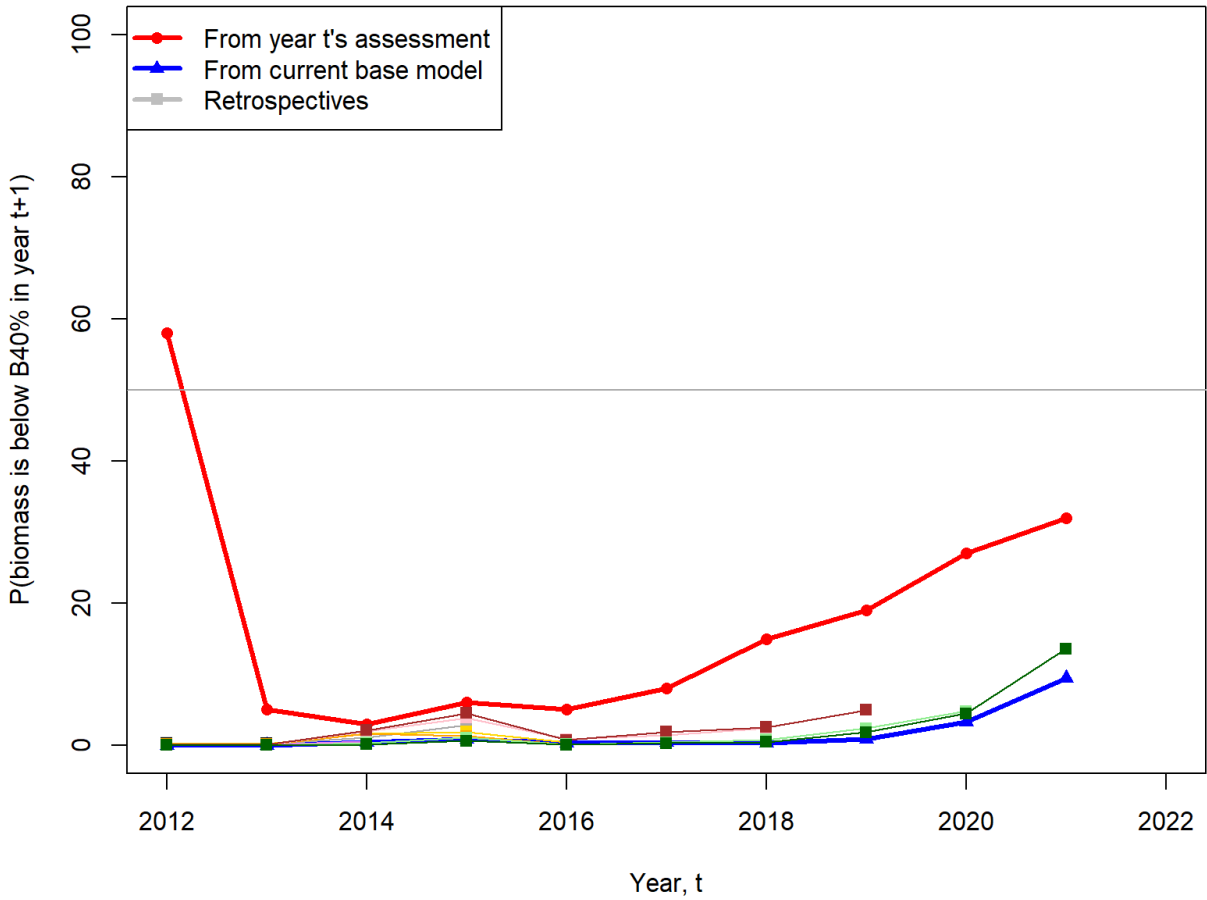


Figure 65. Retrospective results of Figure 59 for $P(B_{t+1} < B_{40\%})$ for each year t .

A BASE MODEL MCMC DIAGNOSTICS

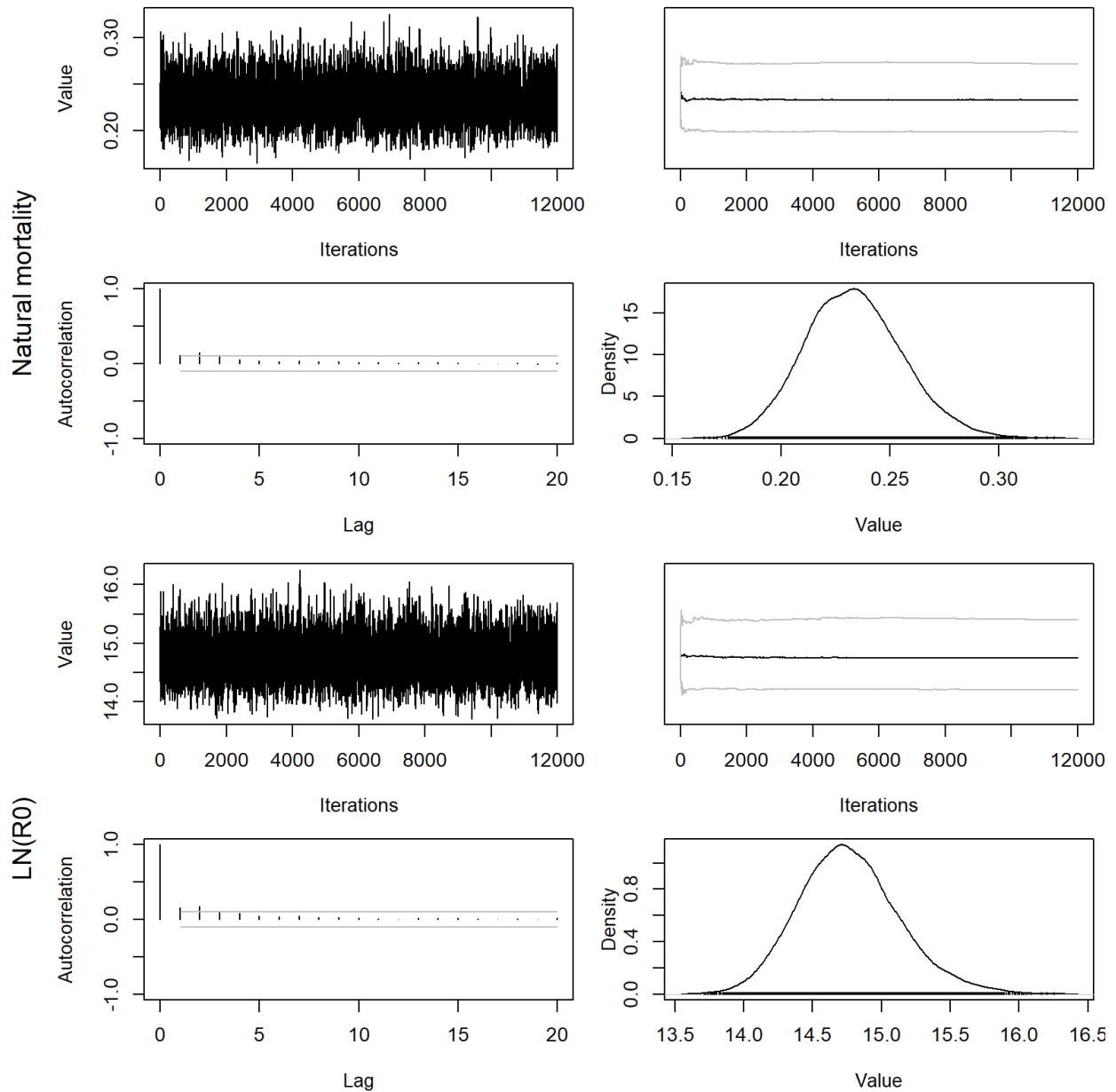


Figure A.1. Summary of MCMC diagnostics for natural mortality (upper panels) and the log of mean unfished equilibrium recruitment ($\log(R_0)$; lower panels) in the base model. Top sub-panels show the trace of the sampled values across iterations (absolute values, top left; cumulative running mean with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

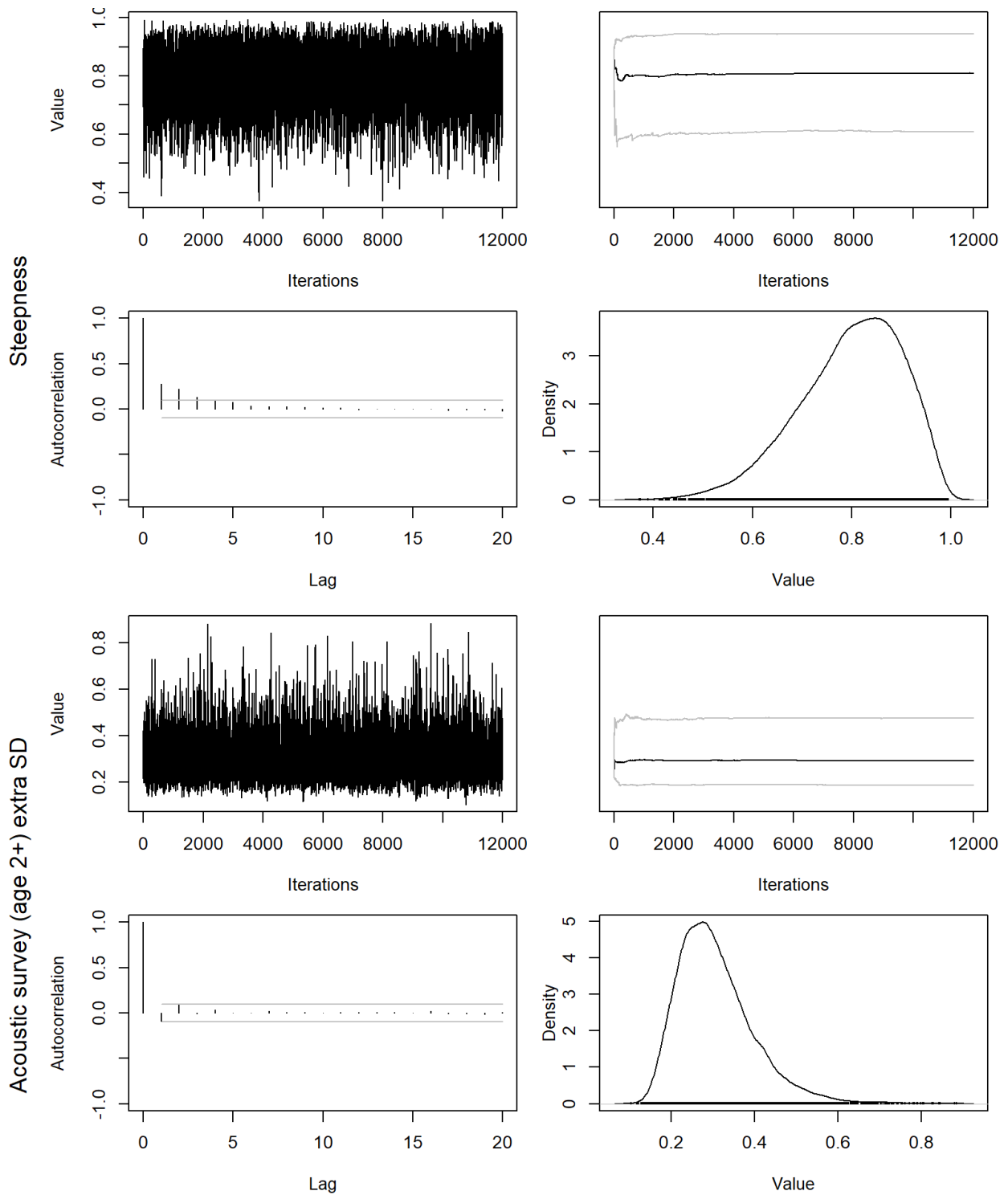


Figure A.2. Summary of MCMC diagnostics for steepness (upper panels) and the additional standard deviation (SD) in the biomass index (lower panels) in the base model. Sub-panel descriptions as in Figure A.1.

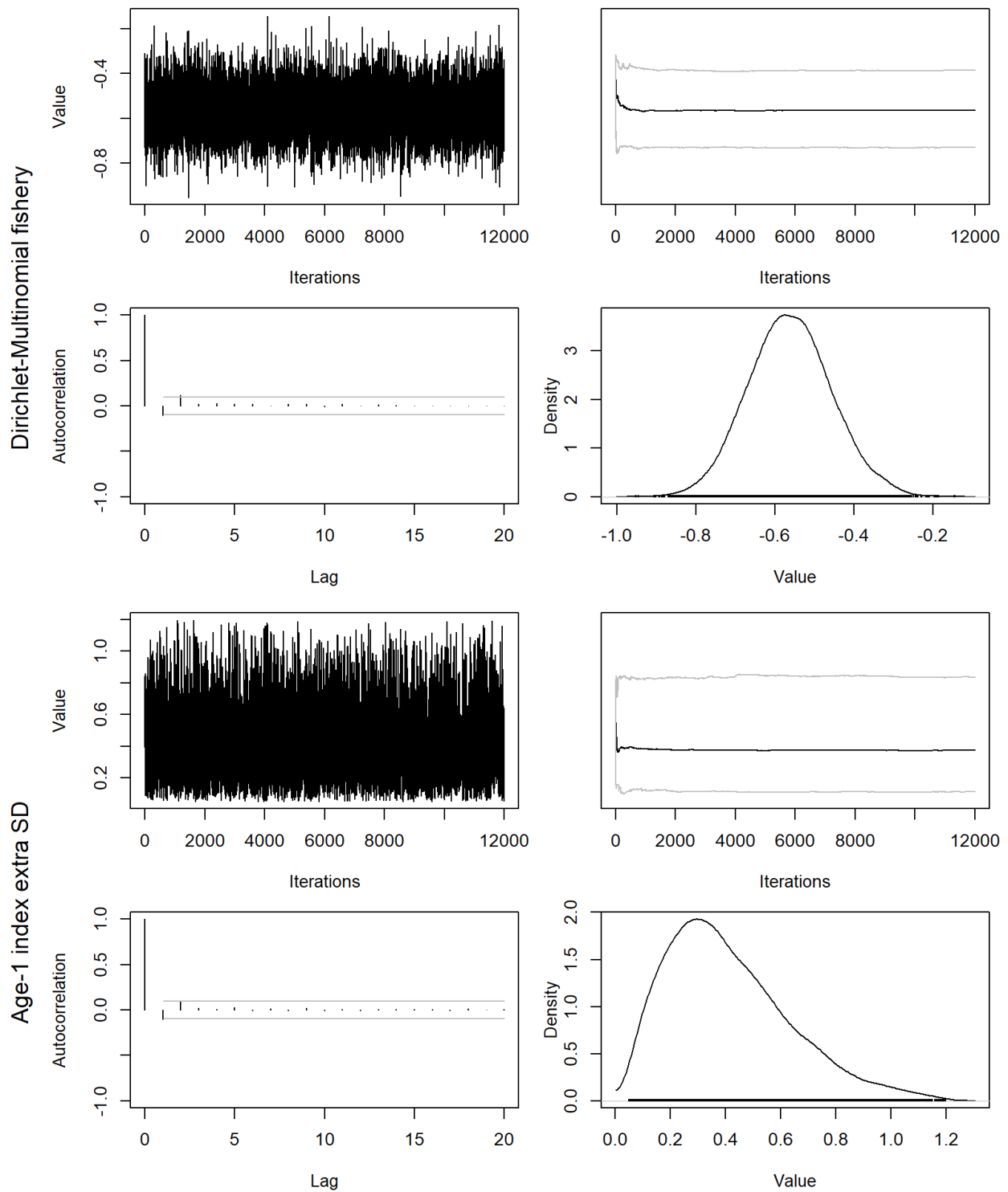


Figure A.3. Summary of MCMC diagnostics for the Dirichlet-multinomial age-composition parameters for the fishery (θ_{fish} , upper panels) and the survey (θ_{surv} , lower panels) in the base model. Sub-panel descriptions as in Figure A.1.

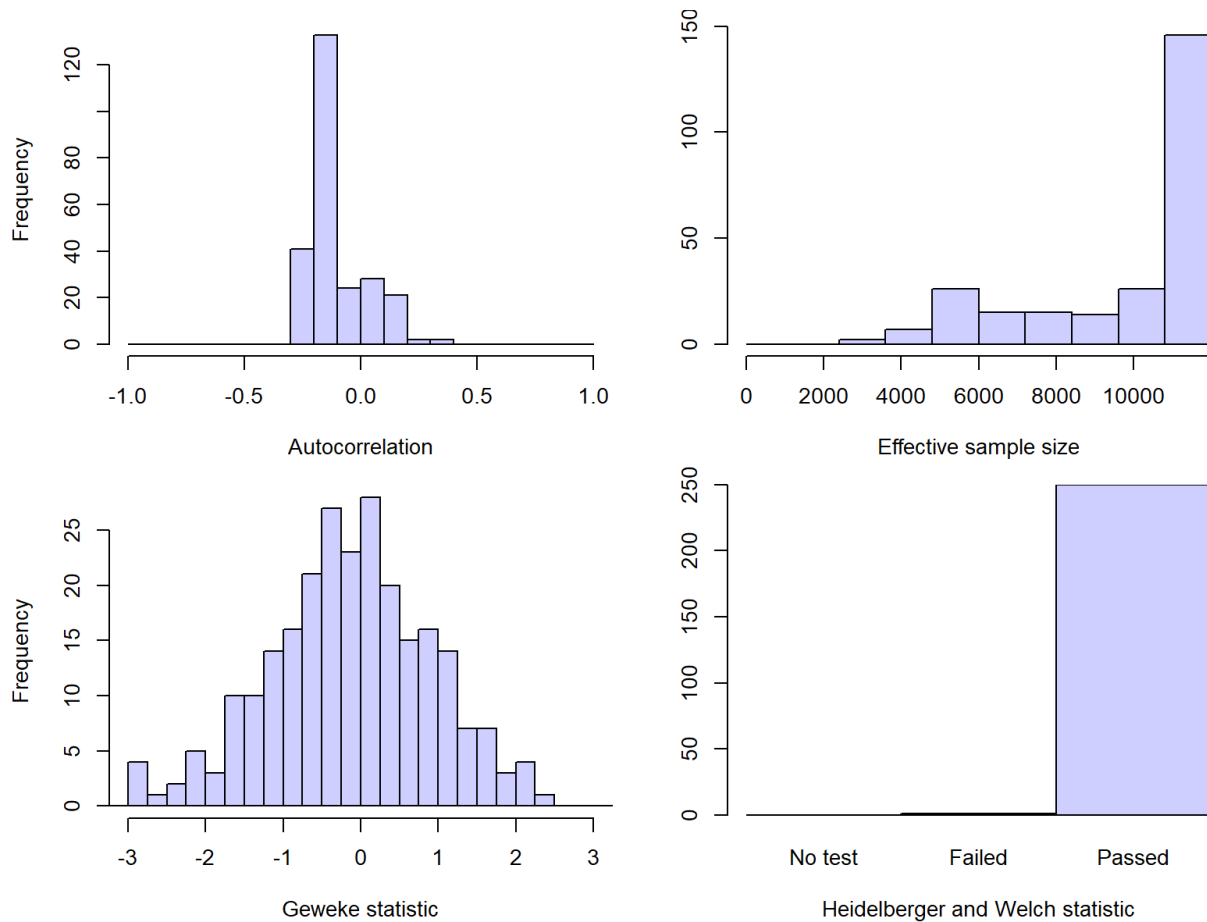


Figure A.4. Summary histograms of MCMC diagnostics for all base model parameters. The level of autocorrelation in the chain (distribution across lag times, i.e., distance between samples in the chain, shown in the top left panel) influences the effective sample size (top right panel) used to estimate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

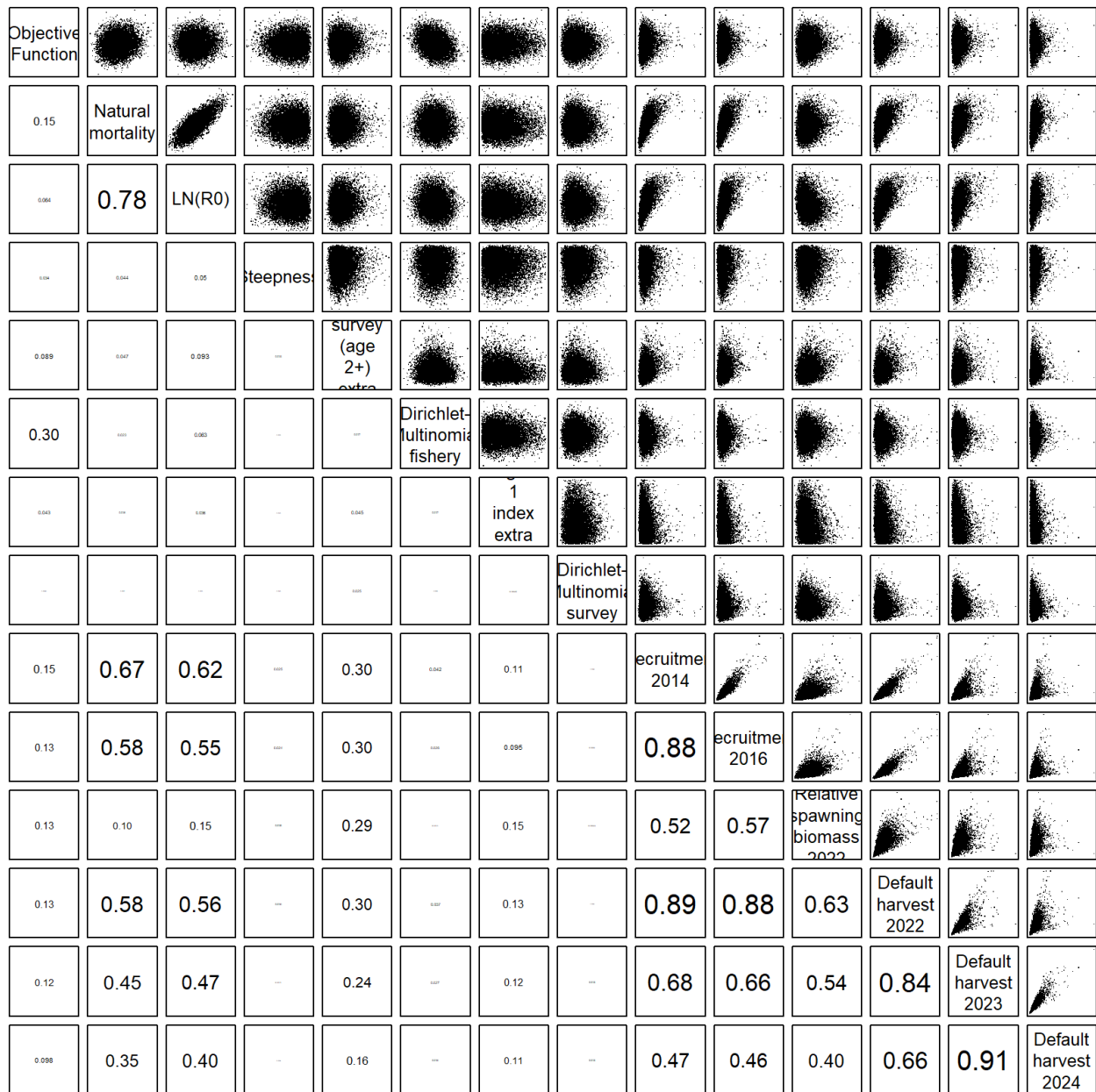


Figure A.5. Posterior correlations among key base-model parameters and derived quantities. Numbers refer to the absolute correlation coefficients, with font size proportional to the square root of the coefficient.

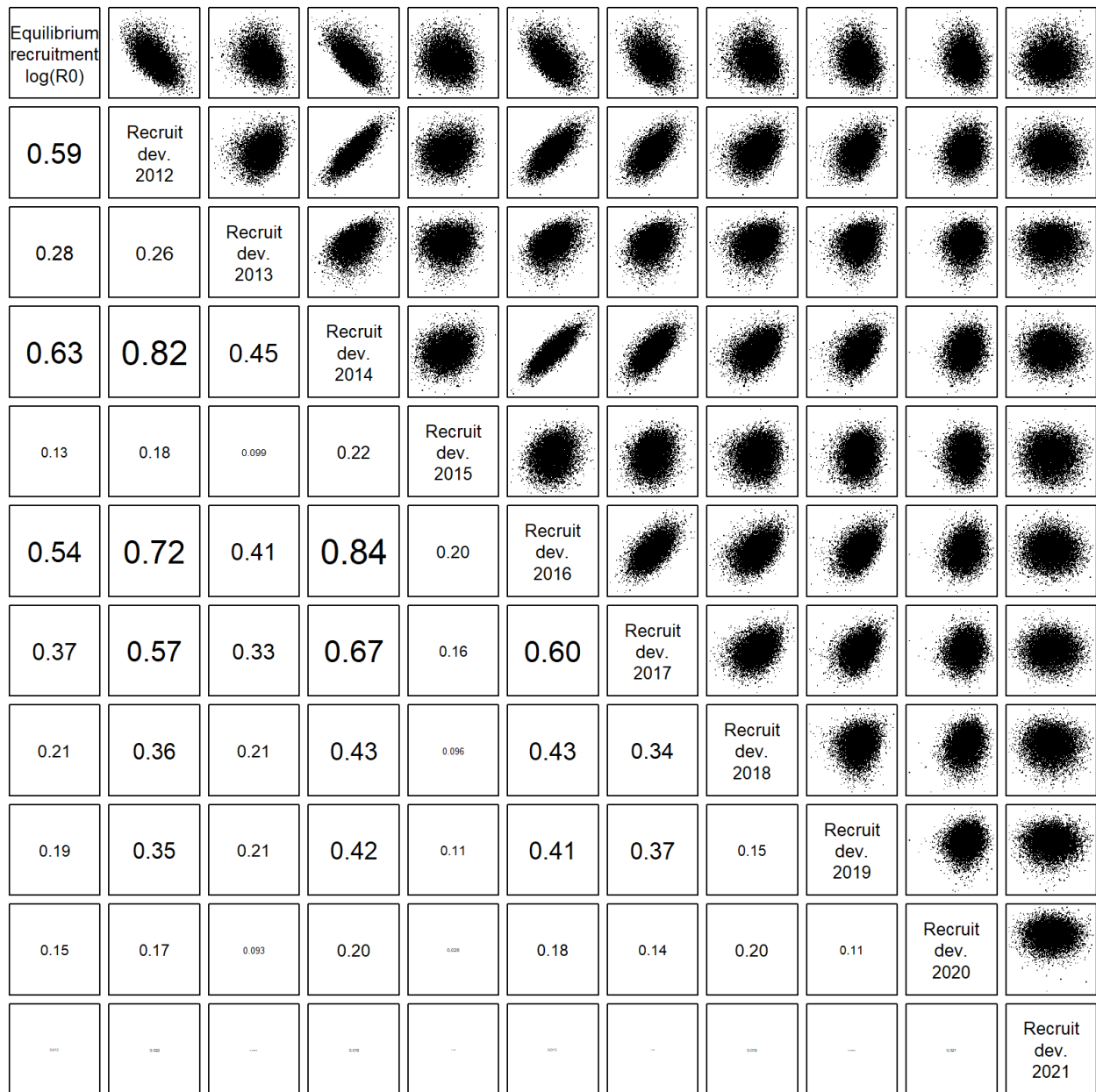


Figure A.6. Posterior correlations among recruitment deviations from recent years and equilibrium recruitment. Numbers refer to the absolute correlation coefficients, with font size proportional to the square root of the coefficient.

B SCIENTIFIC REVIEW GROUP (SRG) REQUESTS FROM 2022 MEETING

This appendix summarizes results produced in response to the Scientific Review Group requests made during the virtual meeting to be held from 14th to 17th February 2022.

B.1 DAY 1

Request 1:

Provide the sum of the recruitment deviates in the main period for the base model and the model without the age-1 index. Also, multiply this sum by the estimated R_0 to determine the average recruitment over the main period (or just calculate the average recruitment?).

JTC Response:

The JTC produced the following table that provides summary characteristics for recruitment during the main recruitment period (1970–2020) for four models: the base model, the sensitivity model that excludes the age-1 index, the sensitivity model that fixes steepness at 1.0, and last year’s (2021) base model. The sum of the recruitment deviates differed slightly among models and, in particular, the difference between the 2021 and 2022 base model was negligible. Average recruitment also differed slightly among models, but was 24% above the median estimate of R_0 from the 2022 base model (2,535 million fish). A consequence of this discrepancy is that equilibrium-based reference points are being estimated using productivity that is not as high as the main recruitment period would otherwise suggest. The JTC plans to investigate the consequences of this inconsistency as part of ongoing dynamic reference point work as highlighted in Section 3.3.

Table B.1. Summary of characteristics for recruitment during the main recruitment period.

Model	Deviates Sum	Average Recruitment (millions)
2022 Base	8.38	3,143
2022 No age-1 index	7.97	2,953
2022 Steepness is 1	7.64	3,090
2021 Base	8.30	2,884

Request 2:

Investigate the fishing intensity decision table to make sure that the numbers are correct. For example, the fishing intensities should be the same for rows with the same 2022 catch. And, please verify that the projections are correct.

JTC Response:

The request was completed during the meeting. The fishing intensity decision tables have been corrected, and the corrected versions are included in this assessment document.

B.2 DAY 2

Request 3:

The SRG requests two additional runs of the model to explore the impact of reducing or increasing the weight assigned to the age composition data from the hydroacoustic survey. We recommend fixing the Dirichlet-multinomial survey weighting parameter to the median of the posterior, and then in run 1, multiplying the input sample size by 0.2, and in run 2 multiplying the input sample size by 2. Run 3, estimate the D-M theta parameter for the alternative input sample size run that multiplies base case input sample size by 2. Runs using MLE estimates would be sufficient, with MCMC runs conducted if possible. Report the posterior distribution for theta, when estimated, and compare to the estimated theta from the base assessment. Report the typical sensitivity plots and fits to the survey age comps (e.g., bottom of Figure 20).

JTC Response:

The JTC configured and ran the requested three additional model runs in MCMC to compare them to the base model. Downweighting (run 1) and upweighting (run 2) survey age compositions when the theta parameter was fixed resulted in very minor changes to survey fit (Figures B.2.1 and B.2.2). Upweighting these data while also estimating the theta parameter (run 3) had no noticeable affect on the age composition fit, but did result in a nearly halving of the survey weight (as expected) and a more normal posterior distribution (Figure B.2.3). Spawning stock biomass and stock size (relative spawning biomass) were largely unaffected by these sensitivity runs (Figure B.2.4). However, there were minor changes in recruitment and in the overall fit to the acoustic survey biomass index (Figure B.2.5). Overall, the largest changes were associated with the downweighting run for specific years (e.g., 2003), where the relatively less important survey age compositions (in terms of total likelihood) in this case gave other data points (e.g., fishery age compositions) more flexibility (relative to the base model) to influence fits (Figure B.2.5, bottom panel).

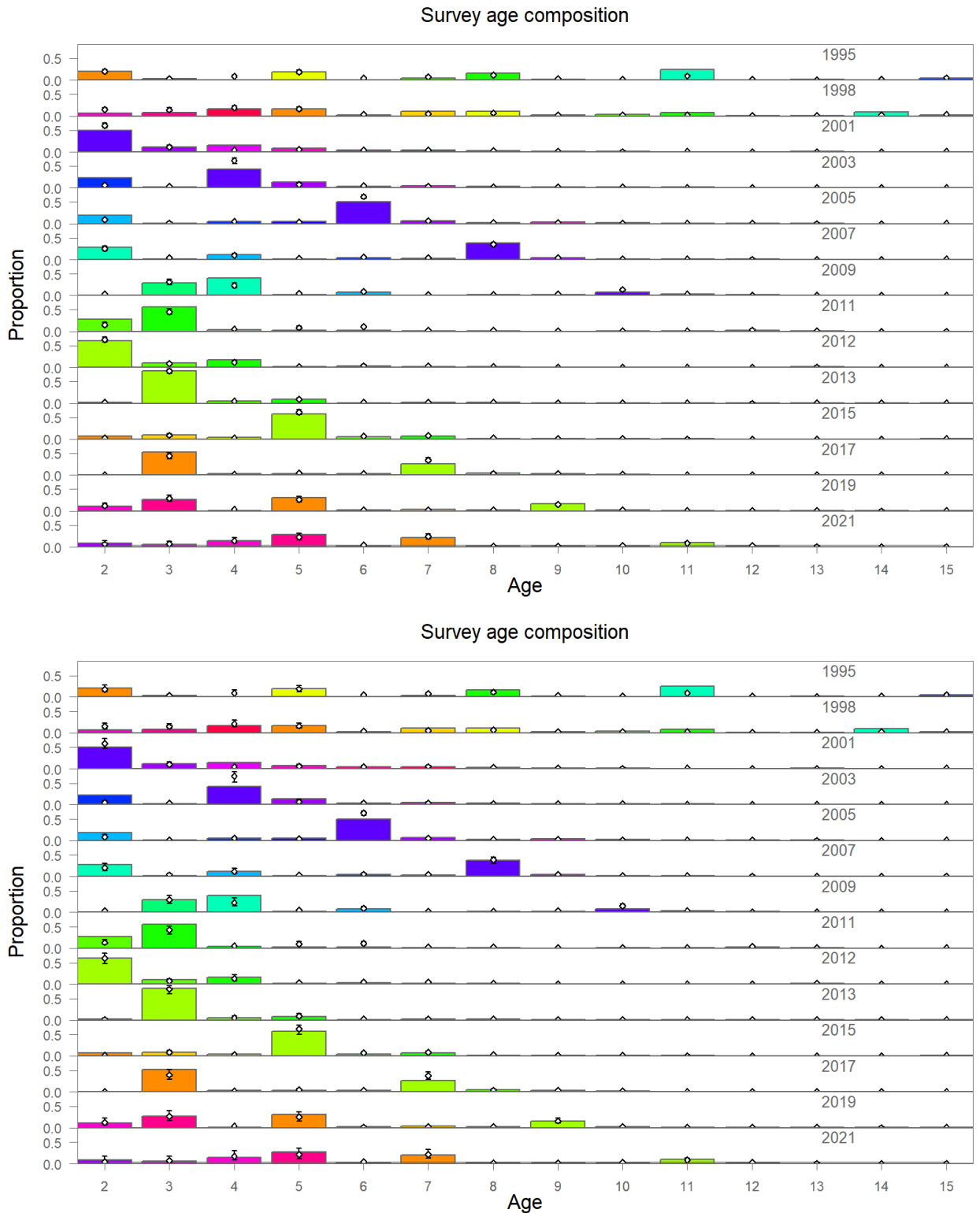


Figure B.2.1. Base model fits to the observed acoustic survey age-composition data for the base (top) and alternative run 1 (bottom) models. Colored bars show observed proportions with colors following each cohort across years. Points with intervals indicate median expected proportions and 95% credibility intervals from the MCMC calculations.

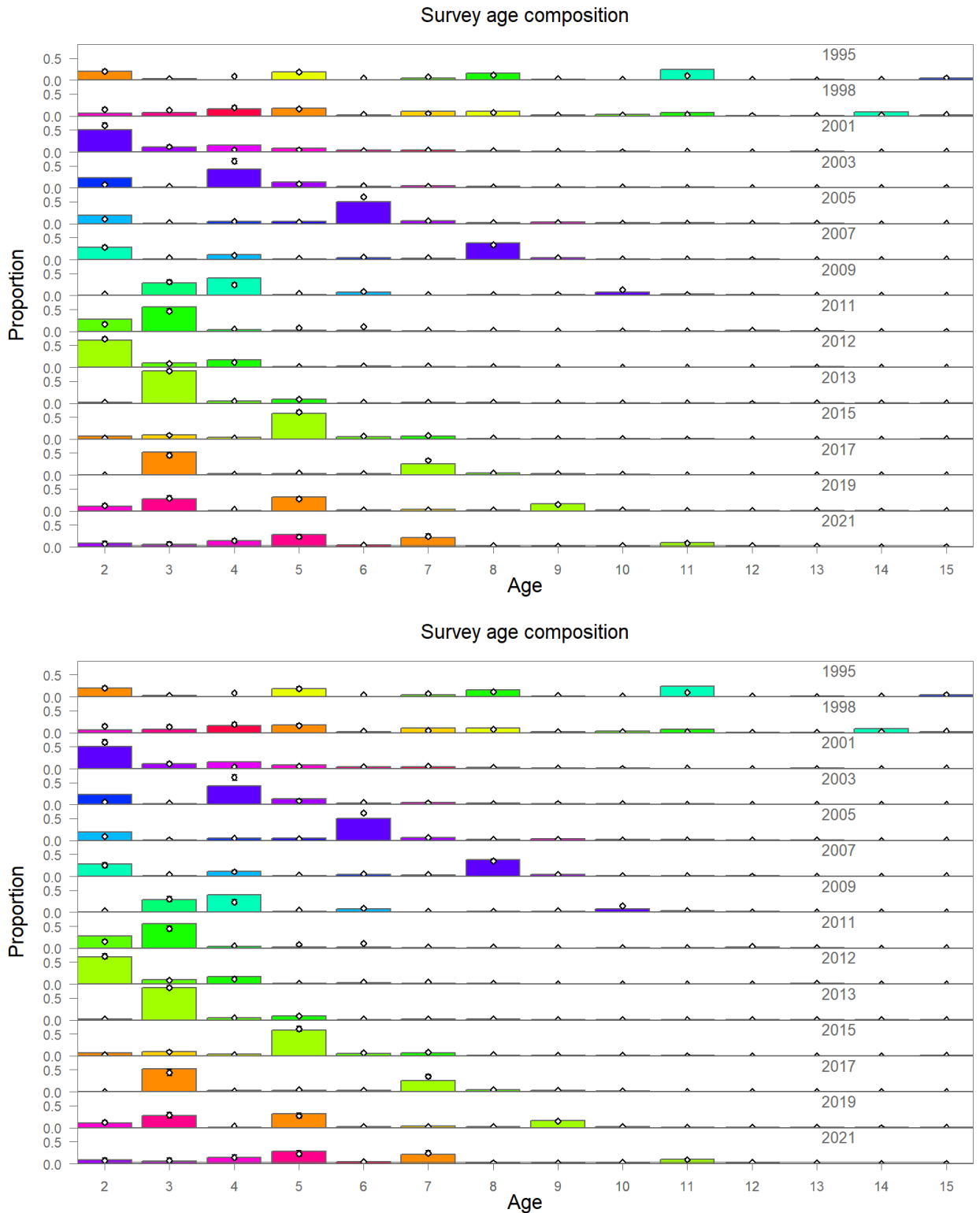


Figure B.2.2. Base model fits to the observed acoustic survey age-composition data for the alternative run 2 (top) and alternative run 3 (bottom) models. Colored bars show observed proportions with colors following each cohort across years. Points with intervals indicate median expected proportions and 95% credibility intervals from the MCMC calculations.

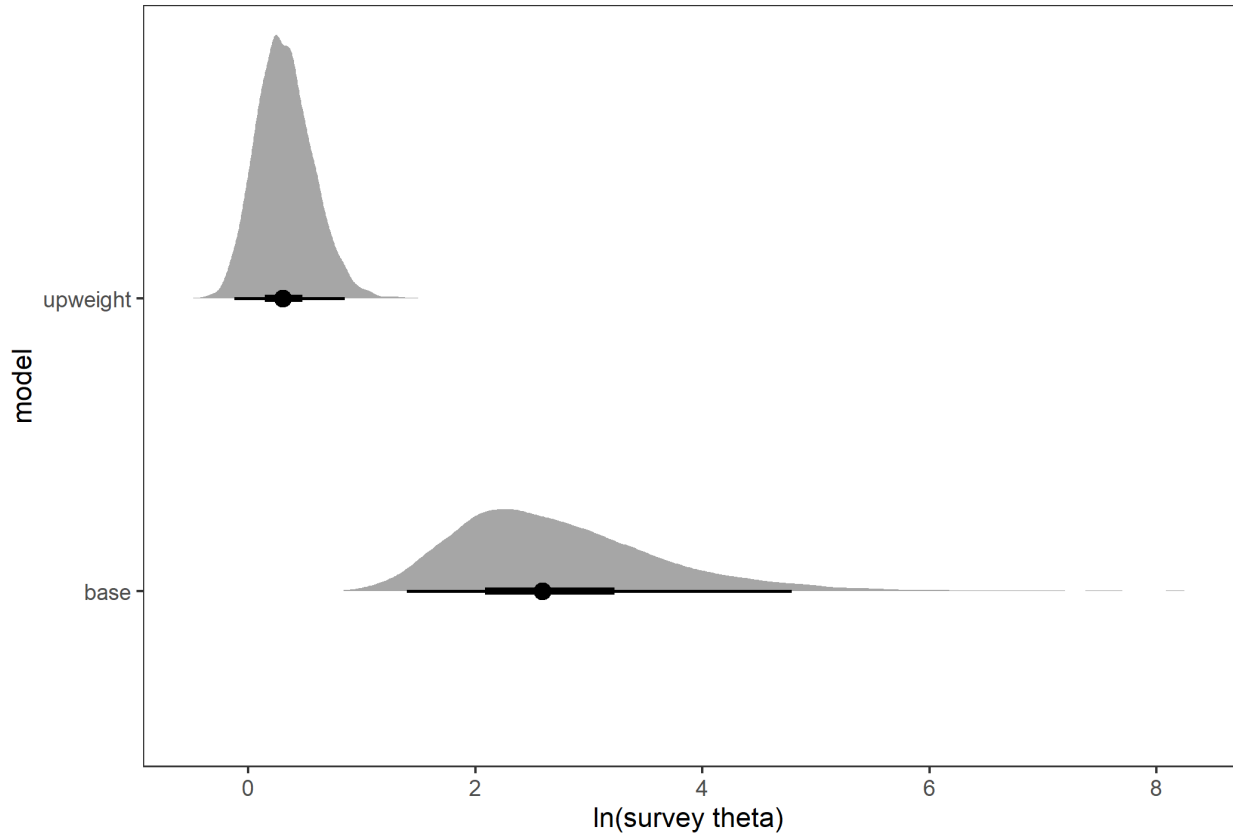


Figure B.2.3. The posterior distribution is shown for the survey theta parameter for the base (bottom) and alternative run 3 (top) models. Distribution summaries are provided by the black circle (median) thick bar (50% quantile), and thin bar (90% quantile).

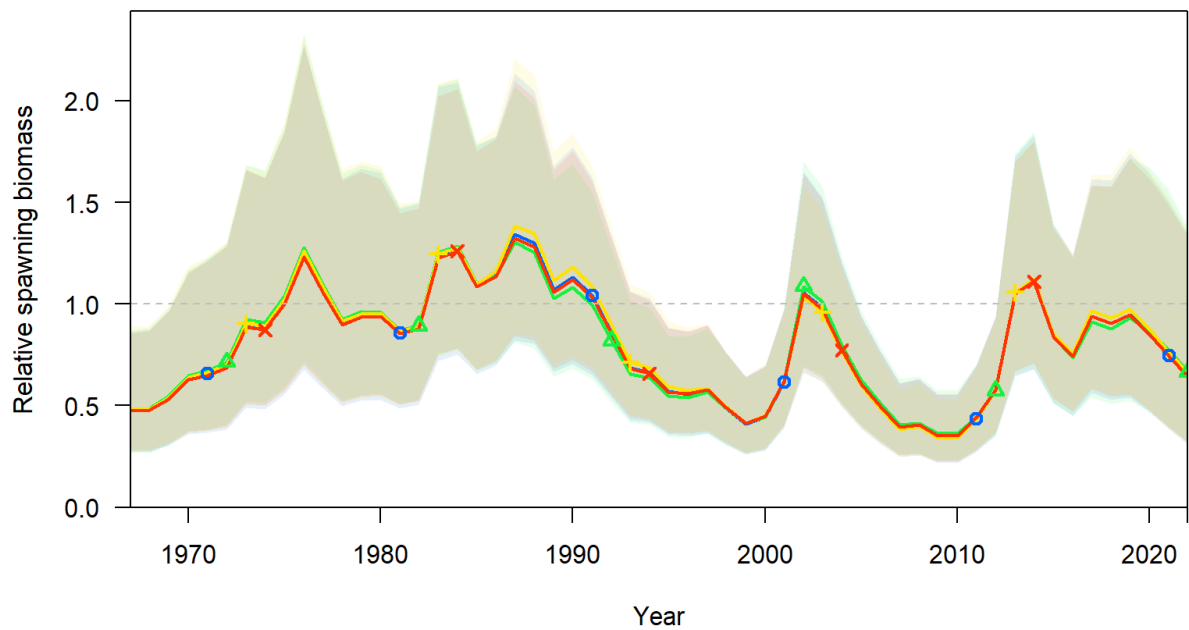
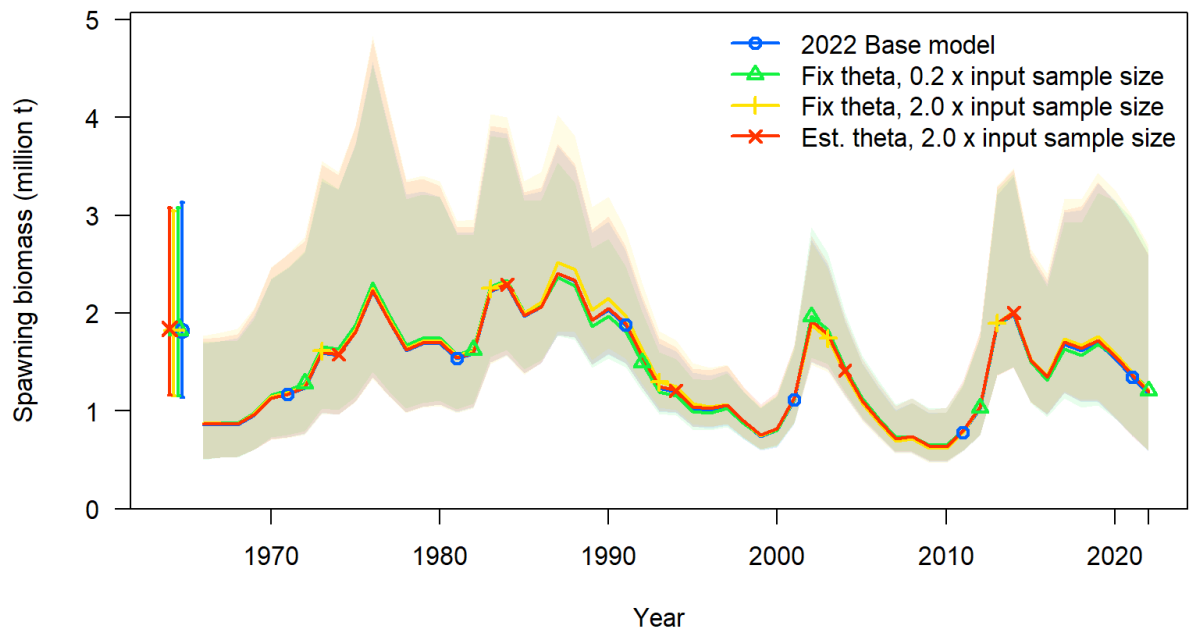


Figure B.2.4. MCMC estimates of spawning biomass (top) and stock status (relative spawning biomass; bottom) for the base model and the three alternative model runs.

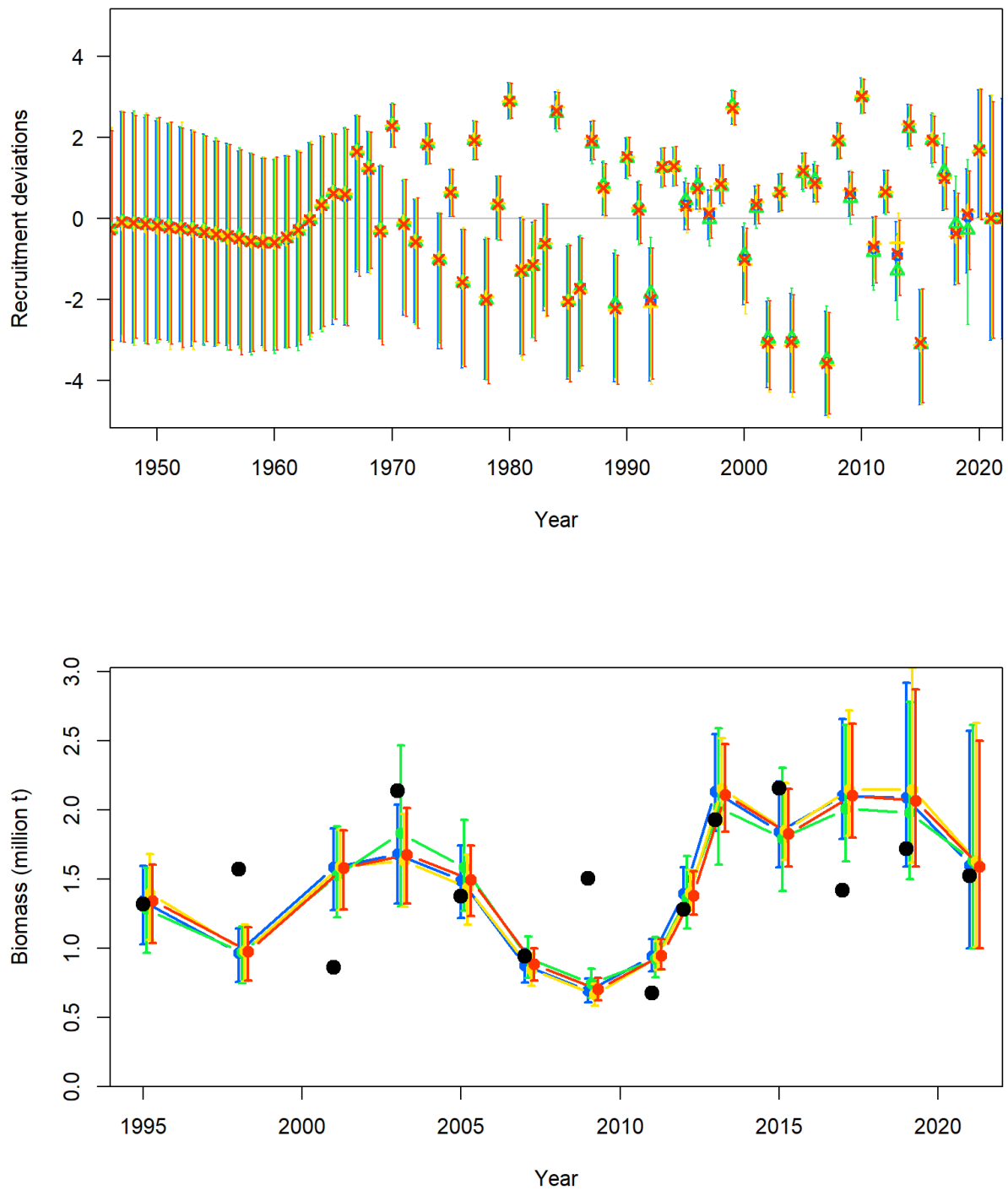


Figure B.2.5. MCMC estimates of recruitment deviations (top) and the fit to the biomass index (bottom) for the base model and the three alternative model runs.

B.3 FURTHER ANALYSES

Several other data and model explorations were conducted during the review panel week. In particular, the JTC responded to an ‘informal’ SRG request to run an additional projection using a constant catch of 525,000 t and show results in decision tables in the final assessment document (see Appendix I). In addition to SRG Request 3, a closer look at the posterior distribution of the survey weighting factor (back-transformed survey Dirichlet-Multinomial theta parameter) was conducted to evaluate estimation properties near the upper bound of one (Figure B.3.1). An additional sensitivity run (in MLE) was conducted to examine how the stock trajectory (Figure B.3.2) and recruitment (Figure B.3.3) are influenced by the removal of the most recent (2021) and the two most recent (2019 and 2021) age-1 index data points relative to the base model. Overall, removing these data points reduces the size of the 2020 year class and the 2018 year class (as expected), which alters the stock trajectory in the final years of the time series.

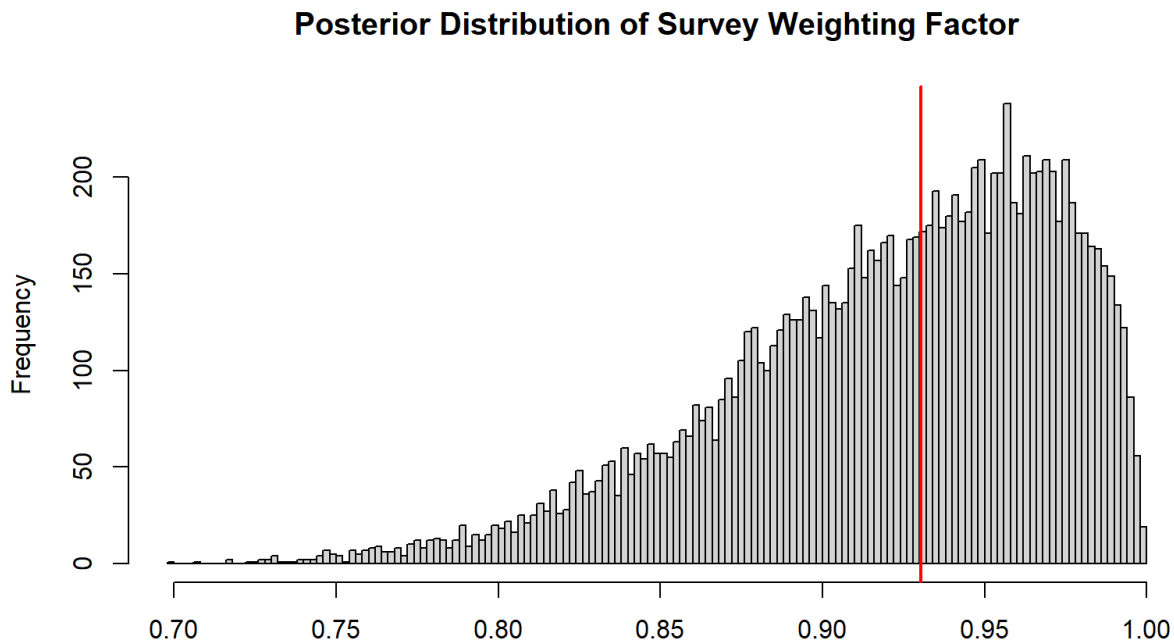


Figure B.3.1. Posterior distribution of the weighting factor for survey age composition data from the base model.

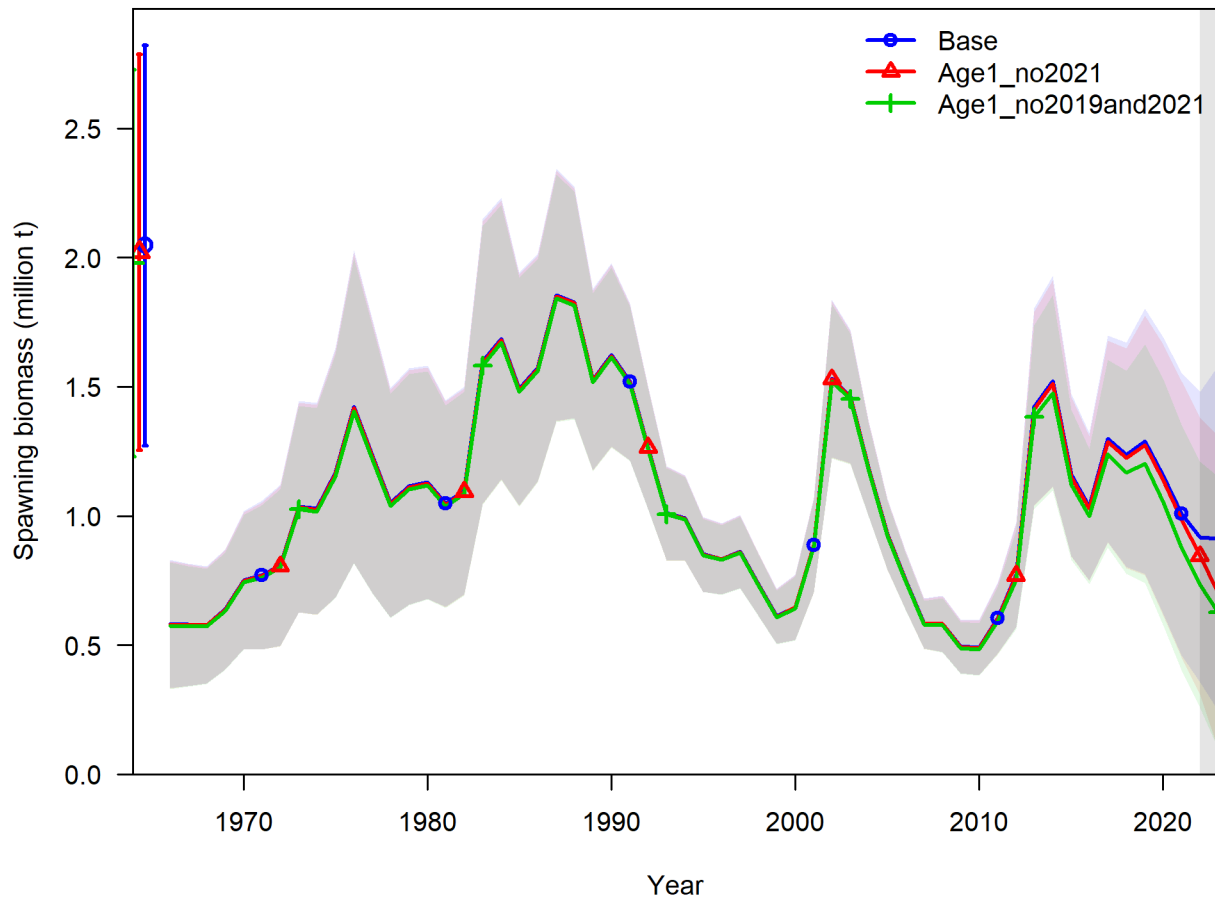


Figure B.3.2. Maximum likelihood estimates of spawning stock biomass for the base model and alternative models that systematically remove recent age-1 data points.

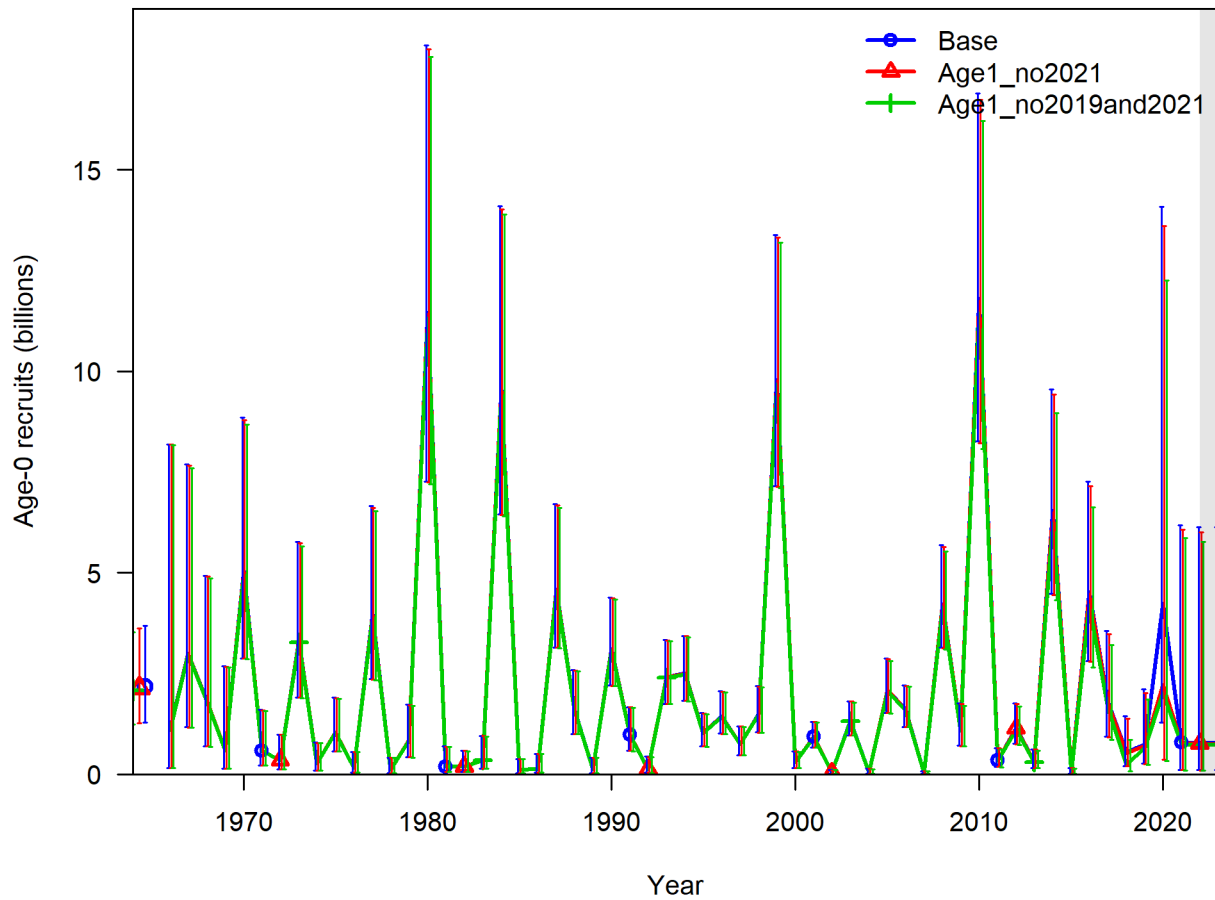


Figure B.3.3. Maximum likelihood estimates of recruitment for the base model and alternative models that systematically remove recent age-1 data points.

C GLOSSARY OF TERMS AND ACRONYMS USED IN THIS DOCUMENT

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

ABC: Acceptable biological catch. See below.

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

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

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

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

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

B_0 : The unfished equilibrium female spawning biomass.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

spawning ratio). Therefore

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

MCMC: Markov-Chain Monte-Carlo (see above).

MLE: Maximum likelihood estimate (see above).

MSE: Management Strategy Evaluation (see above).

MSY: Maximum sustainable yield (see above).

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

NA: Not available.

National Marine Fisheries Service: See NOAA Fisheries below.

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

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

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

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

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

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

OM: Operating Model (see above).

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

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

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

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

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

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

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

q : Catchability (see above).

R_0 : Estimated annual recruitment at unfished equilibrium.

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

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

Relative fishing intensity: See definition of fishing intensity.

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

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

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

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

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

Simulation: A model evaluation under a particular state of nature, including combinations of parameters controlling stock productivity, stock status, and the time series of recruitment deviations. In this assessment, there are 12,005 simulations used to characterize alternative states of nature, each of which are based on a sample from the posterior distribution of the parameters, as calculated using MCMC, for a particular model (e.g., the base model).

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

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

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

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

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

SPR: Spawning potential ratio (see above).

SPR_{40%}: See target spawning potential ratio.

SS: Stock Synthesis (see below).

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

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

Target spawning potential ratio (SPR_{40%}): The spawning potential ratio of 40%, where the 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 spawning biomass of $B_{40\%}$ because $F_{\text{SPR}=40\%}$ is defined in terms of the spawning potential ratio which depends on the spawning biomass *per recruit*.

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

TAC: Total allowable catch (see below).

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

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

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

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

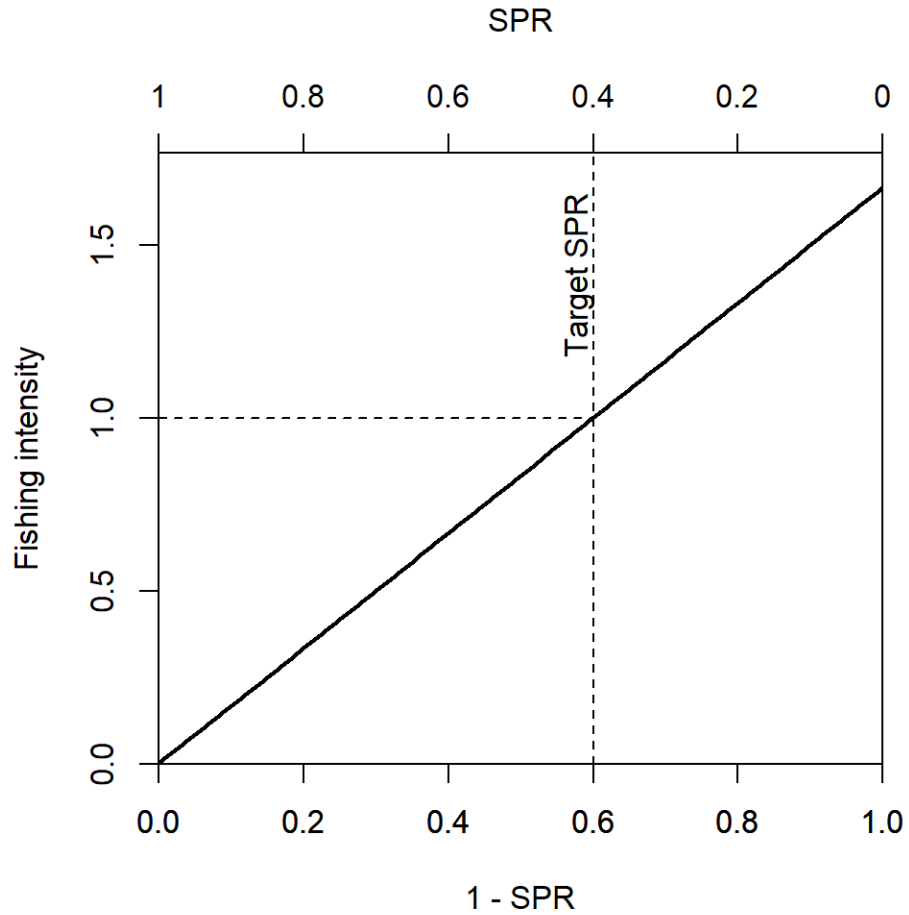


Figure C.1. Fishing intensity as a function of SPR (top axis) and 1-SPR (bottom axis); given the target SPR of 40%, the bold line is simply $1/0.6$, as shown in equation (C.5).

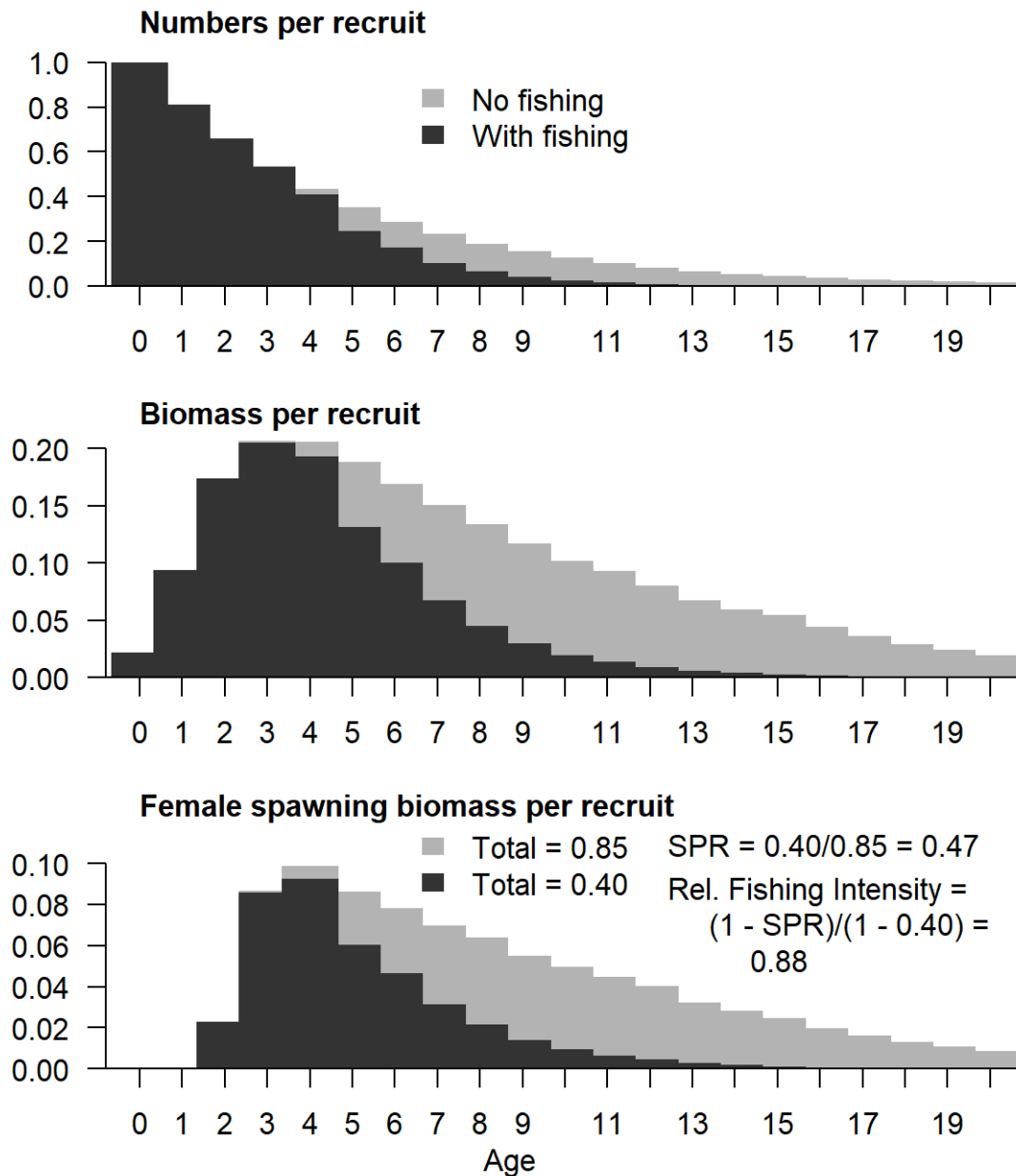


Figure C.2. Illustration of the spawning potential ratio (SPR) calculation based on the combination of maturity and fecundity used in the model, using the maximum likelihood estimates of natural mortality, selectivity, and fishing mortality in the final year of the base model from the 2021 assessment (Johnson et al., 2021).

D REPORT OF THE 2021 PACIFIC HAKE FISHERY IN CANADA

Prepared by the Canadian Advisory Panel and submitted for inclusion in this assessment document on January 4, 2022.

While there was some exploratory hake fishing in early April, significant effort and catch didn't start until late April and early May and continued through to mid October. The fishery ended in early November. A total of 55,771 tonnes of hake was caught in 2021 which equates to 53% of the Adjusted TAC of 104,480 tonnes

Low hake abundance, choke species such as Rougheye/Blackspotted and Bocaccio, and COVID related restrictions all negatively impacted the Canadian offshore hake fishery in 2021.

Hake fishing occurred from the southern Canada/US border all the way up to lower Queen Charlotte Sound both on the shelf and off the edge at depths between 40-180 fathoms.

The general view from the Canadian fleet is that, especially in the shallower depths on the shelf or just off the edge, the hake abundance was lower in 2021, with much more time spent searching for fish, and when found was patchy and couldn't sustain effort as long as in 2020, which was also poorer than 2019. This impacted all vessels, especially vessels delivering fresh fish for shoreside processing.

Fishing was much more difficult this year. The season started later than normal and ended earlier. Some wet boats never left the dock and others had short season because it wasn't economically viable. The abundance in Canada was considerably lower. Towing time was almost double last year's and there was considerably more searching for fish. Catches were sporadic throughout the season due in part to reduced abundance but also due to concentrated effort on the shelf. Most of the fishing was on the shelf in shallower water due to restrictive Rougheye/Blackspotted rockfish quota availability that moved vessels away from the deeper sets.

A significant share of the catch occurred south between the Canada/US border and Tofino in depths ranging from 40 - 180 fathoms. There was also an amount of catch more north between Brooks Peninsula and Cape Scott Channel in depths ranging from 65 - 165 fathoms. Generally the fish were caught deeper in the spring (120 - 180 fathoms) and shallower in the summer (40 - 70 fathoms).

Most of the fish were the same size and year class. The average size this year was approximately 800 grams round weight. There were very few signs of small fish (less than 500 grams).

Off the edge and in the deeper water there was Rougheye/Blackspotted and Pacific Ocean Perch rockfish bycatch that moved the fleet onto the shelf and into shallower areas. On the shelf the primary bycatch problem this year was Walleye pollock which became limiting on the fishery because of the quantity of catch relative to the pollock TAC for the area. Also in the shallows there was bycatch of smaller quantities of Bocaccio, greenies, brownies, Pacific Ocean Perch, canaries, redstripes and juvenile sablefish.

E REPORT OF THE 2021 PACIFIC HAKE FISHERY IN THE UNITED STATES

Prepared by the United States Advisory Panel and submitted for the Canada/US Joint Management Committee's and the Joint Technical Committee's consideration on January 25, 2022.

The Mothership (MS), Catcher Processor (CP), and Shoreside (SS) sectors of the U.S. fishery started on May 15, 2021. The Tribal sector also began fishing in the spring and operated throughout the 2021 season; however, effort was limited to shoreside deliveries largely via use of a tender vessel. Consistent with normal fishing patterns, the SS sector ramped-up across the spring and continued to harvest and process its allocation throughout the summer, while the MS and CP sectors completed their spring fishery in June and then paused hake fishing and processing until after the completion of the Bering Sea pollock fishery. Relative to 2020, although still significant, the direct and indirect impacts of COVID-19 had less of an effect on the industry. Overall, effort in the spring fishery was close to normal, especially in comparison to 2020 where COVID-19 outbreaks caused several processor closures and vessel port calls. Nonetheless, several vessels had delays to their start in the at-sea sector due to COVID related issues and the ongoing challenges associated with maintaining a full labor force were still significant for many shoreside and at-sea processors throughout the 2021 season.

Fishery performance overall and throughout the 2021 season was very good in terms of catch per unit effort (CPUE), fish size, wide spread availability on the grounds and in proximity to the plants, and lower than normal incidental catch rates for the typical rockfish and Chinook bycatch species. During the spring fishery, participants reported stronger schools of fish than in recent years with fishing effort spread out along the coast from north to south and in both deep and shallow bottom depths. Over the course of the 2021 season, the at-sea sectors caught fish in the 500–700 gram range, as well as significant amounts of hake of about 400 grams (on average) in May and October. There was consistent, but limited catch of hake larger than 600 grams, primarily in October, and trace amounts of smaller hake (less than 250 grams) were encountered throughout the season. In general, fish size remained consistent throughout the year with the SS plants noting little change in quality, size, and condition through the spring, summer and fall. Throughout the entire year, fish quality was excellent with "healthy and fat" fish being reported by at-sea and shoreside processors alike.

Fall fishery effort in the at-sea sectors began in mid-September, with CPs fishing the second week of September and MS operations starting back up in late September/early October. Nine CPs and three MS vessels participated in the fall fishery, with some vessels out of commission for maintenance and shipyard work. Participating vessels reported excellent fishing and the best fall fishing seen in recent years, especially in September and early October. A series of major storms in mid/late October and typical hake migratory patterns reduced fishery productivity later in the fall. SS operations began to taper off by mid-October. MS operations ended in mid- October. CP operations ended in mid-November. While bycatch patterns were generally typical in the fall at-sea fishery, the occurrence of large amounts of less typical species, such as jack mackerel, were challenging because these species were often mixed with dense hake schools.

Hake were present consistently in the U.S. zone throughout the 2021 season. Fishing was good on strong schools from the start of the fishery in May up to mid-October, when extraordinarily strong storms hampered fishing effort. Bycatch monitoring and avoidance continued to be a primary driver of U.S. fishing patterns. In addition to usual species of concern (widow rockfish, canary rockfish, darkblotched rockfish, yellowtail rockfish, sablefish, and Chinook salmon), the emergence of unusually large amounts of "new" species, such as shortbelly rockfish, jack mackerel, and pacific (blue) mackerel proved challenging at times. No significant bycatch was observed in the SS sector other than a few trips with some darkblotched rockfish and shortbelly rockfish. The SS sector also reported that bycatch of yellowtail rockfish, which can be constraining for some vessels, was very low overall in 2021, despite some early season encounters, particularly in the mothership sector. Fishery participants believe that the lower than normal bycatch correlates, in part, to the improved CPUE experienced in 2021. The use of cooperatives in each sector of the non-tribal fishery, near real-time observer data, and third-party monitoring by Sea State Inc. continue to provide fishery participants the necessary tools to closely monitor fishery progress, share information broadly across the fishery, and minimize bycatch of non-target species.

Overall, the U.S. harvest in 2021 decreased slightly from 287,314 in 2020 to 269,300 in 2021 [these values may be slightly different than in the stock assessment due to the timing of data extraction]. Utilization rates were generally consistent with those projected by industry at the March 2021 JMC meeting - SS sector before Tribal release was 99% (89% following Tribal release), CP sector before Tribal release was 100% (90% following Tribal release), and MS sector was 48% before Tribal release (43% following Tribal release). Utilization in the MS sector, as projected pre-season, was low due to several processors being unable to participate in the spring fishery and/or in the fall fishery due to shipyard schedules.

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	0.2328
SR_LN(R0)	14.7459
SR_BH_steep	0.8097
Q_extraSD_Acoustic_Survey(2)	0.2921
Q_extraSD_Age1_Survey(3)	0.3729
ln(DM_theta)_1	-0.5640
ln(DM_theta)_2	2.5911
Early_InitAge_20	-0.2660
Early_InitAge_19	-0.0845
Early_InitAge_18	-0.1166
Early_InitAge_17	-0.1476
Early_InitAge_16	-0.1375
Early_InitAge_15	-0.1887
Early_InitAge_14	-0.2449
Early_InitAge_13	-0.2748
Early_InitAge_12	-0.3444
Early_InitAge_11	-0.3956
Early_InitAge_10	-0.4370
Early_InitAge_9	-0.4872
Early_InitAge_8	-0.5658
Early_InitAge_7	-0.5776
Early_InitAge_6	-0.5737
Early_InitAge_5	-0.5105
Early_InitAge_4	-0.2729
Early_InitAge_3	-0.0279
Early_InitAge_2	0.3361
Early_InitAge_1	0.6390
Early_RecrDev_1966	0.5557
Early_RecrDev_1967	1.6629
Early_RecrDev_1968	1.2233
Early_RecrDev_1969	-0.2866
Main_RecrDev_1970	2.2834
Main_RecrDev_1971	-0.1026
Main_RecrDev_1972	-0.5596
Main_RecrDev_1973	1.8386
Main_RecrDev_1974	-1.0125
Main_RecrDev_1975	0.6442
Main_RecrDev_1976	-1.5929
Main_RecrDev_1977	1.9306
Main_RecrDev_1978	-1.9982
Main_RecrDev_1979	0.3540
Main_RecrDev_1980	2.9040
Main_RecrDev_1981	-1.3204
Main_RecrDev_1982	-1.1599
Main_RecrDev_1983	-0.6202
Main_RecrDev_1984	2.6682
Main_RecrDev_1985	-2.0324
Main_RecrDev_1986	-1.7199
Main_RecrDev_1987	1.9185

Continued on next page

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

Parameter	Posterior median
Main_RecrDev_1988	0.7689
Main_RecrDev_1989	-2.1931
Main_RecrDev_1990	1.5051
Main_RecrDev_1991	0.2673
Main_RecrDev_1992	-2.0571
Main_RecrDev_1993	1.2529
Main_RecrDev_1994	1.2805
Main_RecrDev_1995	0.3267
Main_RecrDev_1996	0.7386
Main_RecrDev_1997	0.1090
Main_RecrDev_1998	0.8359
Main_RecrDev_1999	2.7395
Main_RecrDev_2000	-1.0088
Main_RecrDev_2001	0.3372
Main_RecrDev_2002	-3.0505
Main_RecrDev_2003	0.6371
Main_RecrDev_2004	-3.0549
Main_RecrDev_2005	1.1730
Main_RecrDev_2006	0.8745
Main_RecrDev_2007	-3.5619
Main_RecrDev_2008	1.9189
Main_RecrDev_2009	0.6161
Main_RecrDev_2010	3.0217
Main_RecrDev_2011	-0.7372
Main_RecrDev_2012	0.6504
Main_RecrDev_2013	-0.9190
Main_RecrDev_2014	2.2808
Main_RecrDev_2015	-3.1123
Main_RecrDev_2016	1.9404
Main_RecrDev_2017	1.0013
Main_RecrDev_2018	-0.3602
Main_RecrDev_2019	0.0382
Main_RecrDev_2020	1.7023
Late_RecrDev_2021	0.0135
ForeRecr_2022	-0.0019
ForeRecr_2023	-0.0010
ForeRecr_2024	-0.0113
ForeRecr_2025	0.0017
AgeSel_P3_Fishery(1)	2.8066
AgeSel_P4_Fishery(1)	0.9516
AgeSel_P5_Fishery(1)	0.4182
AgeSel_P6_Fishery(1)	0.1705
AgeSel_P7_Fishery(1)	0.4977
AgeSel_P4_Acoustic_Survey(2)	0.6090
AgeSel_P5_Acoustic_Survey(2)	-0.2089
AgeSel_P6_Acoustic_Survey(2)	0.3369
AgeSel_P7_Acoustic_Survey(2)	0.3010
AgeSel_P3_Fishery(1)_DEVadd_1991	0.5694
AgeSel_P3_Fishery(1)_DEVadd_1992	0.0172
AgeSel_P3_Fishery(1)_DEVadd_1993	-0.0044
AgeSel_P3_Fishery(1)_DEVadd_1994	0.1477

Continued on next page

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

Parameter	Posterior median
AgeSel_P3_Fishery(1)_DEVadd_1995	-0.1868
AgeSel_P3_Fishery(1)_DEVadd_1996	0.4585
AgeSel_P3_Fishery(1)_DEVadd_1997	0.1223
AgeSel_P3_Fishery(1)_DEVadd_1998	0.2156
AgeSel_P3_Fishery(1)_DEVadd_1999	1.0463
AgeSel_P3_Fishery(1)_DEVadd_2000	0.5485
AgeSel_P3_Fishery(1)_DEVadd_2001	0.0317
AgeSel_P3_Fishery(1)_DEVadd_2002	0.1142
AgeSel_P3_Fishery(1)_DEVadd_2003	0.0093
AgeSel_P3_Fishery(1)_DEVadd_2004	0.3059
AgeSel_P3_Fishery(1)_DEVadd_2005	-0.0111
AgeSel_P3_Fishery(1)_DEVadd_2006	0.5804
AgeSel_P3_Fishery(1)_DEVadd_2007	0.6228
AgeSel_P3_Fishery(1)_DEVadd_2008	-0.0389
AgeSel_P3_Fishery(1)_DEVadd_2009	0.4600
AgeSel_P3_Fishery(1)_DEVadd_2010	1.0105
AgeSel_P3_Fishery(1)_DEVadd_2011	-0.0879
AgeSel_P3_Fishery(1)_DEVadd_2012	0.1264
AgeSel_P3_Fishery(1)_DEVadd_2013	0.2513
AgeSel_P3_Fishery(1)_DEVadd_2014	0.3063
AgeSel_P3_Fishery(1)_DEVadd_2015	-0.7004
AgeSel_P3_Fishery(1)_DEVadd_2016	-0.0153
AgeSel_P3_Fishery(1)_DEVadd_2017	-0.4442
AgeSel_P3_Fishery(1)_DEVadd_2018	-1.2163
AgeSel_P3_Fishery(1)_DEVadd_2019	0.7653
AgeSel_P3_Fishery(1)_DEVadd_2020	0.0614
AgeSel_P3_Fishery(1)_DEVadd_2021	-0.4093
AgeSel_P4_Fishery(1)_DEVadd_1991	0.4003
AgeSel_P4_Fishery(1)_DEVadd_1992	0.5842
AgeSel_P4_Fishery(1)_DEVadd_1993	0.7935
AgeSel_P4_Fishery(1)_DEVadd_1994	0.1847
AgeSel_P4_Fishery(1)_DEVadd_1995	0.2125
AgeSel_P4_Fishery(1)_DEVadd_1996	-0.3888
AgeSel_P4_Fishery(1)_DEVadd_1997	1.2684
AgeSel_P4_Fishery(1)_DEVadd_1998	0.9844
AgeSel_P4_Fishery(1)_DEVadd_1999	-0.1373
AgeSel_P4_Fishery(1)_DEVadd_2000	0.8035
AgeSel_P4_Fishery(1)_DEVadd_2001	0.9247
AgeSel_P4_Fishery(1)_DEVadd_2002	0.7298
AgeSel_P4_Fishery(1)_DEVadd_2003	0.6709
AgeSel_P4_Fishery(1)_DEVadd_2004	0.4712
AgeSel_P4_Fishery(1)_DEVadd_2005	0.6443
AgeSel_P4_Fishery(1)_DEVadd_2006	-0.0433
AgeSel_P4_Fishery(1)_DEVadd_2007	0.2130
AgeSel_P4_Fishery(1)_DEVadd_2008	0.3281
AgeSel_P4_Fishery(1)_DEVadd_2009	0.7339
AgeSel_P4_Fishery(1)_DEVadd_2010	0.0975
AgeSel_P4_Fishery(1)_DEVadd_2011	1.0757
AgeSel_P4_Fishery(1)_DEVadd_2012	0.1515
AgeSel_P4_Fishery(1)_DEVadd_2013	0.8444
AgeSel_P4_Fishery(1)_DEVadd_2014	0.4757

Continued on next page

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

Parameter	Posterior median
AgeSel_P4_Fishery(1)_DEVadd_2015	0.1534
AgeSel_P4_Fishery(1)_DEVadd_2016	-0.8996
AgeSel_P4_Fishery(1)_DEVadd_2017	-0.4454
AgeSel_P4_Fishery(1)_DEVadd_2018	-0.6087
AgeSel_P4_Fishery(1)_DEVadd_2019	-0.6279
AgeSel_P4_Fishery(1)_DEVadd_2020	0.7887
AgeSel_P4_Fishery(1)_DEVadd_2021	0.2146
AgeSel_P5_Fishery(1)_DEVadd_1991	-0.8639
AgeSel_P5_Fishery(1)_DEVadd_1992	0.0814
AgeSel_P5_Fishery(1)_DEVadd_1993	-0.0088
AgeSel_P5_Fishery(1)_DEVadd_1994	0.9066
AgeSel_P5_Fishery(1)_DEVadd_1995	0.2672
AgeSel_P5_Fishery(1)_DEVadd_1996	-0.3085
AgeSel_P5_Fishery(1)_DEVadd_1997	-0.1269
AgeSel_P5_Fishery(1)_DEVadd_1998	-0.6460
AgeSel_P5_Fishery(1)_DEVadd_1999	0.1100
AgeSel_P5_Fishery(1)_DEVadd_2000	-0.1992
AgeSel_P5_Fishery(1)_DEVadd_2001	0.3217
AgeSel_P5_Fishery(1)_DEVadd_2002	0.5338
AgeSel_P5_Fishery(1)_DEVadd_2003	0.7376
AgeSel_P5_Fishery(1)_DEVadd_2004	0.6815
AgeSel_P5_Fishery(1)_DEVadd_2005	0.7167
AgeSel_P5_Fishery(1)_DEVadd_2006	-0.0178
AgeSel_P5_Fishery(1)_DEVadd_2007	-0.1210
AgeSel_P5_Fishery(1)_DEVadd_2008	-0.3526
AgeSel_P5_Fishery(1)_DEVadd_2009	-0.2210
AgeSel_P5_Fishery(1)_DEVadd_2010	0.5041
AgeSel_P5_Fishery(1)_DEVadd_2011	-0.7138
AgeSel_P5_Fishery(1)_DEVadd_2012	0.2092
AgeSel_P5_Fishery(1)_DEVadd_2013	-0.2536
AgeSel_P5_Fishery(1)_DEVadd_2014	-0.5302
AgeSel_P5_Fishery(1)_DEVadd_2015	0.0176
AgeSel_P5_Fishery(1)_DEVadd_2016	-0.0988
AgeSel_P5_Fishery(1)_DEVadd_2017	-0.0942
AgeSel_P5_Fishery(1)_DEVadd_2018	-0.2028
AgeSel_P5_Fishery(1)_DEVadd_2019	-0.0971
AgeSel_P5_Fishery(1)_DEVadd_2020	0.9385
AgeSel_P5_Fishery(1)_DEVadd_2021	0.6209
AgeSel_P6_Fishery(1)_DEVadd_1991	-0.0685
AgeSel_P6_Fishery(1)_DEVadd_1992	-0.4786
AgeSel_P6_Fishery(1)_DEVadd_1993	-0.0320
AgeSel_P6_Fishery(1)_DEVadd_1994	-0.0981
AgeSel_P6_Fishery(1)_DEVadd_1995	0.7762
AgeSel_P6_Fishery(1)_DEVadd_1996	-0.1299
AgeSel_P6_Fishery(1)_DEVadd_1997	-0.3329
AgeSel_P6_Fishery(1)_DEVadd_1998	0.3926
AgeSel_P6_Fishery(1)_DEVadd_1999	-0.3866
AgeSel_P6_Fishery(1)_DEVadd_2000	0.1833
AgeSel_P6_Fishery(1)_DEVadd_2001	-0.1495
AgeSel_P6_Fishery(1)_DEVadd_2002	0.1641
AgeSel_P6_Fishery(1)_DEVadd_2003	0.2860

Continued on next page

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

Parameter	Posterior median
AgeSel_P6_Fishery(1)_DEVadd_2004	-0.5762
AgeSel_P6_Fishery(1)_DEVadd_2005	0.2854
AgeSel_P6_Fishery(1)_DEVadd_2006	0.2223
AgeSel_P6_Fishery(1)_DEVadd_2007	-0.2124
AgeSel_P6_Fishery(1)_DEVadd_2008	0.2526
AgeSel_P6_Fishery(1)_DEVadd_2009	-0.2059
AgeSel_P6_Fishery(1)_DEVadd_2010	-0.4795
AgeSel_P6_Fishery(1)_DEVadd_2011	-0.1893
AgeSel_P6_Fishery(1)_DEVadd_2012	-0.4579
AgeSel_P6_Fishery(1)_DEVadd_2013	0.0192
AgeSel_P6_Fishery(1)_DEVadd_2014	-0.0071
AgeSel_P6_Fishery(1)_DEVadd_2015	-0.0509
AgeSel_P6_Fishery(1)_DEVadd_2016	-0.0881
AgeSel_P6_Fishery(1)_DEVadd_2017	-0.1909
AgeSel_P6_Fishery(1)_DEVadd_2018	-0.2842
AgeSel_P6_Fishery(1)_DEVadd_2019	0.1682
AgeSel_P6_Fishery(1)_DEVadd_2020	-0.3696
AgeSel_P6_Fishery(1)_DEVadd_2021	0.5184
AgeSel_P7_Fishery(1)_DEVadd_1991	-0.0850
AgeSel_P7_Fishery(1)_DEVadd_1992	0.0870
AgeSel_P7_Fishery(1)_DEVadd_1993	-0.3695
AgeSel_P7_Fishery(1)_DEVadd_1994	0.1206
AgeSel_P7_Fishery(1)_DEVadd_1995	-0.1228
AgeSel_P7_Fishery(1)_DEVadd_1996	0.4123
AgeSel_P7_Fishery(1)_DEVadd_1997	0.1384
AgeSel_P7_Fishery(1)_DEVadd_1998	-0.4982
AgeSel_P7_Fishery(1)_DEVadd_1999	-0.2613
AgeSel_P7_Fishery(1)_DEVadd_2000	-0.0714
AgeSel_P7_Fishery(1)_DEVadd_2001	-0.2752
AgeSel_P7_Fishery(1)_DEVadd_2002	-0.4183
AgeSel_P7_Fishery(1)_DEVadd_2003	-0.2571
AgeSel_P7_Fishery(1)_DEVadd_2004	-0.1619
AgeSel_P7_Fishery(1)_DEVadd_2005	-0.3974
AgeSel_P7_Fishery(1)_DEVadd_2006	-0.3189
AgeSel_P7_Fishery(1)_DEVadd_2007	0.0703
AgeSel_P7_Fishery(1)_DEVadd_2008	-0.1686
AgeSel_P7_Fishery(1)_DEVadd_2009	0.0689
AgeSel_P7_Fishery(1)_DEVadd_2010	-0.5664
AgeSel_P7_Fishery(1)_DEVadd_2011	-0.4960
AgeSel_P7_Fishery(1)_DEVadd_2012	-0.3128
AgeSel_P7_Fishery(1)_DEVadd_2013	0.0929
AgeSel_P7_Fishery(1)_DEVadd_2014	-0.0078
AgeSel_P7_Fishery(1)_DEVadd_2015	-0.5055
AgeSel_P7_Fishery(1)_DEVadd_2016	-0.2630
AgeSel_P7_Fishery(1)_DEVadd_2017	-0.0430
AgeSel_P7_Fishery(1)_DEVadd_2018	0.2419
AgeSel_P7_Fishery(1)_DEVadd_2019	-0.1670
AgeSel_P7_Fishery(1)_DEVadd_2020	0.0243
AgeSel_P7_Fishery(1)_DEVadd_2021	-0.3508

G SENSITIVITY RUN THAT EXCLUDES THE AGE-1 SURVEY

This appendix contains Bayesian MCMC results for the sensitivity to the base model in which the acoustic survey of age-1 fish which provides information on recruitment is excluded from the data used to fit the assessment (Sections 2.2.1 and 3.8; Table 33). Removing the age-1 index highlights model uncertainty arising from fitting the base model to less data and allows for comparisons with the 2021 base model. This appendix is meant to provide supplemental information, and should not be viewed as an alternative base model.

Removal of the age-1 index from the model decreases the estimates of 2018 and 2020 cohort size (age-0 recruitment). The median 2020 recruitment decreases from 5.2 billion fish (base model, Table 18) to 1.7 billion fish (sensitivity run, Table G.10). Estimates for cohorts born in odd years are similar between the two models because the age-1 index is generally only available in odd years (Figures 55 and G.1). An exception is estimates of the 2011 cohort which do not appear to stabilize until age four in the sensitivity compared to stabilizing at age two in the base model due to the information in additional survey in 2012. The estimated time series of spawning biomass in the sensitivity run is similar to the time series estimated using the base model when removing up to 4 years of data, yet is higher when removing 5 years of data (Figure G.2).

The largest recent cohort was born in 2014, and its estimated size when using only data up to age-2 is overestimated when including the age-1 index and underestimated when excluding it, compared to its final estimated size (Figures 55 and G.1). However, both models using data up to age-3 appear to overestimate it by the same amount. The 2016 cohort (the next-largest even-year cohort) shows similar retrospective patterns when including or excluding the age-1 index. The 2018 cohort is expected, using data up to age-2, to be as large as the above-average 2012 cohort when including the age-1 index, but somewhat smaller when excluding it. Both models estimate it to be below-average when using all available data. The 2012 cohort has opposite behavior using data up to age-2, with the age-1 index suggesting it is above average while excluding the age-1 index suggesting it to be below, and both models suggesting it to be above average when using all available data.

Figures G.3–G.11 and Tables G.1–G.10 show further quantities of interest and decision tables from the MCMC results when excluding the age-1 index.

Retrospective analyses of historical performance are given in Figures G.13 and G.14, and discussed with respect to the equivalent base model results (Figures 64 and 65) in Section 3.10.

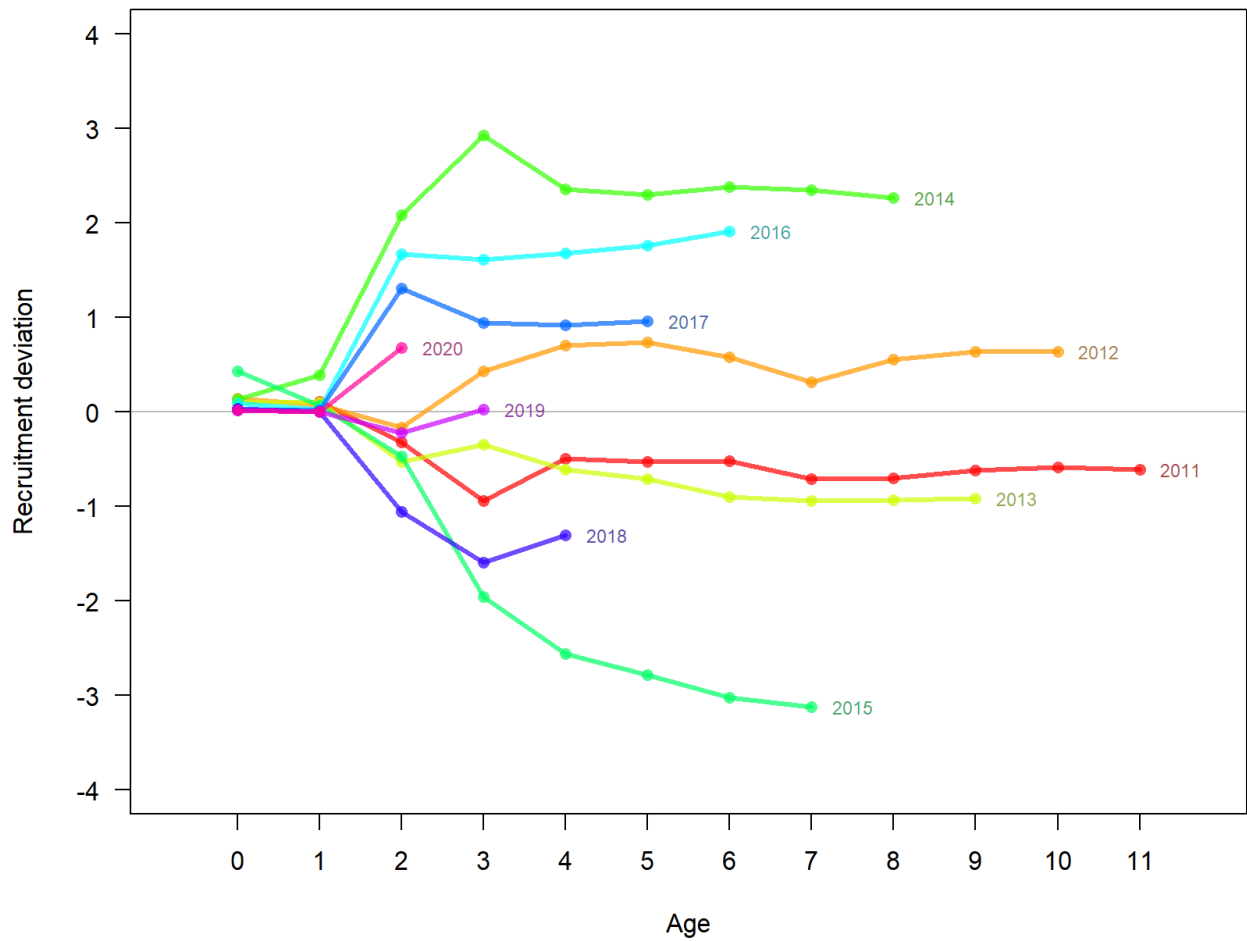


Figure G.1. Retrospective analysis of recruitment deviations from MCMC models over the last 11 years. Recruitment deviations are the log-scale differences between recruitment estimated by the model and expected recruitment from the spawner-recruit relationship. Lines represent estimated recruitment deviations for cohorts from 2011 to 2020, with cohort birth year marked at the right of each color-coded line. Values are estimated by models using data available only up to the year in which each cohort was a given age. Compare with Figure 55 for the base model.

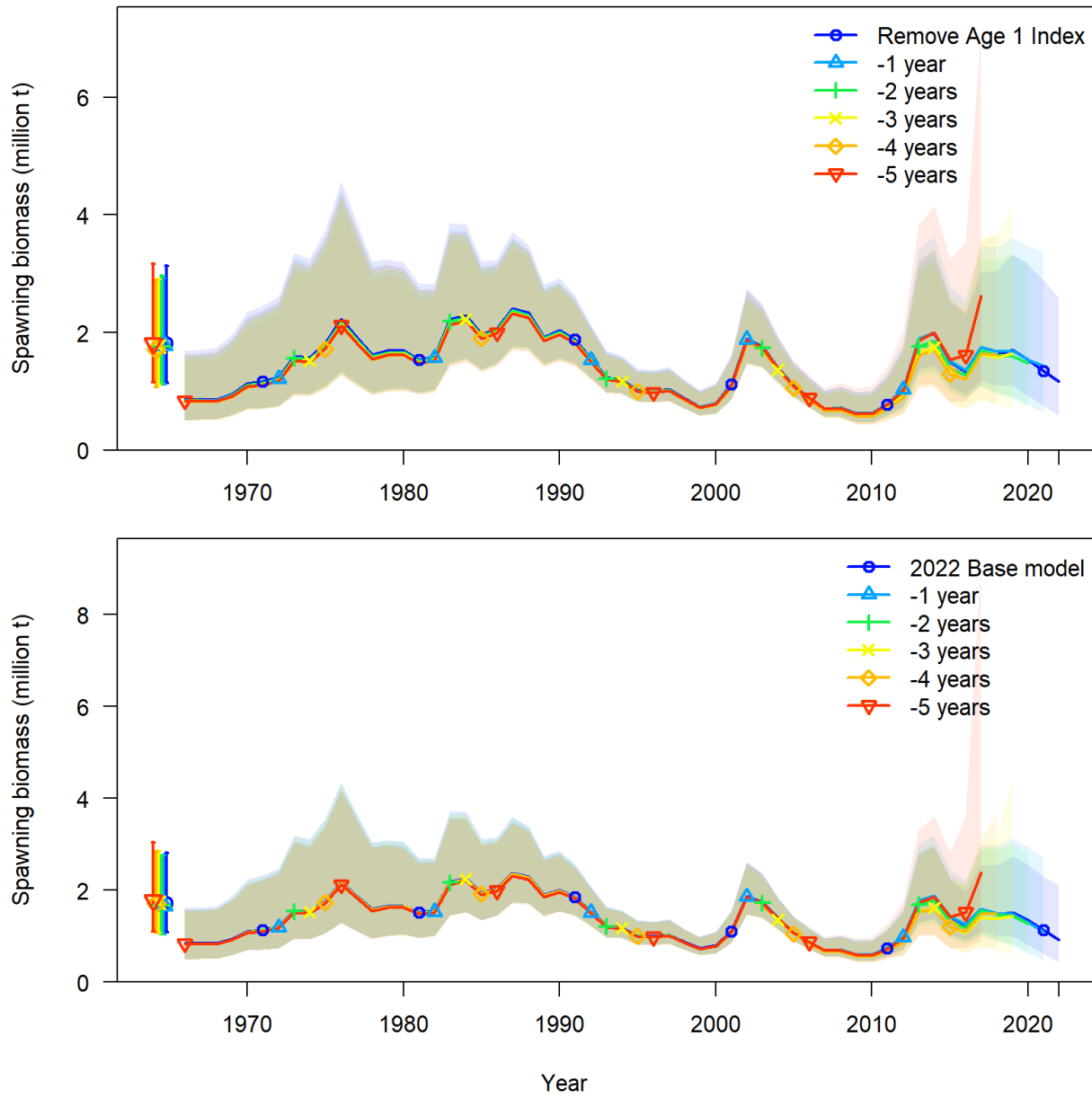


Figure G.2. Spawning biomass from retrospective MCMC model runs and associated uncertainties for the age-1 index sensitivity run (top) and the base model (bottom).

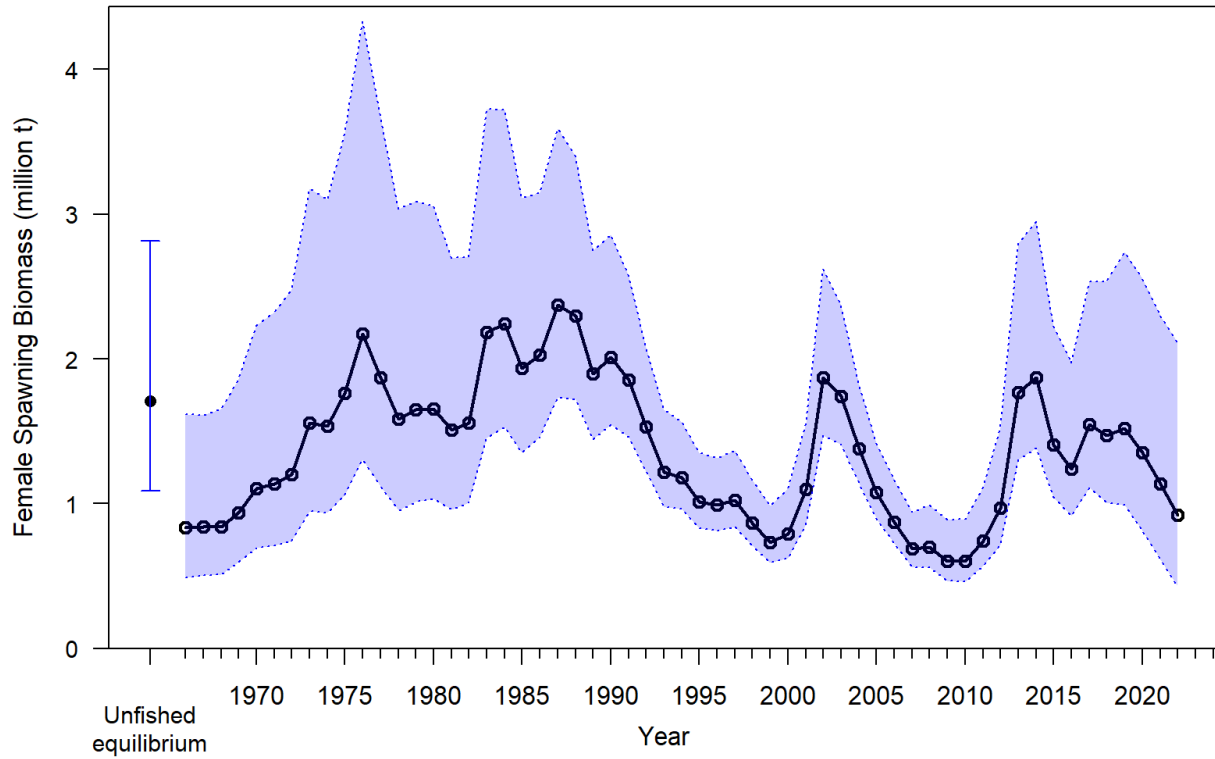


Figure G.3. Median of the posterior distribution for beginning of the year female spawning biomass through 2022 (solid line) with 95% posterior credibility intervals (shaded area). The solid circle with a 95% posterior credibility interval is the estimated unfished equilibrium biomass.

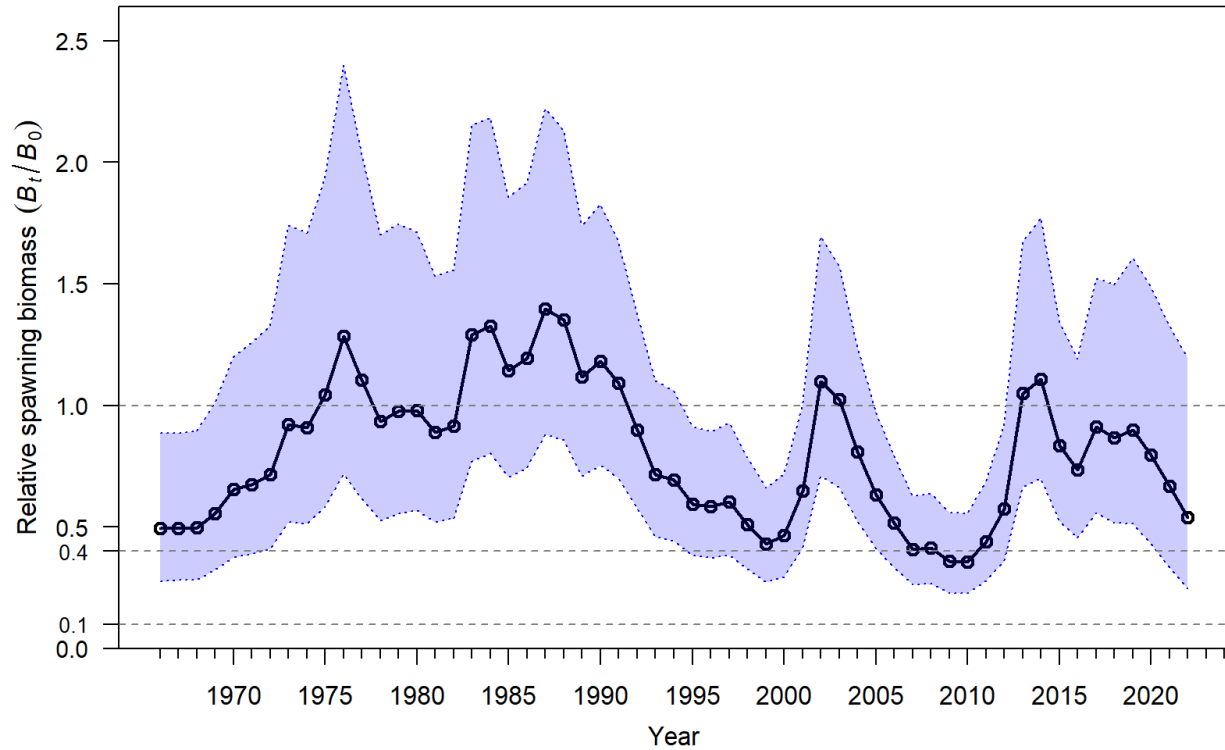


Figure G.4. Median (solid line) of the posterior distribution for relative spawning biomass (B_t/B_0) through 2022 with 95% posterior credibility intervals (shaded area). Dashed horizontal lines show 10%, 40% and 100% levels.

Table G.1. Recent trends in estimated beginning of the year female spawning biomass (thousand t) and spawning biomass level relative to estimated unfished equilibrium.

Year	Spawning biomass (thousand t)			Relative spawning biomass (B_t/B_0)		
	2.5 th percentile	Median	97.5 th percentile	2.5 th percentile	Median	97.5 th percentile
2013	1,304.8	1,770.2	2,796.9	66.4%	105.0%	167.2%
2014	1,385.7	1,870.9	2,949.6	70.0%	110.8%	177.3%
2015	1,045.2	1,408.9	2,228.6	52.4%	83.4%	134.6%
2016	915.9	1,240.5	1,973.1	45.7%	73.4%	119.2%
2017	1,107.8	1,546.6	2,533.5	56.0%	91.3%	152.1%
2018	1,007.0	1,469.0	2,535.5	51.6%	86.8%	149.5%
2019	990.7	1,521.7	2,739.4	51.4%	90.0%	160.6%
2020	815.6	1,351.8	2,555.5	43.0%	79.6%	148.7%
2021	615.8	1,137.5	2,298.2	33.4%	66.9%	132.7%
2022	432.6	921.9	2,113.6	24.7%	53.9%	119.5%

Table G.2. Estimates of recent recruitment (millions of age-0) and recruitment deviations, where deviations below (above) zero indicate recruitment below (above) that estimated from the stock-recruit relationship.

Year	Absolute recruitment (millions)			Recruitment deviations		
	2.5 th percentile	Median	97.5 th percentile	2.5 th percentile	Median	97.5 th percentile
2012	967.7	1,580.7	2,950.9	0.117	0.639	1.144
2013	125.3	356.3	858.7	-1.968	-0.915	-0.132
2014	5,551.7	8,491.8	15,248.1	1.767	2.267	2.768
2015	8.1	39.1	153.0	-4.618	-3.120	-1.827
2016	3,399.1	5,776.3	11,390.0	1.321	1.912	2.503
2017	1,061.3	2,300.6	5,352.7	0.166	0.961	1.710
2018	27.9	239.0	1,100.8	-3.398	-1.306	0.132
2019	237.6	918.9	2,956.3	-1.248	0.030	1.133
2020	66.2	1,733.3	27,916.7	-2.542	0.679	3.402
2021	43.0	902.9	18,483.5	-2.942	0.055	2.954

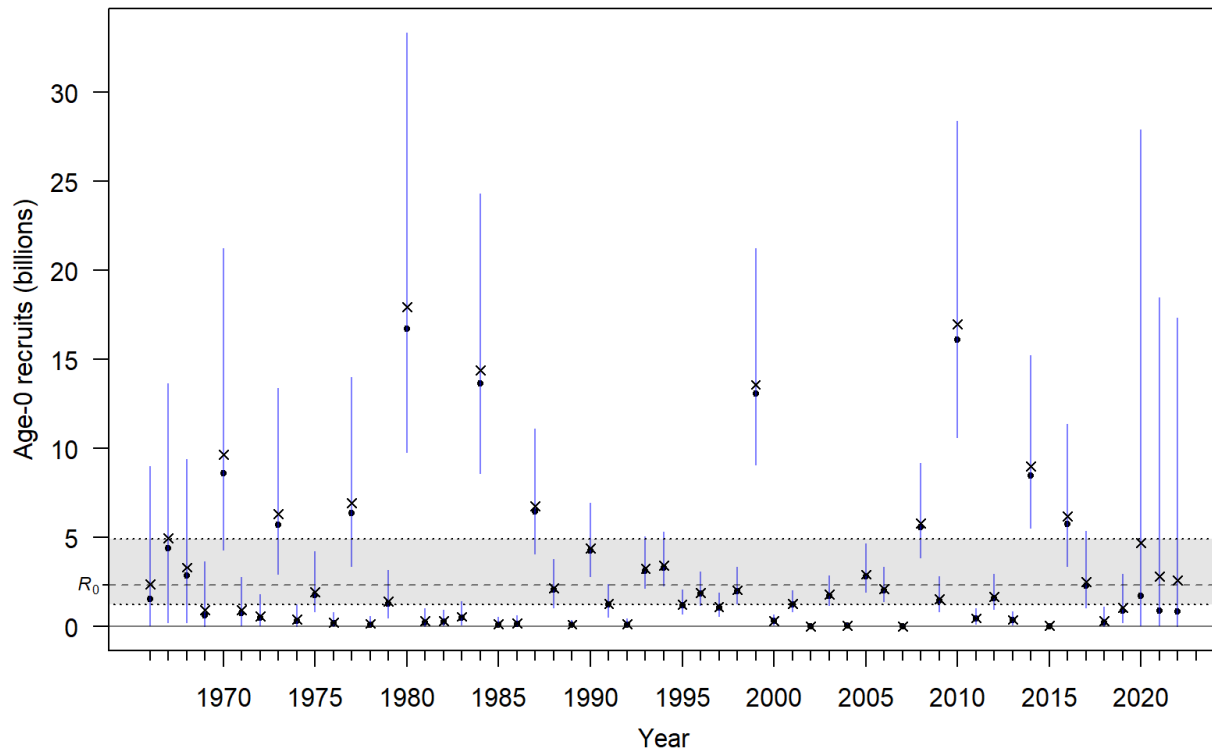


Figure G.5. Medians (solid circles) and means (\times) of the posterior distribution for recruitment (billions of age-0) with 95% posterior credibility intervals (blue lines). The median of the posterior distribution for mean unfishes equilibrium recruitment (R_0) is shown as the horizontal dashed line with a 95% posterior credibility interval shaded between the dotted lines.

Table G.3. Recent estimates of relative fishing intensity, $(1-SPR)/(1-SPR_{40\%})$, and exploitation fraction (catch divided by age-2+ biomass).

Year	Relative fishing intensity			Exploitation fraction		
	2.5 th percentile	Median	97.5 th percentile	2.5 th percentile	Median	97.5 th percentile
2012	0.424	0.666	0.939	0.036	0.057	0.078
2013	0.410	0.639	0.846	0.044	0.069	0.094
2014	0.383	0.608	0.834	0.045	0.071	0.096
2015	0.265	0.452	0.669	0.039	0.062	0.084
2016	0.465	0.727	0.984	0.057	0.092	0.126
2017	0.496	0.777	1.121	0.077	0.127	0.177
2018	0.457	0.726	1.050	0.059	0.103	0.152
2019	0.455	0.731	1.022	0.062	0.112	0.173
2020	0.380	0.635	0.903	0.068	0.129	0.215
2021	0.341	0.590	0.874	0.063	0.127	0.234

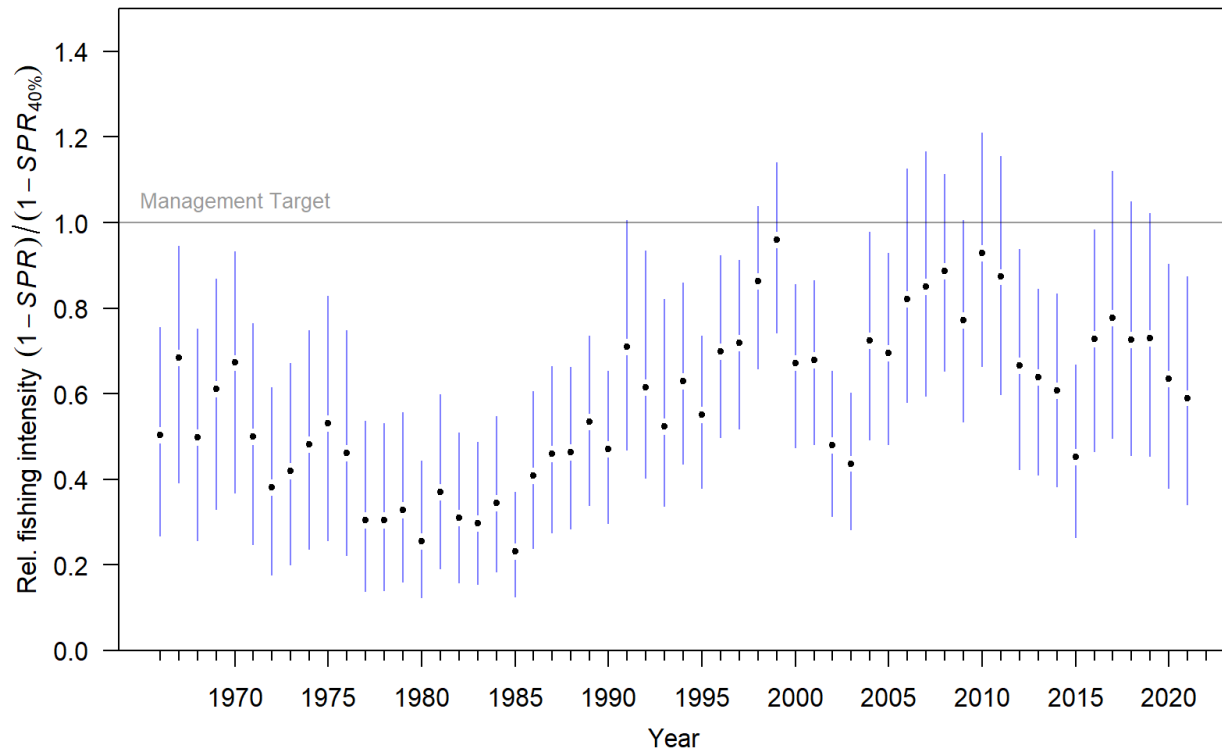


Figure G.6. Trend in median relative fishing intensity (relative to the SPR management target) through 2021 with 95% posterior credibility intervals. The management target defined in the Agreement is shown as a horizontal line at 1.0.

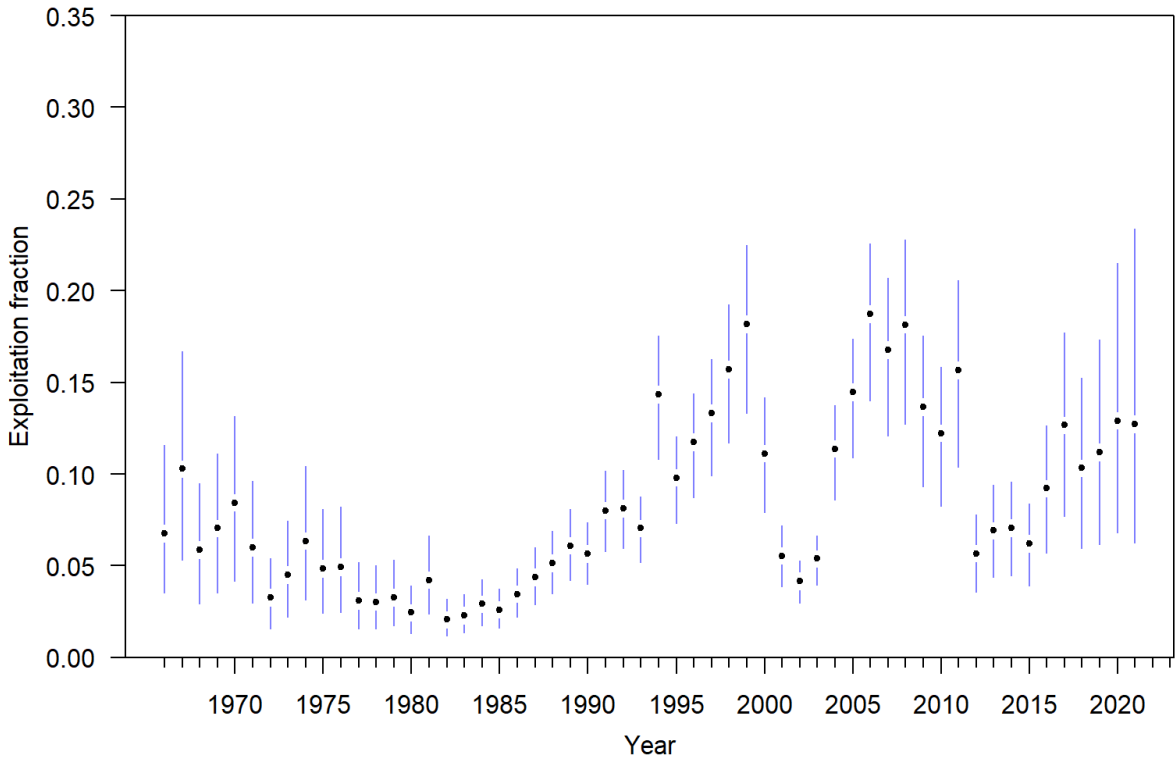


Figure G.7. Trend in median exploitation fraction (catch divided by age-2+ biomass) through 2021 with 95% posterior credibility intervals.

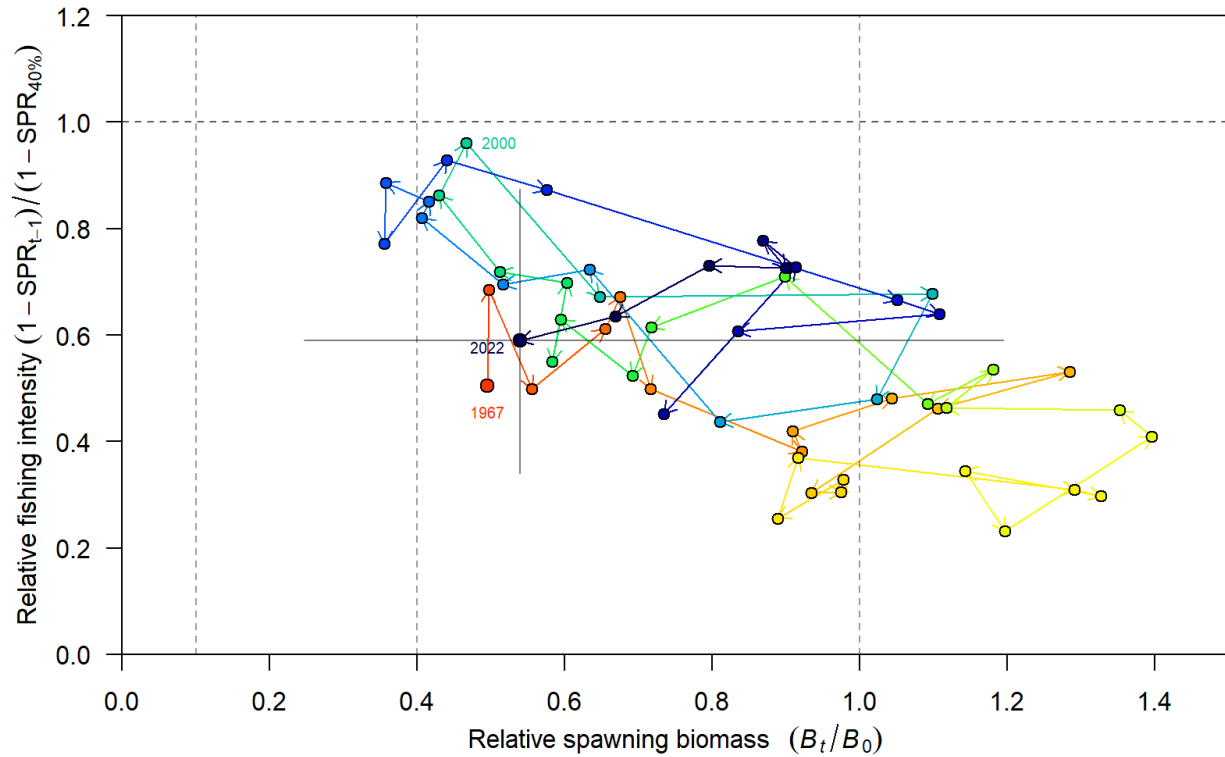


Figure G.8. Estimated historical path of median relative spawning biomass in year t and corresponding median relative fishing intensity in year $t - 1$, as for Figure 34. Labels show the start year, end year and year of highest relative fishing intensity; labels correspond to year t (i.e., year of the relative spawning biomass). Gray bars span the 95% credibility intervals for 2022 relative spawning biomass (horizontal) and 2021 relative fishing intensity (vertical).

Table G.4. For the alternative run, summary of median and 95% credibility intervals of equilibrium reference points. Equilibrium reference points were computed using 1966–2021 averages for mean size-at-age and selectivity-at-age.

Quantity	2.5 th percentile	Median	97.5 th percentile
Unfished female spawning biomass (B_0 , thousand t)	1,091	1,708	2,814
Unfished recruitment (R_0 , millions)	1,253	2,364	4,932
Reference points (equilibrium) based on $F_{\text{SPR}=40\%}$			
Female spawning biomass at $F_{\text{SPR}=40\%}$ ($B_{\text{SPR}=40\%}$, thousand t)	353	604	1,001
SPR at $F_{\text{SPR}=40\%}$	–	40%	–
Exploitation fraction corresponding to $F_{\text{SPR}=40\%}$	15.9%	18.4%	21.2%
Yield associated with $F_{\text{SPR}=40\%}$ (thousand t)	157	288	532
Reference points (equilibrium) based on $B_{40\%}$ (40% of B_0)			
Female spawning biomass ($B_{40\%}$, thousand t)	436	683	1,125
SPR at $B_{40\%}$	40.6%	43.6%	51.6%
Exploitation fraction resulting in $B_{40\%}$	12.3%	16.2%	19.4%
Yield at $B_{40\%}$ (thousand t)	158	281	520
Reference points (equilibrium) based on estimated MSY			
Female spawning biomass (B_{MSY} , thousand t)	269	439	797
SPR at MSY	22.5%	29.9%	47.0%
Exploitation fraction corresponding to SPR at MSY	14.4%	25.7%	35.0%
MSY (thousand t)	165	304	575

Table G.5. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year. Catch alternatives are based on: constant catches (rows a, b, c, d, f, g, i, k, l), including catch similar to 2021 (row f) and to the (unilaterally summed) TAC from 2021 (row l); and non-constant catches that result in annual 10% declines in catch (rows e, h, j), median relative fishing intensity of 100% (row m), median catch estimated via the default harvest policy ($F_{SPR=40\%}=40:10$, row n), and the fishing intensity that results in a 50% probability that the median projected catch will remain the same in 2022 and 2023 (row o).

Management Action			Biomass at start of year	Resulting relative spawning biomass		
				5%	50%	95%
Catch year	Catch (t)		Start of 2022	0.28	0.54	1.05
a:	2022	0	Start of 2023	0.30	0.60	1.55
	2023	0	Start of 2024	0.31	0.64	1.90
	2024	0	Start of 2025	0.33	0.69	1.89
b:	2022	180,000	Start of 2023	0.26	0.56	1.50
	2023	180,000	Start of 2024	0.23	0.55	1.81
	2024	180,000	Start of 2025	0.20	0.55	1.76
c:	2022	225,000	Start of 2023	0.25	0.54	1.49
	2023	225,000	Start of 2024	0.21	0.53	1.78
	2024	225,000	Start of 2025	0.17	0.52	1.73
d:	2022	270,000	Start of 2023	0.24	0.53	1.47
	2023	270,000	Start of 2024	0.19	0.51	1.76
	2024	270,000	Start of 2025	0.13	0.48	1.69
e: 10% reduction	2022	320,000	Start of 2023	0.23	0.52	1.46
	2023	288,000	Start of 2024	0.17	0.49	1.74
	2024	259,200	Start of 2025	0.12	0.47	1.68
f: 2021 catch	2022	325,000	Start of 2023	0.22	0.51	1.46
	2023	325,000	Start of 2024	0.16	0.48	1.72
	2024	325,000	Start of 2025	0.10	0.44	1.65
g:	2022	350,000	Start of 2023	0.22	0.51	1.45
	2023	350,000	Start of 2024	0.15	0.47	1.71
	2024	350,000	Start of 2025	0.09	0.42	1.63
h: 10% reduction	2022	350,000	Start of 2023	0.22	0.51	1.45
	2023	315,000	Start of 2024	0.16	0.48	1.72
	2024	283,500	Start of 2025	0.10	0.45	1.66
i:	2022	380,000	Start of 2023	0.21	0.50	1.44
	2023	380,000	Start of 2024	0.14	0.46	1.70
	2024	380,000	Start of 2025	0.08	0.40	1.61
j: 10% reduction	2022	380,000	Start of 2023	0.21	0.50	1.44
	2023	342,000	Start of 2024	0.15	0.46	1.71
	2024	307,800	Start of 2025	0.09	0.43	1.64
k:	2022	430,000	Start of 2023	0.20	0.49	1.43
	2023	430,000	Start of 2024	0.12	0.43	1.68
	2024	430,000	Start of 2025	0.07	0.36	1.58
l: 2021 TAC	2022	473,880	Start of 2023	0.19	0.47	1.42
	2023	473,880	Start of 2024	0.10	0.41	1.65
	2024	473,880	Start of 2025	0.06	0.33	1.54
m: FI= 100%	2022	550,826	Start of 2023	0.17	0.45	1.39
	2023	425,597	Start of 2024	0.10	0.40	1.64
	2024	342,937	Start of 2025	0.06	0.36	1.57
n: default HR	2022	550,826	Start of 2023	0.17	0.45	1.39
	2023	431,164	Start of 2024	0.09	0.40	1.64
	2024	352,312	Start of 2025	0.06	0.36	1.57
o: C2022= C2023	2022	458,930	Start of 2023	0.19	0.48	1.42
	2023	458,908	Start of 2024	0.11	0.42	1.66
	2024	364,516	Start of 2025	0.06	0.37	1.58

Table G.6. Forecast quantiles of Pacific Hake relative fishing intensity $(1-SPR)/(1-SPR_{40\%})$, expressed as a proportion, for the 2022–2024 catch alternatives presented in Table g. Values greater than 1 indicate relative fishing intensities greater than the $F_{SPR=40\%}$ harvest policy calculated using baseline selectivity.

Management Action			Relative fishing intensity		
	Catch year	Catch (t)	5%	50%	95%
a:	2022	0	0.00	0.00	0.00
	2023	0	0.00	0.00	0.00
	2024	0	0.00	0.00	0.00
b:	2022	180,000	0.29	0.52	0.81
	2023	180,000	0.27	0.53	0.86
	2024	180,000	0.23	0.55	0.92
c:	2022	225,000	0.34	0.61	0.91
	2023	225,000	0.32	0.62	0.98
	2024	225,000	0.29	0.65	1.06
d:	2022	270,000	0.40	0.68	0.98
	2023	270,000	0.38	0.70	1.07
	2024	270,000	0.34	0.74	1.18
e: 10% reduction	2022	320,000	0.45	0.74	1.05
	2023	288,000	0.40	0.74	1.12
	2024	259,200	0.33	0.73	1.20
f: 2021 catch	2022	325,000	0.45	0.75	1.06
	2023	325,000	0.43	0.79	1.17
	2024	325,000	0.39	0.84	1.30
g:	2022	350,000	0.48	0.78	1.09
	2023	350,000	0.46	0.83	1.22
	2024	350,000	0.42	0.88	1.32
h: 10% reduction	2022	350,000	0.48	0.78	1.09
	2023	315,000	0.43	0.78	1.17
	2024	283,500	0.35	0.78	1.27
i:	2022	380,000	0.51	0.81	1.12
	2023	380,000	0.49	0.87	1.26
	2024	380,000	0.45	0.92	1.35
j: 10% reduction	2022	380,000	0.51	0.81	1.12
	2023	342,000	0.46	0.82	1.22
	2024	307,800	0.38	0.83	1.31
k:	2022	430,000	0.55	0.87	1.17
	2023	430,000	0.54	0.93	1.32
	2024	430,000	0.49	1.00	1.37
l: 2021 TAC	2022	473,880	0.58	0.91	1.21
	2023	473,880	0.57	0.98	1.35
	2024	473,880	0.53	1.06	1.38
m: FI= 100%	2022	550,826	0.64	0.97	1.28
	2023	425,597	0.54	0.96	1.34
	2024	342,937	0.42	0.93	1.36
n: default HR	2022	550,826	0.64	0.97	1.28
	2023	431,164	0.55	0.96	1.34
	2024	352,312	0.43	0.95	1.36
o: C2022= C2023	2022	458,930	0.57	0.89	1.20
	2023	458,908	0.56	0.96	1.34
	2024	364,516	0.44	0.95	1.36

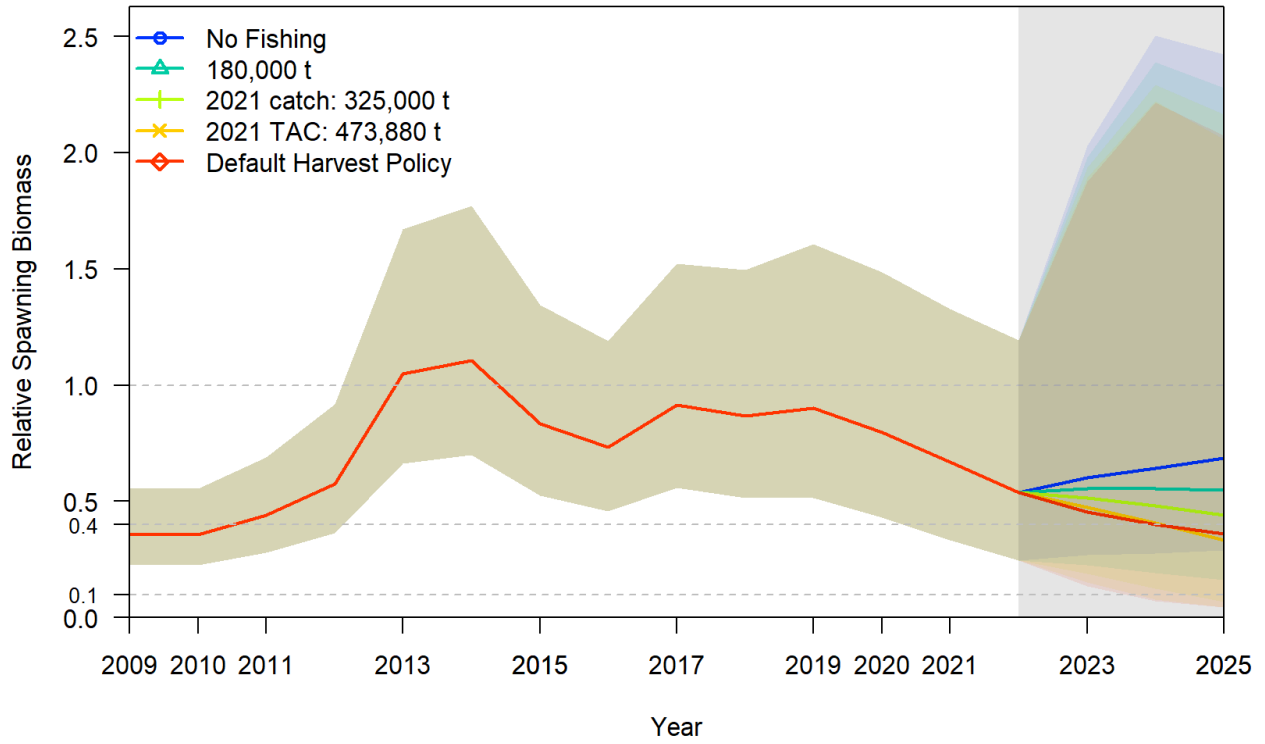


Figure G.9. Time series of estimated relative spawning biomass to 2022 from the base model, and forecast trajectories to 2025 (grey region) for several management actions defined in Table G.5, with 95% posterior credibility intervals.

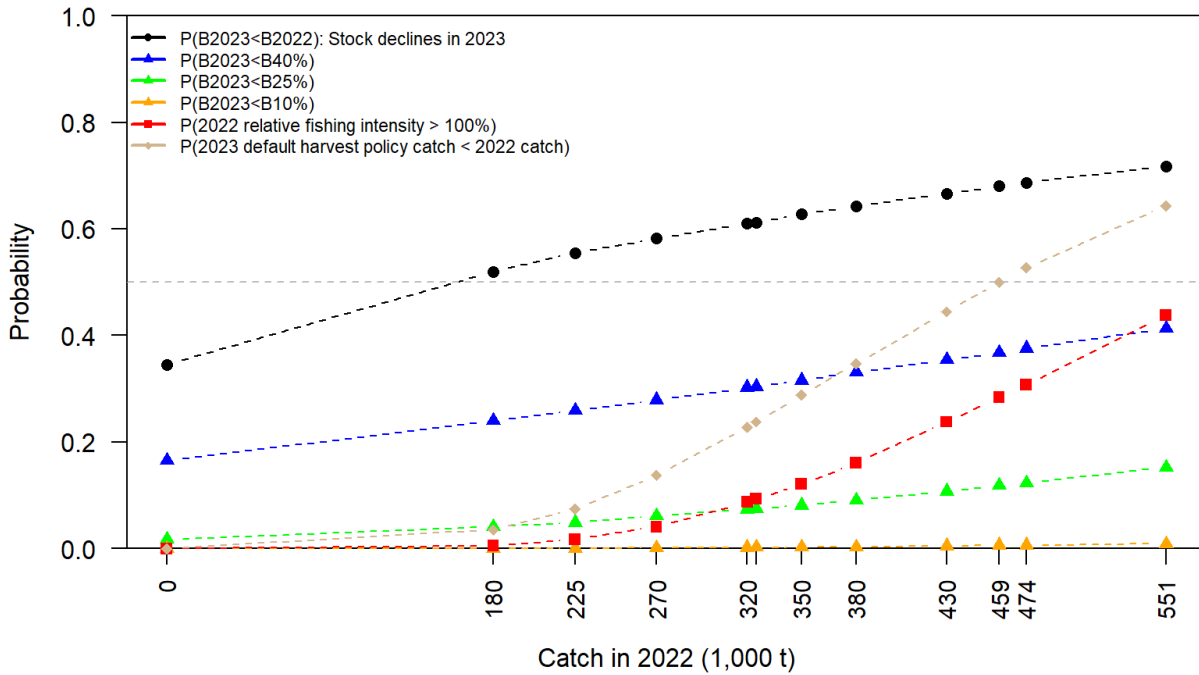


Figure G.10. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2023 default harvest policy catch for alternative 2022 catch options (explained in Table G.5) as listed in Table G.7. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table G.7. Probabilities related to spawning biomass, relative fishing intensity, and the 2023 default harvest policy catch for alternative 2022 catch options (explained in Table G.5).

Catch in 2022	Probability B ₂₀₂₃ < B ₂₀₂₂	Probability B ₂₀₂₃ < B _{40%}	Probability B ₂₀₂₃ < B _{25%}	Probability B ₂₀₂₃ < B _{10%}	Probability 2022 relative fishing intensity > 100%	Probability 2023 default harvest policy catch < 2022 catch
a: 0	35%	17%	2%	0%	0%	0%
b: 180,000	52%	24%	4%	0%	1%	4%
c: 225,000	55%	26%	5%	0%	2%	7%
d: 270,000	58%	28%	6%	0%	4%	14%
e: 320,000	61%	30%	7%	0%	9%	23%
f: 325,000	61%	30%	8%	0%	9%	24%
g: 350,000	63%	32%	8%	0%	12%	29%
h: 350,000	63%	32%	8%	0%	12%	29%
i: 380,000	64%	33%	9%	0%	16%	35%
j: 380,000	64%	33%	9%	0%	16%	35%
k: 430,000	67%	35%	11%	0%	24%	44%
l: 473,880	69%	38%	12%	1%	31%	53%
m: 550,826	72%	41%	15%	1%	44%	64%
n: 550,826	72%	41%	15%	1%	44%	64%
o: 458,930	68%	37%	12%	1%	28%	50%

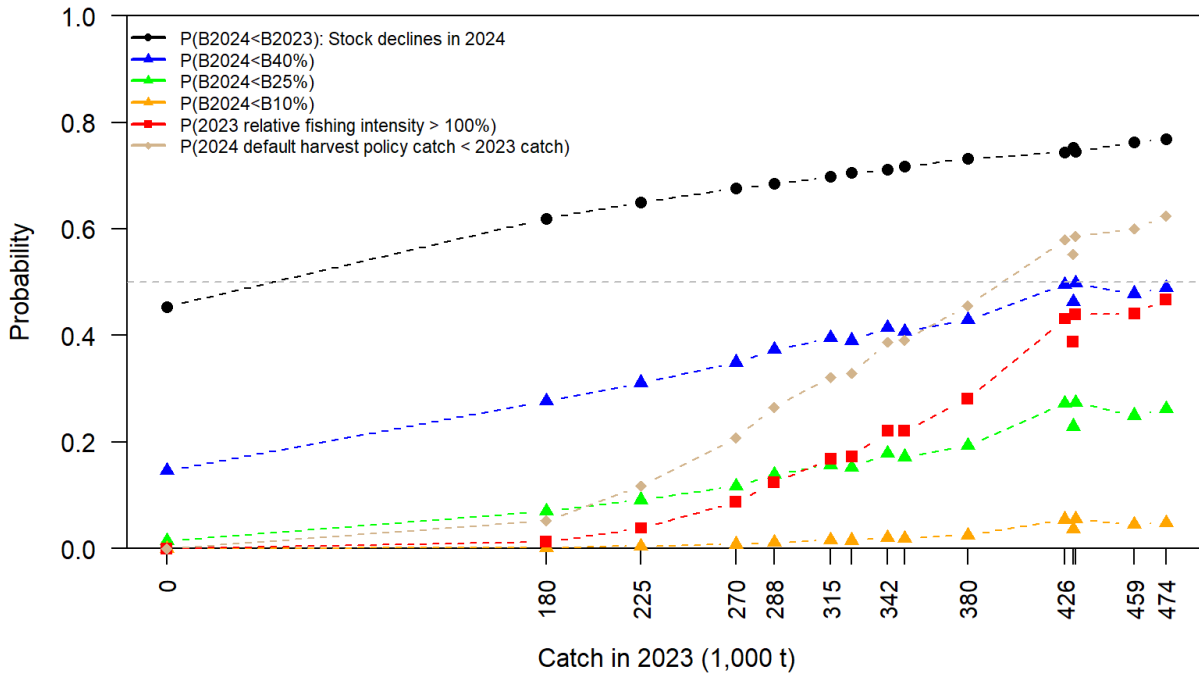


Figure G.11. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2024 default harvest policy catch for alternative 2023 catch options (including associated 2022 catch; catch options explained in Table G.5) as listed in Table G.8. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table G.8. Probabilities related to spawning biomass, relative fishing intensity, and the 2024 default harvest policy catch for alternative 2023 catch options, given the 2022 catch shown in Table G.7 (catch options explained in Table G.5).

Catch in 2023	Probability B ₂₀₂₄ < B ₂₀₂₃	Probability B ₂₀₂₄ < B _{40%}	Probability B ₂₀₂₄ < B _{25%}	Probability B ₂₀₂₄ < B _{10%}	Probability 2023 relative fishing intensity > 100%	Probability 2024 default harvest policy catch < 2023 catch
a: 0	45%	15%	1%	0%	0%	0%
b: 180,000	62%	28%	7%	0%	1%	5%
c: 225,000	65%	31%	9%	0%	4%	12%
d: 270,000	68%	35%	12%	1%	9%	21%
e: 288,000	68%	37%	14%	1%	12%	27%
f: 325,000	70%	39%	15%	2%	17%	33%
g: 350,000	72%	41%	17%	2%	22%	39%
h: 315,000	70%	40%	16%	2%	17%	32%
i: 380,000	73%	43%	19%	2%	28%	46%
j: 342,000	71%	42%	18%	2%	22%	39%
k: 430,000	75%	46%	23%	4%	39%	55%
l: 473,880	77%	49%	26%	5%	47%	62%
m: 425,597	74%	50%	27%	5%	43%	58%
n: 431,164	75%	50%	27%	6%	44%	59%
o: 458,908	76%	48%	25%	5%	44%	60%

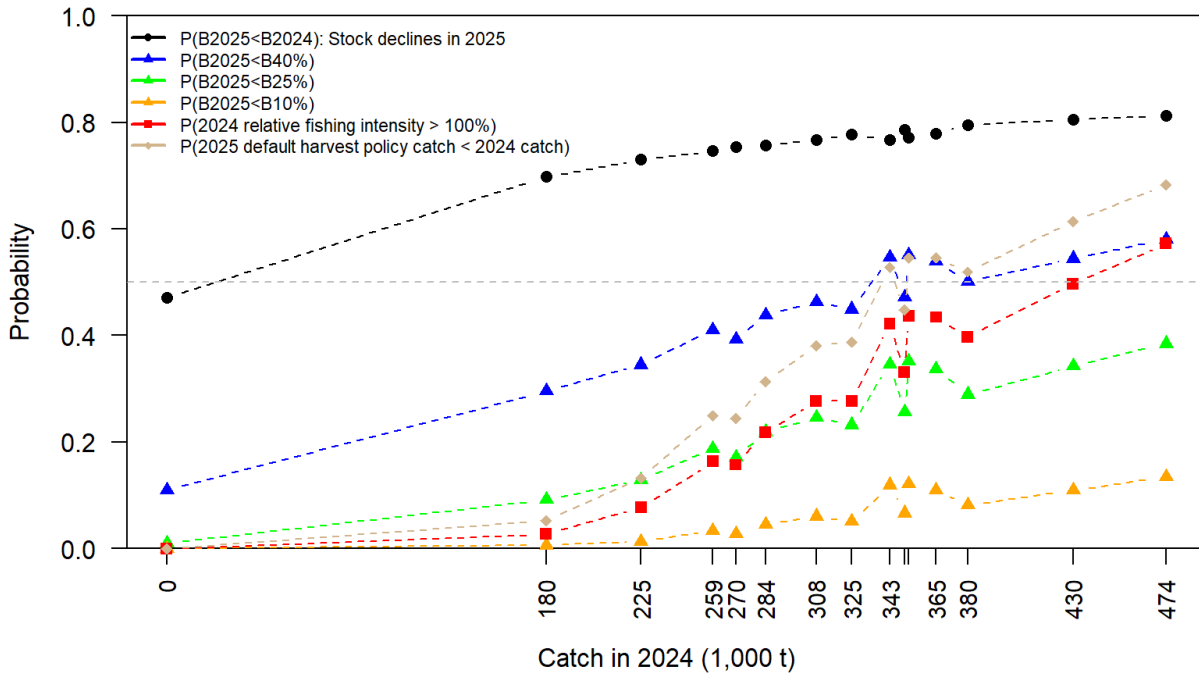


Figure G.12. Graphical representation of the probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options (including associated 2022 and 2023 catches; catch options explained in Table G.5) as listed in Table G.9. The symbols indicate points that were computed directly from model output and lines interpolate between the points.

Table G.9. Probabilities related to spawning biomass, relative fishing intensity, and the 2025 default harvest policy catch for alternative 2024 catch options, given the 2022 and 2023 catches shown in Tables G.7 and G.8 (catch options explained in Table G.5).

Catch in 2024	Probability $B_{2025} < B_{2024}$	Probability $B_{2025} < B_{40\%}$	Probability $B_{2025} < B_{25\%}$	Probability $B_{2025} < B_{10\%}$	Probability 2024 relative fishing intensity > 100%	Probability 2025 default harvest policy catch < 2024 catch
a: 0	47%	11%	1%	0%	0%	0%
b: 180,000	70%	30%	9%	1%	3%	5%
c: 225,000	73%	35%	13%	1%	8%	13%
d: 270,000	75%	39%	17%	3%	16%	24%
e: 259,200	75%	41%	19%	3%	16%	25%
f: 325,000	78%	45%	23%	5%	28%	39%
g: 350,000	79%	47%	26%	7%	33%	45%
h: 283,500	76%	44%	22%	5%	22%	31%
i: 380,000	80%	50%	29%	8%	40%	52%
j: 307,800	77%	46%	25%	6%	28%	38%
k: 430,000	81%	54%	34%	11%	50%	61%
l: 473,880	81%	58%	38%	13%	57%	68%
m: 342,937	77%	55%	35%	12%	42%	53%
n: 352,312	77%	55%	35%	12%	44%	55%
o: 364,516	78%	54%	34%	11%	43%	55%

Table G.10. Estimated numbers-at-age at the beginning of the year from the base model (posterior medians; million).

Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1966	1,536	1,396	812	452	278	178	129	102	84	69	59	49	41	34	28	23	19	15	12	10	32
1967	4,383	1,218	1,109	634	344	206	131	90	72	59	49	42	35	29	24	20	16	13	11	9	39
1968	2,862	3,504	970	858	471	247	145	84	59	47	38	32	27	22	18	15	13	11	9	7	39
1969	633	2,282	2,791	759	659	352	183	102	59	41	33	27	22	19	16	13	11	9	7	6	39
1970	8,615	503	1,817	2,174	571	480	253	124	69	40	28	22	18	15	13	11	9	7	6	5	36
1971	780	6,841	399	1,409	1,619	412	339	164	81	45	26	18	15	12	10	8	7	6	5	4	31
1972	496	620	5,425	311	1,081	1,215	304	240	115	57	32	19	13	10	8	7	6	5	4	3	28
1973	5,721	395	493	4,262	240	825	922	224	176	85	42	23	14	10	8	6	5	4	4	3	26
1974	322	4,537	313	388	3,281	182	621	669	162	127	62	30	17	10	7	5	5	4	3	3	23
1975	1,757	257	3,600	245	298	2,467	135	440	475	115	90	44	21	12	7	5	4	3	3	2	20
1976	188	1,396	204	2,821	189	225	1,854	98	318	344	83	65	32	16	9	5	4	3	2	2	18
1977	6,363	150	1,108	161	2,182	145	171	1,367	72	234	252	61	48	23	11	6	4	3	2	2	15
1978	125	5,054	119	873	126	1,690	111	129	1,034	54	177	190	46	36	18	9	5	3	2	2	14
1979	1,302	100	4,008	94	683	98	1,305	85	98	787	41	134	144	35	27	13	7	4	2	2	13
1980	16,741	1,033	80	3,162	73	529	75	985	64	74	593	31	101	109	26	21	10	5	3	2	12
1981	245	13,288	822	63	2,477	57	410	57	751	49	56	453	24	77	83	20	16	8	4	2	11
1982	287	195	10,536	647	49	1,902	43	305	43	558	36	42	337	18	57	62	15	12	6	3	11
1983	504	228	155	8,316	505	38	1,464	33	230	32	421	27	32	254	13	43	47	11	9	4	11
1984	13,674	399	182	123	6,505	392	29	1,112	25	175	24	320	21	24	193	10	33	35	9	7	13
1985	119	10,863	318	144	96	5,042	302	22	842	19	132	18	242	16	18	145	8	25	27	6	17
1986	171	94	8,621	252	112	75	3,904	230	17	641	14	101	14	184	12	14	111	6	19	20	19
1987	6,480	136	75	6,789	195	87	57	2,916	172	12	479	11	75	11	138	9	10	83	4	14	30
1988	2,067	5,144	108	59	5,248	149	66	42	2,149	127	9	352	8	55	8	101	7	8	61	3	33
1989	107	1,643	4,075	85	46	4,002	112	48	31	1,574	93	7	258	6	40	6	74	5	6	45	27
1990	4,256	85	1,305	3,189	65	34	2,965	79	34	22	1,116	66	5	183	4	29	4	53	3	4	51
1991	1,230	3,377	67	1,023	2,460	49	26	2,161	58	25	16	813	48	3	133	3	21	3	38	2	40
1992	119	979	2,674	50	705	1,831	35	18	1,552	42	18	11	584	34	2	96	2	15	2	28	31
1993	3,142	94	777	2,096	36	496	1,353	24	13	1,077	29	12	8	405	24	2	66	1	10	1	41
1994	3,323	2,497	75	612	1,569	25	354	973	17	9	775	21	9	6	291	17	1	48	1	7	30
1995	1,217	2,638	1,983	58	472	1,110	17	223	614	11	6	489	13	6	4	184	11	1	30	1	24
1996	1,842	966	2,093	1,566	45	360	772	11	148	407	7	4	324	9	4	2	122	7	1	20	16
1997	1,061	1,464	766	1,577	1,146	32	262	484	7	93	255	5	2	203	5	2	1	76	5	0	23
1998	1,973	843	1,162	603	1,101	773	21	163	303	4	58	159	3	2	127	3	1	1	48	3	15
1999	13,097	1,566	669	901	378	758	459	13	102	190	3	36	100	2	1	80	2	1	1	30	11
2000	310	10,394	1,242	487	593	216	480	280	8	62	116	2	22	61	1	1	49	1	1	0	25
2001	1,254	247	8,244	975	355	425	146	303	176	5	39	73	1	14	38	1	0	31	1	0	16
2002	31	996	196	6,492	719	240	285	96	200	117	3	26	48	1	9	25	0	0	20	1	11
2003	1,736	24	790	155	5,020	526	170	202	68	142	83	2	18	34	0	7	18	0	0	14	8
2004	56	1,378	19	626	121	3,775	380	121	144	49	101	59	2	13	24	0	5	13	0	0	16
2005	2,816	45	1,093	15	465	74	2,627	254	81	96	33	68	39	1	9	16	0	3	9	0	11
2006	2,036	2,236	35	862	11	325	45	1,691	164	52	62	21	43	25	1	6	10	0	2	6	7

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Year	Age																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
2007	24	1,614	1,770	25	614	7	198	27	1,022	99	31	37	13	26	15	0	3	6	0	1	8
2008	5,567	19	1,279	1,348	16	405	4	117	16	606	59	19	22	8	16	9	0	2	4	0	5
2009	1,467	4,417	15	973	897	11	243	2	65	9	337	33	10	12	4	9	5	0	1	2	3
2010	16,100	1,167	3,504	12	684	622	7	155	2	41	6	215	21	7	8	3	5	3	0	1	3
2011	442	12,760	926	2,668	8	376	395	5	104	1	28	4	144	14	4	5	2	4	2	0	3
2012	1,581	352	10,100	715	1,577	5	255	276	3	73	1	19	3	101	10	3	4	1	3	2	2
2013	356	1,256	279	7,824	523	1,060	3	182	197	2	52	1	14	2	72	7	2	3	1	2	2
2014	8,492	282	996	219	5,800	387	770	2	122	132	2	35	0	9	1	48	5	1	2	1	3
2015	39	6,732	224	773	159	4,267	281	528	2	84	91	1	24	0	6	1	33	3	1	1	2
2016	5,776	31	5,333	175	586	117	3,126	208	393	1	62	67	1	18	0	5	1	25	2	1	3
2017	2,301	4,581	24	3,820	128	421	83	2,204	147	278	1	44	48	1	13	0	3	0	17	2	2
2018	239	1,823	3,600	17	2,718	88	293	54	1,437	96	180	1	29	31	0	8	0	2	0	11	3
2019	919	190	1,408	2,632	12	1,944	63	193	35	948	63	119	0	19	20	0	5	0	1	0	9
2020	1,733	731	150	1,037	1,928	8	1,319	41	124	23	613	41	77	0	12	13	0	3	0	1	6
2021	903	1,368	579	118	797	1,292	5	853	26	80	15	396	26	50	0	8	8	0	2	0	5
2022	836	715	1,082	456	90	582	847	3	554	17	52	9	258	17	32	0	5	6	0	1	3

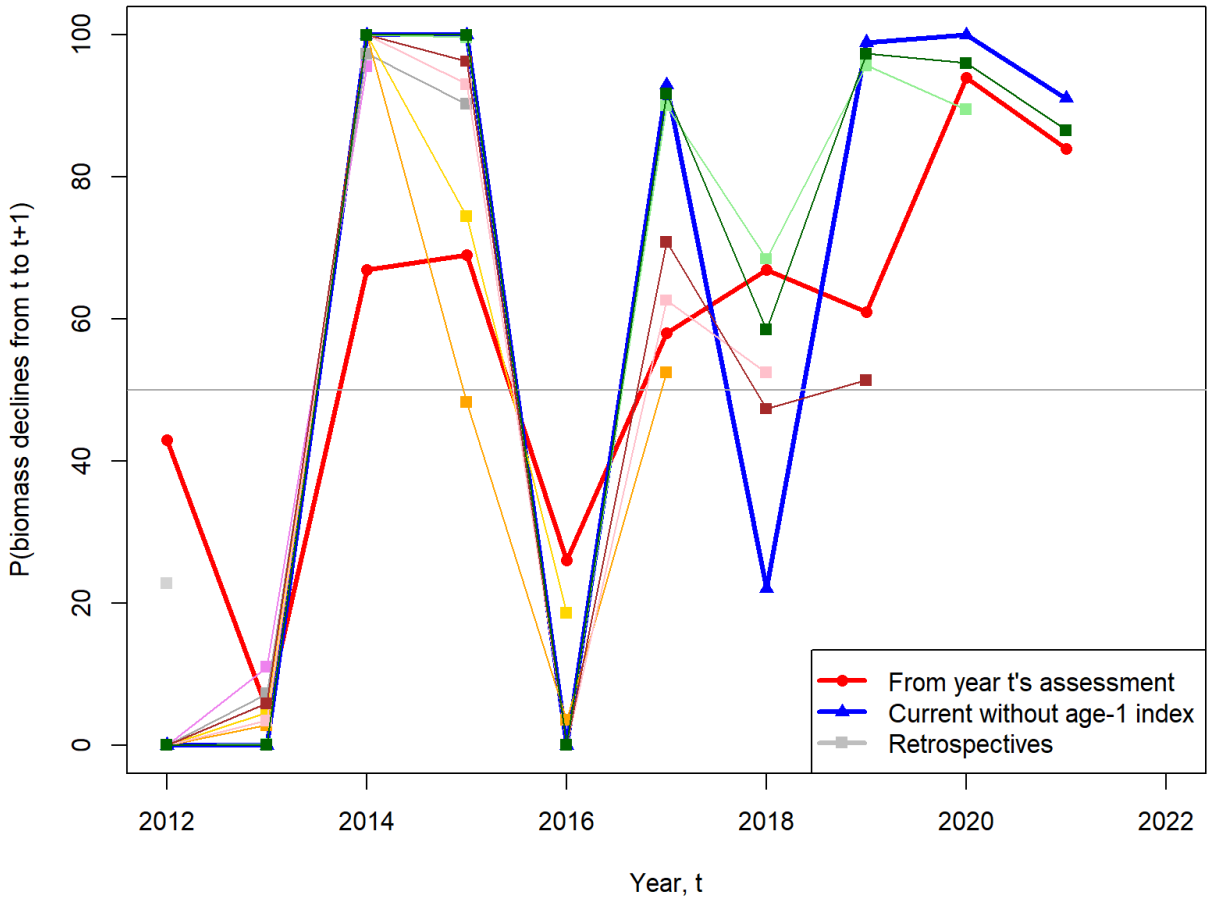


Figure G.13. Equivalent of Figure 64 for the age-1 sensitivity run, showing retrospective analysis of the probabilities of decline.

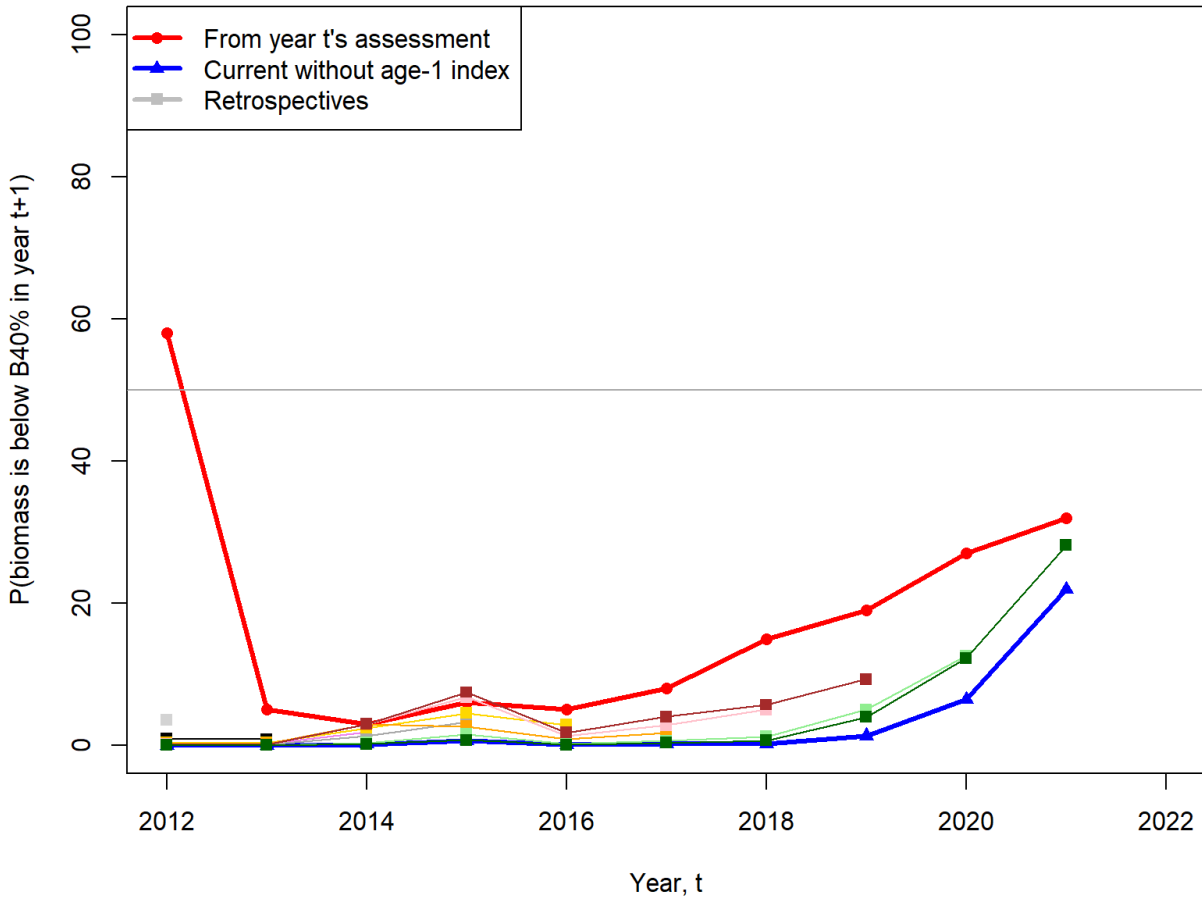


Figure G.14. Equivalent of Figure 65 for the age-1 sensitivity run, showing retrospective analysis of $P(B_{t+1} < B_{40\%})$ for each year t .

H OPTIONS TO FURTHER CONVEY RECRUITMENT VARIABILITY

This appendix contains some ideas to develop an extra figure to further convey recruitment variability in an intuitive way.

Variability in annual recruitment is a key feature of the Pacific Hake stock. This is demonstrated in figures of the estimated recruitment of age-0 fish in each year, as shown in Figure 28 and the equivalent figure from the 2021 assessment (Johnson et al., 2021), reproduced below as Figure H.1.

However, we realised that these figures may not clearly or intuitively convey certain aspects. To understand this, the JTC sent a survey to all participants of the Pacific Hake process, who were asked to anonymously answer the following question (via a Google Form that included a copy of the relevant Figure H.1):

“Figure e in the 2021 Pacific Hake stock assessment document shows the estimated recruitment each year. From this figure what do you think the chance (probability) is that the 2014 cohort is at least as large as the 2010 cohort? Please give a percentage or a range, and feel free to add any text if you like. All answers are anonymous. Thanks.”

Survey results are given in Figure H.2, showing a wide range of answers. However, from the full MCMC results, the estimated probability that ‘the 2014 cohort is at least as large as the 2010

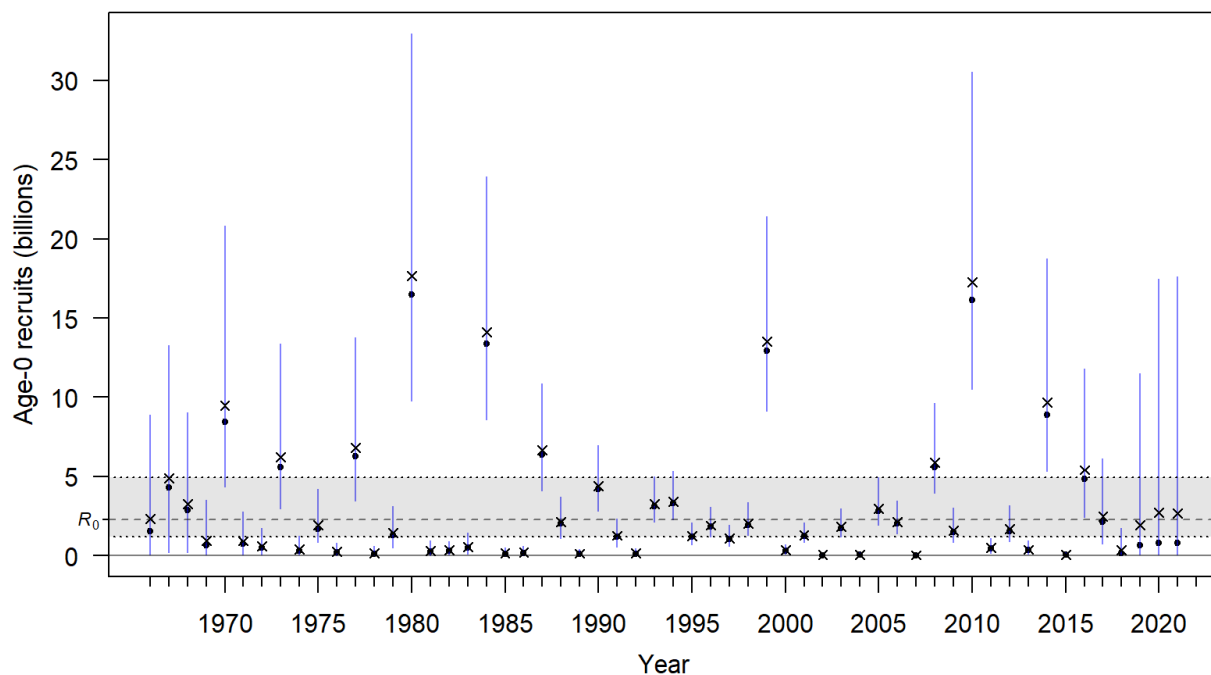


Figure H.1. Recruitment Figure e (or Figure 26) from the 2021 assessment (Johnson et al., 2021). Medians (solid circles) and means (\times) of the posterior distribution for recruitment (billions of age-0 fish) with 95% posterior credibility intervals (blue lines). The median of the posterior distribution for mean unfished equilibrium recruitment (R_0) is shown as the horizontal dashed line with a 95% posterior credibility interval shaded between the dotted lines.

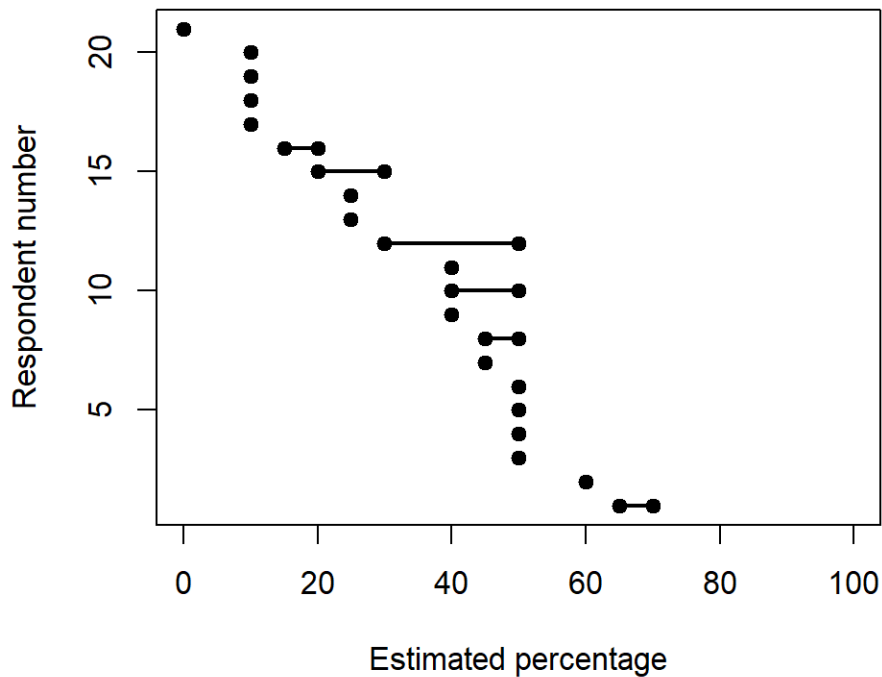


Figure H.2. Results from 21 respondents giving their estimated probability, as a percentage, that the 2014 cohort is at least as large as the 2010 cohort, based on Figure H.1. Respondents gave either single estimates (dots) or a range (dots connected by lines). A further respondent answered ‘Low’ (not shown), and an answer of 0.4 is assumed to mean 40% (not 0.4%).

cohort’ is in fact 0%, a value that was only considered by one respondent. Therefore it seems appropriate to explain this discrepancy and to derive a more intuitive figure to complement the existing figure.

The reason for asking about comparing the 2014 cohort to the 2010 cohort is that the 2010 cohort is the largest for some time (Figure H.1), with 1999 looking somewhat comparable. Thus, people familiar with Pacific Hake have an intuition about the 2010 cohort being very large. Also, the probability that the 2014 cohort could be as large as the 2010 cohort was explicitly calculated to be 4.8% in the 2018 assessment (Edwards et al., 2018b); we return to this later.

Also, the y-axis in Figure H.1 is in terms of billions of age-0 fish. While this is a sensible unit for recruitment, it may not be a very intuitive scale. So it can be desirable to want to compare the size of cohorts with the huge 2010 cohort, as people have some intuition regarding the 2010 cohort (i.e. that it was huge).

In Figure H.1 the credible interval for the 2014 recruitment extends above the median for the 2010 recruitment, and thus intuitively it certainly appears that there is some (non-zero) chance that 2014

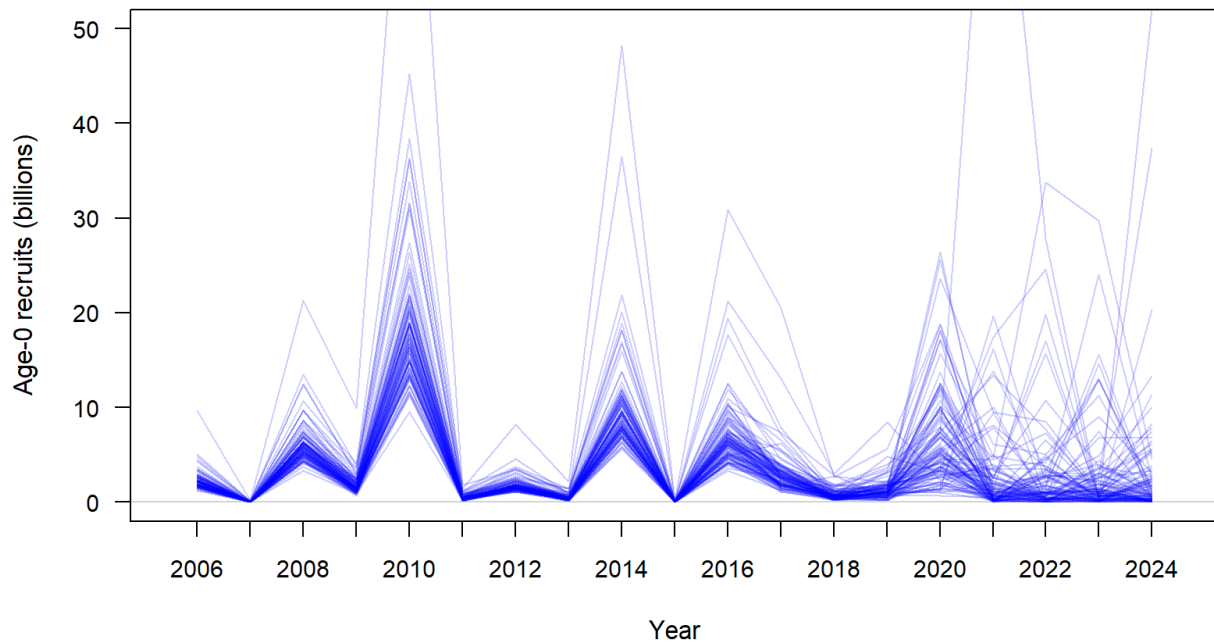


Figure H.3. A subsample of 100 MCMC time series estimates of recruitment, for the current assessment model. Each time series corresponds to a particular MCMC sample, that has its own estimates of all parameters and variables. These are combined to give the familiar recruitment Figure 28, similar to that from last year’s assessment shown in Figure H.1.

could be larger than 2010. However, the reason that the estimated probability of the 2014 cohort being larger than the 2010 cohort is 0% is because larger values of 2014 recruitment are associated with large values of 2010 recruitment. This is clear when looking at individual time series of recruitment for a subsample of the MCMC samples (Figures H.3 and H.4). [From here on we are using results from this year’s base model, since they are very similar to those from last year’s recruitment estimates (Figure H.1), up until 2019 for which there is now more data].

The individual samples in Figures H.3 and H.4 rarely overlap, so that a high recruitment in 2010 corresponds to a high recruitment in 2014. This breaks down in the final years (explained later).

To show this more clearly, we can divide each individual recruitment time series (MCMC sample) by its value for 2010 (Figure H.5). By definition, all samples are 1 for 2010. Figure H.5 shows that none of the 2014 recruitments (for any of the 100 MCMC samples shown) reach the 2010 value. By showing the same results (for all MCMC samples) in terms of medians and 95% credible intervals (Figure H.6), we can see that relative to 2010 the 2014 recruitment is definitely not as large.

Showing the same results for all years (Figure H.7), including projection years, we see that:

- the 2014 cohort is definitely smaller than the 2010 cohort, whereas intuition (Figure H.2) from the usual plots is that it could possibly be as large as the 2010 cohort;

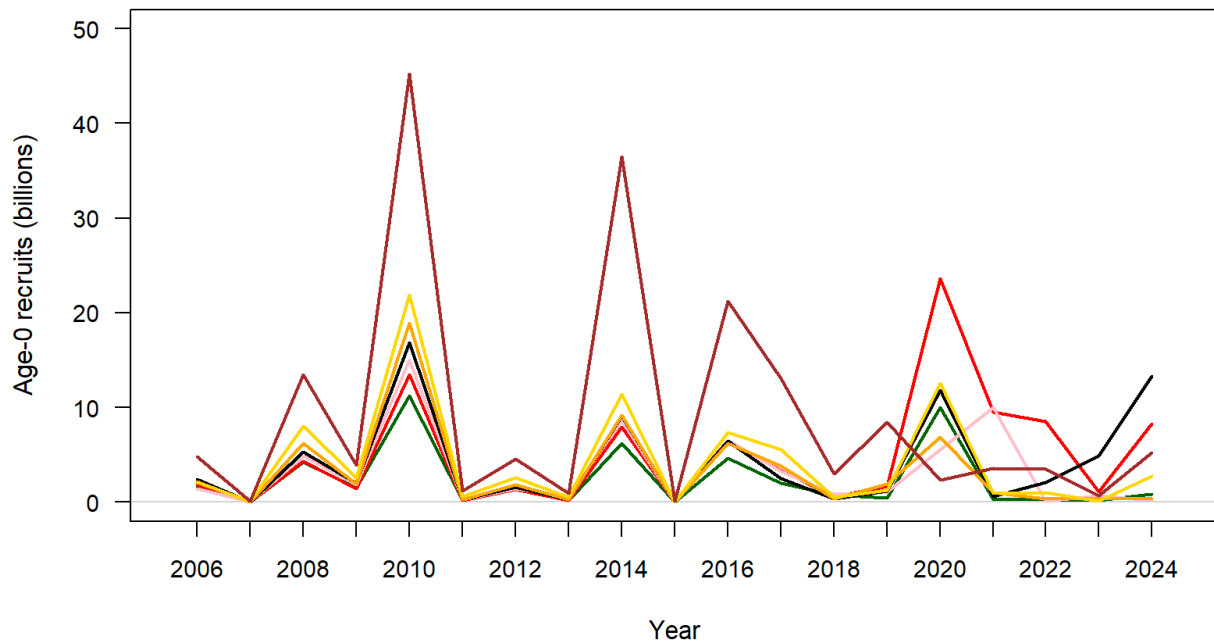


Figure H.4. As for Figure H.3 but for just 10 colour-coded samples to show their non-overlapping nature (this expectedly breaks down in the final years due to a lack of data and random sampling).

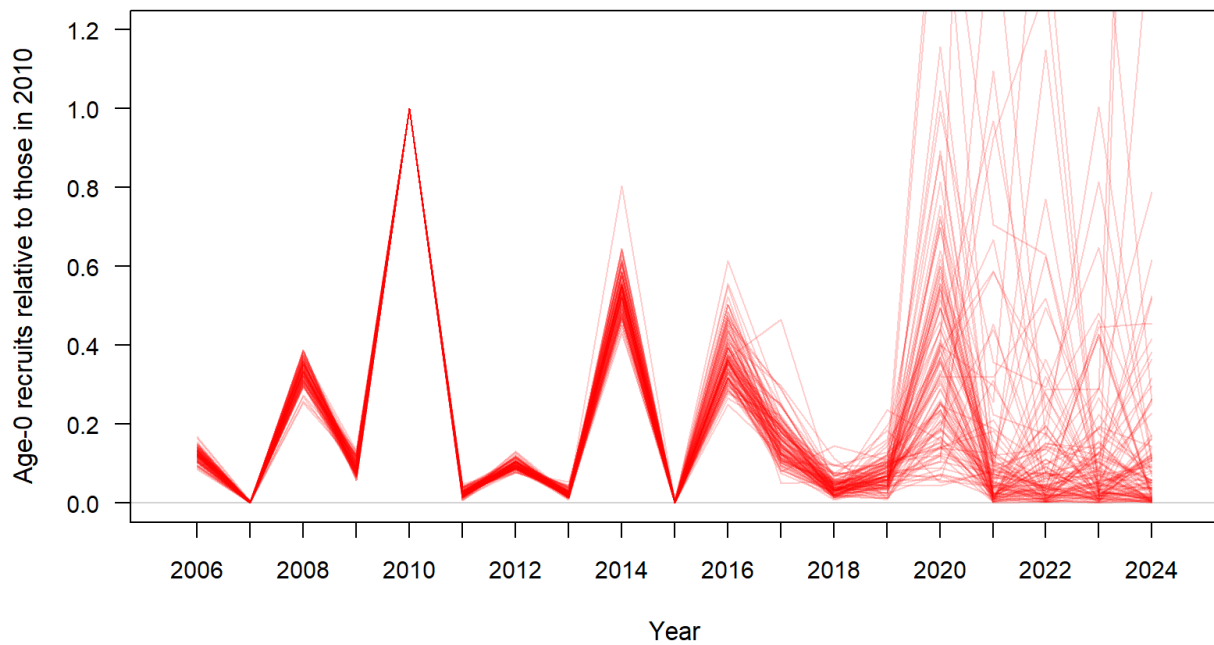


Figure H.5. Trace plots for the 100 MCMC samples in Figure H.3, but with each sample divided by its estimate of the 2010 recruitment. Red is used to indicate this division by the 2010 recruitment.

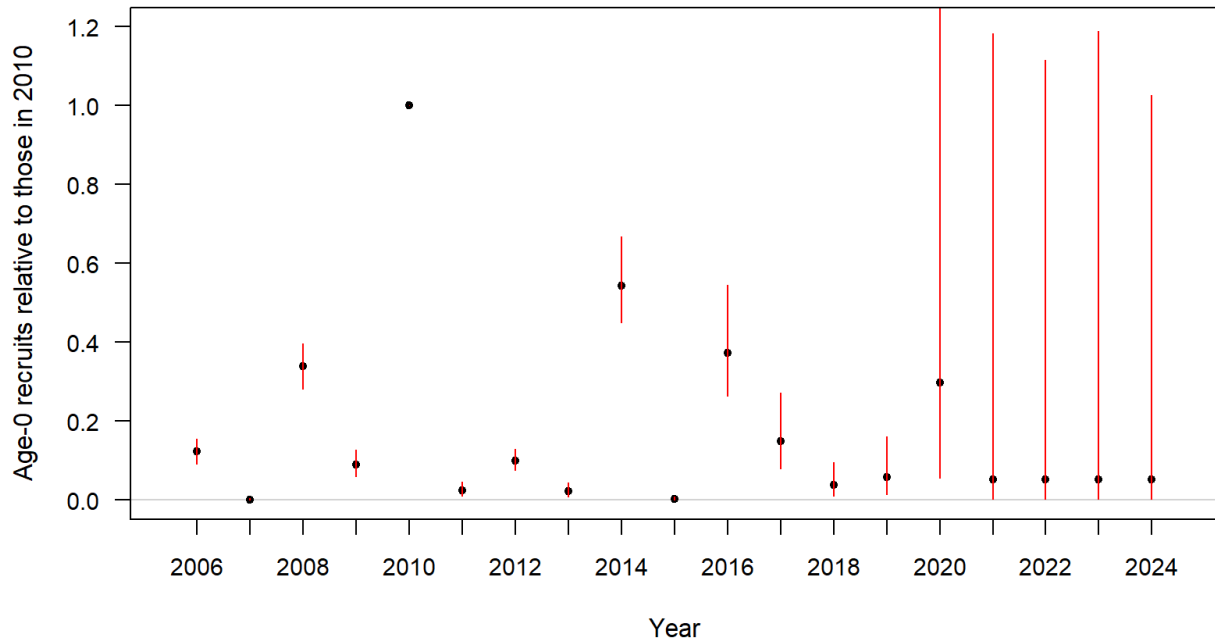


Figure H.6. Estimated recruitments divided by the estimated 2010 recruitment. Medians (solid circles) of the resulting posterior distribution for recruitment relative to that in 2010, with 95% posterior credibility intervals (red lines).

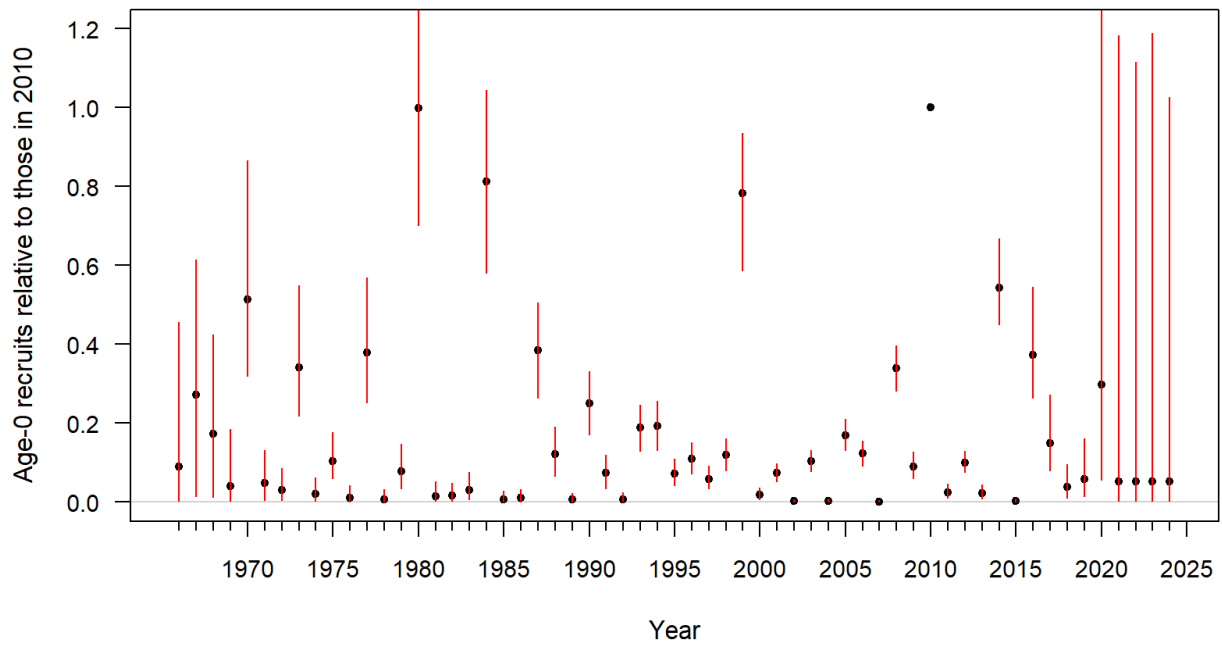


Figure H.7. Estimated recruitments divided by the estimated 2010 recruitment. The same as Figure H.6, but for all years.

-
- there have only been two past recruitment events (1980 and 1984) that might be as large as in 2010. Whereas Figure 28 suggests that 1970, 1999 and 2014 could also possibly be larger than in 2010, giving an over-optimistic impression of how often we can expect cohorts the size of the 2010 cohort to occur.
 - with the very limited data available, the 2020 cohort is expected to be above average, with a chance of being as large as the 2010 cohort, but most likely being roughly only a third of the size of the 2010 cohort (from looking at where the median is for 2020).
 - there are no data to inform the 2021 recruitment, and so for that and the 2022-2024 projection years, the model is allowing recruitments as large as 2010, although half of the projected recruitments are very low (below the dots representing the medians), as expected from the lognormal recruitment deviations used in the model.

The explicit MCMC subsamples for projection years (Figures H.3, H.4 and H.5) make it clear how the projection years do have recruitment time series that cross each other. This is because the recruitment deviation for each MCMC sample each year is based on a random draw from the lognormal distribution stock recruitment (and then applied to the stock-recruitment curve for that MCMC sample, based on the sample's estimated parameters).

In the 2018 assessment the probability that the 2014 cohort was larger than the 2010 cohort was explicitly calculated to be 4.8% (Edwards et al., 2018*b*). The only age composition data informing the size of the 2014 cohort at that time would have been from the fishery when the cohort was of age 1, 2, and 3, and from the survey age when it was of age 3 (the 2017 survey). Figure e from 2018 has the median for 2014 above the lower end of the 2010 credible interval (unlike Figure 28). Now that there are more data available regarding the 2014 cohort (compared to the 2018 assessment) the probability is estimated to be 0%. More data allows for more certainty (less uncertainty) in such a calculation, hence why the probability can change with later assessments.

Given this analysis, we can maybe include the resulting Figure H.7 in future assessments, and hope that it gives a more intuitive understanding of the scale of recruitments. Participants in the Pacific Hake process have an intuition that the 2010 is a very large recruitment event – Figure H.7 shows how it is the largest for at least 30 years, and that such large cohorts are rarer than is inferred from Figure 28.

I ADDITIONAL FORECAST CATCH LEVELS

This appendix contains decision tables for additional forecast catch levels requested by JMC or AP members.

Table I.1. Forecast quantiles of Pacific Hake relative spawning biomass at the beginning of the year, for the extra constant catch alternative of 525,000 t.

Management Action			Biomass at start of year	Resulting relative spawning biomass		
Catch year	Catch (t)	5%		50%	95%	
			Start of 2022	0.35	0.65	1.19
Extra	2022	525,000	Start of 2023	0.31	0.69	1.54
	2023	525,000	Start of 2024	0.21	0.62	1.68
	2024	525,000	Start of 2025	0.11	0.50	1.61

Table I.2. Forecast quantiles of Pacific Hake fishing intensity at the beginning of the year, for the extra constant catch alternative of 525,000 t.

Management Action			Relative fishing intensity		
Catch year	Catch (t)	5%	50%	95%	
Extra	2022	525,000	0.54	0.84	1.11
	2023	525,000	0.54	0.88	1.24
	2024	525,000	0.50	0.91	1.32