

Status of Vermilion rockfish (*Sebastes miniatus*) along the US
West - Oregon coast in 2021

by
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Contents

Executive Summary	i
Stock	i
Landings	i
Data and Assessment	iii
Stock Biomass	iii
Recruitment	vi
Exploitation Status	viii
Ecosystem Considerations	x
Reference Points	x
Management Performance	xiii
Unresolved Problems and Major Uncertainties	xiii
Scientific Uncertainty	xiv
Harvest Projections and Decision Table	xiv
Research and Data Needs	xvii
 1 Introduction	 1
1.1 Basic Information	1
1.2 Life History	1
1.3 Ecosystem Considerations	2
1.4 Historical and Current Fishery Information	3
1.5 Summary of Management History and Performance	4
 2 Data and Model Inputs	 4
2.1 Fishery-Dependent Data	4
2.1.1 Commercial	4
2.1.2 Recreational	6
2.1.3 Index of Abundance	8
2.2 Fishery-Independent Data	10
2.3 Biological Parameters	11
2.3.1 Growth (Length-at-Age)	11

2.3.2	Ageing Precision and Bias	11
2.3.3	Natural Mortality	12
2.3.4	Maturation and Fecundity	13
2.3.5	Length-Weight Relationship	13
2.3.6	Sex Ratio	13
2.3.7	Steepness	14
3	Assessment Model	14
3.1	Summary of Previous Assessments	14
3.1.1	Modelling Platform	14
3.1.2	Bridging Analysis	14
3.2	Model Structure and Assumptions	15
3.2.1	Estimated and Fixed Parameters	15
3.2.2	Data Weighting	15
3.3	Model Selection and Evaluation	16
3.4	Summary of Previous Assessments and Reviews	16
3.4.1	History of Modeling Approaches	16
3.4.2	Most Recent STAR Panel and SSC Recommendations (not required for an update assessment)	17
3.5	Reference Model Diagnostics and Results	17
3.5.1	Model Convergence and Acceptability	17
3.5.2	Reference Model Outputs	18
3.6	Uncertainty exploration	20
3.6.1	Sensitivity Analyses	20
3.6.2	Likelihood Profiles	23
3.6.3	Retrospective Analysis	24
3.7	Management	25
3.7.1	Reference Points	25
3.7.2	Unresolved Problems and Major Uncertainties	25
3.7.3	Harvest Projections and Decision Tables	26
3.7.4	Evaluation of Scientific Uncertainty	26
3.8	Research and Data Needs	26

4	Acknowledgments	27
5	References	29
6	Tables	31
7	Figures	61
8	Appendix A: Detailed Fit to Length Composition Data	110
9	Appendix B: Fit to Conditional-Age-at-Length Composition Data	113
10	Appendix C: Fit to Conditional-Age-at-Length Composition Data	117
11	Appendix D: Numbers at Age Plot	128
11.1	Females	128
11.2	Males	128
12	Appendix E: Numbers at Length Plot	130
12.1	Females	130
12.2	Males	131

Executive Summary

Stock

This assessment reports the status of vermillion rockfish (*Sebastes miniatus*) off Oregon state using data through 2020. Vermilion rockfish are also found in California (their core range) and Washington waters of the U.S. West Coast, and those are treated in separate stock assessments given different management considerations and exploitation histories. There is substantial biogeographic separation in the populations off Oregon and Washington, thus justifying separation of those populations into different management units and stock assessments.

Landings

Vermilion rockfish have been caught mainly by hook and line gear in commercial and recreational fisheries (Figure i). Commercial catches ramped up in the late 1960s followed by decreasing catches since the mid-1980s. Recreational catches started to increase in the 1980s, fluctuating over time, with high catches over the last several years (Table i).

Table i: Recent landings by fleet and total landings summed across fleets.

Year	Commercial	Recreational	Total Landings
2011	2.95	6.10	9.05
2012	2.79	9.15	11.94
2013	3.42	6.30	9.73
2014	2.28	3.95	6.23
2015	1.47	4.65	6.12
2016	2.02	3.69	5.71
2017	3.26	8.80	12.06
2018	3.09	9.20	12.29
2019	3.86	9.25	13.11
2020	3.05	8.24	11.29

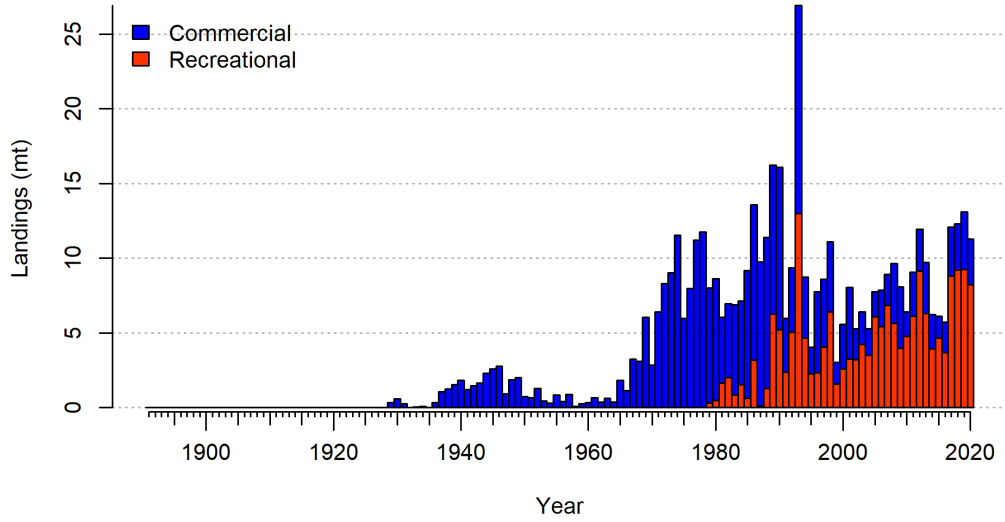


Figure i: Landings by fleet used in the reference model where catches in metric tons by fleet are stacked.

Data and Assessment

The stock assessment for vermilion rockfish off Oregon was developed using the length- and age-structured model Stock Synthesis (version 3.30.16). No previous stock assessment for vermilion rockfish off Oregon has been conducted. Model structure included two fleets (commercial and recreational) and one fishery-based index of abundance. Life history parameters were sex-specific (i.e., a two-sex model) with natural mortality and growth parameters estimated, along with recruitment. The model covers the years 1892 to 2020, with a 12 year forecast beginning in 2021.

This assessment integrates data and information from multiple sources into one modeling framework. Specifically, the assessment uses landings data, length and conditional age-at-length composition data (using ageing error matrices to incorporate ageing imprecision) for each fishery, and one index of abundance based on the recreational fishery; fixed parameterizations of weight-at-length, maturity-at-length, and fecundity-at-length, the Beverton-Holt stock-recruitment steepness value and recruitment variability. Estimated values include initial population scale ($\ln R_0$), natural mortality and growth for each sex, asymptotic selectivity and recruitment deviations. The base model was tuned to account for the weighting of the length and age data and index variances (which was estimated), as well as the specification of recruitment variance and recruitment bias adjustments. Derived quantities include the time series of spawning biomass, age and size structure, and current and projected future stock status.

Within model uncertainty is explicitly included in this assessment by parameter estimation uncertainty, while among model uncertainty is explored through sensitivity analyses addressing alternative input assumptions such as data treatment and weighting, and model specification sensitivity to the treatment of life history parameters, selectivity, and recruitment. A reference model was selected that best fit the observed data while concomitantly balancing the desire to capture the central tendency across those sources of uncertainty, ensure model realism and tractability, and promote robustness to potential model misspecification.

Stock Biomass

Spawning output (in millions of eggs; meggs) instead of spawning biomass is used to report the mature population scale because fecundity is nonlinearly related to body female weight. The estimated spawning output at the beginning of 2021 was 21 meggs (~95 percent asymptotic intervals: 10 to 33 meggs, Table ii and Figure ii), which when compared to unfished spawning output (29) meggs gives a relative stock status level of 73 percent (~95 percent asymptotic intervals: 48 to 98 percent, Figure iii). Overall, spawning output declined with the onset of increasing commercial removals in the 1960s and continued to decline with the increase in recreational catches through the 1990s, even dropping below the target relative stock size.

The largest of the estimated recruitment pulses since the mid 1990s (that are supported by each of the data sets) caused a sharp increase in spawning output through the mid 2010s, followed by another decline. The minimum relative stock size of 34 percent of unfished levels is estimated to have occurred in 1995. Currently the stock is estimated well above the management target of $SB_{40\%}$ in 2021 and is estimated to have remained above the target since 2000 (Table ii and Figure iii).

Table ii: Estimated recent trend in spawning output and the fraction unfished and the 95 percent intervals.

Year	Spawning Output	Lower Interval	Upper Interval	Fraction Unfished	Lower Interval	Upper Interval
2011	27.41	14.59	40.23	0.94	0.65	1.22
2012	27.04	14.33	39.75	0.92	0.65	1.20
2013	26.42	13.82	39.02	0.90	0.63	1.18
2014	25.87	13.42	38.32	0.88	0.61	1.16
2015	25.47	13.23	37.70	0.87	0.61	1.14
2016	24.94	12.97	36.92	0.85	0.59	1.11
2017	24.38	12.69	36.07	0.83	0.58	1.08
2018	23.26	11.85	34.67	0.80	0.55	1.04
2019	22.25	11.05	33.45	0.76	0.52	1.00
2020	21.47	10.34	32.60	0.73	0.49	0.98
2021	21.35	10.06	32.65	0.73	0.48	0.98

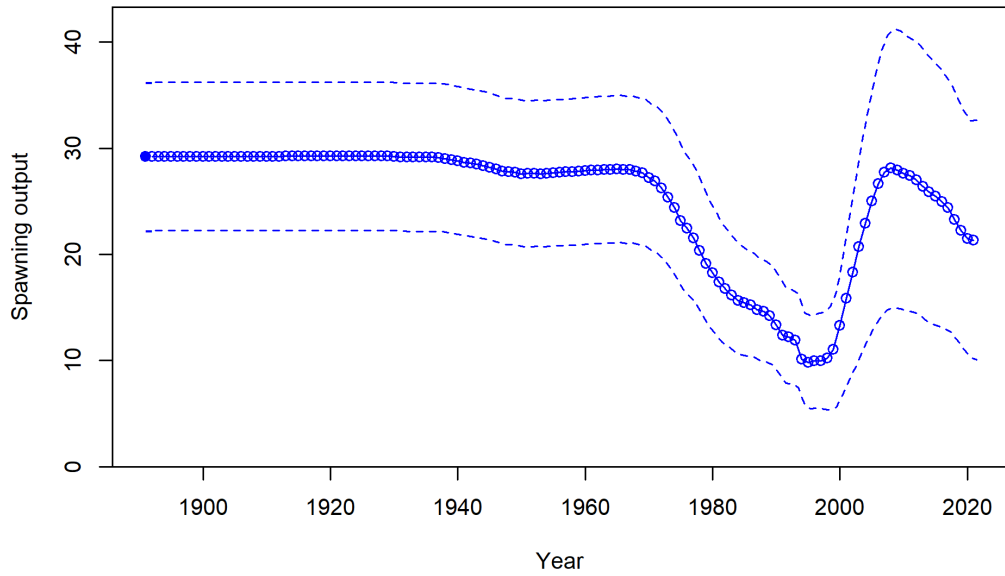


Figure ii: Estimated time series of spawning output (circles and line: median; light broken lines: 95 percent intervals) for the base model.

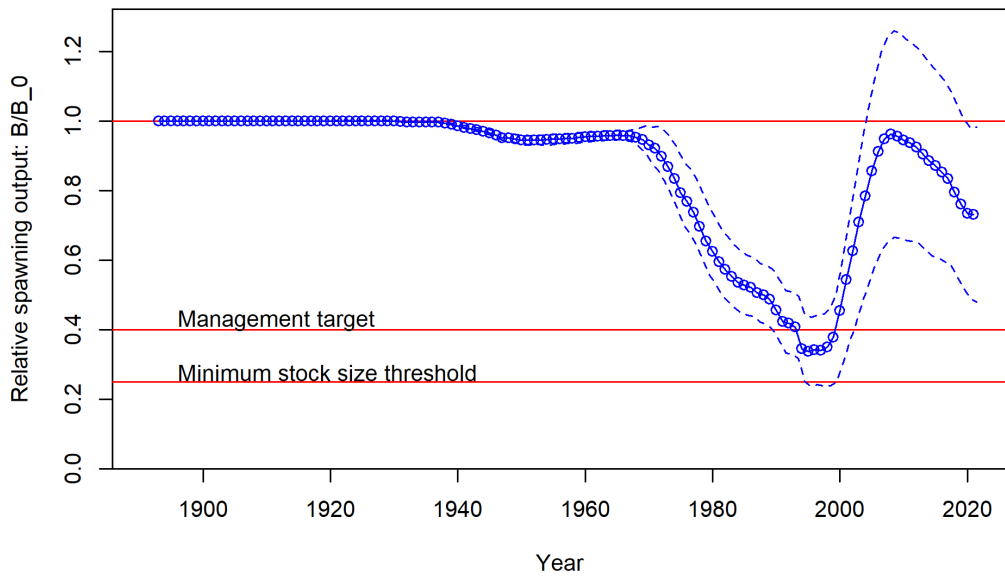


Figure iii: Estimated time series of fraction of unfished spawning output (circles and line: median; light broken lines: 95 percent intervals) for the base model.

Recruitment

Informative recruitment begins in the 1960s and peaks in the 1990s (Table iii and Figure iv). Data were most informative from the the 1990s to the mid-2010s. Peaks years of recruitments are found in years 1993, 1994, 1998, 2005 and 2015 (Figure v). Overall, the vermilion rockfish stock has not been reduced to levels that would provide considerable information on how recruitment compensation changes across spawning biomass levels (i.e., inform the steepness parameter). Thus, all recruitment is based on a fixed assumption about steepness ($h = 0.72$) and recruitment variability ($\sigma_R = 0.6$).

Table iii: Estimated recent trend in recruitment (1000s of fish) and recruitment deviations and the 95 percent intervals.

Year	Recruit- ment	Lower Interval	Upper Interval	Recruit- ment Devia- tions	Lower Interval	Upper Interval
2011	6.69	3.07	14.55	-0.73	-1.34	-0.12
2012	23.17	12.48	43.01	0.51	0.15	0.87
2013	9.65	4.34	21.42	-0.36	-1.00	0.28
2014	31.41	15.11	65.28	0.82	0.29	1.36
2015	78.28	36.66	167.13	1.74	1.16	2.31
2016	11.62	3.82	35.39	-0.32	-1.39	0.74
2017	15.03	4.59	49.17	-0.06	-1.23	1.11
2018	14.79	4.53	48.24	-0.07	-1.24	1.09
2019	14.71	4.51	48.02	-0.07	-1.24	1.09
2020	14.64	4.48	47.84	-0.07	-1.24	1.09
2021	15.77	4.89	50.88	0.00	-1.18	1.18

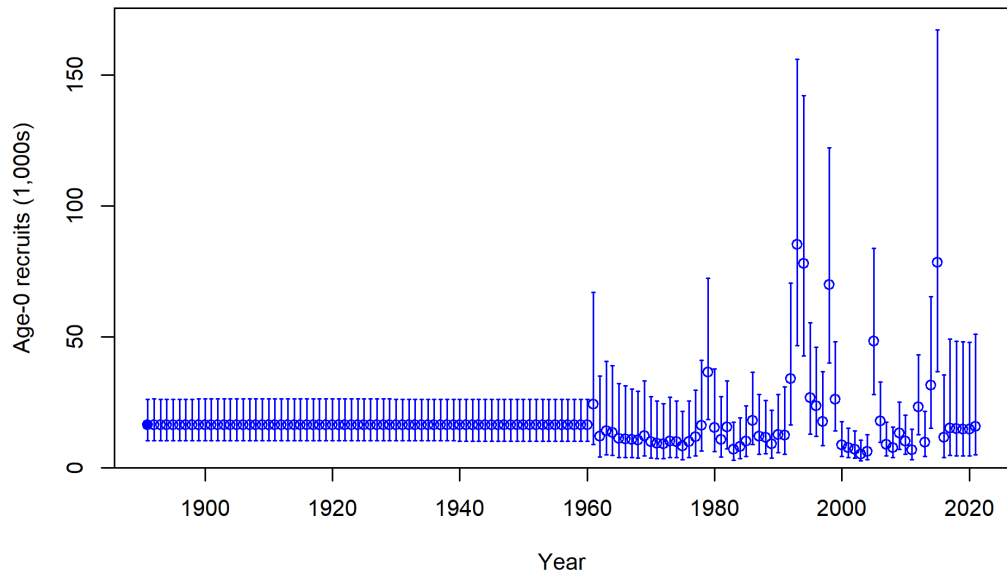


Figure iv: Estimated time series of age-0 recruits (1000s) for the base model with 95 percent intervals.

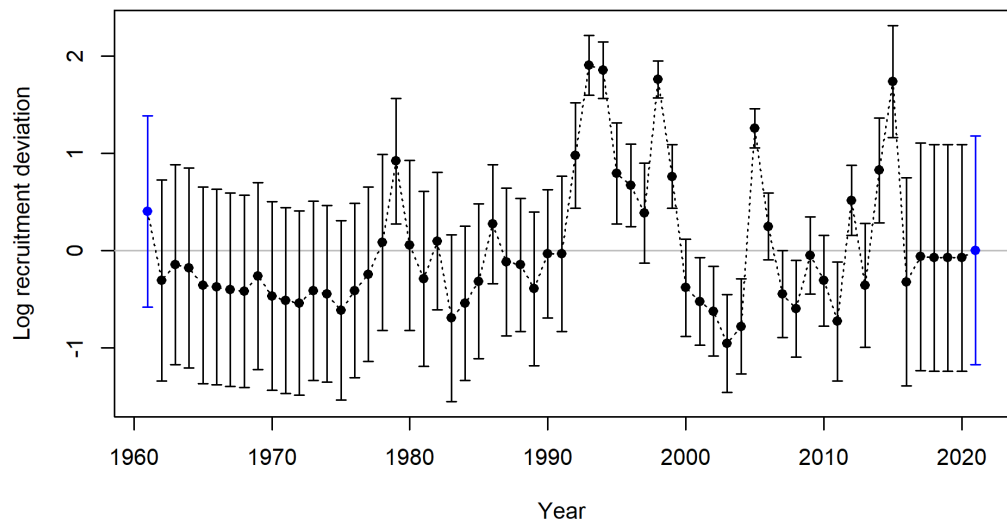


Figure v: Estimated time series of recruitment deviations.

Exploitation Status

Trends in fishing intensity ($1 - \text{SPR}$) largely mirrored that of landings until the 1990s when recruitment pulses overcame the catches to lower overall fishing intensity (Figure vi). The maximum fishing intensity was 0.84 in 1993, above the target SPR-based harvest rate of 0.50 ($1 - \text{SPR}_{50\%}$). Current levels of 0.47 for 2020 are near the fishing limit. Fishing intensity over the past decade has ranged between 0.27 and 0.51 and the exploitation rate has been high (0.02 - 0.05, Table iv). Current estimates indicate that vermilion rockfish spawning output is much greater than than the target biomass level ($\text{SB}_{40\%}$), though fishing intensity remains near target F_{MSY} proxy harvest rate.

Table iv: Estimated recent trend in the 1-SPR where SPR is the spawning potential ratio the exploitation rate, and the 95 percent intervals.

Year	1-SPR	Lower Interval	Upper Interval	Exploita- tion Rate	Lower Interval	Upper Interval
2011	0.35	0.20	0.50	0.03	0.02	0.04
2012	0.43	0.26	0.59	0.04	0.02	0.06
2013	0.38	0.22	0.53	0.03	0.02	0.05
2014	0.28	0.15	0.41	0.02	0.01	0.03
2015	0.28	0.15	0.41	0.02	0.01	0.03
2016	0.27	0.15	0.40	0.02	0.01	0.03
2017	0.47	0.30	0.63	0.05	0.02	0.07
2018	0.48	0.31	0.65	0.05	0.03	0.07
2019	0.51	0.33	0.69	0.05	0.03	0.08
2020	0.47	0.29	0.64	0.05	0.02	0.07

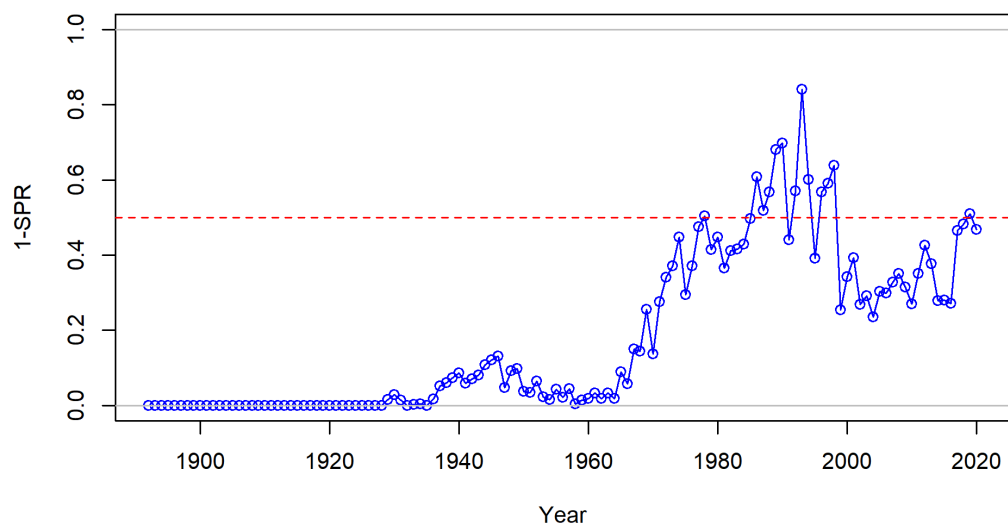


Figure vi: Estimated 1 - relative spawning ratio (SPR) by year for the base model. The management target is plotted as a red horizontal line and values above this reflect harvest in excess of the proxy harvest rate.

Ecosystem Considerations

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

Reference Points

The 2021 spawning biomass relative to unfished equilibrium spawning biomass is well above the management target of 40 percent of unfished spawning biomass. The relative biomass and the ratio of the estimated SPR to the management target ($SPR_{50\%}$) across all model years are shown in Figure vii where warmer colors (red) represent early years and colder colors (blue) represent recent years. There have been periods where the stock status has decreased below the target and fishing intensity has been higher than the target fishing intensity based on $SPR_{50\%}$. Figure viii shows the equilibrium curve based on a steepness value fixed at 0.72 with vertical dashed lines to indicate the estimate of fraction unfished at the start of 2021 (current) and the estimated management targets calculated based on the relative target biomass (B target), the SPR target, and the maximum sustainable yield (MSY).

Reference points were calculated using the estimated selectivities and catch distributions among fleets in the most recent year of the model, 2020 (Table v). Sustainable total yield, removals, using an $SPR_{50\%}$ is 7.95 mt. The spawning output equivalent to 40 percent of the unfished spawning output ($SO_{40\%}$) calculated using the SPR target ($SPR_{50\%}$) was 13.04 meggs. Recent removals have been close to the point estimate of potential long-term yields calculated using an $SPR_{50\%}$ reference point and the population size has been relatively decreasing toward the target over the past few years.

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

	Estimate	Lower Interval	Upper Interval
Unfished Spawning Output	29.24	22.19	36.29
Unfished Age 3+ Biomass (mt)	354.37	278.67	430.07
Unfished Recruitment (R_0)	16.33	8.52	24.13
Spawning Output (2021)	21.35	10.06	32.65
Fraction Unfished (2021)	0.73	0.48	0.98
Reference Points Based $SB_{40\%}$			
Proxy Spawning Output $SB_{40\%}$	11.70	8.88	14.51

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

	Estimate	Lower Interval	Upper Interval
SPR Resulting in SB _{40%}	0.46	0.46	0.46
Exploitation Rate Resulting in SB _{40%}	0.06	0.05	0.07
Yield with SPR Based On SB _{40%} (mt)	8.32	5.57	11.07
<u>Reference Points Based on SPR Proxy for MSY</u>			
Proxy Spawning Output (SPR ₅₀)	13.04	9.90	16.19
SPR ₅₀	0.50		
Exploitation Rate Corresponding to SPR ₅₀	0.05	0.04	0.06
Yield with SPR ₅₀ at SB SPR (mt)	7.95	5.32	10.57
<u>Reference Points Based on Estimated MSY Values</u>			
Spawning Output at MSY (SB MSY)	8.04	6.28	9.81
SPR MSY	0.35	0.34	0.35
Exploitation Rate Corresponding to SPR MSY	0.09	0.07	0.11
MSY (mt)	8.82	5.89	11.76

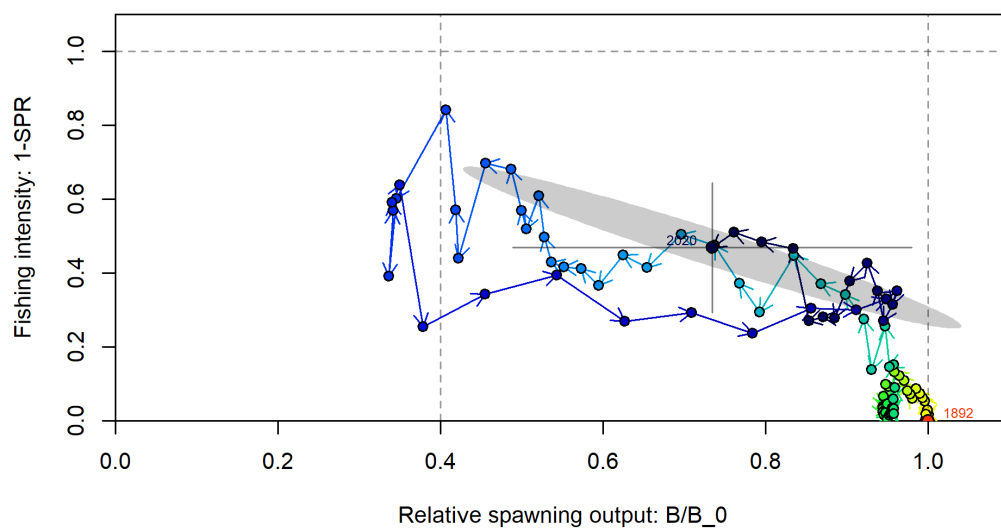


Figure vii: Phase plot of estimated 1-SPR versus fraction unfished for the base model.

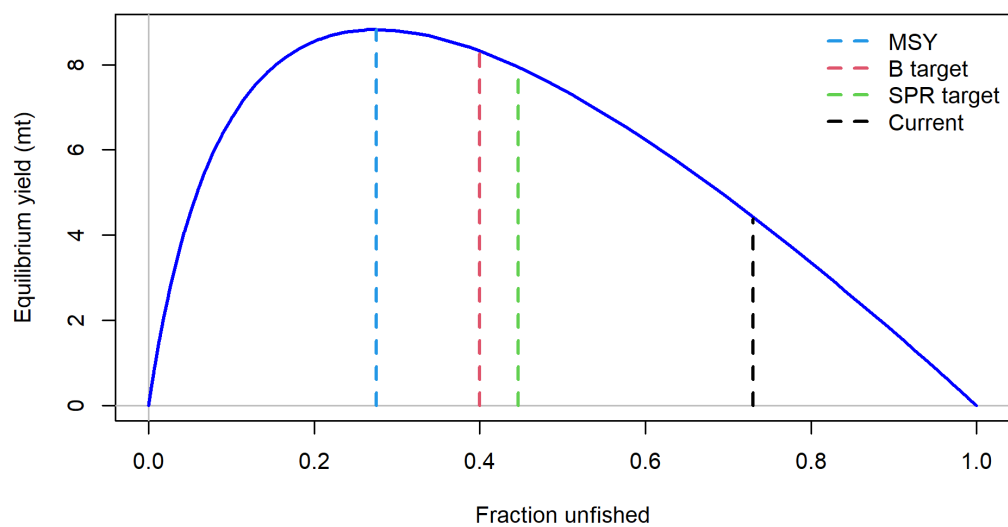


Figure viii: Equilibrium yield curve for the base case model. Values are based on the 2020 fishery selectivities and with steepness fixed at 0.80.

Management Performance

Exploitation on vermilion rockfish increased starting around 1960 and reached a high in the early 1990s. Since that time, catch has mostly fluctuated between 5 and 10 mt per year, with some years exceeding 10 mt, particularly in the last 4 years. The last ten years of the vermilion rockfish component acceptable biological catch (ABC) and annual catch limit (ACL) (which are equivalent) of the Minor Shelf Rockfish North Complex has been set, by definition, below the overfishing limit (OFL) (Table vi). The vermilion rockfish component OFL for this Complex has been exceeded by the Oregon removals in the most recent 4 years.

Table vi: The OFL, ABC, ACL, landings, and the estimated total mortality in metric tons.

Year	OFL	ABC	ACL	Landings	Est. Total Mortality
2011	11.1	5.6	5.6	9.1	9.1
2012	11.1	5.6	5.6	11.9	11.9
2013	9.7	8.1	8.1	9.7	9.7
2014	9.7	8.1	8.1	6.2	6.2
2015	9.7	8.1	8.1	6.1	6.1
2016	9.7	8.1	8.1	5.7	5.7
2017	9.7	8.1	8.1	12.1	12.1
2018	9.7	8.1	8.1	12.3	12.3
2019	9.7	8.1	8.1	13.1	13.1
2020	9.7	8.1	8.1	11.3	11.3

Unresolved Problems and Major Uncertainties

Natural mortality (M) was estimated by the model, though vermilion rockfish longevity is not well understood in Oregon. While the estimated sex-specific M values seem well within reason, the model remains sensitive to the choice of this parameter, and therefore improving the M prior (the prior used in this model may be centered on the higher end) while continuing to collect age data for future estimation within the model is important. This also plays through the collection of lengths to go with ages to continue to improve the estimation of age and growth. Future work on improving point estimates and possibly investigate time-varying life history parameters could improve model fits.

Functional maturity (Head et al. 2020) is an emerging concept in reproductive biology capturing physiological behaviors such as delayed maturity, skipped spawning and atresia

and correcting for them in the length at maturity relationship. Investigating functional maturity could improve the application of maturity in the model.

Fishery-independent surveys would add additional support for those trends seen using fishery-based data.

Scientific Uncertainty

The model-estimated uncertainty around the 2021 spawning biomass was $\sigma = 0.27$ and the uncertainty around the OFL was $\sigma = 0.31$. This is likely an underestimate of overall uncertainty because of the necessity to fix some parameters such as steepness, as well as a lack of explicit incorporation of model structural uncertainty.

Harvest Projections and Decision Table

A ten year (2023-2032) projection of the reference model with removals in 2021 and 2022 provided by the Groundfish Management Team for each fleet under the category 1 (sigma=0.5) time-varying buffer using $P^* = 0.45$ and 40-10 ABC control rule is provided in Table vii.

Table vii: Projections of potential OFLs (mt), ABCs (mt), the buffer (ABC = buffer x OFL), estimated spawning biomass, and fraction unfished for Oregon portion of the vermilion stock. The North of 40°10'N OFL and ABC for 2021 and 2022 are included for comparison.

Year	OFL 40°10'N	ACL 40°10'N	Predicted OFL	ABC Catch	Buffer	Spawning Output	Fraction Unfished
2021	9.70	8.10	13.01	12.96	1.00	21.37	0.73
2022	9.70	8.10	13.35	12.96	1.00	21.53	0.73
2023	-	-	13.41	12.54	0.94	21.75	0.74
2024	-	-	13.29	12.36	0.93	21.85	0.75
2025	-	-	13.03	12.06	0.93	21.74	0.74
2026	-	-	12.72	11.73	0.92	21.46	0.73
2027	-	-	12.41	11.38	0.92	21.08	0.72
2028	-	-	12.10	11.05	0.91	20.65	0.71
2029	-	-	11.82	10.74	0.91	20.20	0.69
2030	-	-	11.56	10.45	0.90	19.75	0.68
2031	-	-	11.31	10.18	0.90	19.33	0.66
2032	-	-	11.08	9.94	0.90	18.92	0.65

The decision table (Table viii) was constructed using female and male natural mortality to

define the low and high states of nature. The multi-parameter likelihood profile was used to find the low (Female $M = 0.07092$; Male $M = 0.06525$) and high (Female $M = 0.08527$; Male $M = 0.07845$) female and male natural mortality values that produce -log likelihood values +0.66 units from the reference -log likelihood value. These correspond to the 12.5% and 87.5% quantiles (standard quantiles used in west coast decision tables). The catch rows in the table were based on three proposed catch streams: 1. $P^* = 0.45$, $\sigma = 0.5$ 2. $P^* = 0.40$, $\sigma = 0.5$ 3. An equilibrium catch based on the F_{MSY} proxy using $SPR = 0.5$.

Across all states of nature and catch streams, vermilion rockfish relative stock size never falls below the target relative stock size of 40%. Both P^* approaches lower the stock status from the high relative stock size values, while the F_{MSY} proxy does not. The mismatch in the corresponding steepness value ($h = 0.6$) that matches MSY at $SPR = 0.5$ with the steepness value in the stock assessment ($h = 0.72$) that corresponds to an MSY SPR of 0.35 explains why this constant catch will maintain the stock at very high relative stock status levels.

Table viii: Decision table summary of 10 year projections beginning in 2023 for alternative states of nature based on an axis of uncertainty about female and male natural mortality for the reference model. Columns range over low (12.5 quantile), mid (reference model), and high states (87.5 quantile) of nature and rows range over different catch level assumptions. Values in italics indicate years where the stock size prevented the full catch removals.

	Year	Catch	Female M = 0.071; Male =0.065		Female M = 0.079; Male =0.073		Female M = 0.085; Male =0.079	
			Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished
P*=0.45 sigma=0.5	2021	12.96	17.70	0.62	21.37	0.73	24.46	0.79
	2022	12.96	17.76	0.62	21.53	0.73	24.68	0.80
	2023	12.60	17.89	0.63	21.79	0.74	25.01	0.81
	2024	12.45	17.93	0.63	21.92	0.75	25.20	0.82
	2025	12.19	17.81	0.63	21.85	0.74	25.16	0.82
	2026	11.89	17.56	0.62	21.63	0.74	24.93	0.81
	2027	11.56	17.23	0.60	21.29	0.72	24.58	0.80
	2028	11.24	16.86	0.59	20.90	0.71	24.16	0.78
	2029	10.93	16.46	0.58	20.48	0.70	23.70	0.77
	2030	10.63	16.06	0.56	20.04	0.68	23.23	0.75
	2031	10.36	15.67	0.55	19.62	0.67	22.76	0.74
	2032	10.10	15.29	0.54	19.21	0.65	22.31	0.72
P*=0.4 sigma=0.5	2021	12.96	17.70	0.62	21.37	0.73	24.46	0.79
	2022	12.96	17.76	0.62	21.53	0.73	24.68	0.80
	2023	11.77	17.89	0.63	21.79	0.74	25.01	0.81
	2024	11.60	18.00	0.63	21.99	0.75	25.27	0.82
	2025	11.34	17.96	0.63	21.99	0.75	25.30	0.82
	2026	11.04	17.78	0.62	21.84	0.74	25.14	0.82
	2027	10.72	17.53	0.62	21.58	0.73	24.87	0.81
	2028	10.41	17.22	0.60	21.25	0.72	24.51	0.79
	2029	10.10	16.89	0.59	20.89	0.71	24.11	0.78
	2030	9.82	16.56	0.58	20.52	0.70	23.70	0.77
	2031	9.55	16.23	0.57	20.15	0.69	23.29	0.76
	2032	9.29	15.91	0.56	19.80	0.67	22.89	0.74
Equilibrium yield from FMSY proxy of SPR=0.5	2021	12.96	17.70	0.62	21.37	0.73	24.46	0.79
	2022	12.96	17.76	0.62	21.53	0.73	24.68	0.80
	2023	7.95	17.89	0.63	21.79	0.74	25.01	0.81
	2024	7.95	18.32	0.64	22.30	0.76	25.58	0.83
	2025	7.95	18.59	0.65	22.62	0.77	25.92	0.84
	2026	7.95	18.72	0.66	22.75	0.77	26.05	0.84
	2027	7.95	18.73	0.66	22.75	0.77	26.03	0.84
	2028	7.95	18.66	0.66	22.65	0.77	25.89	0.84
	2029	7.95	18.53	0.65	22.47	0.76	25.67	0.83
	2030	7.95	18.36	0.64	22.25	0.76	25.39	0.82
	2031	7.95	18.16	0.64	21.99	0.75	25.09	0.81
	2032	7.95	17.94	0.63	21.71	0.74	24.76	0.80

Research and Data Needs

1. Resolution in stock structure. Continued sampling of vermilion rockfish in Oregon would allow for more genetic understanding of population structure. In addition, consideration of fishery similarities between northern California (north of Cape Mendocino) and southern Oregon may be worth further consideration to see if that is a better grouping of stocks compared to combining central and northern California.
2. Continued quantification of ageing error. The CARE exchange has high value in general to further our ability to understand the inherent variability of reading ageing structures, and should be strongly supported.
3. The life history parameters are all assumed constant through time. This assumption of stationarity is one of convenience and parsimony. Any insight into the changing of life history values or differing productivity regimes could help refine these assumptions.
4. Natural mortality proved the source of greatest uncertainty in the model. While empirical methods can help define priors for natural mortality, good sampling of age structure or direct measures (e.g., tagging) are preferred. Oregon's robust sampling program may include ways to collect data that can directly improve natural mortality estimation and reduce model uncertainty.
5. Ongoing sampling of biological data will remain a core component of information in the stock assessment and needs to be continued and supported.
6. A fishery-independent index of abundance would be a welcome inclusion in this assessment, along with the ongoing development of the ORBS index (e.g., the appropriateness of applying the Stephens-MacCall filtering method to fisheries data; how to treat months with different management measures).
7. The large uncertainty estimated in this stock assessment was limited given the asymptotic, symmetric variance estimation from the maximum likelihood estimation method. While a Bayesian model was considered and even explored for this model, it was not included due to challenges in implementation and lack of enough time to achieve a converged model. Continued development of Bayesian approaches to characterizing uncertainty are strongly encouraged.
8. Ensemble modelling may be another potential tool to incorporate model uncertainty beyond within model variance estimation that should be considered.
9. Fishery selectivity continues to be challenging to represent, and are key parameters in the model. Blocks in selectivity and whether there are *a priori* reasons to expect any dome-shaped selectivity deserve continued thought. The change of selectivity within a year (e.g., some seasons have depth restriction, others do not) should also be a topic of discussion.

1 Introduction

1.1 Basic Information

This assessment reports the status of vermilion rockfish (*Sebastes miniatus*) off the waters of Oregon state using data through 2020. Vermilion rockfish range from Prince William Sound, Alaska, to central Baja California at depths of 6 m to 436 m (Love et al. 2002). They are most commonly found from southern Oregon to Punta Baja, Mexico at depths of 50 m to 150 m (Hyde and Vetter 2009). Hyde et al. [hyde_cryptic_2008] describe an additional cryptic species related to vermilion rockfish, the sunset rockfish (*Sebastes crocotulus*). They note that vermilion rockfish reside in shallower depths (<100 m) compared to sunset rockfish. Sunset rockfish tend to be more southerly, and are not encountered in Oregon, so this assessment focuses only on vermilion rockfish. Adult vermilion rockfish tend to cluster on high relief rocky outcrops (Love et al. 2002) and kelp forests (Hyde and Vetter 2009). North of Point Conception, some adults are shallower, living in caves and cracks (Love et al. 2002). Vermilion rockfish have shown high site fidelity (Hannah and Rankin 2011 (only tagged 1 vermilion rockfish); Lea et al. 1999), and low average larval dispersal distance (Hyde and Vetter 2009). Lowe et al. (2009) suggested vermilion rockfish have a lower site fidelity than previously believed, but they acknowledged that their observations of movements to different depths may have been due to the reality of a shallower species and a deeper species.

The stock designation of Oregon waters was based on the California stock having a separate exploitation history as well as a much larger stock density. Vermilion rockfish are not as abundant north of California, but still provide some fishing opportunities (Hannah and Kautzi 2012). The separation of Oregon and Washington into distinct management units, and thus separate stock assessments, were based on the observation that most vermilion rockfish in Oregon are taken off southern Oregon, while most of the habitat and take of vermilion rockfish off Washington was in the very northern portion of the Washington coast (Figure 1). Ninety percent of the total mortality in Oregon is from the southern part of the state (south of Pt. Arago), while ninety-seven percent comes from the northern portion of Washington (Figure 2). This large area of separation, low movement of larvae and adults, and the biogeographic barriers of the Columbia River outfall and lack of rocky habitat in southern Washington all support separate Oregon-Washington management units.

1.2 Life History

The approximate average lifespan for vermilion rockfish is 60 years, with females living longer and growing larger than their male counterparts. 50% are mature at 5 years and about 37 cm, with males probably maturing at shorter lengths than females (Love et al. 2002).

Vermilion rockfish are viviparous, and release 63,000 to 2,600,000 eggs per season. In southern California, vermilion rockfish larvae are released between July and March. In central and northern California, this release occurs in September, December, and April-June (Love et al. 2002). In Oregon, fertilized females with ripe ovaries are encountered from April to October (Hannah and Kautzi 2012), with larval release sometime during and after that period. Larval release in fall and winter is not common among other rockfish species. Hyde and Vetter (2009) suggest that low larval dispersal may be due to weak poleward flow of nearshore waters corresponding with peak vermilion rockfish larval release.

Young-of-the-year (YOY) vermilion rockfish settle out of the plankton during two recruitment periods per year, first from February to April and a second from August to October, and settlement has been observed in May off southern California (Love et al. 2002). There is no information on YOY settlement in Oregon. Larvae measure about 4.3 mm. Both young-of-the-year vermilion rockfish and sunset rockfish are mottled brown with areas of black, and older juveniles turn a mottled orange or red color (Love et al. 2012). Juvenile fish are found individually from 6 m to 36 m, living near sand and structures. After two months, juveniles travel deeper and live on low relief rocky outcrops and other structures (Love et al. 2002).

Adult vermilion rockfish predominantly eat smaller fish, though sometimes they pursue euphausiids and other various macroplankton (Phillips 1964). Love (2002) noted their diet to include octopus, salps, shrimps, and pelagic red crabs.

1.3 Ecosystem Considerations

This stock assessment does not explicitly incorporate trophic interactions, habitat factors or environmental factors into the assessment model, but a brief description of likely or potential ecosystem considerations are provided below.

Vermilion rockfish feed on a wide range of both pelagic and benthic prey items, including forage fish species such as anchovies and mesopelagic fishes, squid, krill and octopus, as well as sporadically abundant pelagic organisms such as pyrosomes, salps and pelagic red crabs (Phillips 1964; Love et al. 2002). Interestingly, other rockfishes (either juvenile or adult stages) have not been documented as prey for vermilion rockfish as they have for other larger *Sebastes* species (e.g., cowcod, bocaccio and yelloweye rockfish). Pelagic and benthic juvenile vermilion rockfish are likely preyed upon by the same wide range of predators that prey on juveniles and adults of other rockfish species, including seabirds, piscivorous fishes, and marine mammals.

As with most other rockfish and groundfish in the California Current, recruitment, or cohort (year-class) strength appears to be highly variable for the vermilion rockfish, with only a

modest apparent relationship to spawning output. Oceanographic and ecosystem factors are widely recognized to be key drivers of recruitment variability for most species of groundfish, as well as most elements of California Current food webs. Empirical estimates of recruitment from pelagic juvenile rockfish surveys have been used to inform incoming year class strength for some of these stocks, however vermilion and sunset rockfish are rarely encountered in these surveys. Specifically, only 47 of nearly 300,000 total juvenile *Sebastes* encountered in juvenile surveys since 2001 were identified as vermilion or sunset rockfish (Field et al. 2021). Previous studies have demonstrated that large-scale oceanographic drivers, such as the relative transport of subarctic waters (typically indicated by relative sea level) tend to relate to a substantial fraction of overall groundfish recruitment trends and ecosystem productivity Schroeder et al. (2019). Although it is feasible that ecosystem factors, the results of pre-recruit surveys for co-occurring species, or the results of other groundfish assessments might ultimately be used to forecast recruitment for more data-limited stocks such as vermilion rockfish, as suggested by (Thorson and Ward 2014), such approaches would require more development and evaluation. Consequently, environmental factors are not explicitly considered in this assessment.

1.4 Historical and Current Fishery Information

Off the coast of Oregon, vermilion rockfish is caught in both commercial and recreational fisheries. The landings from the commercial fishery were minimal until the mid-1960s. Following the development of the nearshore commercial fishery in the late 1990s, Oregon Department of Fish and Wildlife (ODFW) implemented a state-permitted limited access fishery that regulated fleet size, period landing limits and established harvest guidelines (Rodonsky et al. 2020). Vermilion rockfish is one of multiple rockfish species that are commonly landed as a part of the nearshore commercial groundfish fishery. Currently, this commercial fishery is centered on the southern Oregon coast, where most of the vermilion rockfish commercial landings occur. Two types of state limited entry permits are issued for this fishery, with and without a nearshore endorsement. Limited entry permit holders without a nearshore endorsement may land commercial quantities of black and blue rockfish under state trip limits, with an additional total of 15 lbs per day of any combination of other nearshore groundfish species and two rockfish species with Federal designation as shelf rockfish. These include tiger and vermilion rockfish. Vessels that have a nearshore endorsement permit may land commercial quantities of other nearshore groundfish species up to the state's cumulative trip limits and the Federal limits for tiger and vermilion rockfish. There are no state trip limits set for vermilion rockfish.

This analysis assesses the stock off the Oregon coast as a separate stock from other populations off the West Coast based on the sedentary nature of vermilion rockfish, which likely limits flow of fish between California and Washington. The substrate of the northern Oregon and southern Washington coast is primarily sandy bottom and combined with the Columbia River plume between Oregon and Washington these factors create a natural separation between the

Oregon and Washington populations. Additionally, the exploitation history and magnitude of removals off the Oregon coast has been dramatically lower than removals off the California coast. The recreational fishery off the coast of Oregon developed during the 1970s, with the first recorded landings of vermillion rockfish in 1979. Vermilion rockfish is not commonly encountered in the recreational fishery, but recreational removals have generally increased across time as this fishery has developed (Table 1).

1.5 Summary of Management History and Performance

Vermilion rockfish is managed by the Pacific Fishery Management Council (PFMC) as a part of the Shelf Rockfish North and Shelf Rockfish South complexes. The North and South areas are split at N. 40°10' Lat. N. off the West Coast. The complex is managed based on a complex level overfishing limit (OFL) and annual catch limit (ACL). The OFL and ACL values for the complex are determined by summing the species specific OFLs and ACLs managed within the complex. Removals for species within the Rockfish complex are managed and tracked against the complex total OFL and ACL, rather than on a species by species basis. The OFL and ACLs for vermillion rockfish North of 40°10' Lat. N. management area and the total removals are shown in Table 2. There are no state-specific allocations of this complex and so removals are evaluated at the regional level (North of 40°10'N).

2 Data and Model Inputs

A description of each data source is provided below (Figure 3).

2.1 Fishery-Dependent Data

2.1.1 Commercial

2.1.1.1 Landings

In Oregon, historical commercial landings from 1892 to 1986 were provided by ODFW (Karnowski et al. 2014). Historical landings were consistent but minimal (< 1 mt) until the mid-1960s, except for a period from the mid-1930s to the late 1940s, during which landings increased to a high of 2.8 mt and declined again to under one mt. From 1965 to 1986, landings averaged 6.6 mt annually. Primary gear types during this historical period included longline and troll gears. However, ODFW commercial samplers suggest that these troll landings were

primarily landed on hook and line gear, but not separated by gear type on the fish tickets (pers. comm. M. Freeman, ODFW).

Landings from 1987 – 1999 were compiled from a combination of PacFIN, the central repository for West coast commercial landings (extracted on 11/17/2020), and a separate ODFW reconstruction that delineated species-specific landings in the unspecified categories on PacFIN (e.g. URCK and POP1, ODFW 2017). Vermilion rockfish landings from this reconstruction were substituted for the URCK and POP1 landings available from PacFIN, and added to PacFIN landings from other categories for a complete time series during this time period. Commercial landings from 2000 – 2020 are available on PacFIN (extracted on 11/17/2020 and 02/18/2021). Vermilion rockfish is one of several rockfish species landed by a nearshore, primarily live-fish fixed gear fishery centered on Oregon’s southern coast. Following the development of this nearshore commercial fishery in the late 1990s, ODFW implemented a state-permitted limited access fishery that regulated fleet size, period landing limits and established harvest guidelines (Rodomsky et al. 2020). Vermilion rockfish are landed almost exclusively with hook and line and bottom longline gear. On average, 99.8% of vermilion rockfish landings are from these two gear types (2000 – 2020). Landings from all other gear types, including fish pot and trawl, are minimal relative to jig and longline gears and sporadic. Commercial landings peaked in 1993 at 13.9 mt before declining and fluctuating between 1.5 and 4.8 mt (2000 – 2020). Landings in 2020 were 3.3 mt. Table 1 provides landings by fleet over time.

2.1.1.2 Lengths

Commercial vermilion rockfish length samples are available from PacFIN from 1999 – 2020 ($n = 2,355$). Table 3 shows sample size by year and fleet and Figure 4 shows the length compositions across time. These samples were extracted on 02/24/2021. Approximately 47.9% of these samples are females ($n = 1,129$) and 51.9% are males ($n = 1,222$). Only four fish were unsexed. The majority (93.3%) are from the southern Oregon coast, centered in Port Orford (67.4%) and Gold Beach (25.8%), where the majority of permit holders for the commercial nearshore fishery are based and where most of the landings are made. The majority of length samples are from vermilion rockfish landed to the fresh (dead) market (93.5%). Additionally, special projects length samples collected from the commercial fishery are available from PacFIN from 2000 - 2006, 2008 - 2009, and 2012 ($n = 381$; extracted on 02/24/2021). Special projects samples were not included in the length compositions used in this model as they were not randomly sampled from the fishery.

2.1.1.3 Ages

There were 896 commercial age samples available from 2004 and 2007 - 2020 (Table 4). Approximately, 50.1% of samples were males ($n = 449$) and 49.9% were females ($n = 447$). As with the length samples, the vast majority of samples are from the southern Oregon coast (95.8%, $n = 858$), including Port Orford (73.4%) and Gold Beach (22.3%).

2.1.2 Recreational

2.1.2.1 Removals

Recreational landings and estimated discards are available in Table 1.

2.1.2.1.1 Historic Ocean Boat Landings (1979–2000)

Recently, the Oregon Department of Fish and Wildlife (ODFW) undertook an effort to comprehensively reconstruct all marine fish recreational ocean boat landings prior to 2001 (pers. comm. A. Whitman, ODFW). Reconstructed catch estimates from the Oregon Recreational Boat Survey (ORBS) improve upon estimates from the federal Marine Recreational Fisheries Statistical Survey (MRFSS), which have known biases related to effort estimation and sampling (Van Voorhees et al. 2000) that resulted in catch estimates considered implausible by ODFW. However, the ORBS sample estimates are known to lack the comprehensive spatial and temporal coverage of MRFSS. Addressing this coverage issue is a major part of this reconstruction. In general, the base data and methodology for these reconstructed estimates are consistent with recent assessments for other nearshore species (Dick et al. 2016; Dick et al. 2018; Haltuch et al. 2018; Cope et al. 2019).

Prior to 2001, ORBS monitored marine species in both multi-species categories, such as rockfish, flatfish, and other miscellaneous fishes, and as individual species, such as lingcod or Pacific halibut. For this comprehensive reconstruction, four species categories were selected to reconstruct, including rockfish, lingcod, flatfish and miscellaneous, which constitute the bulk of the managed marine fish species. Vermilion rockfish are a component of the rockfish species category.

Category-level estimates were expanded to account for gaps in sampling coverage in two separate pathways. First, estimates from five major ports were expanded to include unsampled winter months in years lacking complete coverage. Expansions were based on available year-round sampling data and excluded years where regulations may have impacted the temporal distribution of catch. Second, all other minor port estimates were expanded to include seasonal estimates in years lacking any sampling based on the amount of minor port catch as compared to all major port estimates. A subset of landings were sampled by ORBS for species compositions within these categories. Once category-level landings were comprehensive in space and time, species compositions were applied for the three multi-species categories, including rockfish, flatfish and miscellaneous fish. Borrowing rules for species compositions were specific to the category and determined based on a series of regression tree analyses that detailed the importance of each domain (year, month, port and fishing mode) to variability in compositions.

Ocean boat estimates from 1979–2000 in numbers of fish of vermilion rockfish from the above described methods were converted to biomass using biological samples from MRFSS (pers. comm. A. Whitman, ODFW). MRFSS biological data are available from 1980–1989 and 1993–2000. An annual average weight was applied to the total annual number of fish to obtain an annual landings estimate in biomass. Several years of missing biological data (1979, 1990–1992) were filled in using neighboring years or interpolation. These landings in biomass were provided by ODFW and do not include an estimate of discards. In order to account for historical discards, 6% was added to landings from 1979–2000. This discard mortality estimate is an average of the annual discard mortality from 2001–2020 available on RecFIN. Landings during this time period gradually increase to a peak of 13.0 mt in 1993 and fluctuate between four and six mt following that peak.

2.1.2.1.2 Modern Ocean Boat Landings (2001–2020)

Recreational landings for ocean boat modes from 2001–2020 are available from RecFIN. Both retained and released estimates of mortality are included, though retained mortality contributes the vast majority to total mortality. Release mortality is estimated from angler-reported release rates and the application of discard mortality rates from the PFMC. From 2001–2020, landings averaged 5.8 mt, ranging from 3.2 to 9.3 mt. In 2020, ocean boat landings were 8.9 mt.

2.1.2.1.3 Shore and Estuary Landings (1980–2020)

The ODFW does not currently sample shore and estuary boat fishing trips, and in recent assessments, ODFW has provided reconstructed species-specific estimates of shore and estuary landings from 1980–2020 (Berger et al. 2015, Dick et al. 2018, Cope et al. 2019). When investigating shore and estuary data for this species, there were virtually no records of shore and estuary landings of vermilion rockfish, and so these were not included for this assessment.

2.1.2.2 Lengths

Recreational length samples were obtained from three sources: MRFSS, RecFIN (ORBS) and ODFW special project sampling. Table 3 details sample sizes by year and fleet. From 1980–1989 and from 1993–2000, the MRFSS program collected samples from ocean areas only ($n = 403$). ODFW provided MRFSS samples with the addition of a column that flagged length values imputed from weights to allow for selection of directly measured values. From 1980–1989, total lengths (mm) were collected by MRFSS, which were converted to fork length. From 1993 – 2000, fork length (mm) was collected. Only samples that were measured directly were used in the assessment model. These included samples from 1993–2000 only.

Length samples from 2001–2020 from the ORBS sampling program are available on RecFIN (n = 11,081). All ORBS samples are by fork length (mm). All samples are from ocean trips. Special projects samples collected by ODFW staff from the recreational fishery are provided from 1998 – 2001 (n = 54) but were not used in the length compositions for the assessment model.

2.1.2.3 Ages

There were 1,180 recreational age samples available from 2005–2020 (Table 4). Approximately, 46.0% of samples were males (n = 543) and 53.7% were females (n = 634). There were three unsexed samples (0.25%). As with the length samples, the vast majority of samples are from the southern Oregon coast (80.6%, n = 951), primarily from Charleston (24.0%), Gold Beach (19.2%), Bandon (18.2%), and Brookings (18.1%).

2.1.3 Index of Abundance

2.1.3.1 Oregon ORBS Dockside Index (2001-2020)

Trip-level catch-per-unit-effort data from ORBS dockside sampling was obtained from ODFW on 04/15/2021. To mitigate the confounding of hourly effort associated with these trips with travel, the travel time was subtracted from the hours fished. Travel time was stratified by boat type (charter and private) and was calculated as boat type-specific speeds (13 mph for charter boat trips and 18 mph for private boat trips) multiplied by twice the distance between the port of origin and the reef that was fished. CPUE, expressed in terms of fish per angler-hour, was calculated by multiplying the number of anglers and the adjusted travel time. The database contains information on catch by species (number of retained fish), effort (angler hours), sample location (port where data were collected), date, bag limits, boat type (charter or private), and trip type (e.g., bottom associated fish).

2.1.3.1.1 ORBS CPUE Data Preparation, Filtering, and Sample Sizes

In order to define effective fishing effort for vermilion rockfish (i.e. identify trips that were likely to catch the species), the method of Stephens and MacCall (2004) was used to predict the probability of catching a vermilion rockfish given the occurrence of other species in the catch. The unfiltered data set contained 411,528 trips. Multiple standardized filters are applied to ORBS trip-level data in order to remove outliers and data unsuitable for an index. These filters include trips with incorrect interview times, which impact calculation of effort, unreasonably long or short trips, and retaining bottomfish target trips. There were 117,042 trips available for the application of the Stephens-MacCall filter (Table 5). Species that are rarely encountered will provide little information about the likelihood of catching vermilion

rockfish, and so 47 “indicator” species that were caught in at least 30 Oregon trips (Figure 5) were used to predict vermilion rockfish catch. Catch of these commonly-encountered species in a given trip was coded as presence/absence (1/0) and treated as a categorical variable in the Stephens-MacCall logistic regression analysis.

The top six species with a high probability of co-occurrence with vermilion rockfish include Other Rockfish, olive rockfish, copper rockfish, quillback rockfish, lingcod and China rockfish, all of which are commonly associated with rocky reef and kelp habitats in nearshore waters. The top six species were all strongly associated with vermilion rockfish (significantly different from zero at the $\alpha = 0.05$ level). The six species with the lowest probability of co-occurrence were buffalo sculpin, butter sole, greenstriped rockfish, striped seaperch, jack mackerel, and sand sole. These species are not commonly caught during the same trip as vermilion rockfish, presumably due to different habitat associations and fishing techniques. The Area Under the Characteristics curve (AUC) for this model is 0.7931; (Figure 6), a significant improvement over a random classifier (AUC = 0.5). AUC represents the probability that a randomly chosen observation of presence would be assigned a higher ranked prediction than a randomly chosen observation of absence. Stephens-MacCall proposed filtering (excluding) trips from the index standardization based on a criterion of balancing the number of false positives (FP) and false negatives (FN). The FN trips were retained, assuming that catching a vermilion rockfish indicates that a nonnegligible fraction of the fishing effort occurred in habitat where the species occurs. Only “true negatives” (the 103,762 trips that neither caught a vermilion rockfish, nor were predicted to catch them by the model) were excluded from the index standardization.

After filtering for species composition, further filters were explored for fishing closures and catches exceeding bag limits, but these were not needed. The final dataset also excluded data from several ports with extremely small sample sizes and finally, trips that met criteria for irrational effort reporting (i.e., implausible values) or extreme catch rates (Table 5).

2.1.3.1.2 ORBS CPUE Standardization: Model Selection, Fits, and Diagnostics

Data at the port level were sparse for all months and years, so trips to north and south ‘subregions’ and to season (a compilation of winter and summer months) in order to facilitate data categories conducive to exploring interactions between subregion and year. Vermilion rockfish are rarely encountered by the recreational fleet. In order to focus any signal coming from this index, the above filtered dataset was further refined by retaining only trips that occurred in the southern megaregion, where the majority of the recreational and commercial catch occurs, and during the summer months (May – September; (Figure 7). Raw catch rate data suggested that trends in CPUE over time diverged substantially by subregion. Further, ports in the south coast generally have difficult bars in the winter, restricting most of the recreational effort to summertime.

A delta-Generalized Linear Model (GLM) approach was used to model CPUE. Apart from differences in catch rate among month, and year, we also considered changes associated with boat type (charter and private; (Figure 8)), the bag limit for vermilion rockfish, and the depths available to the recreational fleet for fishing. The binomial component for catch occurrence was modeled using a logit link function while the log of positive CPUE was modeled with a Gaussian distribution and an identity link function. Based on the Akaike Information Criterion (AIC), the binomial model selected as the best predictor of ORBS catch rates included year, boat type, and the open depths available to fishing (Table 6). Residuals from the binomial component of the delta-model are not expected to be normally distributed, so quantile residuals (Dunn and Smyth 1996) were simulated using the R package DHARMA (Hartig 2021). Effective sample sizes prevented the direct comparison of the model predicted values to the standardized residuals (Figure 9, right panel); however, examination of the QQ plot residuals and the results of tests for outliers and differing distributions indicated no significant issues (Figure 9, left panel), indicating that despite a small sample size, the model approximated the data reasonably well. The positive model selected, again based on AIC, included year, boat type, month and an interaction term with year: boat type (Table 6). Again, effective sample sizes prevented the comparison of model predicted values to the standardized residuals (Figure 10, right panel) but no other significant issues were identified (Figure 10, left panel). Given that only a single subregion was included in this model selection procedure, an area-weighted model was not used for vermilion rockfish, as has been used for other nearshore species in recent assessments, such as cabezon (Cope et al. 2019) or blue rockfish (Dick et al. 2018).

To estimate the uncertainty in the final index of abundance, it is necessary to account for the correlation structure between parameters within the binomial and lognormal components of the model, as well as with the combined (binomial and lognormal components) delta-model. The `rstanarm` package (Goodrich et al. 2020) in R was used to replicate the best models using diffuse prior distributions that replicated point estimates from the maximum likelihood fits. The advantage of this approach is that the calculation of the index (summing relevant model parameters and combining model components) can be applied to posterior draws, preserving the correlation structure and propagating uncertainty into the final index (Figure 11; Table 7). As an additional diagnostic, replicate data sets were generated from the posterior predictive distribution, and compared the maximum likelihood estimates from the model components to the median estimates from the posterior distribution. As expected, the model closely matches the distribution from replicate data (Figures 12 and 13).

2.2 Fishery-Independent Data

There are limited sources of fishery-independent information for vermilion rockfish in Oregon. Oregon has a number of state-specific small-scale fishery-independent surveys that were explored for this assessment. Vermilion rockfish are encountered in very limited numbers

in ODFW’s hook and line survey within Oregon’s marine reserve system. Other sources of fishery-independent information, such as ROV and video lander surveys, also encounter vermilion but in extremely limited numbers.

Trawl surveys (Triennial survey, Alaskan slope survey and the West Coast Groundfish Bottom Trawl Survey) routinely considered in groundfish stock assessments potentially provide fishery-independent abundance and biological data off the Oregon coast. However, those surveys do not cover vermilion rockfish habitat in Oregon, and vermilion rockfish are sparsely encountered, therefore indices of abundance were not calculated from these survey and biological data were not used.

2.3 Biological Parameters

2.3.1 Growth (Length-at-Age)

The length-at-age was estimated for female and male vermilion rockfish using data from collections sampling the commercial and recreational fisheries off the coast of Oregon from years 2004-2020 (Table 4). Figure 14 shows the lengths and ages for all years by sex and data source as well as predicted von Bertalanffy growth function (VBGF) fits to the data. Females grow larger than males and sex-specific growth parameters were estimated at the following values:

$$\text{Females } L_{\infty} = 57.2 \text{ cm}; k = 0.146; t_0 = -0.65$$

$$\text{Males } L_{\infty} = 54.2 \text{ cm}; k = 0.18; t_0 = 0$$

The estimated VBGF parameters provided initial values for the estimation of growth in the model, as all age and length data are included in the model. The resultant growth curves estimated by the model are presented in Figure 15. Sensitivity to the treatment of growth parameters (fixed or estimated) are explored through sensitivity analyses.

2.3.2 Ageing Precision and Bias

Counting ages from ageing structures in long-lived temperate fishes is challenging. Ages derived from these structures can be hard to reproduce within and between readers (i.e., imprecision), and may not contain the true age (i.e., bias). Stock assessment outputs can be affected by bias and imprecision in ageing, thus it is important to quantify and integrate this source of variability when fitting age data in assessments. In Stock Synthesis, this is done by

including ageing error matrices that include the mean age (row 1) and standard deviation in age (row 2). Ageing bias is implemented when the inputted mean age deviates from the expected middle age for any given age bin (e.g., 1.75 inputted versus 1.5 being the true age); ageing imprecision is given as the standard deviation for each age bin (row 2).

Ageing error matrices for commercial and recreational fisheries respectively were calculated using within reader comparisons ($n = 181$ for commercial; $n = 237$ for recreational). An additional ageing error matrix was constructed from the Committee of Age Reading Experts (CARE) otolith exchange, where an exchange of 43 individuals was done among ODFW, WDFW, SWFSC, and NWFSC. The ODFW internal reads were used in the reference model, with the CARE comparison explored in a sensitivity model run.

Estimation of ageing error matrices used the approach of Punt et al. (2008) and release 1.1.0 of the R package `nwfscAgeingError` (Thorson et al. 2012). The ageing error matrix offers a way to calculate both bias and imprecision in age reads. Reader 1, the primary reader of the ages used in the stock assessment, is always considered unbiased, but may be imprecise. Several model configurations are available for exploration based on either the functional form (e.g., constant CV, curvilinear standard deviation, or curvilinear CV) of the bias in reader 2 or in the precision of the readers. Model selection uses AIC corrected for small sample size (AICc), which converges to AIC when sample sizes are large. Bayesian Information Criterion (BIC) was also considered when selecting a final model. Table 8 provides model selection results.

The ODFW intralab comparison supported imprecision with a curvilinear standard deviation for the recreational fishery, and a linear one for commercial. The CARE comparison was also linear, with a bit higher standard deviation. The functional forms for each matrix are given in Figure 16.

2.3.3 Natural Mortality

Natural mortality was not directly measured, so life-history based empirical relationships were used. The Natural Mortality Tool (NMT; <https://github.com/shcaba/Natural-Mortality-Tool>), a Shiny-based graphical user interface allowing for the application of a variety of natural mortality estimators based on measures such as longevity, size, age and growth, and maturity, was used to obtain estimates of natural mortality. The NMT currently provides 22 options, including the Hamel (2015) method, which is a corrected form of the Then et al. (2015) functional regression model and is a commonly applied method for west coast groundfish. The NMT also allows for the construction of a natural mortality prior weighted across methods by the user.

We assumed the age of 54 years to represent the practical longevity (i.e., 90% of the commonly seen maximum age of 60) for both females and males, though the absolute oldest age in Oregon was >60 years. In the larger biomass, higher sampled area of California, ages 80+ were even encountered. Empirical M estimators using the von Bertalanffy growth parameters were also considered, but they produced unreasonably high estimates (2-3 times higher than the longevity estimates). This is likely explained by the fact that while vermilion rockfish have protracted longevity at L_∞ . Additionally, the FishLife (Thorson et al. 2017b) estimate was included, though, given the source of FishLife data is FishBase, there is a good chance the estimates of M are also from methods using longevity, though the actual source of longevity in FishLife was unknown. The final composite M distribution (Figure 17) is based on 4 empirical estimators, and result in a median value of 0.1. We assume a lognormal distribution with a standard deviation of 0.438 (Hamel 2015) for the purposes of the prior used to estimate M . This creates a wide prior to allow the data in the model to also influence the final estimated value of M . We also explore sensitivity to these assumptions of natural mortality through likelihood profiling.

2.3.4 Maturation and Fecundity

Maturity-at-length is based on the work of Hannah and Kautzi (2012) which estimated the 50 percent size-at-maturity of 39.4 cm off Oregon, though the slope of the maturity curve was not provided. Looking at the data provided in the reference, and length at 95% maturity was assumed at 48 cm, resulting in a slope of -0.34. Maturity was assumed to stay asymptotic for larger fish (Figure 18) as no functional maturity estimate was available (Head et al. 2020).

The fecundity-at-length was provided by E.J. Dick (SWFSC), and is consistent with what is being used for the California vermilion rockfish assessments. The fecundity relationship for vermilion rockfish was estimated equal to $Fec=4.32e-07L^{3.55}$ in millions of eggs where L is length in cm. Fecundity-at-length is shown in Figure 19.

2.3.5 Length-Weight Relationship

The length(cm)-weight(kg) relationship for vermilion rockfish was estimated outside the model using biological data available from the Oregon commercial fishery, the only sources for sex-specific information on length and weight (Figure 20). The estimated length-weight relationship for female fish was $W=2.60642e-05L^{2.93}$ and males at $W=3.7636e-05L^{2.83}$.

2.3.6 Sex Ratio

No information on the sex ratio at birth was available so it was assumed to be 50:50.

2.3.7 Steepness

The Thorson-Dorn rockfish prior (developed for use West Coast rockfish assessments) conducted by James Thorson (personal communication, NWFSC, NOAA) and reviewed and endorsed by the Scientific and Statistical Committee (SSC) in 2017, has been a primary source of information on steepness for rockfishes. This approach, however, was subsequently rejected for future analysis in 2019 when the new meta-analysis resulted in a mean value of approximately 0.95. In the absence of a new method for generating a prior for steepness the default approach reverts to the previously endorsed method, the 2017 prior for steepness (h ; beta distribution with $\mu=0.72$ and $\sigma=0.15$) is retained.

3 Assessment Model

3.1 Summary of Previous Assessments

Vermilion rockfish in Oregon has not been previously assessed in full, so this is the first benchmark for this management unit. Depletion-based Stock Reduction Analysis (DB-SRA) assuming 40% depletion in 2009 was used to set annual catch limits (ACLs) for vermilion rockfish since 2010 (Dick and MacCall 2010). The total vermilion rockfish OFL in 2011 was 319.5 mt. The mean sustainable yield for the northern portion was estimated to be 11.1 mt, just 3.5% of the total OFL. Most of this allocation would be expected to come from California, as the population of vermilion rockfish continues to be smaller north of California.

3.1.1 Modelling Platform

Stock Synthesis version 3.30.16 was used as the statistical catch-at-age modelling framework. The SS-DL tool (<https://github.com/shcaba/SS-DL-tool>) was used for model exploration, likelihood profiling, and sensitivity analyses. The companion R package `r4ss` (version 1.38.0) along with R version 4.0.5 were used to investigate and plot model fits.

3.1.2 Bridging Analysis

No analysis bridging the DB-SRA model and Stock Synthesis model was conducted given the significant differences (e.g., DB-SRA is provided the relative stock status value) between

the methods. It is well documented already that SS can mimic DB-SRA approaches (Cope 2013).

3.2 Model Structure and Assumptions

Stock Synthesis is an age-structured modelling framework that allow for the inclusion of removal histories, length and age compositions and abundance indices. The Oregon vermilion rockfish model assessment assumes a two removal fleets (mainly a recreational fishery in the contemporary period, though commercial removals are present and were more prominent historically) with removals beginning in 1892. The Oregon recreational abundance index is the one fishery-dependant data source used to measure abundance trends. Selectivities for the fleet and survey were specified using the double normal parameterization within SS where selectivity was fixed to be asymptotic with the ascending slope and size of maximum selectivity parameters estimated. Life history parameters are sex-specific, with one growth type, and assumed stationary. Recruitment assumes a Beverton-Holt stock-recruit relationship and recruitment deviations are estimated.

3.2.1 Estimated and Fixed Parameters

All life history parameters are estimated except the CV at length at t_0 . Estimated parameters in the model are natural mortality (M) and all growth parameters (L_∞ , k , t_0 , CV at L_∞ ; length CV at t_0 was fixed as it had little impact on the model) were estimated, as were the two selectivity parameters for each fleet and the survey, the log of the initial recruitment ($\log R_0$), and recruitment deviations. Length at maturity, fecundity-weight, and length-weight relationship, steepness (h) and recruitment variance were all fixed. Sensitivity scenarios and likelihood profiles were used to explore uncertainty in the values of the natural mortality and growth parameters. When estimating parameters, the prior for natural mortality was assumed lognormal with a standard deviation of 0.438 (based on the prior developed using the Natural Mortality Tool (see Biology section for more details); growth parameters were estimated with no priors.

3.2.2 Data Weighting

The reference model estimates additional variance on the Oregon recreational survey data to allow the model to balance model fit to that data while acknowledging that variances may be underestimated in the index standardization. The input CVs range from 1%-7%, which is very small (Table 7). A sensitivity was run with no extra variance estimated, as well as removal of the index data.

Initial sample sizes for the commercial and recreational length and conditional age-at-length compositions were based on the number of fish sampled. The method of Francis (2011, equation TA1.8) was then used to balance the length and conditional age-at-length composition data among other inputs and likelihood components. The Francis method treats mean length and age as indices, with effective sample size defining the variance around the mean. If the variability around the mean does not encompass model predictions, the data should be down-weighted until predictions fit within the intervals. This method accounts for correlation in the data (i.e., the multinomial distribution), but can be sensitive to years that are outliers, as the amount of down-weighting is applied to all years within a data source, and are not year-specific. Sensitivities were performed examining different data-weighting treatments: 1) the Dirichlet-Multinomial approach (Thorson et al. 2017a), 2) the McAllister-Ianelli Harmonic Mean approach (McAllister and Ianelli 1997), or 3) no data-weighting of lengths.

3.3 Model Selection and Evaluation

The base assessment model for Oregon vermilion rockfish was developed to balance parsimony and realism, and the goal was to estimate a spawning output trajectory and realtive stock status for the population of vermilion rockfish in state and federal waters off Oregon. The model contains many assumptions to achieve parsimony and uses different data types and sources to estimate reality. A series of investigative model runs were done to achieve the final base model. These include considerations of model structure, data and parameter treatment, estimation phasing, and jittered starting values to achieve a converged and balanced model that provides sensible parameter estimates and derived quantities.

3.4 Summary of Previous Assessments and Reviews

There are no previous assessments for the Oregon vermilion rockfish management unit, thus no summary of previous assessments or reviews.

3.4.1 History of Modeling Approaches

The previous treatment of vermilion rockfish that contained the area of Oregon was the application of DB-SRA in order to determine OFLs, and was not a model to provide estimates of stock status.

3.4.2 Most Recent STAR Panel and SSC Recommendations (not required for an update assessment)

There are no recent STAR or SSC recommendations regarding Oregon vermilion rockfish.

3.5 Reference Model Diagnostics and Results

3.5.1 Model Convergence and Acceptability

While there is no definitive measure of model convergence, several measures are routinely applied. These criteria include a low maximum gradient (1.38574×10^{-4}), inversion of the Hessian (passed), reasonable parameter values (passed), and acceptable fits to data (passed).

An extra effort was given to ensure the model did not rest on a local likelihood minimum. This was done by starting the minimization process from dispersed parameter values away from the maximum likelihood estimates to determine if the approach found a better model fit (i.e., minimum negative log-likelihood value). Starting parameters used a jitter shift value of 0.001. This was repeated 100 times with 12 out of 100 runs returned to the reference model likelihood (Figure 21). A better fit, lower negative log-likelihood model was not found in any of remaining 96 runs. The model did not experience convergence issues when provided reasonable starting values. Through the jittering and likelihood profiles, the present reference model represents the best fit to the data given the assumptions made.

3.5.1.1 Fits to the Data

3.5.1.1.1 Lengths

Fits to the length data are examined based on the Pearson residuals-at-length, the annual mean lengths, and aggregated length composition data for the commercial and recreational fleets. Fits to the annual length composition are shown in Appendix A. Lengths are generally sampled better in the recreational fishery and after year 2000.

Pearson residuals of fits to the commercial fishery length data are generally low with no distinct pattern of misfitting despite lower sample sizes (Figure 22). Model fits to the commercial fishery mean lengths, assuming Francis data-weighting, show increasing female and males lengths until after 2009, after which mean lengths are relatively stable, with a small drop in size in the most recent year (Figure 23).

Pearson residuals of fits to the combined sex recreational fishery length data are also generally low, though with small bands of misfitting (Figure 22). These small bands are not deemed concerning given the small residuals and that recruitments are estimated. Model fits to the recreational fishery mean lengths, assuming Francis data-weighting, show a very similar trend as the commercial mean lengths, with increasing lengths until after 2009, after which mean lengths are relatively stable, with a drop in size in the most recent year (Figure 24).

Aggregate fits over year by fleet are shown in Figure 25. The model fits the aggregate lengths for the sexed commercial fishery fleet and unsexed recreational female length data well. The commercial fishery data are fit less well given the smaller sample sizes.

3.5.1.1.2 Conditional Age at Length

Fits to the conditional age at length data are examined based on the age-at-length Pearson residuals, the annual mean ages, and mean age at length by year for the commercial and recreational fleet samples. The maximum size of the Pearson residuals for both fleets was large (maximum = 30.56 and 30.63 for commercial and recreational samples, respectively; Appendix B), due to the inclusion of very small but aged as older fish. Most of the residuals were small and unnoteworthy and demonstrate the expected shape of the growth curve. As with the lengths, the mean age by year increased then leveled off, though the recreational mean ages continue to increase in the most recent years (Figures 26 and 27). The mean age for commercial stocks were generally around 15 years old, whereas the recreational ages are around 18 years old. Fits to the mean ages by length bins show acceptable fits consistent with model expectations Appendix C.

3.5.1.1.3 ORBS Survey Index of Abundance

The fit to the ORBS recreational survey index are generally good and consistent with other model sources as the trend shows a population increasing in the early 2000s then leveling off and dropping over recent years (Figure 28). The decreasing trend is more consistent over the last decade than indicated in the lengths or ages. Initial variance for the survey is extremely small, though it only took a small amount of added variance to fit the index (0.08). The catchability coefficient (q) 0.003 was analytically solved for and very small relative to the total an absolute measure ($q=1$), a typical result of a fishery-based abundance index.

3.5.2 Reference Model Outputs

3.5.2.1 Parameter Estimates

A total of sixteen primary parameters were estimated, along with sixty recruitment deviations. The reference model parameter estimates along with asymptotic standard errors are shown in Table 9 and the likelihood components are shown in Table 10. Estimates of derived reference points and approximate 95 percent asymptotic confidence intervals are provided in Table 11.

The natural mortality for females and males was estimated at 0.08 and 0.073 yr⁻¹, respectively. These values are below the mean prior value, but not unreasonable given the corresponding longevities would be between 67 and 75 years old and the sampled maximum age of 68 came from a fished population.

The estimates of sex-specific growth parameters showed some differences from the externally estimated starting values (Table 9 and Figure 15). While L_{∞} was similar to the external estimates, the model estimated k for female and male fish were greater than the values estimated externally (0.146 for females and 0.175 yr⁻¹ for males). The majority of female and male vermilion rockfish growth occurs at younger ages, reaching near maximum length by age 20-25, depending upon sex, with female vermilion rockfish reaching larger maximum lengths (Figure 15).

The estimated logistic selectivity curves for the commercial and recreational fishery look plausible (i.e., as a model convergence check for realism, the selectivity curves are not overtly outrageous) for each fishery and are very similar to each other (Figure 29). Length at 50% selectivity (commercial = 43.67 cm; recreational = 44.44 cm) was between the length at 50% (39.4 cm) and 95% maturity (48 cm). Future assessments could opt for parsimony and combine these two fisheries into one combined selectivity, though the model had no issue adding two more parameters given the available length data.

The time series of estimated recruitments and annual recruitment deviations are shown in Figures 30 and 31. Years with the highest recruitment deviations were estimated to have occurred in 1993-1994, 1998, 2005, and 2015. The variance check on the recruitment deviations indicates well informed recruitments from 1980 to 2015, providing justification for the estimation of recruitment. Recruitment deviations after 2015 are relatively uninformed (Figure 32) with estimated deviations near zero where recruitment is estimated primarily based on the spawner-recruit curve (Figure 33). The recruitment bias adjustment applied within the model across years is shown in Figure 34.

3.5.2.2 Population Trajectory

The predicted spawning output (in millions of eggs) is provided in Table 12 and plotted in Figure 35. Estimated spawning output shows a large decline starting in the 1970s, with a continued decline into the late 1990s. This tracks the time period of major removals, though removals have stayed somewhat elevated since. Strong recruitments since the 1990s have

supported the elevated catches. The estimate of total biomass over time, which tracks that of spawning output, is shown in Figure 36.

Relative spawning output declined below the management target ($SB_{40\%}$) by the 1990s, but quickly rebounded to high relative spawning output, but has declined over the past 10 years (Figure 37). The relative stock status at the start of 2021 (0.73) is estimated to be well above the rockfish relative biomass target of 0.4. Uncertainty intervals are wide given the number of estimated parameters, and indicate the population never goes below the management target ($SB_{40\%}$). The strong recruitment events that are supported by all fishery-dependent data sources are responsible for the dramatic increase and elevated stock status. Numbers of age-0 individuals indicate those years of particularly strong recruitment (Figure 30).

3.6 Uncertainty exploration

3.6.1 Sensitivity Analyses

Sensitivity analyses were conducted to evaluate model sensitivity to alternative data treatment and model specifications.

3.6.1.1 Data treatment sensitivities

Data treatments explored were as follows:

- Data removal (fixed life history, no recruitment estimation)
 1. Fishery length data only (no catches)
 2. Catch and lengths only
 3. Catch and lengths only with Francis weighting
 4. Catch, lengths, and ages with Francis weighting
 5. Catch, length, age, and indices with Francis weighting
 6. Catch, length, age, and indices with Francis weighting and extra index variance
 7. Catch, length, age, and indices with Francis weighting, estimate life history
- Data weighting
 8. Dirichlet data-weighting
 9. McAllister-Ianelli data weighting

- 10. No data-weighting
- Ageing error
 - 11. Using ageing error from CARE exchange
- Length treatment
 - 12. Use option sex = 3 to maintain sex ratio in commercial data

Likelihood values and estimates of key parameters and derived quantities from each sensitivity are available in Table 13. Derived quantities relative to the reference model are provided in Figure 38. Time series of spawning output and relative spawning output are shown in Figures 39 and 40.

Deterministic length-based (with or without catches) models with fixed life history values view the stock scale and status to be below that of the reference model, though above the limit reference point. Bringing in the age data, while still fixing life history and not estimating recruitment, significantly raises the stock scale to above the reference model, though the stock status is similar to the reference model. Introduction of the index made little difference to the relative stock status. Estimating the life history values, even without estimating recruitment, brought the scale back in line with the reference model. The other data treatments, including data weighting options, did very little to change the results from the reference model.

3.6.1.2 Model specification sensitivities

Model specifications looked at the estimation of individual and combinations of life history parameters, the estimation of recruitment, and the treatment of fecundity and selectivity. All scenarios match the reference model specifications in all other aspects unless otherwise stated.

- Life history estimation
 - Fix natural mortality (M)
 - 1. Fix M
 - 2. Fix M and CV_{old}
 - 3. Fix M , t_0 and CV_{old}
 - 4. Fix M , k , t_0 and CV_{old}
 - Fix growth parameters
 - 5. Fix all growth parameters

- 6. Fix L_∞ , k , and t_0
- 7. Fix k , and CV_{old}
- 8. Fix L_∞ and CV_{old}
- 9. Est L_∞ for females only
- 10. Est L_∞ for males only
- 11. 5 growth platoons instead of one
- Recruitment estimation and variability (σ_R). All years are estimated with bias correction applied.
 - 12. No recruitment estimation
 - 13. No recruitment estimation and fixed life history parameters
 - 14. Estimate recruitment for all years in the model
 - 15. $\sigma_R = 0.45$
 - 16. $\sigma_R = 0.75$
- Miscellaneous
 - 17. Fecundity proportional to weight
 - 18. Estimate dome-shaped selectivity
 - 19. Estimate dome-shaped selectivity after 2003 for recreational fishery

Likelihood values and estimates of key parameters and derived quantities from each sensitivity are available in Tables 14 and 15. Derived quantities relative to the reference model are provided in Figure 41. Time series of spawning output and relative spawning output are shown in Figures 42 and 43.

Fixing M to the higher prior mean value while estimating L_∞ raised both the beginning and ending stock scale and overall ending year relative stock status. Fixing growth but estimating M dropped stock scale, but preserved the stock status. Allowing either L_∞ or k to be estimated increased both stock scale and status. Fixing the life history parameters except for female L_∞ also raised stock scale and status, though estimating males L_∞ made little difference to model results. Further investigation of the affects of life history values are provided in the likelihood profiles (next section).

Fixing recruitment dropped the scale and status of the stock a little, fixing life history values again increased those derived outputs. Recruitment estimation (assuming $\sigma_R = 0.6$) was not sensitive to a range of σ_R values or estimation of all years of recruitment. While the truncated time series of recruitment can be considered parsimonious, the addition of estimating all recruitment years adds additional uncertainty to the stock status measure earlier in the time series.

The remaining model specifications did little to change the reference model results. Estimating dome-shaped selectivity after 2003 for the recreational fishery (based on the possibility that fishing restriction in part of the year could possibly limit access to bigger individuals) does result in dome-shaped selectivity for the recreational fishery, it provides only a slightly better fit (based on AIC) to the data and does not change the scale or status of the stock. An even better fit to the data is achieved if 2001 (not coinciding with management changes), though again the derived quantities of scale and status do not change. The improved fits are not sufficient evidence that a selectivity block is needed, though whether and where blocks may be most appropriate is worth future consideration.

Overall, there were no model specification sensitivity scenarios that caused the population to drop significantly below the reference model estimate of stock status, only above. When stock scale changed from the reference model, unfished and current stock size usually varied in the same direction, with current stock size changing more, leading to increases in the relative stocks status.

3.6.2 Likelihood Profiles

Likelihood profiles were conducted for $\ln(R_0)$, steepness (h), female and male natural mortality (M) values separately and varying together, female and male maximum length (L_∞), female and male growth coefficient (k), female and male variability of size at maximum age. In addition, joint profiles over L_∞ and k (that maintains a correlation structure -0.97 between the parameters consistent with the model calculation of that correlation) were done for females and males separately. Female and male natural mortality was also covaried based on the offset in values from the reference model. Likelihood profiles were conducted by fixing the featured parameter(s) at specific values across a range of values and estimating the remaining parameters. A likelihood profile offers insight into model information on a given parameter or parameter pairing, while providing an additional way to describe uncertainty in the parameter by indentifying the range of parameters within 1.96 likelihood units of the reference model.

The $\ln(R_0)$ profiles show strong support for the maximum likelihood value of 2.79 (Figure 44). Population size expectedly increases as $\ln(R_0)$ increases, with the increase in current biomass happening quicker than initial biomass, thus relative stock status increase towards unfished at high $\ln(R_0)$ values. This is explained by the harvest rate decreasing because the removal history is fixed and becomes relatively smaller compared to the overall biomass. All data sets were mostly consistent in the information content in the profile, though the length data contained the least amount of information on $\ln(R_0)$.

The steepness profile showed little information content for this parameter (Figure 45). Despite low information content, model output show little sensitivity for $h > 0.45$, with values for

relative stock status ranging between 0.7 and 0.8. Scale outputs (SB_0 and SB_{2021}) also showed little change across steepness values. The recruitment likelihood was the biggest driver of steepness towards a value of 1 (Figure 45).

Natural mortality profiles for females (Figure 46) and males (Figure 47) are consistent with each other and show a range of M values for females and males supported by the data. These values are distinctly below the mean of the prior (0.1) for both sexes. The combined profile that varies female and male M based on the reference offset together at the same changing value behave directionally most like the female likelihood support values in the range of the individual parameter likelihoods (Figure 48). Scale and relative stock status are affected by this parameter, with the current spawning output being affected more than initial biomass. This is particularly true as M gets larger, creating much higher biomass and higher relative stock status. The uncertainty in the relative stock status ranges from 0.05 to 0.09, very consistent with the asymptotic uncertainty intervals for this value from in reference model. Comparing the asymmetric range of relative stock status estimates in the profiled values (Figure 49) to the normally distributed uncertainty envelope in the reference model (Figure 37), one can clearly see the overestimation of the low end of relative stock status when assuming a normal error distribution. The index provided the strongest data signal for natural mortality, with length and age data being much less informative, but not inconsistent with the index.

Female (Figures 50 to 52) and male (Figures 53 to 55) growth profiles show strong signals in the data to estimate L_∞ , k , and length CV at maximum age. Lengths and ages are the primary data supporting L_∞ values similar to the externally estimated values for each sex, but k values higher than the externally estimated values. A more realistic profile that maintains the negative correlation between L_∞ and k showing similar behavior as the two separate profiles (Figures 56 and 57). Changing either value affects stock scale, though relative stock status seems robust over a wide range of values. The profile over the length variability at maximum age also has a distinct influence on stocks scale, but relative stock status is again robust to most values (Figure 52). The female length CV at the oldest age had the biggest influence on stock status as the CV got higher, though still a small affect compared to the uncertainty in the model. Overall, the influence of growth values seems to make the population stock status increase slightly.

3.6.3 Retrospective Analysis

A ten-year retrospective analysis was conducted by running the model and sequentially removing one year of data up through minus 10 years. Retrospective spawning output (Figure 58) and relative stock status (Figure 59) estimates were generally within the confidence intervals of the reference model, though removing 8 to 10 years did reveal a retrospective pattern in the terminal year. None of these patterns changed the overall relative stock status of the stock being above the target relative stock status level since 2000.

3.7 Management

3.7.1 Reference Points

Reference points were calculated using the estimated fishery selectivity and removals in the most recent year of the model (2020, Table 11). Sustainable total yields were 7.95 mt when using an $SPR_{50\%}$ reference harvest rate. The spawning output equivalent to 40 percent of the unfished spawning output ($SB_{40\%}$) was 13.04 meggs.

The 2021 spawning output relative to unfished equilibrium spawning output is above the vermilion rockfish relative biomass target of 40 percent (Figure 37). The fishing intensity, $1 - SPR$, of recent years was near or above the harvest rate limit ($SPR_{50\%}$) for most of the 1980s and 1990s. Recent years also show near target fishing levels (Table 12 and Figure 60), highlighting how the sustainability of current fishing levels are very sensitive to incoming recruitment. Table 11 shows the full suite of estimated reference points for the base model and Figure 61 shows the equilibrium curve based on a steepness value fixed at 0.72. Figure 62 shows the time series of biomass and fishing intensity relative to reference points.

3.7.2 Unresolved Problems and Major Uncertainties

Natural mortality (M) was estimated by the model, though vermilion rockfish longevity is not well understood in Oregon. While the estimated sex-specific M values seem well within reason, the model remains sensitive to the choice of this parameter, and therefore improving the M prior (the prior used in this model may be centered on the higher end) while continuing to collect age data for future estimation within the model is important. This also plays through the collection of lengths to go with ages to continue to improve the estimation of age and growth. Future work on improving point estimates and possibly investigate time-varying life history parameters could improve model fits.

Functional maturity (Head et al. 2020) is an emerging concept in reproductive biology capturing physiological behaviors such as delayed maturity, skipped spawning and atresia and correcting for them in the length at maturity relationship. Investigating functional maturity could improve the application of maturity in the model.

Fishery-independent surveys would add additional support for those trends seen using fishery-based data.

3.7.3 Harvest Projections and Decision Tables

A ten year (2023-2032) projection of the reference model with removals in 2021 and 2022 provided by the Groundfish Management Team for each fleet under the category 1 ($\sigma=0.5$) time-varying buffer using $P^* = 0.45$ and 40-10 ABC control rule is provided in Table 16.

The decision table (Table 17) was constructed using female and male natural mortality to define the low and high states of nature. The multi-parameter likelihood profile was used to find the low (Female $M = 0.07092$; Male $M = 0.06525$) and high (Female $M = 0.08527$; Male $M = 0.07845$) female and male natural mortality values that produce -log likelihood values $+0.66$ units from the reference -log likelihood value. These correspond to the 12.5% and 87.5% quantiles (standard quantiles used in west coast decision tables). The catch rows in the table were based on three proposed catch streams:

1. $P^* = 0.45$, $\sigma = 0.5$
2. $P^* = 0.40$, $\sigma = 0.5$
3. An equilibrium catch based on the F_{MSY} proxy using $SPR = 0.5$.

Across all states of natures and catch streams vermilion relative stock size never falls below the target relative stock size of 40%. Both P^* approaches lower the stock status from the high relative stock size values, while the F_{MSY} proxy does not. The mismatch in the corresponding steepness value ($h = 0.6$) that matches MSY at $SPR = 0.5$ with the steepness value in the stock assessment ($h = 0.72$) that corresponds to an MSY SPR of 0.35 explains why this constant catch will maintain the stock at very high relative stock status levels.

3.7.4 Evaluation of Scientific Uncertainty

The estimated uncertainty in the base model around the 2021 spawning output is $\sigma = 0.27$ and the uncertainty in the base model around the 2021 OFL is $\sigma = 0.31$. The estimated model uncertainty was less than the category 1 groundfish data moderate assessment default value of $\sigma = 0.5$.

3.8 Research and Data Needs

1. Resolution in stock structure. Continued sampling of vermilion rockfish in Oregon would allow for more genetic understanding of population structure. In addition, consideration of fishery similarities between northern California (north of Cape Mendocino) and southern Oregon may be worth further consideration to see if that is a better grouping of stocks compared to combining central and northern California.

2. Continued quantification of ageing error. The CARE exchange has high value in general to further our ability to understand the inherent variability of reading ageing structures, and should be strongly supported.
3. The life history parameters are all assumed constant through time. This assumption of stationarity is one of convenience and parsimony. Any insight into the changing of life history values or differing productivity regimes could help refine these assumptions.
4. Natural mortality proved the source of greatest uncertainty in the model. While empirical methods can help define priors for natural mortality, good sampling of age structure or direct measures (e.g., tagging) are preferred. Oregon’s robust sampling program may include ways to collect data that can directly improve natural mortality estimation and reduce model uncertainty.
5. Ongoing sampling of biological data will remain a core component of information in the stock assessment and needs to be continued and supported.
6. A fishery-independent index of abundance would be a welcome inclusion in this assessment, along with the ongoing development of the ORBS index (e.g., the appropriateness of applying the Stephens-MacCall filtering method to fisheries data; how to treat months with different management measures).
7. The large uncertainty estimated in this stock assessment was limited given the asymptotic, symmetric variance estimation from the maximum likelihood estimation method. While a Bayesian model was considered and even explored for this model, it was not included due to challenges in implementation and lack of enough time to achieve a converged model. Continued development of Bayesian approaches to characterizing uncertainty are strongly encouraged.
8. Ensemble modelling may be another potential tool to incorporate model uncertainty beyond within model variance estimation that should be considered.
9. Fishery selectivity continues to be challenging to represent, and are key parameters in the model. Blocks in selectivity and whether there are *a priori* reasons to expect any dome-shaped selectivity deserve continued thought. The change of selectivity within a year (e.g., some seasons have depth restriction, others do not) should also be a topic of discussion.

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6 Tables

Table 1: Catches (mt) by fleet for all years and total catches (mt) summed by year.

Year	Commercial	Recreational	Total Catch
1892	0.00	0.00	0.00
1893	0.00	0.00	0.00
1894	0.00	0.00	0.00
1895	0.00	0.00	0.00
1896	0.00	0.00	0.00
1897	0.00	0.00	0.00
1898	0.00	0.00	0.00
1899	0.00	0.00	0.00
1900	0.00	0.00	0.00
1901	0.00	0.00	0.00
1902	0.00	0.00	0.00
1903	0.00	0.00	0.00
1904	0.00	0.00	0.00
1905	0.00	0.00	0.00
1906	0.00	0.00	0.00
1907	0.00	0.00	0.00
1908	0.00	0.00	0.00
1909	0.00	0.00	0.00
1910	0.00	0.00	0.00
1911	0.00	0.00	0.00
1912	0.00	0.00	0.00
1913	0.00	0.00	0.00
1914	0.00	0.00	0.00
1915	0.00	0.00	0.00
1916	0.00	0.00	0.00
1917	0.00	0.00	0.00
1918	0.00	0.00	0.00
1919	0.00	0.00	0.00
1920	0.00	0.00	0.00
1921	0.00	0.00	0.00
1922	0.00	0.00	0.00
1923	0.00	0.00	0.00
1924	0.00	0.00	0.00
1925	0.00	0.00	0.00
1926	0.00	0.00	0.00
1927	0.00	0.00	0.00
1928	0.00	0.00	0.00
1929	0.32	0.00	0.32
1930	0.58	0.00	0.58
1931	0.28	0.00	0.28
1932	0.00	0.00	0.00

Table 1: Catches (mt) by fleet for all years and total catches (mt) summed by year.
(*continued*)

Year	Commercial	Recreational	Total Catch
1933	0.06	0.00	0.06
1934	0.09	0.00	0.09
1935	0.00	0.00	0.00
1936	0.33	0.00	0.33
1937	1.08	0.00	1.08
1938	1.26	0.00	1.26
1939	1.52	0.00	1.52
1940	1.81	0.00	1.81
1941	1.21	0.00	1.21
1942	1.46	0.00	1.46
1943	1.65	0.00	1.65
1944	2.28	0.00	2.28
1945	2.57	0.00	2.57
1946	2.78	0.00	2.78
1947	0.92	0.00	0.92
1948	1.87	0.00	1.87
1949	2.00	0.00	2.00
1950	0.72	0.00	0.72
1951	0.65	0.00	0.65
1952	1.29	0.00	1.29
1953	0.44	0.00	0.44
1954	0.29	0.00	0.29
1955	0.83	0.00	0.83
1956	0.41	0.00	0.41
1957	0.87	0.00	0.87
1958	0.09	0.00	0.09
1959	0.27	0.00	0.27
1960	0.35	0.00	0.35
1961	0.65	0.00	0.65
1962	0.36	0.00	0.36
1963	0.63	0.00	0.63
1964	0.36	0.00	0.36
1965	1.82	0.00	1.82
1966	1.14	0.00	1.14
1967	3.26	0.00	3.26
1968	3.10	0.00	3.10
1969	6.04	0.00	6.04
1970	2.83	0.00	2.83
1971	6.42	0.00	6.42
1972	8.31	0.00	8.31
1973	9.02	0.00	9.02

Table 1: Catches (mt) by fleet for all years and total catches (mt) summed by year.
(*continued*)

Year	Commercial	Recreational	Total Catch
1974	11.53	0.00	11.53
1975	5.97	0.00	5.97
1976	7.98	0.00	7.98
1977	11.21	0.00	11.21
1978	11.75	0.00	11.75
1979	7.70	0.30	8.00
1980	8.16	0.48	8.64
1981	4.37	1.66	6.03
1982	4.94	2.02	6.96
1983	6.03	0.85	6.88
1984	5.60	1.52	7.12
1985	8.53	0.64	9.17
1986	10.38	3.18	13.56
1987	9.63	0.12	9.75
1988	10.11	1.26	11.37
1989	9.98	6.26	16.23
1990	10.87	5.20	16.07
1991	3.60	2.36	5.96
1992	4.30	5.05	9.35
1993	13.90	13.00	26.90
1994	4.07	4.66	8.72
1995	1.78	2.26	4.04
1996	5.41	2.35	7.76
1997	4.55	4.04	8.59
1998	4.71	6.40	11.11
1999	1.44	1.57	3.01
2000	2.99	2.59	5.58
2001	4.80	3.24	8.04
2002	2.08	3.21	5.28
2003	2.20	4.21	6.41
2004	1.76	3.50	5.26
2005	1.68	6.07	7.74
2006	2.42	5.42	7.85
2007	2.06	6.85	8.91
2008	3.99	5.66	9.64
2009	4.08	3.98	8.06
2010	1.64	4.78	6.42
2011	2.95	6.10	9.05
2012	2.79	9.15	11.94
2013	3.42	6.30	9.73
2014	2.28	3.95	6.23

Table 1: Catches (mt) by fleet for all years and total catches (mt) summed by year.
(*continued*)

Year	Commercial	Recreational	Total Catch
2015	1.47	4.65	6.12
2016	2.02	3.69	5.71
2017	3.26	8.80	12.06
2018	3.09	9.20	12.29
2019	3.86	9.25	13.11
2020	3.05	8.24	11.29

Table 2: The OFL and ACL for vermilion rockfish as a component of the Minor Shelf Rockfish North complex and the total estimated removals of vermilion rockfish in Oregon (including estimated discards). There is no Oregon-specific allocation of Minor Shelf Rockfish North.

Year	OFL	ACL	Total Removals
2011	11.1	5.6	9.1
2012	11.1	5.6	11.9
2013	9.7	8.1	9.7
2014	9.7	8.1	6.2
2015	9.7	8.1	6.1
2016	9.7	8.1	5.7
2017	9.7	8.1	12.1
2018	9.7	8.1	12.3
2019	9.7	8.1	13.1
2020	9.7	8.1	11.3

Table 3: Length samples for Oregon vermilion rockfish. All recreational samples are unsexed.

Year	Recreational	Commercial Male	Commercial Female
1993	23	0	0
1994	26	0	0
1995	17	0	0
1996	29	0	0
1997	41	0	0
1998	84	0	0
1999	78	12	7
2000	36	40	28
2001	224	69	38
2002	450	17	21
2003	742	37	26
2004	410	41	42
2005	958	30	27
2006	597	22	32
2007	823	30	29
2008	734	18	20
2009	501	66	52
2010	632	45	42
2011	724	101	101
2012	918	53	65
2013	646	86	91
2014	370	66	72
2015	294	40	32
2016	270	63	62
2017	543	94	98
2018	575	59	64
2019	607	174	144
2020	63	46	29

Table 4: Commerical and recreational age samples for Oregon vermilion rockfish.

Year	Commercial Male	Commercial Female	Recreational Male	Recreational Female	Recreational Unsexed
	M	F	M	F	U
2004	0	1	0	0	0
2005	0	0	13	33	0
2006	0	0	50	45	0
2007	10	10	46	60	0
2008	5	8	83	90	0
2009	31	25	46	50	0
2010	20	18	37	46	0
2011	53	53	42	59	0
2012	25	33	43	46	0
2013	42	45	40	47	0
2014	34	35	20	23	0
2015	19	16	20	11	1
2016	31	32	9	19	1
2017	47	50	8	21	0
2018	30	34	13	16	0
2019	79	70	39	36	0
2020	23	17	34	32	1

Table 5: Filtering criteria, total records, positive records and percent positive for the ORBS CPUE index for vermilion rockfish.

Filter	Criteria	Total Records	No. Pos	Perc. Pos
All Data	Full data set aggregated to trip	411528	9764	2.40%
Bottomfish trips	Retain bottomfish trips only	133866	8768	6.50%
Trip time length	Remove exceedingly long or short trips (< 1 hr or > 12 hrs)	131655	8759	6.70%
Interview time	Remove trips with interviews within one minute	117042	8759	7.50%
Associated species	Stephens-MacCall filter for associated species	13280	7839	59.00%
Ports with rare catch encounters	Removed trips from Ports 0, 32 and 38	13249	7819	59.00%
Negative effort	Remove trips with negative effort when accounting for travel time	13208	7787	59.00%
Anomalously high catch rates	Removes catch rates above the 99.9 percentile	13194	7773	58.90%
Southern megaregion only	Remove trips from the Northern megaregion due to concerns regarding divergent trends	7956	6432	80.80%
Summer season only	Remove trips from winter months	6841	5530	80.80%

Table 6: Model selection for binomial and positive delta-GLM for Oregon ORBS CPUE index. Selected models are highlighted in grey.

Model	Binomial AIC	Binomial Δ AIC	Positives AIC	Positives Δ AIC
YEAR	6494	-	14705	-
YEAR + BOAT TYPE	6483	11	13021	1684
YEAR + MONTH	6496	2	14640	65
YEAR + BAG LIMIT	6495	1	14705	0
YEAR + OPEN DEPTHS	6487	7	14707	2
YEAR + BOAT TYPE + OPEN DEPTHS	6477	17	-	-
YEAR + BOAT TYPE + OPEN DEPTHS + YEAR:BOAT TYPE	6476	18	-	-
YEAR + BOAT TYPE + MONTH	-	-	12982	1723
YEAR + BOAT TYPE + MONTH + YEAR:BOAT TYPE	-	-	12958	1747

Table 7: Standardized index for the Oregon ORBS dockside index with log-scale standard errors (logSE) and 95 percent highest posterior density (HPD) intervals for vermilion rockfish.

Year	Mean	logSE	Lower HPD	Upper HPD
2001	0.83	0.07	0.72	0.93
2002	0.85	0.07	0.73	0.95
2003	0.84	0.07	0.73	0.93
2004	0.93	0.04	0.85	1.00
2005	1.03	0.02	0.98	1.06
2006	0.78	0.06	0.69	0.87
2007	1.00	0.03	0.95	1.05
2008	0.97	0.03	0.92	1.01
2009	0.96	0.03	0.89	1.01
2010	0.93	0.03	0.88	0.97
2011	0.94	0.03	0.89	0.99
2012	0.96	0.04	0.89	1.02
2013	0.89	0.05	0.80	0.97
2014	0.85	0.06	0.75	0.94
2015	1.06	0.01	1.02	1.08
2016	1.06	0.01	1.03	1.08
2017	0.82	0.04	0.76	0.88
2018	0.95	0.04	0.86	1.01
2019	0.95	0.03	0.88	1.01
2020	0.86	0.05	0.77	0.93

Table 8: Ageing error models and resultant model selection (AICc) values for 9 models of bias and precision explored for each lab used in the vermilion rockfish assessments. Bolded text indicates indicate the chosen model. Model codes: 0= unbiased; 1 = Constant CV; 2 = Curvilinear (SD for precision); 3= Curvilinear CV

Model	Reader 1		Reader 2 (to 4)		Model selection			
	Bias	Precision	Bias	Precision	AICc	Δ AICc	BIC	Δ BIC
ODFW Rec								
1	0	1	0	1	0	26	0	25
2	0	2	0	2	0	4	0	4
3	0	3	0	3	0	0	0	0
4	0	1	1	1	0	16	0	16
5	0	2	1	2	0	15	0	16
6	0	3	1	3	0	15	0	16
7	0	1	2	1	0	24	0	25
8	0	2	2	2	0	24	0	26
9	0	3	2	3	0	28	0	30
ODFW Comm								
1	0	1	0	1	0	0	0	0
2	0	2	0	2	0	4	0	6
3	0	3	0	3	0	4	0	6
4	0	1	1	1	0	0	0	3
5	0	2	1	2	0	4	0	8
6	0	3	1	3	0	8	0	12
7	0	1	2	1	0	39	0	42
8	0	2	2	2	0	10	0	14
9	0	3	2	3	0	9	0	14
CARE								
1	0	1	0	1	0	73	0	64
2	0	2	0	2	0	61	0	54
3	0	3	0	3	0	57	0	50
4	0	1	1	1	0	0	0	0
5	0	2	1	2	0	17	0	18
6	0	3	1	3	0	7	0	8
7	0	1	2	1	0	1	0	3
8	0	2	2	2	0	13	0	16
9	0	3	2	3	0	10	0	13

Table 9: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD).

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
NatM p 1 Fem GP 1	0.080	3	OK	0.00812246	Log Norm (-2.30259, 0.438)
L at Amin Fem GP 1	-17.078	3	OK	3.33389	None
L at Amax Fem GP 1	57.184	3	OK	0.341133	None
VonBert K Fem GP 1	0.146	3	OK	0.00585385	None
CV young Fem GP 1	0.100	-4	-	-	None
CV old Fem GP 1	0.054	4	OK	0.00178057	None
Wtlen 1 Fem GP 1	0.000	-99	-	-	None
Wtlen 2 Fem GP 1	2.930	-99	-	-	None
Mat50% Fem GP 1	39.400	-99	-	-	None
Mat slope Fem GP 1	-0.342	-99	-	-	None
Eggs scalar Fem GP 1	0.000	-3	-	-	None
Eggs exp len Fem GP 1	3.548	-3	-	-	None
NatM p 1 Mal GP 1	0.073	3	OK	0.00789027	Log Norm (-2.30259, 0.438)
L at Amin Mal GP 1	-29.898	3	OK	5.2875	None
L at Amax Mal GP 1	54.193	3	OK	0.245592	None
VonBert K Mal GP 1	0.180	3	OK	0.00749103	None
CV young Mal GP 1	0.100	-4	-	-	None
CV old Mal GP 1	0.045	4	LO	0.00166169	None
Wtlen 1 Mal GP 1	0.000	-99	-	-	None
Wtlen 2 Mal GP 1	2.830	-99	-	-	None
CohortGrowDev	1.000	-1	-	-	None
FracFemale GP 1	0.500	-99	-	-	None
SR LN(R0)	2.793	1	OK	0.243905	None
SR BH steep	0.720	-1	-	-	None
SR sigmaR	0.600	-6	-	-	None
SR regime	0.000	-99	-	-	None
SR autocorr	0.000	-99	-	-	None
Early RecrDev 1961	0.401	3	act	0.502983	dev (NA, NA)

Table 9: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD). (*continued*)

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
Main RecrDev 1962	-0.310	1	act	0.5281	dev (NA, NA)
Main RecrDev 1963	-0.146	1	act	0.525021	dev (NA, NA)
Main RecrDev 1964	-0.181	1	act	0.523987	dev (NA, NA)
Main RecrDev 1965	-0.361	1	act	0.516361	dev (NA, NA)
Main RecrDev 1966	-0.377	1	act	0.512917	dev (NA, NA)
Main RecrDev 1967	-0.403	1	act	0.507653	dev (NA, NA)
Main RecrDev 1968	-0.419	1	act	0.50438	dev (NA, NA)
Main RecrDev 1969	-0.265	1	act	0.489923	dev (NA, NA)
Main RecrDev 1970	-0.469	1	act	0.494869	dev (NA, NA)
Main RecrDev 1971	-0.514	1	act	0.487127	dev (NA, NA)
Main RecrDev 1972	-0.542	1	act	0.48257	dev (NA, NA)
Main RecrDev 1973	-0.416	1	act	0.470845	dev (NA, NA)
Main RecrDev 1974	-0.447	1	act	0.463433	dev (NA, NA)
Main RecrDev 1975	-0.617	1	act	0.470639	dev (NA, NA)
Main RecrDev 1976	-0.413	1	act	0.457774	dev (NA, NA)
Main RecrDev 1977	-0.246	1	act	0.457334	dev (NA, NA)
Main RecrDev 1978	0.083	1	act	0.462145	dev (NA, NA)
Main RecrDev 1979	0.918	1	act	0.329273	dev (NA, NA)
Main RecrDev 1980	0.053	1	act	0.446429	dev (NA, NA)
Main RecrDev 1981	-0.293	1	act	0.459389	dev (NA, NA)
Main RecrDev 1982	0.096	1	act	0.359725	dev (NA, NA)
Main RecrDev 1983	-0.696	1	act	0.438068	dev (NA, NA)
Main RecrDev 1984	-0.544	1	act	0.405129	dev (NA, NA)
Main RecrDev 1985	-0.319	1	act	0.406255	dev (NA, NA)
Main RecrDev 1986	0.271	1	act	0.312356	dev (NA, NA)
Main RecrDev 1987	-0.120	1	act	0.387596	dev (NA, NA)
Main RecrDev 1988	-0.149	1	act	0.349932	dev (NA, NA)
Main RecrDev 1989	-0.394	1	act	0.402682	dev (NA, NA)
Main RecrDev 1990	-0.037	1	act	0.336222	dev (NA, NA)

Table 9: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD). (*continued*)

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
Main RecrDev 1991	-0.035	1	act	0.407393	dev (NA, NA)
Main RecrDev 1992	0.976	1	act	0.27623	dev (NA, NA)
Main RecrDev 1993	1.904	1	act	0.155751	dev (NA, NA)
Main RecrDev 1994	1.855	1	act	0.14828	dev (NA, NA)
Main RecrDev 1995	0.794	1	act	0.264997	dev (NA, NA)
Main RecrDev 1996	0.668	1	act	0.216913	dev (NA, NA)
Main RecrDev 1997	0.384	1	act	0.262629	dev (NA, NA)
Main RecrDev 1998	1.758	1	act	0.0976628	dev (NA, NA)
Main RecrDev 1999	0.759	1	act	0.166544	dev (NA, NA)
Main RecrDev 2000	-0.383	1	act	0.254929	dev (NA, NA)
Main RecrDev 2001	-0.524	1	act	0.228807	dev (NA, NA)
Main RecrDev 2002	-0.626	1	act	0.234313	dev (NA, NA)
Main RecrDev 2003	-0.957	1	act	0.256931	dev (NA, NA)
Main RecrDev 2004	-0.783	1	act	0.249366	dev (NA, NA)
Main RecrDev 2005	1.258	1	act	0.102519	dev (NA, NA)
Main RecrDev 2006	0.247	1	act	0.174997	dev (NA, NA)
Main RecrDev 2007	-0.449	1	act	0.227476	dev (NA, NA)
Main RecrDev 2008	-0.599	1	act	0.254319	dev (NA, NA)
Main RecrDev 2009	-0.052	1	act	0.202398	dev (NA, NA)
Main RecrDev 2010	-0.311	1	act	0.237927	dev (NA, NA)
Main RecrDev 2011	-0.730	1	act	0.312447	dev (NA, NA)
Main RecrDev 2012	0.514	1	act	0.184045	dev (NA, NA)
Main RecrDev 2013	-0.360	1	act	0.324163	dev (NA, NA)
Main RecrDev 2014	0.823	1	act	0.273872	dev (NA, NA)
Main RecrDev 2015	1.738	1	act	0.293244	dev (NA, NA)
Main RecrDev 2016	-0.324	1	act	0.544964	dev (NA, NA)
Main RecrDev 2017	-0.064	1	act	0.596996	dev (NA, NA)
Main RecrDev 2018	-0.075	1	act	0.594571	dev (NA, NA)
Main RecrDev 2019	-0.075	1	act	0.594573	dev (NA, NA)

Table 9: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD). (*continued*)

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
Main RecrDev 2020	-0.075	1	act	0.594573	dev (NA, NA)
ForeRecr 2021	0.000	5	act	0.6	dev (NA, NA)
ForeRecr 2022	0.000	5	act	0.6	dev (NA, NA)
InitF seas 1 flt 1Commercial	0.000	-1	-	-	None
InitF seas 1 flt 2Recreational	0.000	-1	-	-	None
LnQ base Recreational(2)	-5.723	-1	-	-	None
Q extraSD Recreational(2)	0.081	3	OK	0.0227712	None
Size DblN peak Commercial(1)	43.670	2	OK	0.713312	None
Size DblN top logit Commercial(1)	15.000	-1	-	-	None
Size DblN ascend se Commercial(1)	3.728	2	OK	0.182659	None
Size DblN descend se Commercial(1)	-15.000	-1	-	-	None
Size DblN start logit Commercial(1)	-15.000	-2	-	-	None
Size DblN end logit Commercial(1)	15.000	-1	-	-	None
Size DblN peak Recreational(2)	44.443	2	OK	0.828114	None
Size DblN top logit Recreational(2)	15.000	-1	-	-	None
Size DblN ascend se Recreational(2)	4.298	2	OK	0.153315	None
Size DblN descend se Recreational(2)	-15.000	-1	-	-	None
Size DblN start logit Recreational(2)	-15.000	-2	-	-	None
Size DblN end logit Recreational(2)	15.000	-1	-	-	None

Table 10: Likelihood components by source.

Label	Total
TOTAL	2701.16
Catch	0.00
Equil catch	0.00
Survey	-32.83
Length comp	449.80
Age comp	2260.95
Recruitment	22.83
InitEQ Regime	0.00
Forecast Recruitment	0.00
Parm priors	0.40
Parm softbounds	0.00
Parm devs	0.00
Crash Pen	0.00

Table 11: Summary of reference points and management quantities, including estimates of the 95 percent intervals.

	Estimate	Lower Interval	Upper Interval
Unfished Spawning Output	29.24	22.19	36.29
Unfished Age 3+ Biomass (mt)	354.37	278.67	430.07
Unfished Recruitment (R_0)	16.33	8.52	24.13
Spawning Output (2021)	21.35	10.06	32.65
Fraction Unfished (2021)	0.73	0.48	0.98
<u>Reference Points Based $SB_{40\%}$</u>			
Proxy Spawning Output $SB_{40\%}$	11.70	8.88	14.51
SPR Resulting in $SB_{40\%}$	0.46	0.46	0.46
Exploitation Rate Resulting in $SB_{40\%}$	0.06	0.05	0.07
Yield with SPR Based On $SB_{40\%}$ (mt)	8.32	5.57	11.07
<u>Reference Points Based on SPR Proxy for MSY</u>			
Proxy Spawning Output (SPR_{50})	13.04	9.90	16.19
SPR_{50}	0.50		
Exploitation Rate Corresponding to SPR_{50}	0.05	0.04	0.06
Yield with SPR_{50} at SB SPR (mt)	7.95	5.32	10.57
<u>Reference Points Based on Estimated MSY Values</u>			
Spawning Output at MSY (SB MSY)	8.04	6.28	9.81
SPR MSY	0.35	0.34	0.35
Exploitation Rate Corresponding to SPR MSY	0.09	0.07	0.11
MSY (mt)	8.82	5.89	11.76

Table 12: Time series of population estimates from the base model.

Year	Total Biomass (mt)	Spawn- ing Output	Total Biomass 3+ (mt)	Frac- tion Un- fished	Age-0 Re- cruits	Total Mortal- ity (mt)	1-SPR	Ex- ploita- tion Rate
1892	439.44	29.24	354.37	1.00	16.33	0.00	0.00	0.00
1893	439.44	29.24	354.37	1.00	16.33	0.00	0.00	0.00
1894	439.44	29.24	354.37	1.00	16.33	0.00	0.00	0.00
1895	439.44	29.24	354.37	1.00	16.33	0.00	0.00	0.00
1896	439.44	29.24	354.37	1.00	16.33	0.00	0.00	0.00
1897	439.44	29.24	354.37	1.00	16.33	0.00	0.00	0.00
1898	439.44	29.24	354.37	1.00	16.33	0.00	0.00	0.00
1899	439.45	29.24	354.38	1.00	16.33	0.00	0.00	0.00
1900	439.45	29.24	354.38	1.00	16.33	0.00	0.00	0.00
1901	439.46	29.24	354.39	1.00	16.33	0.00	0.00	0.00
1902	439.46	29.24	354.39	1.00	16.33	0.00	0.00	0.00
1903	439.47	29.24	354.40	1.00	16.33	0.00	0.00	0.00
1904	439.47	29.24	354.40	1.00	16.33	0.00	0.00	0.00
1905	439.48	29.24	354.40	1.00	16.33	0.00	0.00	0.00
1906	439.48	29.24	354.41	1.00	16.33	0.00	0.00	0.00
1907	439.49	29.24	354.41	1.00	16.33	0.00	0.00	0.00
1908	439.49	29.24	354.42	1.00	16.33	0.00	0.00	0.00
1909	439.50	29.24	354.42	1.00	16.33	0.00	0.00	0.00
1910	439.50	29.24	354.43	1.00	16.33	0.00	0.00	0.00
1911	439.50	29.24	354.43	1.00	16.33	0.00	0.00	0.00
1912	439.51	29.24	354.43	1.00	16.33	0.00	0.00	0.00
1913	439.51	29.24	354.44	1.00	16.33	0.00	0.00	0.00
1914	439.51	29.24	354.44	1.00	16.33	0.00	0.00	0.00
1915	439.52	29.24	354.44	1.00	16.33	0.00	0.00	0.00
1916	439.52	29.24	354.44	1.00	16.33	0.00	0.00	0.00
1917	439.52	29.24	354.45	1.00	16.33	0.00	0.00	0.00
1918	439.52	29.24	354.45	1.00	16.33	0.00	0.00	0.00
1919	439.52	29.24	354.45	1.00	16.33	0.00	0.00	0.00
1920	439.53	29.25	354.45	1.00	16.33	0.00	0.00	0.00
1921	439.53	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1922	439.53	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1923	439.53	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1924	439.53	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1925	439.54	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1926	439.54	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1927	439.54	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1928	439.54	29.25	354.46	1.00	16.33	0.00	0.00	0.00
1929	439.54	29.25	354.46	1.00	16.33	0.32	0.02	0.00

Table 12: Time series of population estimates from the base model. (*continued*)

Year	Total Biomass (mt)	Spawn- ing Output	Total Biomass 3+ (mt)	Frac- tion Un- fished	Age-0 Re- cruits	Total Mortal- ity (mt)	1-SPR	Ex- ploita- tion Rate
1930	439.22	29.22	354.15	1.00	16.33	0.58	0.03	0.00
1931	438.65	29.17	353.60	1.00	16.33	0.28	0.01	0.00
1932	438.41	29.15	353.36	1.00	16.33	0.00	0.00	0.00
1933	438.46	29.15	353.41	1.00	16.33	0.06	0.00	0.00
1934	438.45	29.15	353.41	1.00	16.33	0.09	0.00	0.00
1935	438.42	29.14	353.38	1.00	16.33	0.00	0.00	0.00
1936	438.48	29.15	353.43	1.00	16.33	0.33	0.02	0.00
1937	438.21	29.13	353.16	1.00	16.33	1.08	0.05	0.00
1938	437.20	29.04	352.18	0.99	16.32	1.26	0.06	0.00
1939	436.04	28.93	351.06	0.99	16.32	1.52	0.07	0.00
1940	434.68	28.81	349.73	0.99	16.31	1.81	0.09	0.01
1941	433.09	28.67	348.18	0.98	16.30	1.21	0.06	0.00
1942	432.17	28.58	347.28	0.98	16.30	1.46	0.07	0.00
1943	431.05	28.48	346.20	0.97	16.29	1.65	0.08	0.00
1944	429.80	28.37	344.98	0.97	16.28	2.28	0.11	0.01
1945	427.98	28.20	343.20	0.96	16.27	2.57	0.12	0.01
1946	425.95	28.02	341.23	0.96	16.26	2.78	0.13	0.01
1947	423.81	27.83	339.15	0.95	16.25	0.92	0.05	0.00
1948	423.64	27.81	338.99	0.95	16.25	1.87	0.09	0.01
1949	422.55	27.71	337.93	0.95	16.25	2.00	0.10	0.01
1950	421.39	27.60	336.80	0.94	16.24	0.72	0.04	0.00
1951	421.58	27.61	336.99	0.94	16.24	0.65	0.03	0.00
1952	421.86	27.64	337.26	0.95	16.24	1.29	0.07	0.00
1953	421.49	27.60	336.90	0.94	16.24	0.44	0.02	0.00
1954	422.00	27.65	337.40	0.95	16.24	0.29	0.02	0.00
1955	422.66	27.71	338.04	0.95	16.25	0.83	0.04	0.00
1956	422.74	27.71	338.12	0.95	16.25	0.41	0.02	0.00
1957	423.26	27.76	338.62	0.95	16.25	0.87	0.04	0.00
1958	423.28	27.77	338.64	0.95	16.25	0.09	0.00	0.00
1959	424.09	27.84	339.43	0.95	16.25	0.27	0.01	0.00
1960	424.68	27.89	340.00	0.95	16.26	0.35	0.02	0.00
1961	465.90	27.94	340.47	0.96	24.28	0.65	0.03	0.00
1962	403.55	27.95	340.62	0.96	11.93	0.36	0.02	0.00
1963	414.94	27.99	341.04	0.96	14.00	0.63	0.03	0.00
1964	412.88	28.01	342.91	0.96	13.46	0.36	0.02	0.00
1965	402.11	28.05	343.41	0.96	11.20	1.82	0.09	0.01
1966	399.83	27.98	342.35	0.96	10.99	1.14	0.06	0.00
1967	397.07	28.00	341.48	0.96	10.66	3.26	0.15	0.01
1968	392.07	27.85	337.60	0.95	10.45	3.10	0.14	0.01

Table 12: Time series of population estimates from the base model. (*continued*)

Year	Total Biomass (mt)	Spawn- ing Output	Total Biomass 3+ (mt)	Frac- tion Un- fished	Age-0 Re- cruits	Total Mortal- ity (mt)	1-SPR	Ex- ploita- tion Rate
1969	396.16	27.68	333.20	0.95	12.13	6.04	0.26	0.02
1970	376.60	27.20	325.25	0.93	9.83	2.83	0.14	0.01
1971	368.96	26.93	319.96	0.92	9.35	6.42	0.28	0.02
1972	358.26	26.27	311.10	0.90	9.04	8.31	0.34	0.03
1973	352.81	25.38	299.94	0.87	10.17	9.02	0.37	0.03
1974	338.80	24.40	287.94	0.83	9.78	11.53	0.45	0.04
1975	316.25	23.17	273.44	0.79	8.17	5.97	0.29	0.02
1976	316.49	22.45	264.80	0.77	9.94	7.98	0.37	0.03
1977	314.55	21.54	254.31	0.74	11.64	11.21	0.47	0.04
1978	323.21	20.35	240.64	0.70	16.00	11.75	0.50	0.05
1979	413.67	19.12	227.10	0.65	36.42	8.00	0.41	0.04
1980	297.90	18.26	218.18	0.62	15.18	8.64	0.45	0.04
1981	268.33	17.37	210.27	0.59	10.61	6.03	0.37	0.03
1982	291.22	16.76	210.62	0.57	15.51	6.96	0.41	0.03
1983	246.19	16.13	209.35	0.55	6.96	6.88	0.42	0.03
1984	250.72	15.67	208.18	0.54	8.03	7.12	0.43	0.03
1985	259.52	15.43	207.85	0.53	9.99	9.17	0.50	0.04
1986	296.13	15.23	204.04	0.52	17.92	13.56	0.61	0.07
1987	257.76	14.78	195.29	0.51	12.00	9.75	0.52	0.05
1988	251.00	14.61	189.96	0.50	11.59	11.37	0.57	0.06
1989	231.49	14.23	184.27	0.49	8.99	16.23	0.68	0.09
1990	238.90	13.32	173.25	0.46	12.64	16.07	0.70	0.09
1991	226.99	12.35	162.55	0.42	12.44	5.96	0.44	0.04
1992	335.74	12.24	161.47	0.42	33.99	9.35	0.57	0.06
1993	592.34	11.88	157.56	0.41	85.18	26.90	0.84	0.17
1994	538.07	10.10	136.62	0.35	77.90	8.72	0.60	0.06
1995	285.19	9.83	138.76	0.34	26.68	4.04	0.39	0.03
1996	287.86	9.98	159.65	0.34	23.52	7.76	0.57	0.05
1997	277.97	9.95	185.00	0.34	17.64	8.59	0.59	0.05
1998	564.54	10.23	206.97	0.35	69.84	11.11	0.64	0.05
1999	362.64	11.06	226.47	0.38	26.07	3.01	0.25	0.01
2000	303.04	13.29	251.43	0.45	8.60	5.58	0.34	0.02
2001	324.23	15.88	282.33	0.54	7.68	8.04	0.39	0.03
2002	341.87	18.32	304.89	0.63	7.06	5.28	0.27	0.02
2003	351.42	20.74	324.24	0.71	5.16	6.41	0.29	0.02
2004	369.98	22.91	337.53	0.78	6.22	5.26	0.24	0.02
2005	593.10	25.03	346.87	0.86	48.35	7.74	0.30	0.02
2006	440.52	26.65	348.61	0.91	17.71	7.85	0.30	0.02
2007	396.51	27.72	346.04	0.95	8.86	8.91	0.33	0.03

Table 12: Time series of population estimates from the base model. (*continued*)

Year	Total Biomass (mt)	Spawn- ing Output	Total Biomass 3+ (mt)	Frac- tion Un- fished	Age-0 Re- cruits	Total Mortal- ity (mt)	1-SPR	Ex- ploita- tion Rate
2008	388.82	28.12	347.92	0.96	7.65	9.64	0.35	0.03
2009	413.30	27.96	345.16	0.96	13.20	8.06	0.31	0.02
2010	394.31	27.64	341.49	0.95	10.18	6.42	0.27	0.02
2011	373.11	27.41	337.52	0.94	6.69	9.05	0.35	0.03
2012	449.25	27.04	330.37	0.92	23.17	11.94	0.43	0.04
2013	369.24	26.42	318.92	0.90	9.65	9.73	0.38	0.03
2014	470.14	25.87	308.01	0.88	31.41	6.23	0.28	0.02
2015	702.32	25.47	302.94	0.87	78.28	6.12	0.28	0.02
2016	360.67	24.94	296.21	0.85	11.62	5.71	0.27	0.02
2017	378.90	24.38	294.20	0.83	15.03	12.06	0.47	0.04
2018	375.26	23.26	298.55	0.80	14.79	12.29	0.48	0.04
2019	373.86	22.25	297.20	0.76	14.71	13.11	0.51	0.04
2020	372.12	21.47	295.82	0.73	14.64	11.29	0.47	0.04
2021	377.77	21.35	295.77	0.73	15.77	11.86	0.47	0.04
2022	376.26	21.60	294.11	0.74	15.79	12.21	0.47	0.04

Table 13: Likelihood, parameter and derived quantities from data treatment sensitivities.

	Ref- er- ence Model	Length Only	CL	CL+Fr	CLA	CLAI	CLAI+xxv	CLAI+xxv	Dir-H let	Mcl	no data wt	CARE AE	Sex=3
AIC	5558.32	459.34	4996.86	351.73	6695.90	6620.96	6499.56	7049.72	6376.70	3758.28	6303.38	5436.42	5256.56
deltaAIC	0.00	-	-	-	1137.58	1062.64	941.24	1491.40	818.38	-	745.06	-	-
		5098.98	561.46	5206.59						1800.04		121.90	301.76
Survey likelihood	-					-	5.82	-	-	-	-	-	-
	32.83					39.28		39.43	32.55	35.00	32.57	33.07	32.46
Length likelihood													
Total	449.80	222.67	2493.43	170.86	218.94	219.67	192.97	918.14	714.45	305.17	710.88	438.60	309.35
Comm	279.22	161.19	603.89	116.44	142.81	143.70	127.32	413.22	297.00	225.57	296.34	271.11	148.33
Rec	170.59	61.48	1889.55	54.43	76.13	75.97	65.66	504.93	417.44	79.60	414.54	167.49	161.02
Age likelihood													
Total	2260.95				3124.01	3124.10	3045.99	2630.13	2296.83	1443.19	2293.35	2214.60	2251.49
Comm	1018.99				1342.01	1341.98	1304.34	1164.52	1035.40	675.41	1033.54	1016.11	1017.05
Rec	1241.97				1782.01	1782.11	1741.66	1465.61	1261.43	767.78	1259.81	1198.50	1234.44
Parameters													
Female M	0.08	0.10	0.10	0.10	0.10	0.10	0.10	0.11	0.07	0.08	0.07	0.08	0.08
Female size at age 0	-	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	-	-	-
	17.08							12.71	13.07	17.71	12.95	19.23	16.57
Female L_{∞}	57.18	57.38	57.38	57.38	57.38	57.38	57.38	57.69	57.77	57.13	57.79	57.02	57.36
Female k	0.15	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.14	0.15	0.14	0.15	0.14
Female $CV@L_{\infty}$	0.05	0.10	0.10	0.10	0.10	0.10	0.10	0.05	0.06	0.06	0.06	0.05	0.05
Male M	0.07	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.07	0.07	0.07	0.07	0.08
Male size at age 0	-	-4.10	-4.10	-4.10	-4.10	-4.10	-4.10	-	-	-	-	-	-
	29.90							30.69	33.02	27.41	33.23	31.87	36.73
Male L_{∞}	54.19	54.67	54.67	54.67	54.67	54.67	54.67	54.31	53.72	54.57	53.70	54.14	53.68
Male k	0.18	0.15	0.15	0.15	0.15	0.15	0.15	0.18	0.19	0.17	0.19	0.18	0.19
Male $CV@L_{\infty}$	0.04	0.10	0.10	0.10	0.10	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.04
$\ln(R_0)$	2.79	8.86	2.76	2.79	3.84	3.84	3.69	3.49	2.64	2.77	2.64	2.77	2.80
ORBS logQ	-5.72					-6.19	-5.94	-5.55	-5.66	-5.70	-5.65	-5.70	-5.73
ORBS extra SD	0.08					0.05		0.05	0.08	0.07	0.08	0.08	0.08
Comm Sel: Peak	43.67	57.77	55.47	55.29	48.60	48.12	48.66	47.57	43.37	44.00	43.33	43.67	43.49
Comm Sel: Asc It	3.73	5.09	4.96	4.96	4.47	4.39	4.46	4.32	3.66	3.81	3.65	3.74	3.70
Rec Sel: Peak	44.44	55.77	53.59	53.28	48.71	48.74	49.12	48.37	44.36	44.91	44.33	44.29	44.08
Rec Sel: Asc It	4.30	5.02	4.92	4.91	4.69	4.69	4.72	4.66	4.27	4.39	4.26	4.28	4.25
Dir Comm Lts									5.51				
Dir Rec Lts									3.20				

Table 13: Likelihood, parameter and derivied quantities from data treatment sensitivities. *(continued)*

	Ref- er- ence Model	Length Only	CL	CL+Fr	CLA	CLAI	CLAI+xv	CLAI+xv	Dir+H let	Mcl	no data wt	CARE AE	Sex=3
Dir Comm Ages											7.95		
Dir Rec Ages											8.18		
<u>Derived quantities</u>													
$S0_0$	29.24	1161.21	19.79	20.41	58.13	58.08	49.67	31.71	31.14	28.61	31.29	28.91	31.76
$S0_{2021}$	21.35	9881.18	6.06	6.75	45.20	45.03	36.16	20.23	22.06	20.81	22.07	20.60	22.78
$Bratio_{2021}$	0.73	0.43	0.31	0.33	0.78	0.78	0.73	0.64	0.71	0.73	0.71	0.71	0.72
MSY_{SPR}	7.95	1679.88	6.98	7.18	19.46	19.28	15.94	12.17	6.94	7.89	6.90	7.93	7.87
F_{SPR}	0.05	0.12	0.09	0.09	0.07	0.07	0.07	0.07	0.05	0.05	0.05	0.05	0.05

Table 14: Likelihood, parameter and derived quantities from life history model specification sensitivities.

	Ref- er- ence Model	Fix M	Fix M , CV_{old}	Fix M , t_0 , CV_{old}	Fix M , k , t_0 , CV_{old}	Fix growth	Fix L_{∞} , k , t_0	Fix k , CV_{old}	Fix L_{∞} , CV_{old}	Est fe- male L_{∞}	Est male L_{∞}	5 GTG
AIC	5558.32	5667.22	6229.06	6286.08	6209.18	6642.56	5877.42	6077.22	6070.28	6348.46	6429.92	5539.36
deltaAIC	0.00	108.90	670.74	727.76	650.86	1084.24	319.10	518.90	511.96	790.14	871.60	- 18.96
Survey likelihood	-	-	-	-	-	-	-	-	-	-	-	-
	32.83	28.86	33.31	34.00	36.58	34.04	34.98	34.75	32.50	34.13	33.23	33.07
<u>Length likelihood</u>												
Total	449.80	429.66	483.64	496.02	405.80	560.59	431.98	365.12	406.44	449.43	476.85	440.03
Comm	279.22	268.19	276.17	291.96	265.54	298.90	278.38	244.45	250.82	263.48	260.89	273.22
Rec	170.59	161.47	207.47	204.06	140.27	261.69	153.60	120.68	155.61	185.95	215.96	166.81
<u>Age likelihood</u>												
Total	2260.95	2262.57	2496.83	2518.37	2574.94	2630.68	2374.68	2549.58	2500.95	2600.60	2612.49	2262.66
Comm	1018.99	1019.11	1146.91	1149.56	1169.71	1178.50	1044.67	1155.63	1138.57	1171.07	1174.95	1019.91
Rec	1241.97	1243.46	1349.92	1368.82	1405.22	1452.18	1330.01	1393.95	1362.38	1429.53	1437.54	1242.75
<u>Parameters</u>												
Female M	0.08	0.10	0.10	0.10	0.10	0.08	0.07	0.16	0.16	0.10	0.10	0.08
Female size at age 0	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	- 16.53
	17.08	16.64	18.44									
Female L_{∞}	57.18	57.17	56.15	58.27	55.58	57.38	57.38	54.70	57.38	55.72	57.38	57.27
Female k	0.15	0.15	0.15	0.11	0.13	0.13	0.13	0.13	0.11	0.13	0.13	0.15
Female $CV@L_{\infty}$	0.05	0.06	0.10	0.10	0.10	0.10	0.06	0.10	0.10	0.10	0.10	0.06
Male M	0.07	0.10	0.10	0.10	0.10	0.06	0.07	0.14	0.14	0.10	0.10	0.07
Male size at age 0	-	-	-	-4.10	-4.10	-4.10	-4.10	-4.10	-4.10	-4.10	-4.10	- 29.75
	29.90	32.00	29.60									
Male L_{∞}	54.19	54.17	54.11	55.65	53.14	54.67	54.67	52.39	54.67	54.67	53.36	54.25
Male k	0.18	0.18	0.17	0.13	0.15	0.15	0.15	0.15	0.13	0.15	0.15	0.18
Male $CV@L_{\infty}$	0.04	0.05	0.10	0.10	0.10	0.10	0.05	0.10	0.10	0.10	0.10	0.05
$\ln(R_0)$	2.79	3.60	3.43	3.26	3.60	2.41	2.59	19.97	19.90	3.56	3.51	2.82
ORBS logQ	-5.72	-6.38	-5.97	-5.55	-6.05	-5.47	-5.81	-	-	-6.24	-6.20	-5.76
								21.38	21.56			
ORBS extra SD	0.08	0.11	0.08	0.07	0.06	0.07	0.07	0.07	0.08	0.07	0.08	0.08
Comm Sel: Peak	43.67	43.77	48.00	52.37	55.21	46.54	43.88	59.68	54.12	51.30	51.17	43.67
Comm Sel: Asc lt	3.73	3.74	4.38	4.78	5.13	4.26	3.82	5.25	4.84	4.84	4.83	3.73

Table 14: Likelihood, parameter and derived quantities from life history model specification sensitivities. The value of HIGH indicates unreasonable values. (*continued*)

	Ref- er- ence Model	Fix M	Fix M , CV_{old}	Fix M , t_0 , CV_{old}	Fix M , k , t_0 , CV_{old}	Fix growth	Fix L_{∞} , k , t_0	Fix k , CV_{old}	Fix L_{∞} , CV_{old}	Est fe- male L_{∞}	Est male L_{∞}	5 GTG
Rec Sel: Peak	44.44	44.74	50.10	52.59	54.28	49.51	45.24	59.22	54.25	51.66	51.48	44.48
Rec Sel: Asc lt	4.30	4.33	4.93	4.99	5.22	4.98	4.47	5.36	5.02	5.08	5.07	4.30
Derived quantities												
$S0_0$	29.24	43.06	34.43	28.99	39.42	22.24	30.95	HIGH	HIGH	38.33	41.50	29.90
$S0_{2021}$	21.35	42.11	32.38	23.90	41.19	15.11	24.18	HIGH	HIGH	40.01	41.85	22.20
$Bratio_{2021}$	0.73	0.98	0.94	0.82	1.04	0.68	0.78	1.30	1.29	1.04	1.01	0.74
MSY_{SPR}	7.95	13.56	11.38	9.27	13.42	6.42	7.08	HIGH	HIGH	13.50	12.69	8.08
F_{SPR}	0.05	0.06	0.07	0.08	0.09	0.05	0.05	0.25	0.17	0.08	0.07	0.05

Table 15: Likelihood, parameter and derivied quantities from model specification sensitivities that consider recruitment, fecundity, and domed selectivity.

	Refer- ence Model	No recs devs	No recs, fixed LH	Est all yrs	$\sigma_R =$ 0.45	$\sigma_R =$ 0.75	fec = wt	Dome- shaped sel	Dome post- 2003
AIC	5558.32	5471.28	7157.20	5696.36	5591.06	5545.00	5558.16	5545.54	5554.70
deltaAIC	0.00	-87.04	1598.88	138.04	32.74	-13.32	-0.16	-12.78	-3.62
Survey likelihood	-32.83	-39.36	-28.85	-33.82	-31.74	-33.52	-32.89	-32.85	-30.38
<u>Length likelihood</u>									
Total	449.80	141.33	739.51	450.113	453.13	448.48	449.79	439.49	444.59
Comm	279.22	96.64	402.88	279.30	279.70	279.10	279.22	272.38	279.50
Rec	170.59	44.70	336.63	170.82	173.43	169.38	170.57	167.12	165.09
<u>Age likelihood</u>									
Total	2260.95	2617.63	2707.06	2260.20	2264.80	2258.79	2260.95	2260.01	2255.70
Comm	1018.99	1158.15	1210.51	1018.93	1019.46	1018.77	1018.97	1018.64	1015.71
Rec	1241.97	1459.49	1496.55	1241.27	1245.34	1240.03	1241.98	1241.37	1240.00
<u>Parameters</u>									
Female M	0.08	0.11	0.10	0.08	0.08	0.08	0.08	0.08	0.08
Female size at age 0	-17.08	-15.66	0.00	-17.11	-16.90	-17.19	-17.06	-17.13	-18.65
Female L_∞	57.18	56.95	57.38	57.18	57.20	57.17	57.19	57.18	57.15
Female k	0.15	0.14	0.13	0.15	0.15	0.15	0.15	0.15	0.15
Female $CV@L_\infty$	0.05	0.06	0.10	0.05	0.05	0.05	0.05	0.05	0.05
Male M	0.07	0.09	0.10	0.07	0.07	0.07	0.07	0.07	0.07
Male size at age 0	-29.90	-38.56	-4.10	-29.87	-30.47	-29.62	-29.89	-30.11	-30.94
Male L_∞	54.19	53.85	54.67	54.19	54.18	54.20	54.19	54.18	54.34
Male k	0.18	0.19	0.15	0.18	0.18	0.18	0.18	0.18	0.18
Male $CV@L_\infty$	0.04	0.05	0.10	0.04	0.04	0.04	0.04	0.04	0.04
$\ln(R_0)$	2.79	3.35	3.32	2.70	2.74	2.86	2.79	2.79	2.72
σ_R	0.60	0.60	0.60	0.60	0.45	0.75	0.60	0.60	0.60
ORBS logQ	-5.72	-5.41	-6.20	-5.70	-5.63	-5.80	-5.72	-5.72	-5.63
ORBS extra SD	0.08	0.05	0.11	0.08	0.09	0.08	0.08	0.08	0.10
Comm Sel: Peak	43.67	47.36	46.88	43.65	43.75	43.63	43.67	43.67	43.37

Table 15: Likelihood, parameter and derived quantities from model specification sensitivities that consider recruitment, fecundity, and domed selectivity. (*continued*)

	Refer- ence Model	No recs devs	No recs, fixed LH	Est all yrs	$\sigma_R =$ 0.45	$\sigma_R =$ 0.75	fec = wt	Dome- shaped sel	Dome post- 2003
Comm Sel: Asc lt	3.73	4.30	4.28	3.73	3.76	3.71	3.73	3.73	3.68
Rec Sel: Peak	44.44	47.54	49.36	44.39	44.60	44.36	44.44	44.43	43.88
Rec Sel: Asc lt	4.30	4.60	4.90	4.29	4.34	4.28	4.30	4.30	4.37
<u>Derived quantities</u>									
$S0_0$	29.24	26.99	34.65	28.38	27.83	30.98	151.56	29.27	30.00
$S0_{2021}$	21.35	16.03	35.18	21.22	18.90	23.63	112.33	21.51	21.35
$Bratio_{2021}$	0.73	0.59	1.02	0.73	0.68	0.76	0.74	0.73	0.72
MSY_{SPR}	7.95	10.88	11.50	7.47	7.53	8.49	8.09	7.94	7.68
F_{SPR}	0.05	0.07	0.07	0.05	0.05	0.05	0.05	0.05	0.05

Table 16: Projections of potential OFLs (mt), ABCs (mt), the buffer (ABC = buffer x OFL), estimated spawning biomass, and fraction unfished for Oregon portion of the vermillion stock. The North of 40°10'N OFL and ABC for 2021 and 2022 are included for comparison.

Year	OFL 40°10'N	ACL 40°10'N	Predicted OFL	ABC Catch	Buffer	Spawning Output	Fraction Unfished
2021	9.70	8.10	13.01	12.96	1.00	21.37	0.73
2022	9.70	8.10	13.35	12.96	1.00	21.53	0.73
2023	-	-	13.41	12.54	0.94	21.75	0.74
2024	-	-	13.29	12.36	0.93	21.85	0.75
2025	-	-	13.03	12.06	0.93	21.74	0.74
2026	-	-	12.72	11.73	0.92	21.46	0.73
2027	-	-	12.41	11.38	0.92	21.08	0.72
2028	-	-	12.10	11.05	0.91	20.65	0.71
2029	-	-	11.82	10.74	0.91	20.20	0.69
2030	-	-	11.56	10.45	0.90	19.75	0.68
2031	-	-	11.31	10.18	0.90	19.33	0.66
2032	-	-	11.08	9.94	0.90	18.92	0.65

Table 17: Decision table summary of 10 year projections beginning in 2023 for alternative states of nature based on an axis of uncertainty about female and male natural mortality for the reference model. Columns range over low (12.5 quantile), mid (reference model), and high states (87.5 quantile) of nature and rows range over different catch level assumptions. Values in italics indicate years where the stock size prevented the full catch removals.

	Year	Catch	Female M = 0.071; Male =0.065		Female M = 0.079; Male =0.073		Female M = 0.085; Male =0.079	
			Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished
P*=0.45 sigma=0.5	2021	12.96	17.70	0.62	21.37	0.73	24.46	0.79
	2022	12.96	17.76	0.62	21.53	0.73	24.68	0.80
	2023	12.60	17.89	0.63	21.79	0.74	25.01	0.81
	2024	12.45	17.93	0.63	21.92	0.75	25.20	0.82
	2025	12.19	17.81	0.63	21.85	0.74	25.16	0.82
	2026	11.89	17.56	0.62	21.63	0.74	24.93	0.81
	2027	11.56	17.23	0.60	21.29	0.72	24.58	0.80
	2028	11.24	16.86	0.59	20.90	0.71	24.16	0.78
	2029	10.93	16.46	0.58	20.48	0.70	23.70	0.77
	2030	10.63	16.06	0.56	20.04	0.68	23.23	0.75
	2031	10.36	15.67	0.55	19.62	0.67	22.76	0.74
	2032	10.10	15.29	0.54	19.21	0.65	22.31	0.72
P*=0.4 sigma=0.5	2021	12.96	17.70	0.62	21.37	0.73	24.46	0.79
	2022	12.96	17.76	0.62	21.53	0.73	24.68	0.80
	2023	11.77	17.89	0.63	21.79	0.74	25.01	0.81
	2024	11.60	18.00	0.63	21.99	0.75	25.27	0.82
	2025	11.34	17.96	0.63	21.99	0.75	25.30	0.82
	2026	11.04	17.78	0.62	21.84	0.74	25.14	0.82
	2027	10.72	17.53	0.62	21.58	0.73	24.87	0.81
	2028	10.41	17.22	0.60	21.25	0.72	24.51	0.79
	2029	10.10	16.89	0.59	20.89	0.71	24.11	0.78
	2030	9.82	16.56	0.58	20.52	0.70	23.70	0.77
	2031	9.55	16.23	0.57	20.15	0.69	23.29	0.76
	2032	9.29	15.91	0.56	19.80	0.67	22.89	0.74
Equilibrium yield from FMSY proxy of SPR=0.5	2021	12.96	17.70	0.62	21.37	0.73	24.46	0.79
	2022	12.96	17.76	0.62	21.53	0.73	24.68	0.80
	2023	7.95	17.89	0.63	21.79	0.74	25.01	0.81
	2024	7.95	18.32	0.64	22.30	0.76	25.58	0.83
	2025	7.95	18.59	0.65	22.62	0.77	25.92	0.84
	2026	7.95	18.72	0.66	22.75	0.77	26.05	0.84
	2027	7.95	18.73	0.66	22.75	0.77	26.03	0.84
	2028	7.95	18.66	0.66	22.65	0.77	25.89	0.84
	2029	7.95	18.53	0.65	22.47	0.76	25.67	0.83
	2030	7.95	18.36	0.64	22.25	0.76	25.39	0.82
	2031	7.95	18.16	0.64	21.99	0.75	25.09	0.81
	2032	7.95	17.94	0.63	21.71	0.74	24.76	0.80

7 Figures

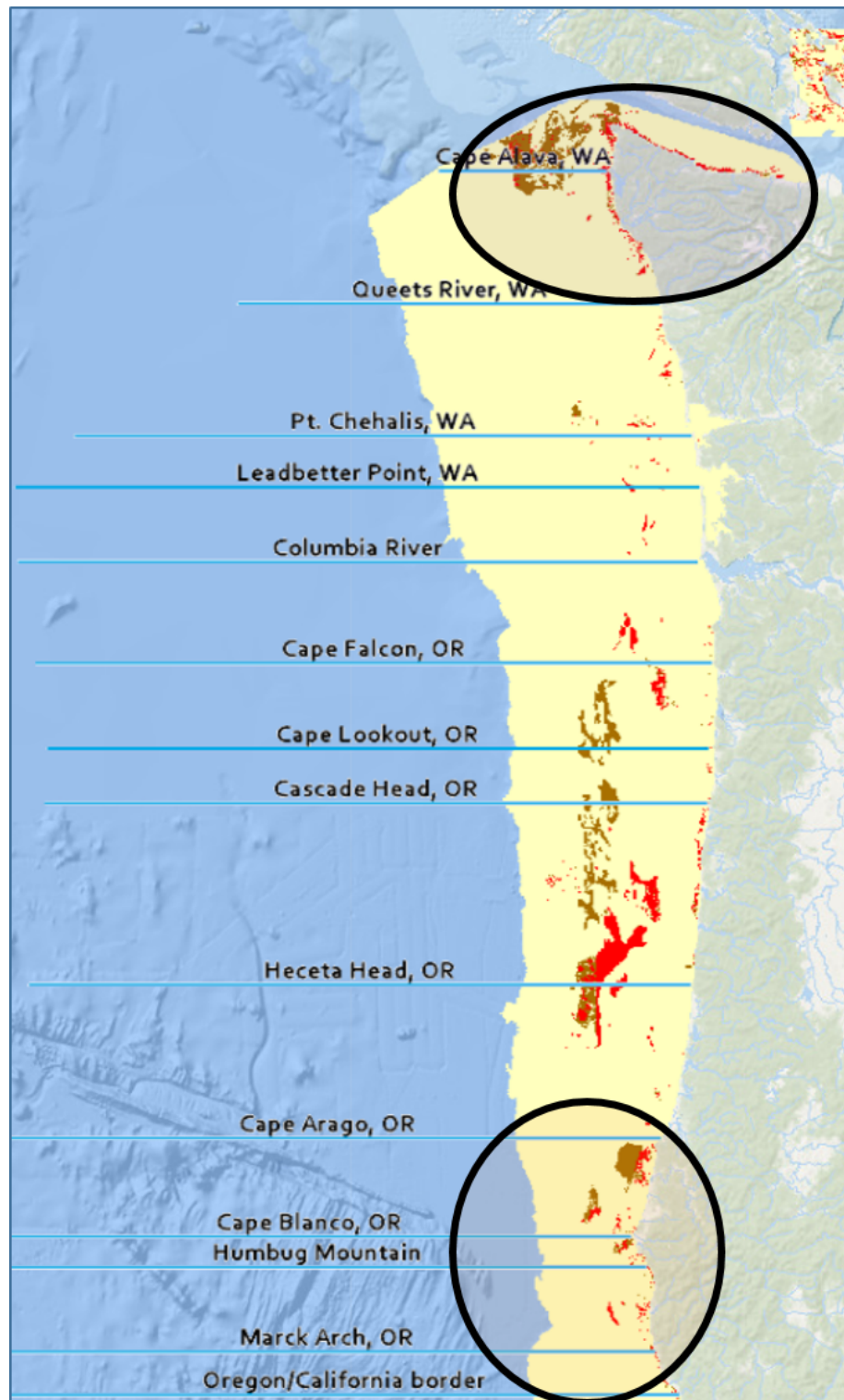


Figure 1: Oregon and Washington coastlines with rocky habitat indicated by brown shaded areas. Circled areas represent areas of primary vermillion rockfish occurrence.

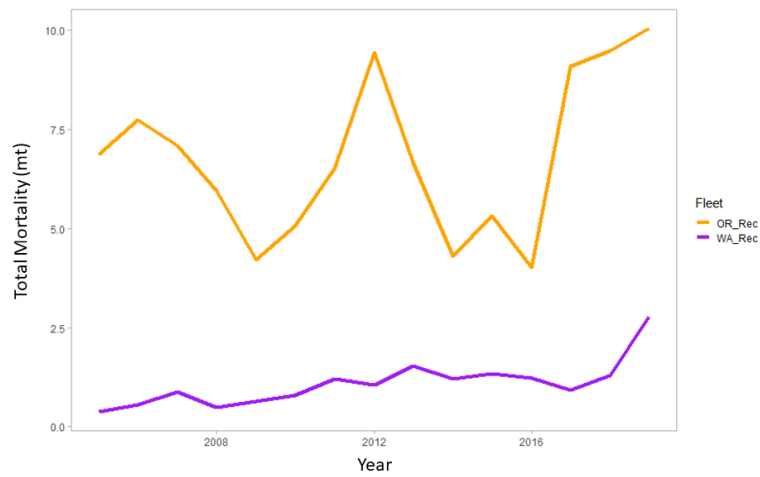


Figure 2: Total mortality from the southern Oregon and northern Washington recreational fisheries. These represent ninety and ninety-seven percent of the total vermilion rockfish removals in each state, respectively.

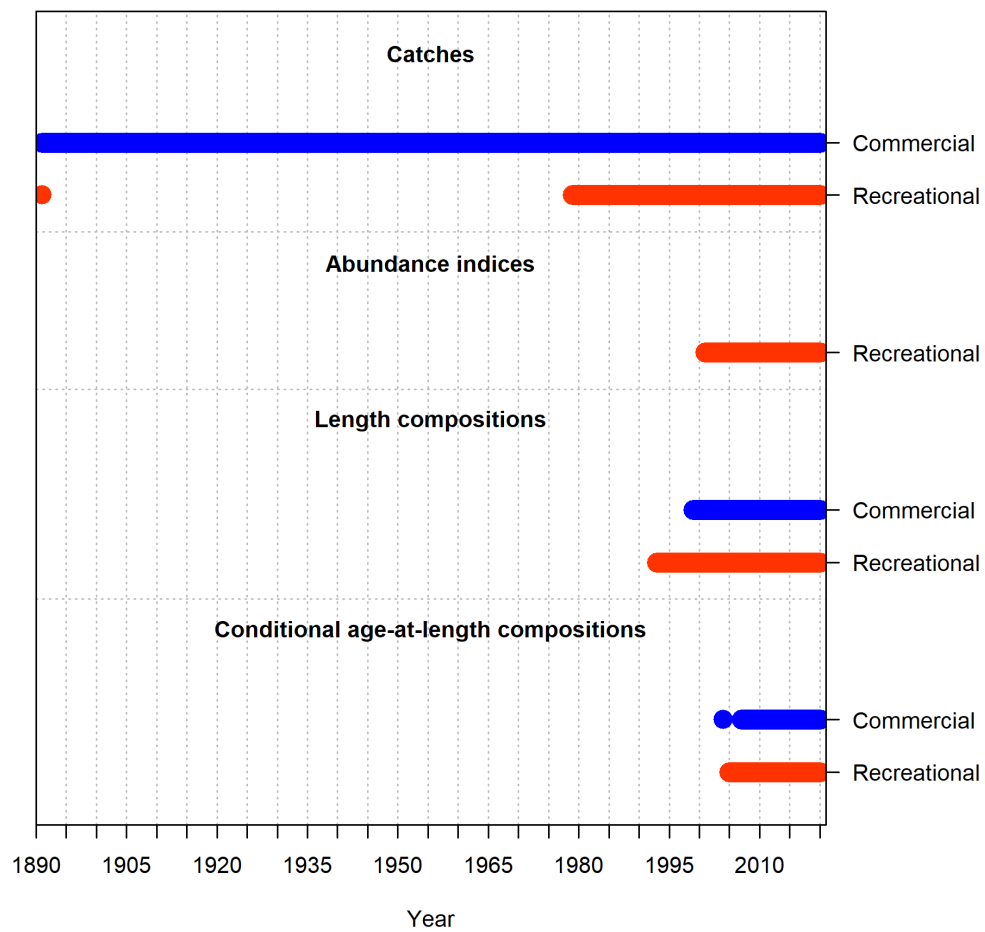


Figure 3: Summary of data sources used in the reference model.

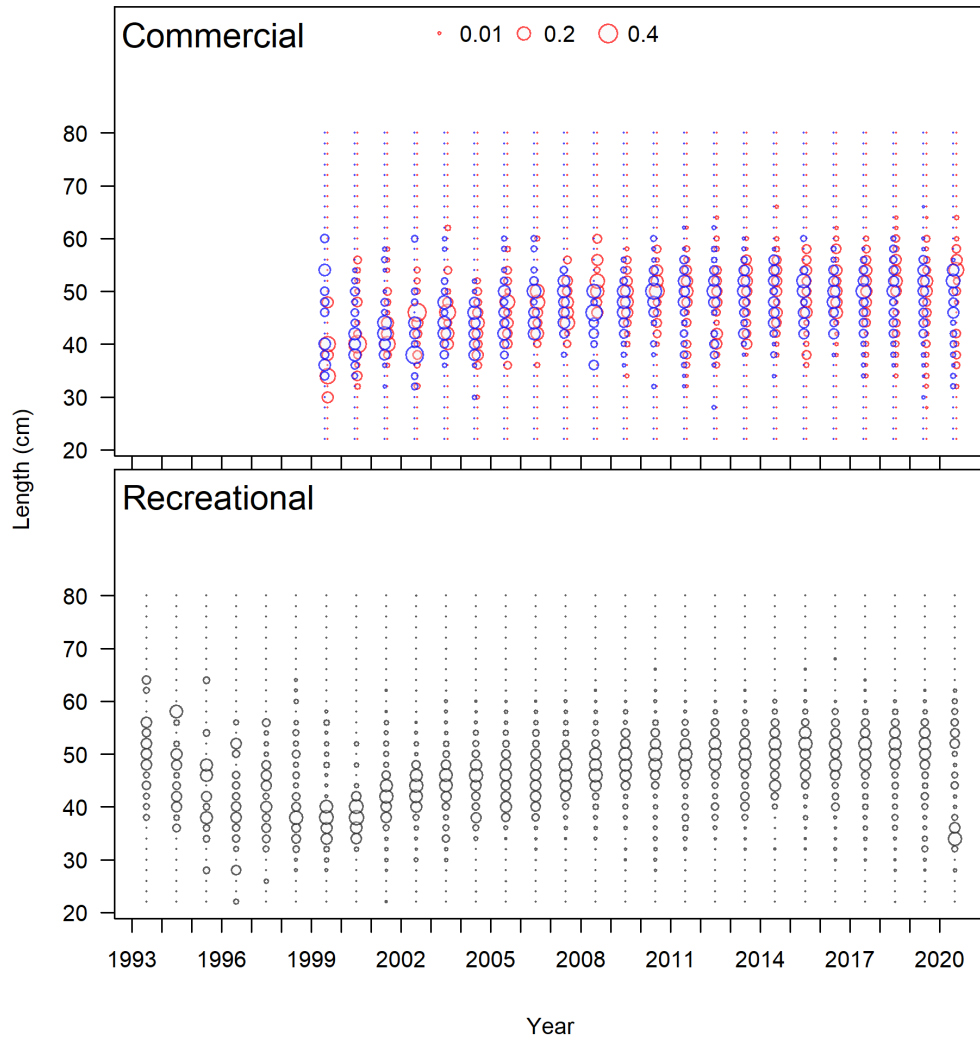


Figure 4: Bubble plot of length compositions by year and fleet. Size of the bubble indicates higher proportion. All proportions within year sum to one.

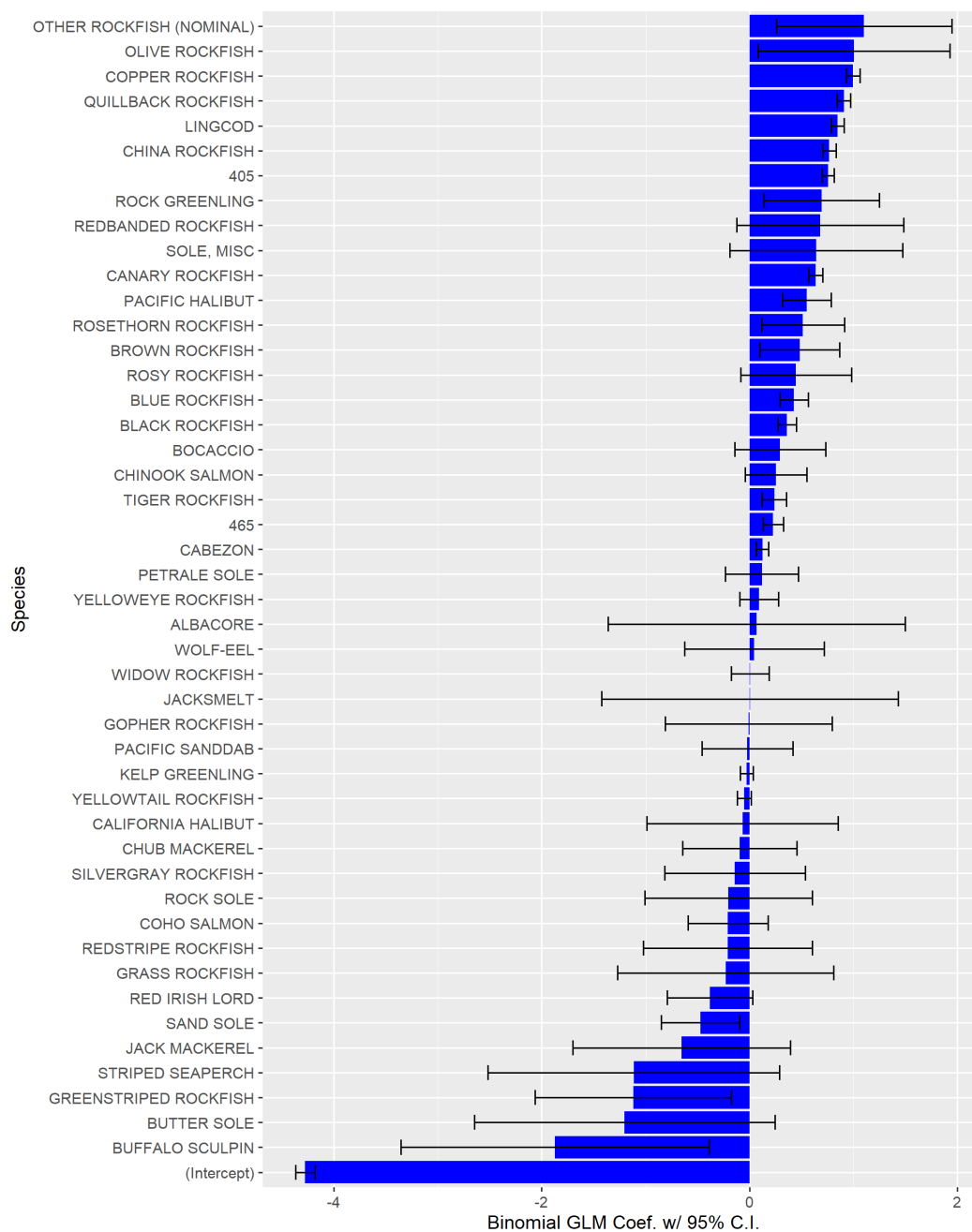


Figure 5: Species coefficients (blue bars) for presence/absence of vermilion rockfish in the ORBS dockside index. Horizontal black bars represent the 95 percent confidence intervals.

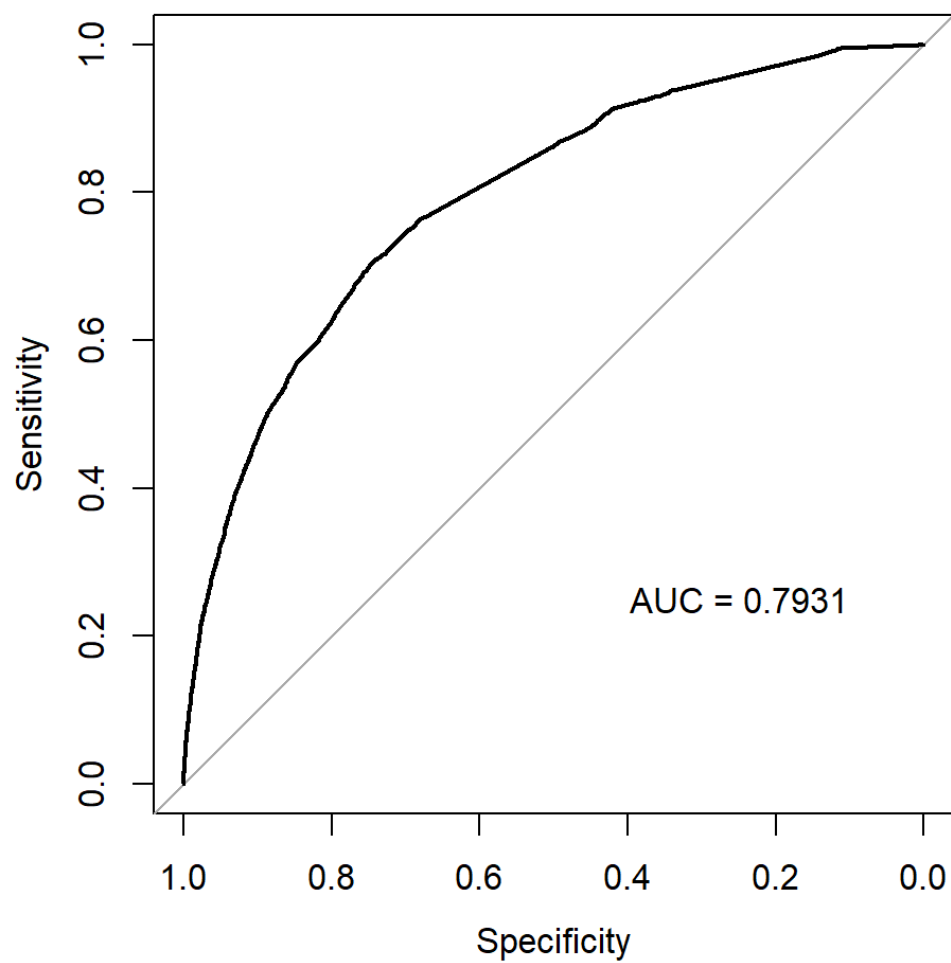


Figure 6: The ORBS dockside area under the characteristic curve (AUC) plot, which represents the probability that a randomly chosen observation of presence would be assigned a higher ranked prediction than a randomly chosen observation of absence. Values much greater than 0.5 indicate a significant improvement over a random classifier (AUC = 0.5).

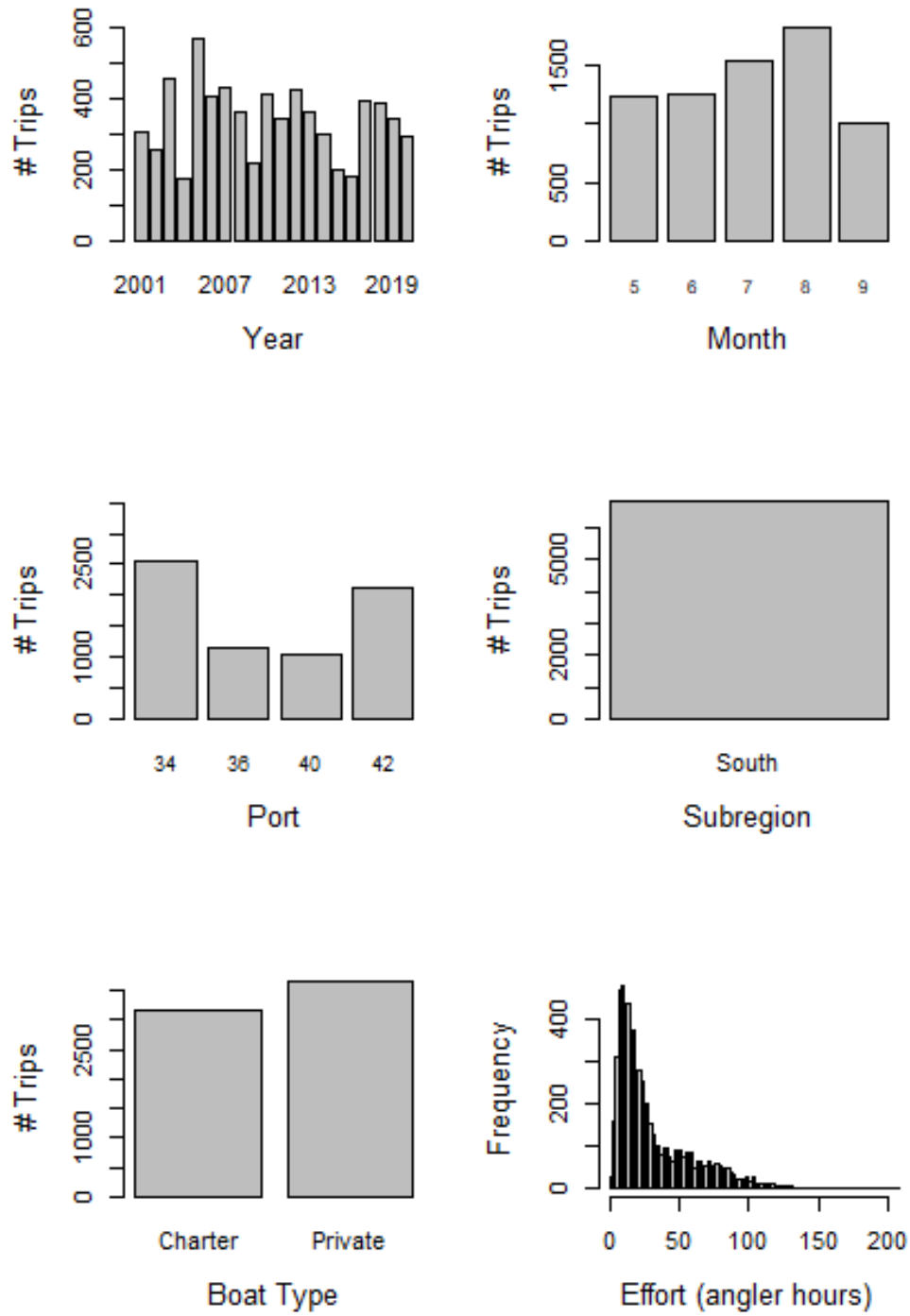


Figure 7: Characterization of the final subset of ORBS dockside data used in the delta-GLM analyses to develop an index for vermilion rockfish.

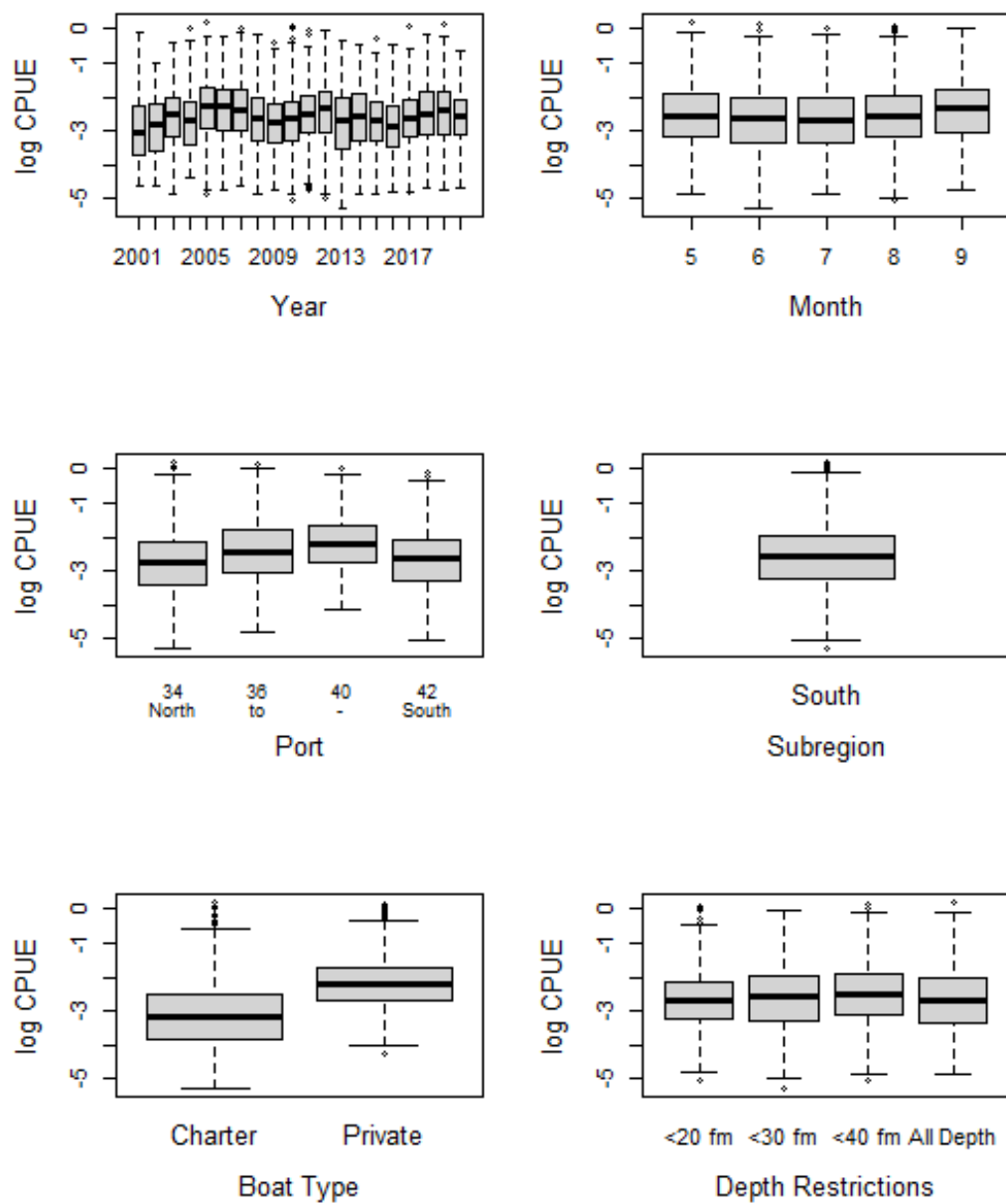


Figure 8: The distribution of trip-level raw positive catch CPUE for the ORBS dockside data relative to potential covariates evaluated in the vermilion rockfish delta-GLM analysis.

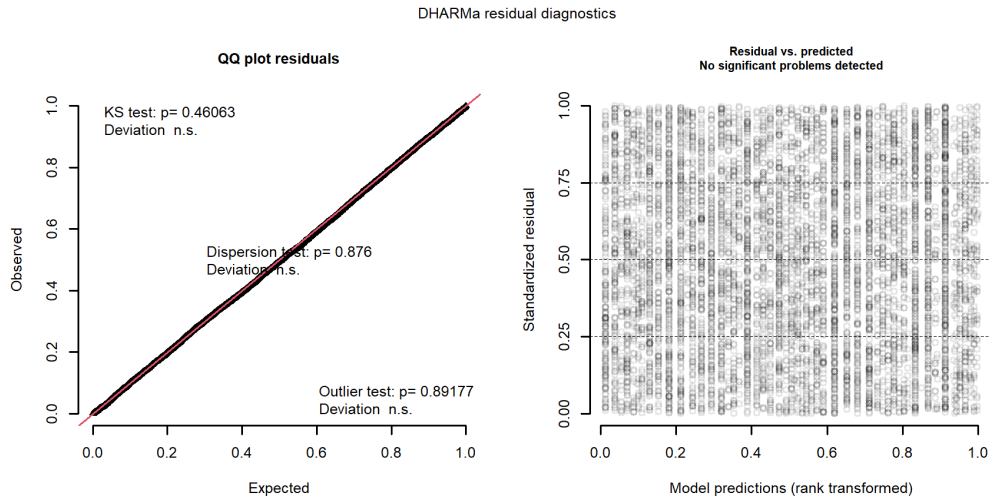


Figure 9: Scaled quantile-quantile plot (left) and rank-transformed versus standardized residuals (right) for the binomial model of the ORBS dockside index.

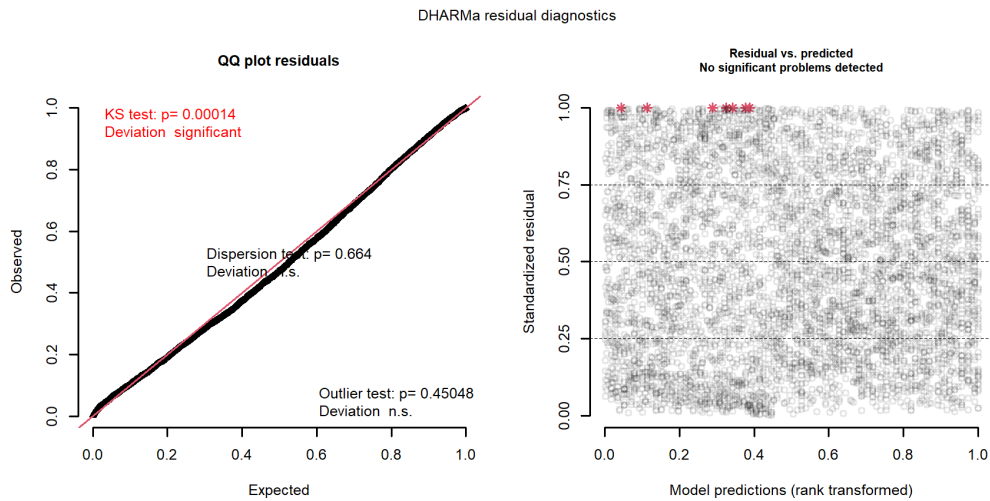


Figure 10: Scaled quantile-quantile plot (left) and rank-transformed versus standardized residuals (right) for the positive model of the ORBS dockside index.

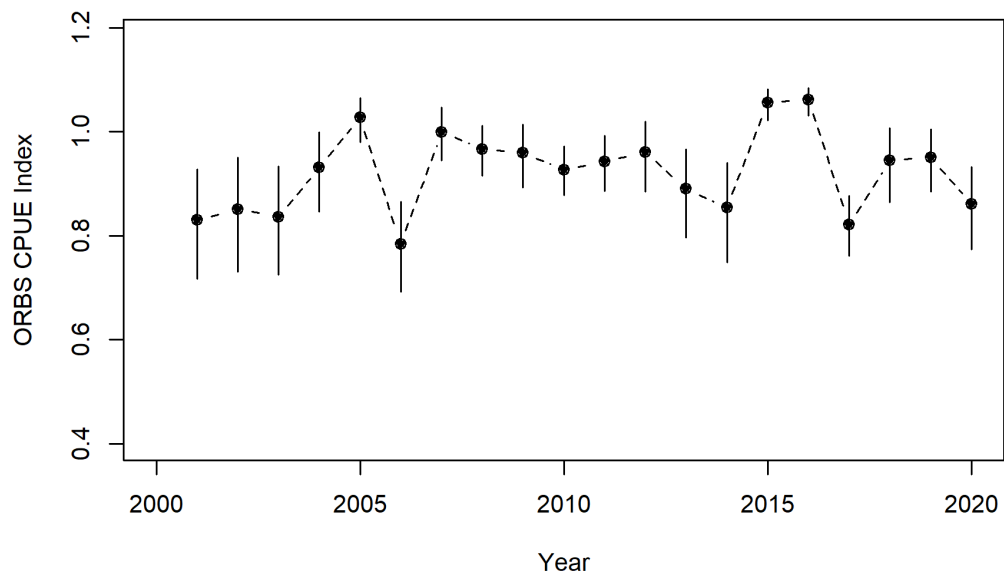


Figure 11: Final ORBS dockside index for vermilion rockfish.

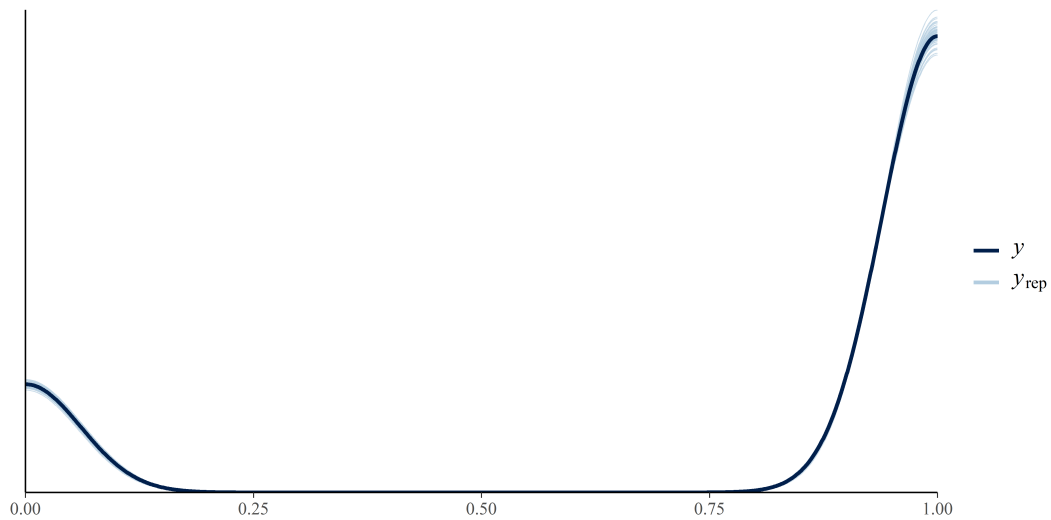


Figure 12: Comparison of data distribution for vermilion rockfish CPUE to model-generated replicate data sets used to evaluate uncertainty for the binomial model component.

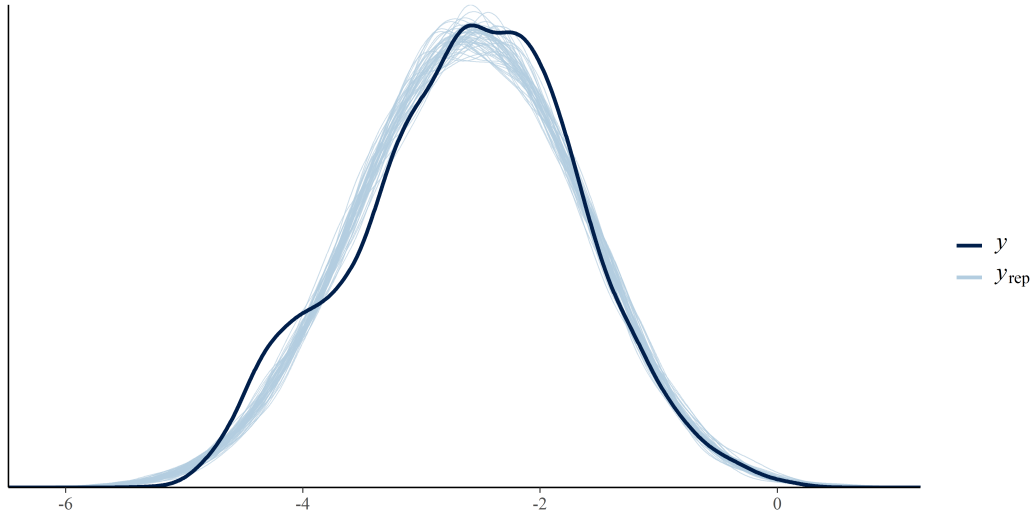


Figure 13: Comparison of data distribution for vermilion rockfish CPUE to model-generated replicate data sets used to evaluate uncertainty for the positive model component.

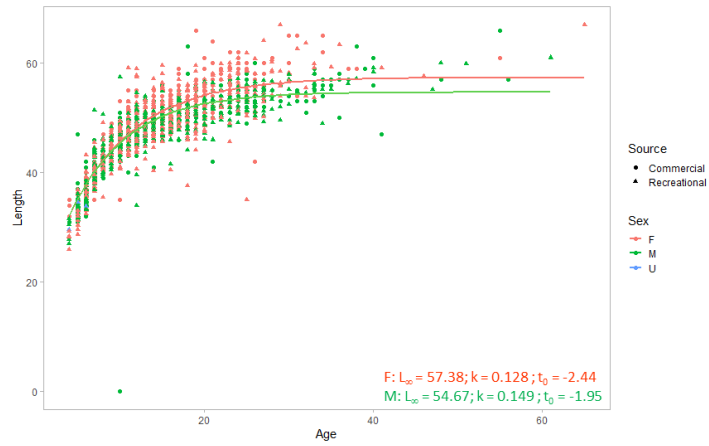


Figure 14: Observed length-at-age by data source and sex. Lines indicate fits to the von Bertalanffy growth equation, with parameter estimates provided in the bottom right corner of the figure.

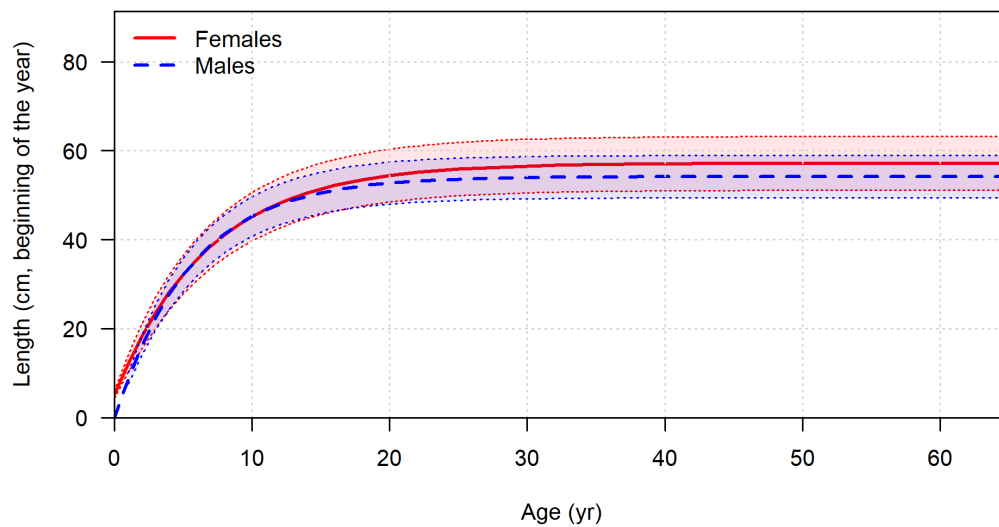


Figure 15: Model estimated length-at-age in the beginning of the year. Shaded area indicates 95 percent distribution of length-at-age around the estimated growth curve.

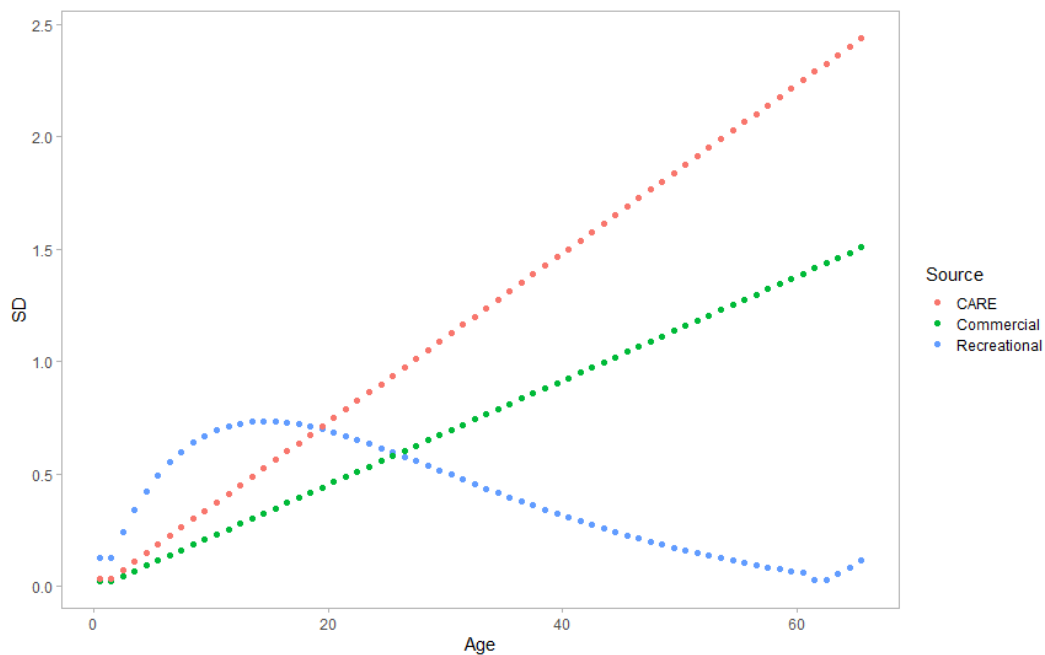


Figure 16: Ageing error matrix (age by standard deviation (SD)) values by source. The commercial and recreational matrices are based on intra-reader comparisons.

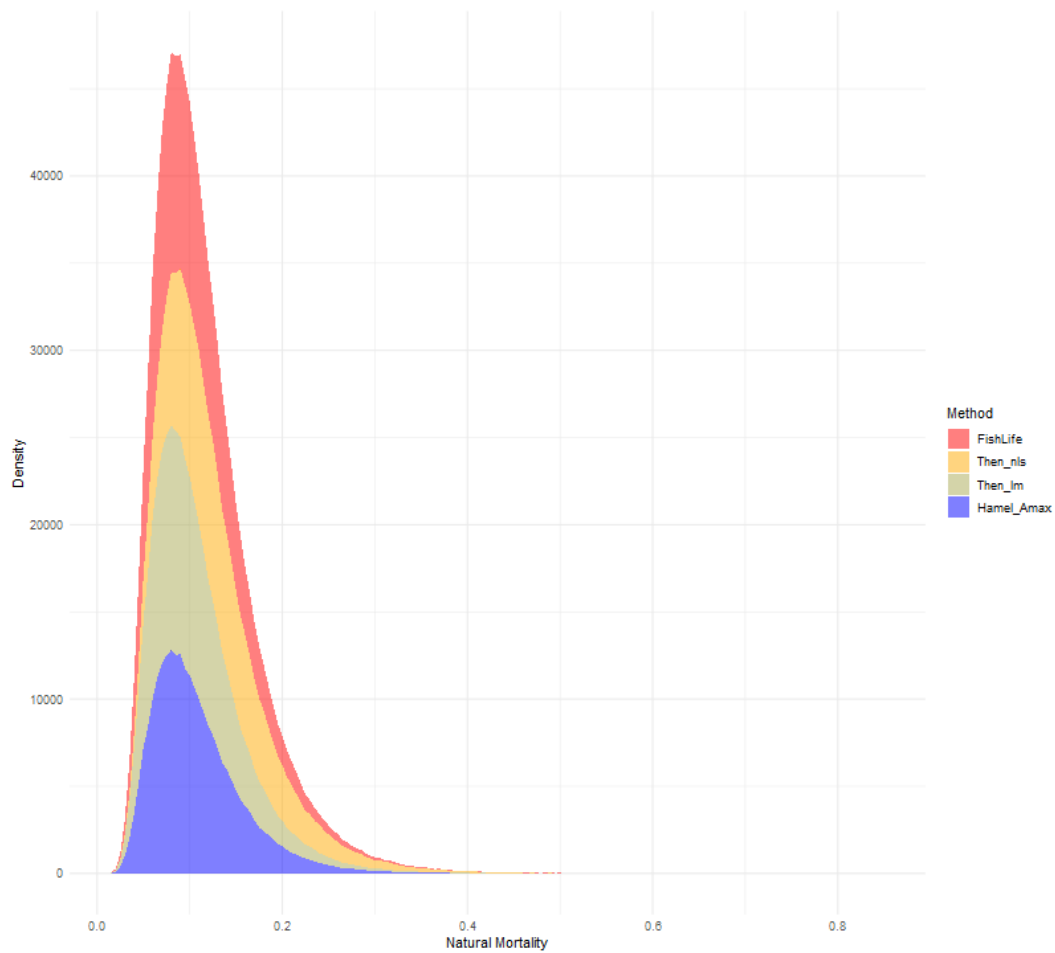


Figure 17: Composite natural mortality distribution for vermilion rockfish using four longevity estimators each with a $SD = 0.438$ presuming a lognormal error distribution.

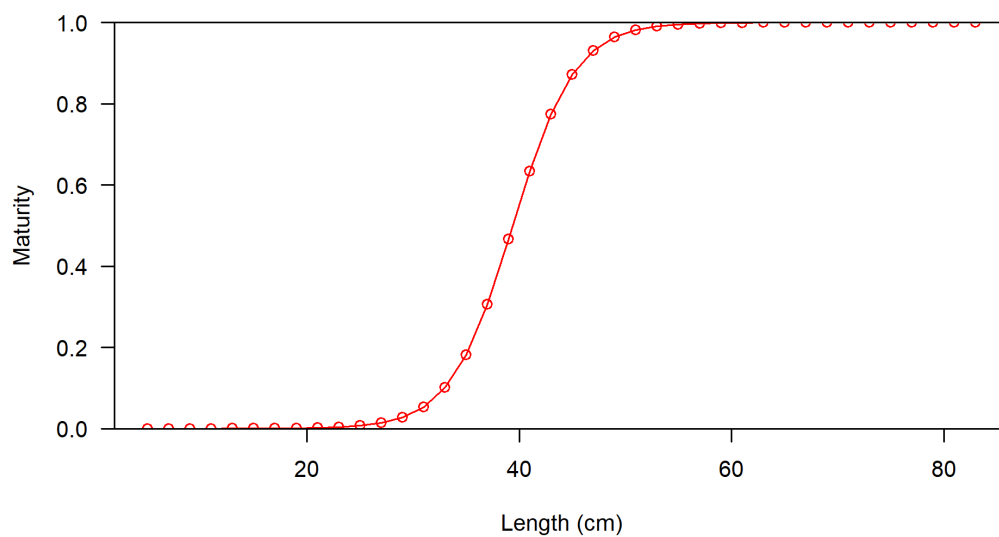


Figure 18: Maturity as a function of length (cm).

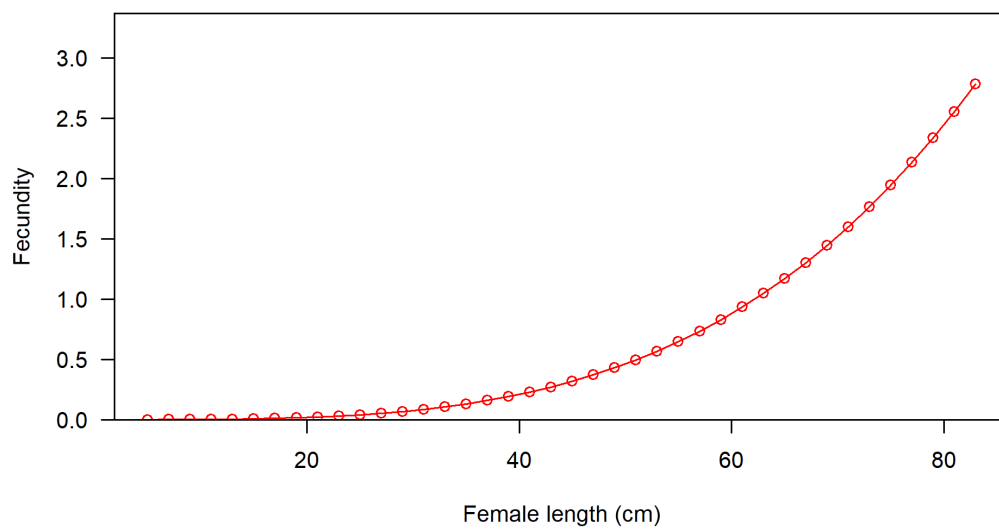


Figure 19: Fecundity (kg) as a function of length (cm).

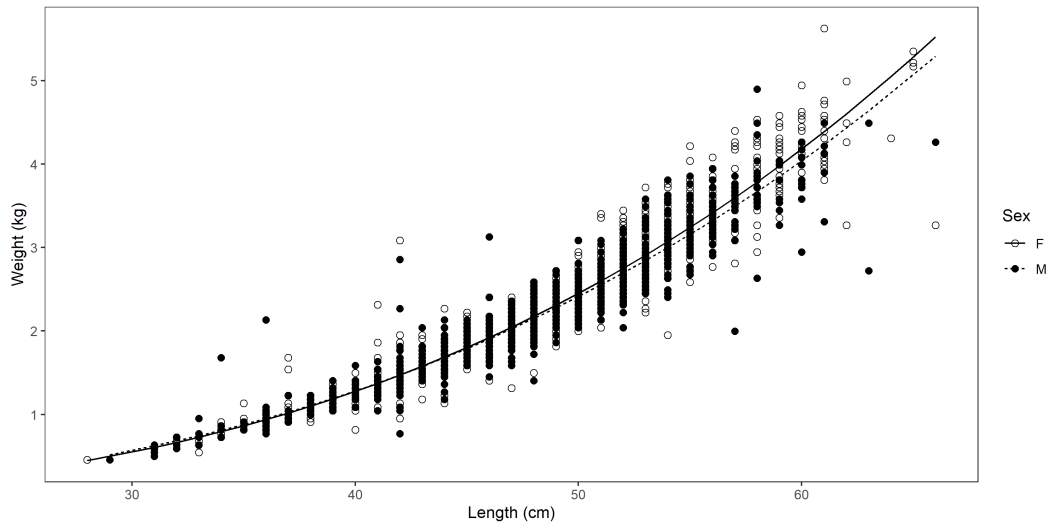


Figure 20: Sex-specific length (cm)-weight (kg) data and fits to commercially-derived vermilion rockfish samples.

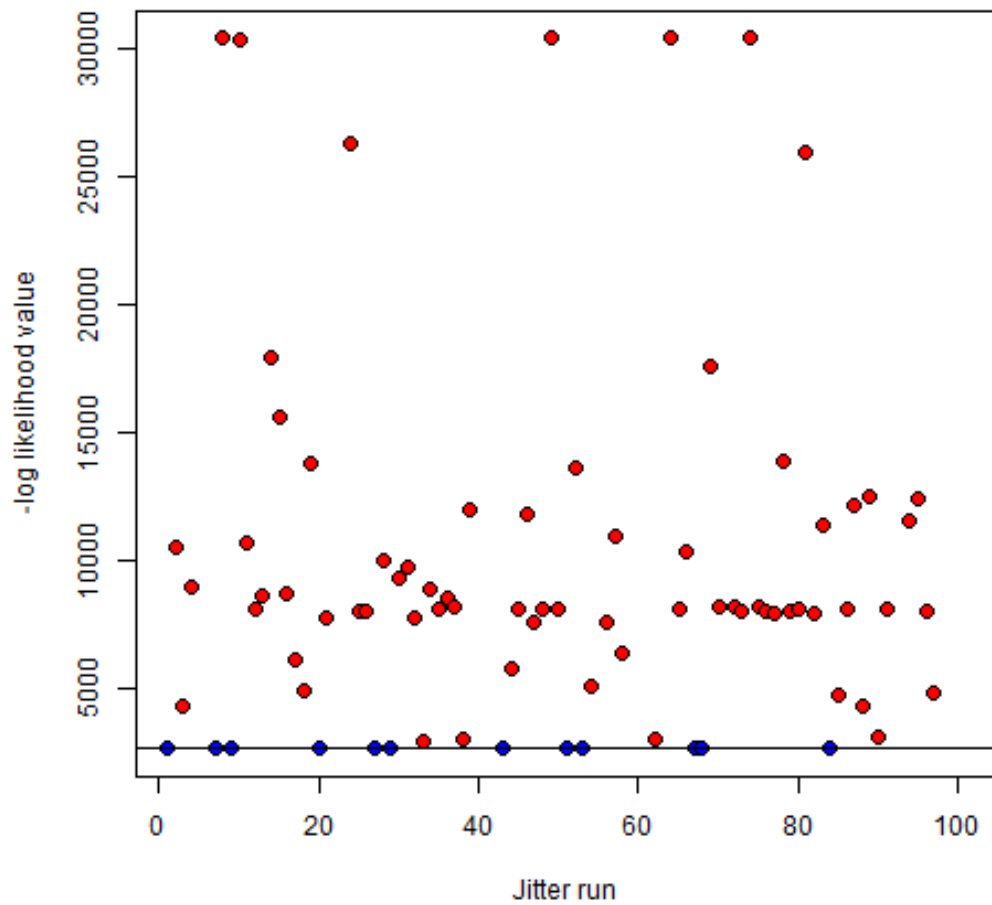


Figure 21: Jitter runs for the vermilion rockfish reference model, with jitter run number on the x-axis and -log likelihood value on the y-axis. Blue dot are models that match the likelihood value of the reference model, while red dots deviate from the reference model. All red dots are above the blue dots, indicating no better fit to the reference model was found.

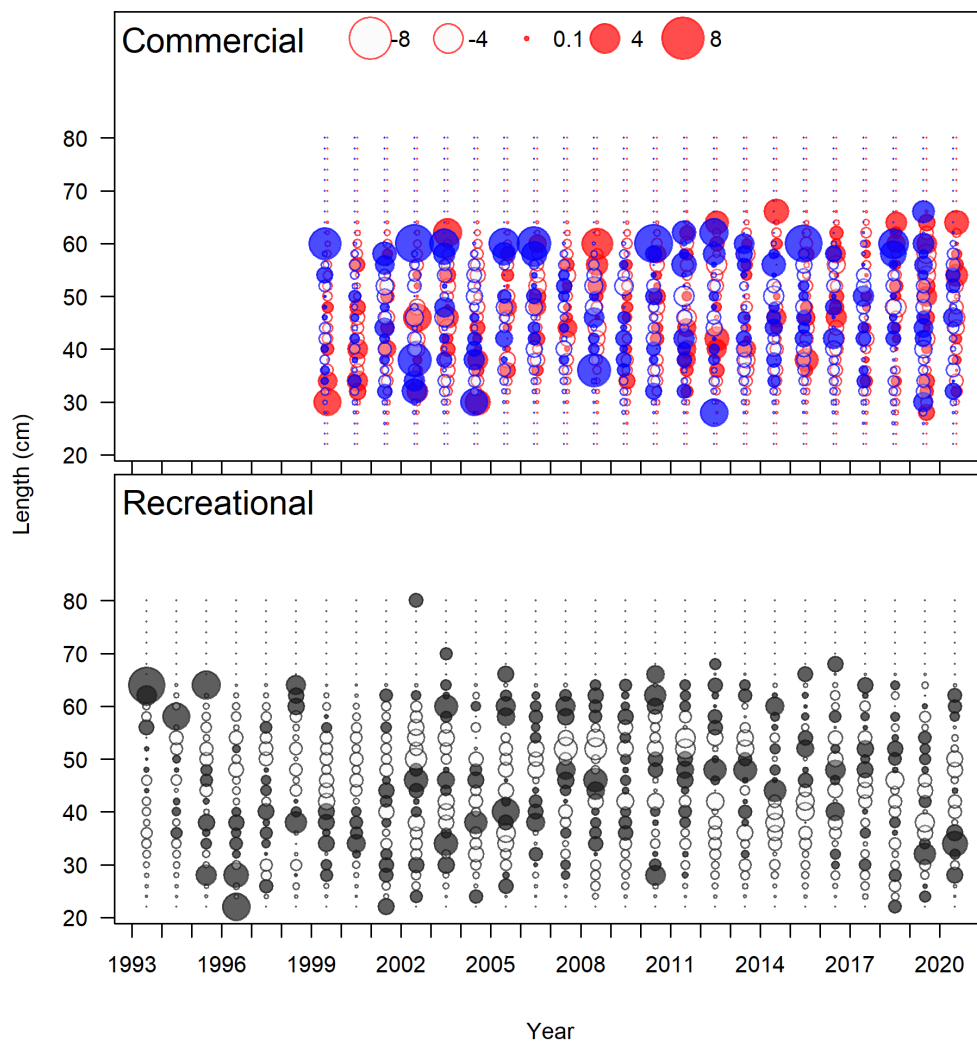


Figure 22: Pearson residuals for the commercial (top panel) and recreational (bottom panel) fleet. Closed bubble are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

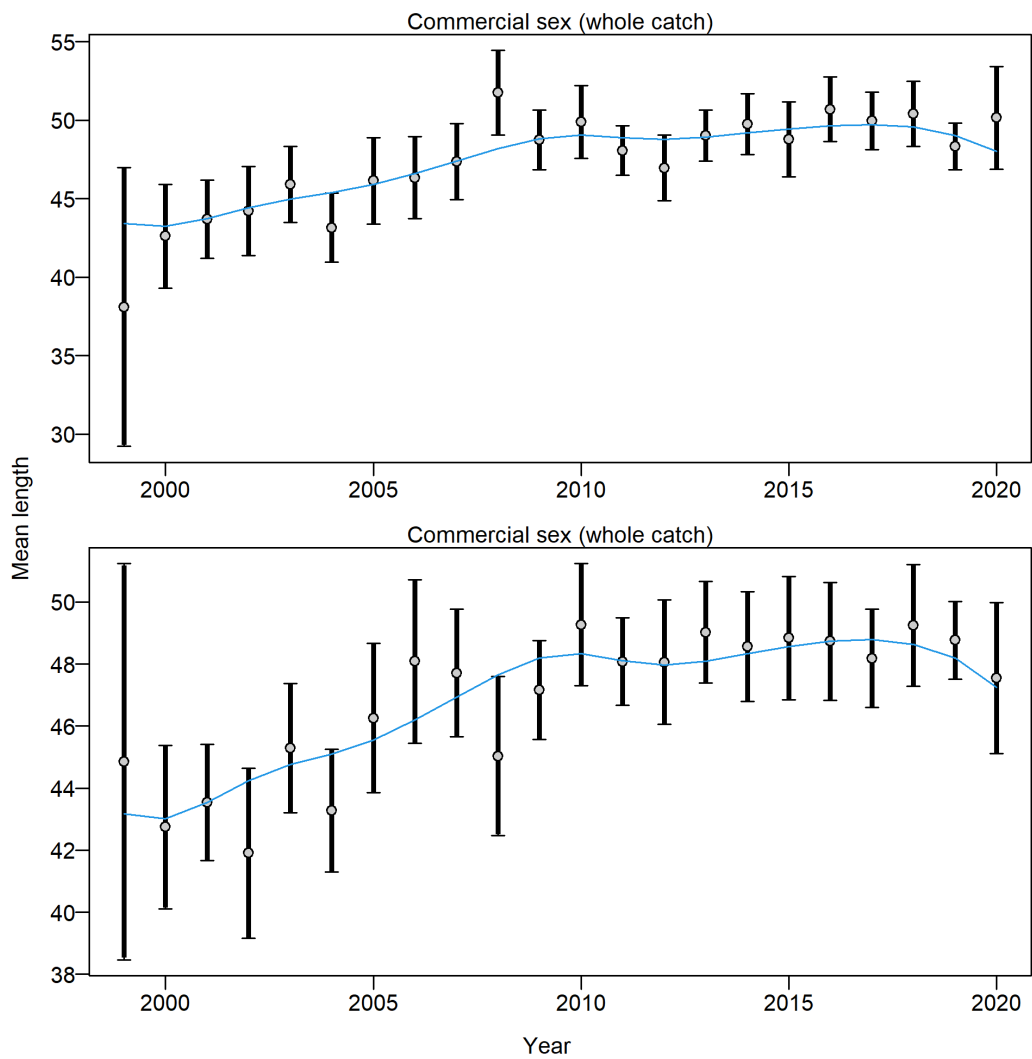


Figure 23: Mean length (cm) index from the commercial fishery with 95 percent confidence intervals based on sample sizes and data weighting.

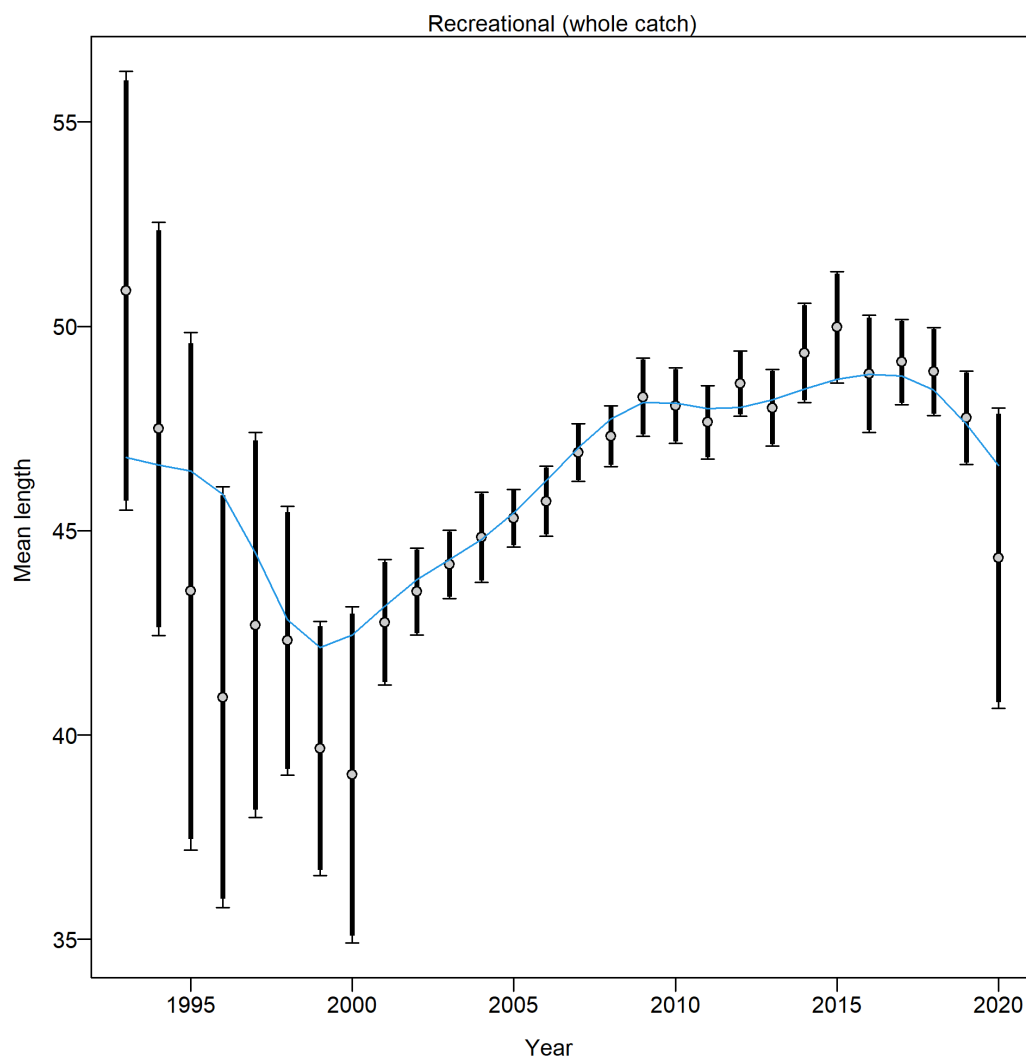


Figure 24: Mean length (cm) index from the recreational fishery with 95 percent confidence intervals based on sample sizes and data weighting.

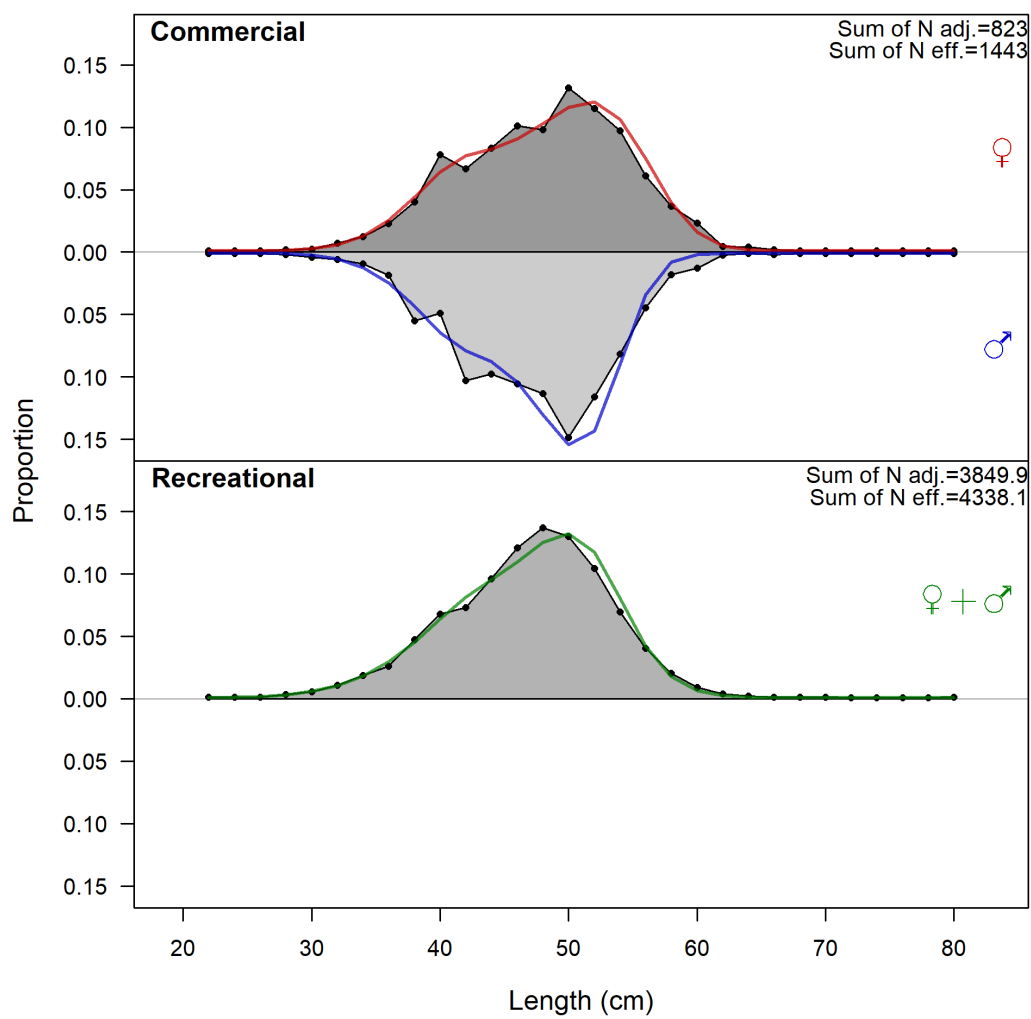


Figure 25: Aggregated length (cm) compositions over all years.

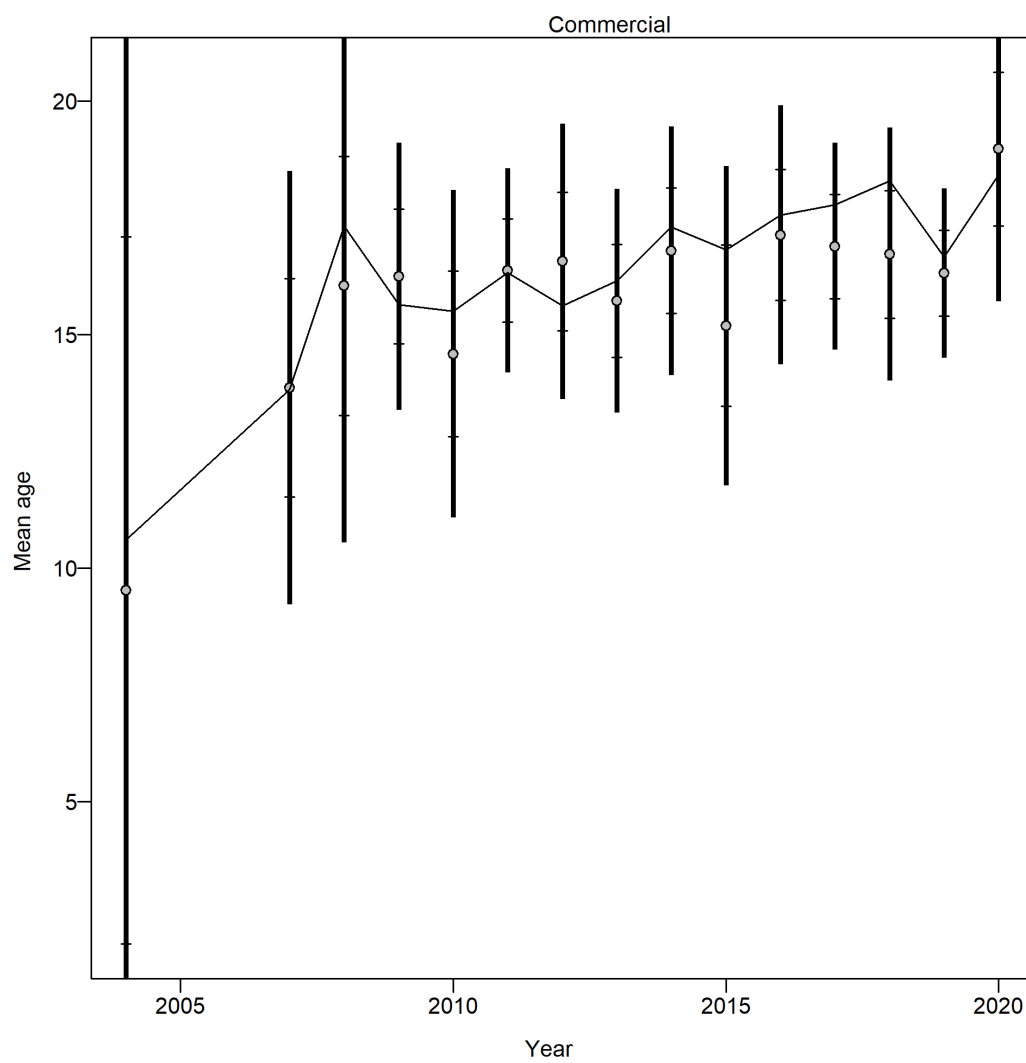


Figure 26: Mean age from conditional age-at-length data for the commercial fishery.

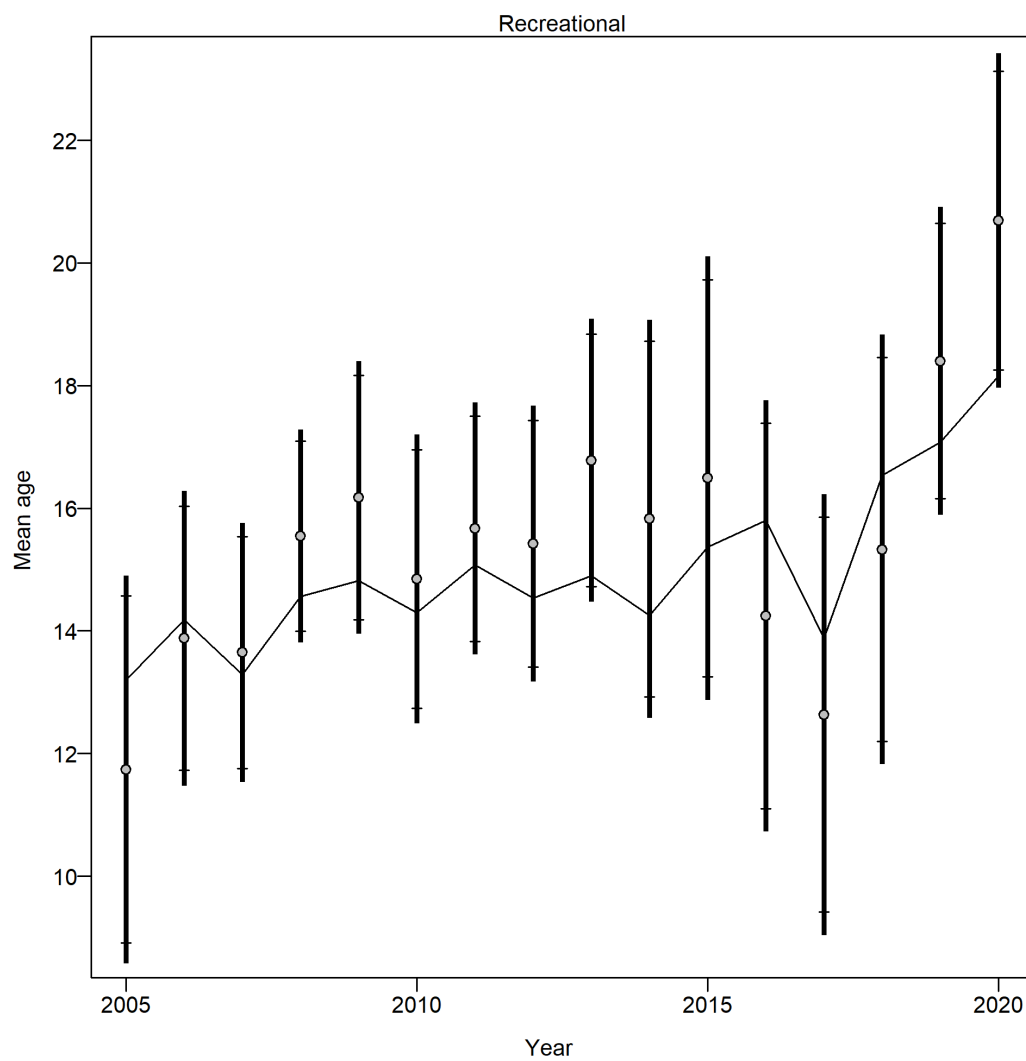


Figure 27: Mean age observations from the conditional age-at-length data from the recreational fishery.

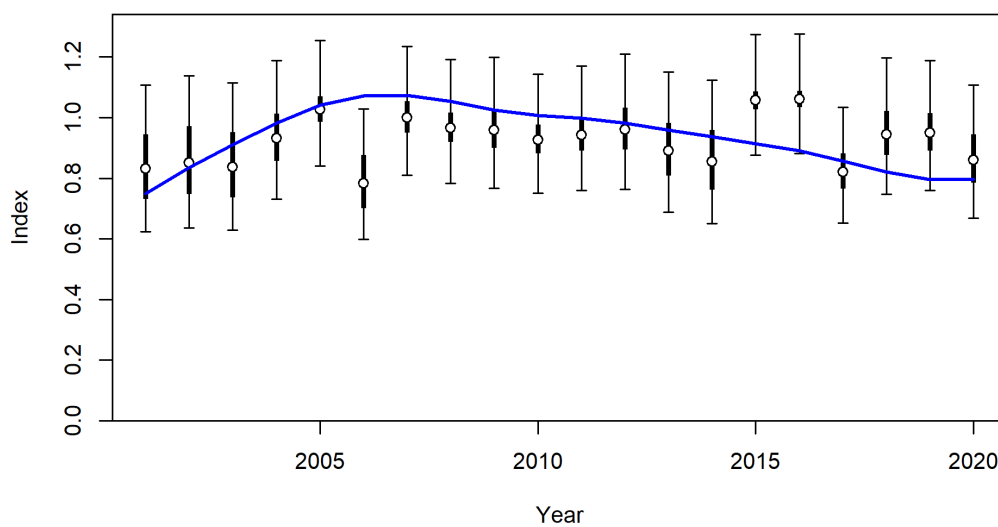


Figure 28: Fit to the ORBS recreational survey index of abundance.

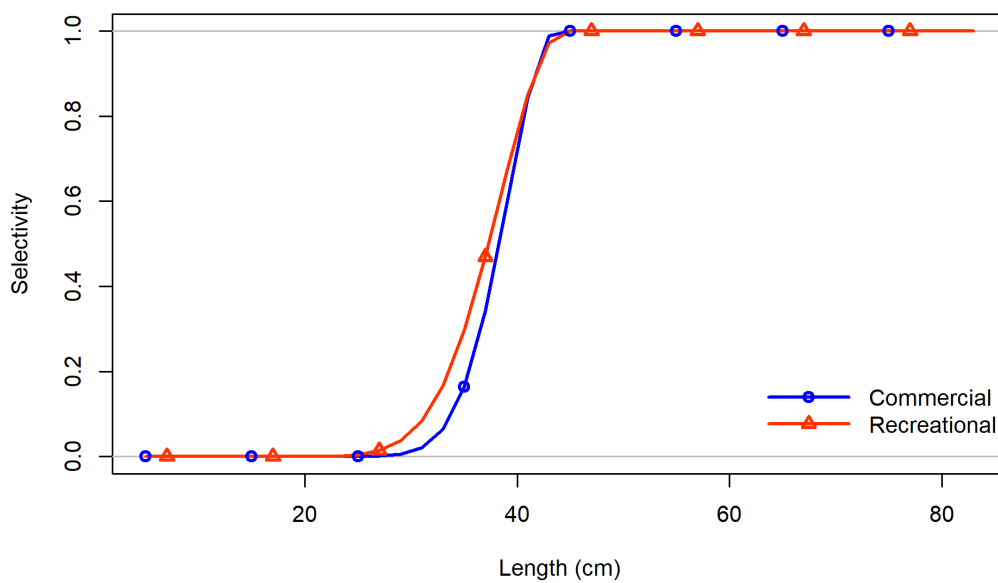


Figure 29: Length-based selectivity curves for the commercial and recreational fisheries.

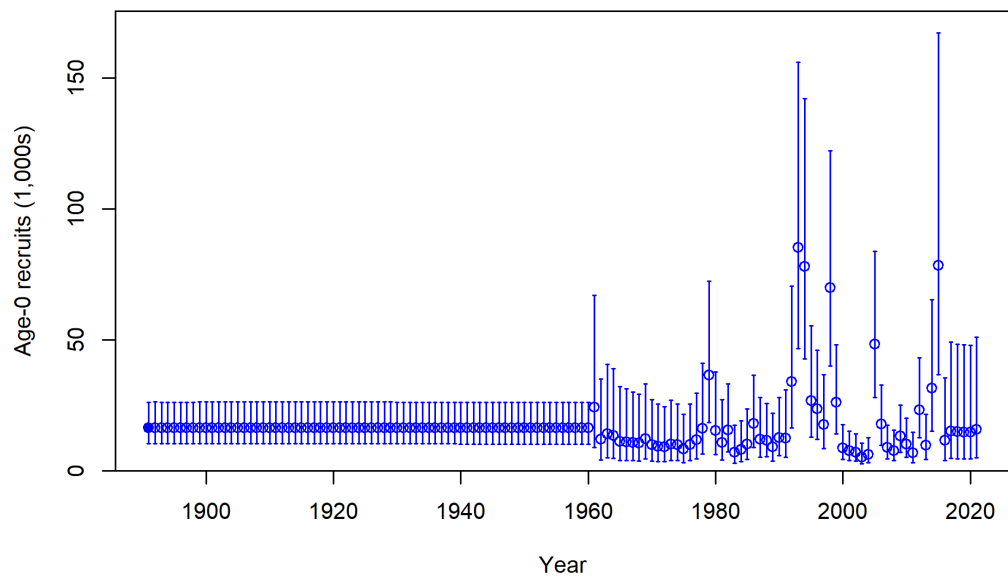


Figure 30: Estimated time series of age-0 recruits (1000s).

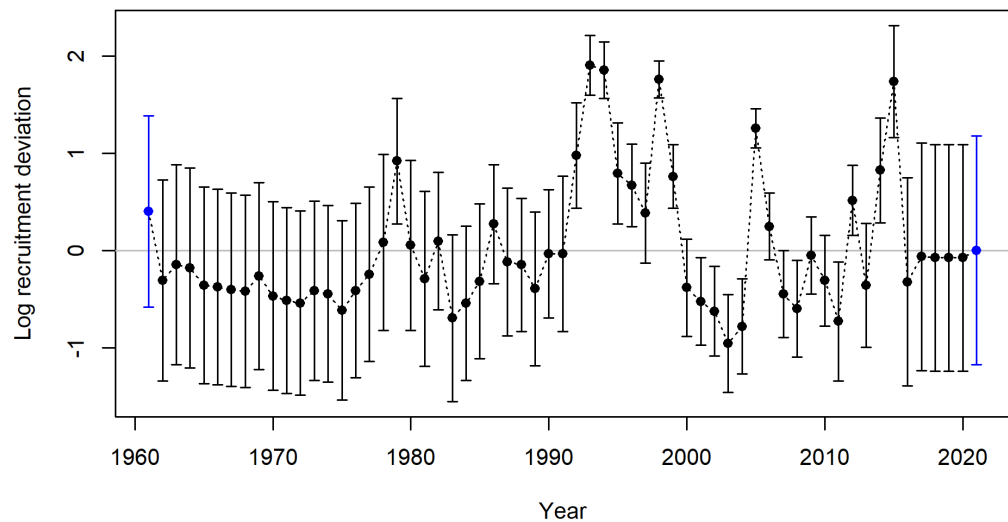


Figure 31: Estimated time series of recruitment deviations.

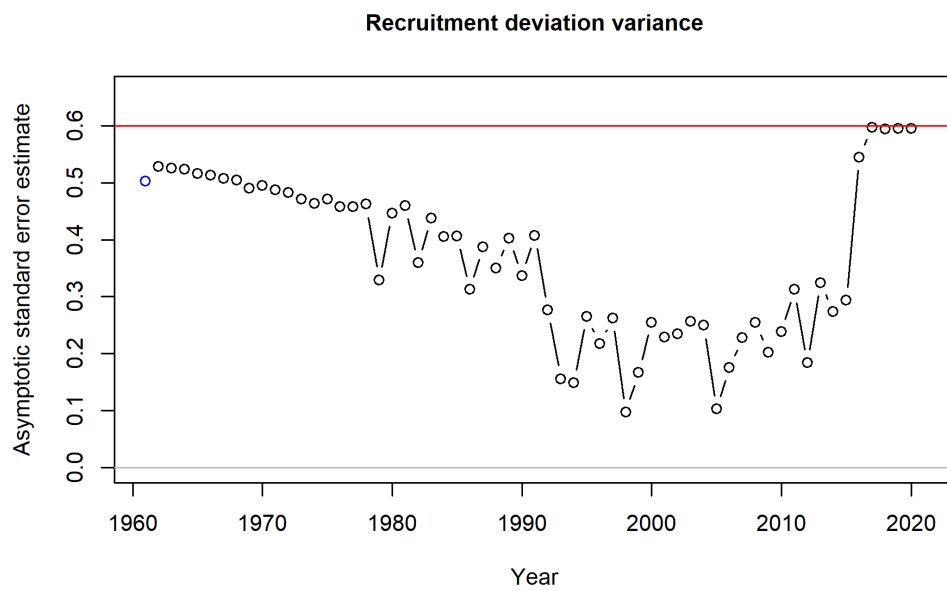


Figure 32: Recruitment deviations variance by year. This plot tracks the information content contained in each recruitment deviation. Values below the red line (assumed recruitment variability) indicates years with more informed recruitment deviations.

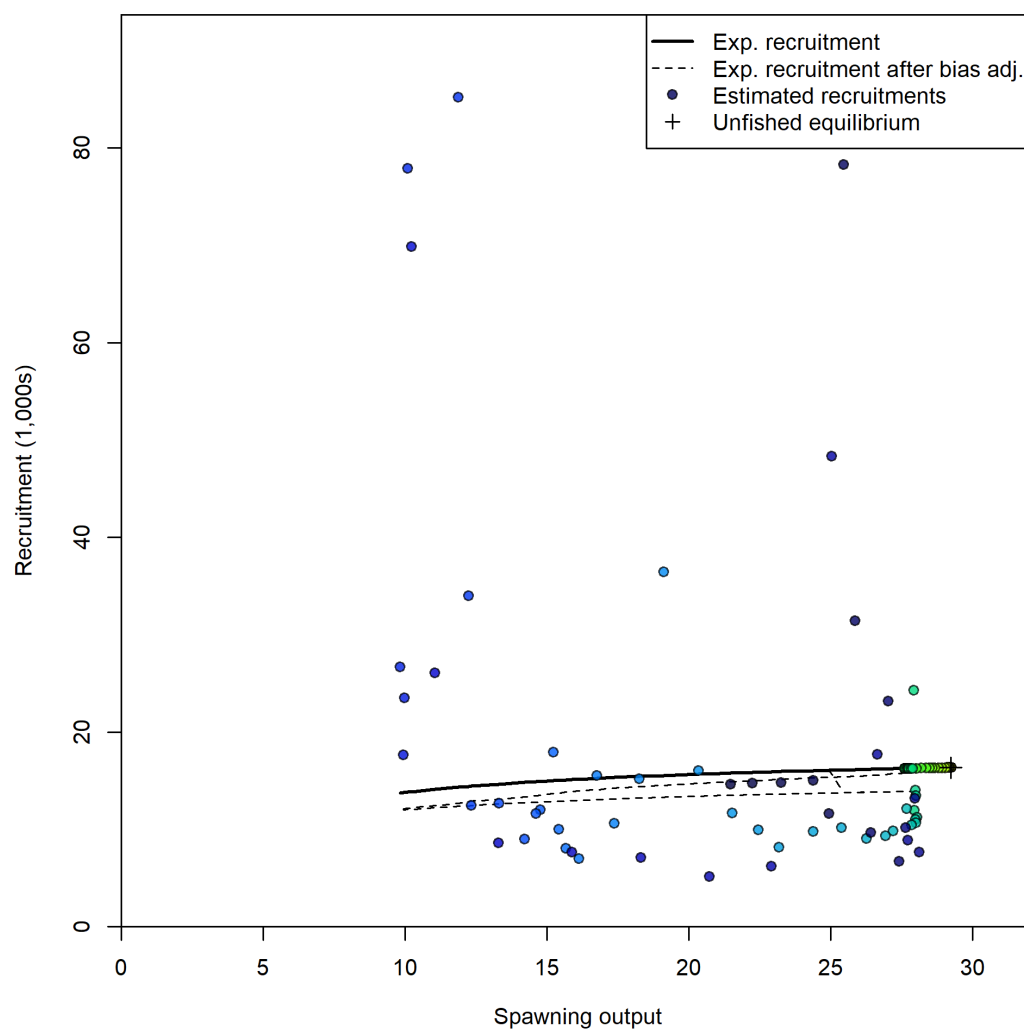


Figure 33: Stock-recruit curve where point color indicates year, with warmer colors (yellow to green) indicating earlier years and cooler colors (blue) showing later years.

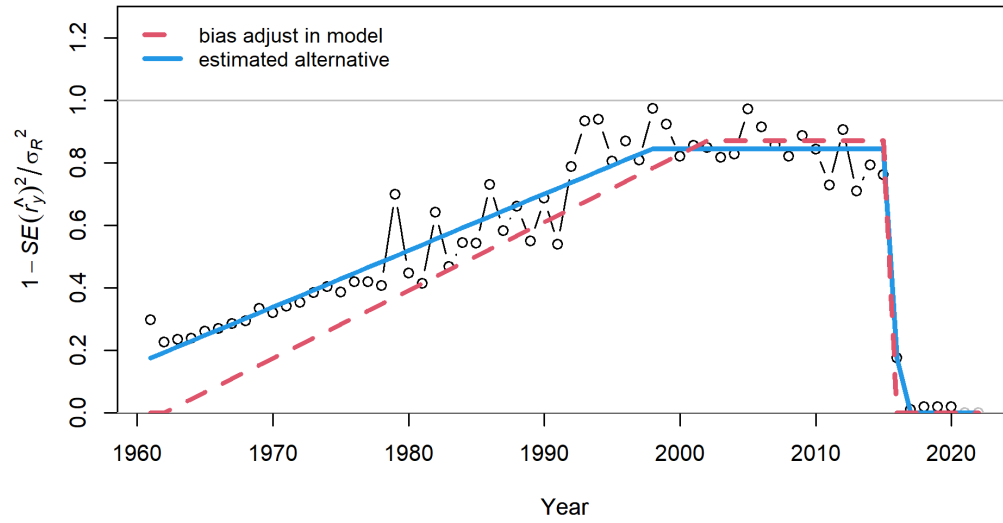


Figure 34: Recruitment bias adjustment applied in the reference model.

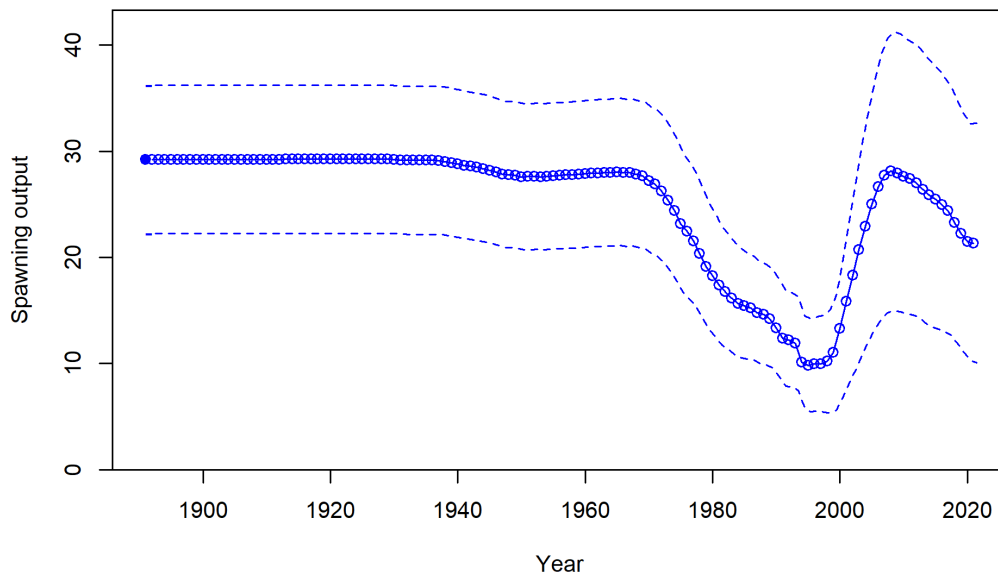


Figure 35: Estimated time series of spawning output (in millions of eggs).

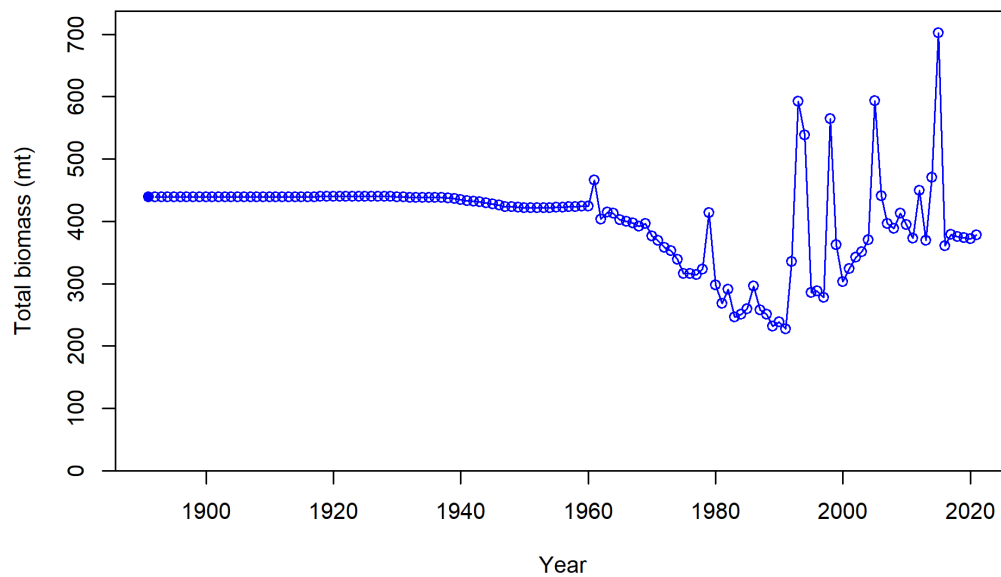


Figure 36: Estimated time series of total biomass (mt).

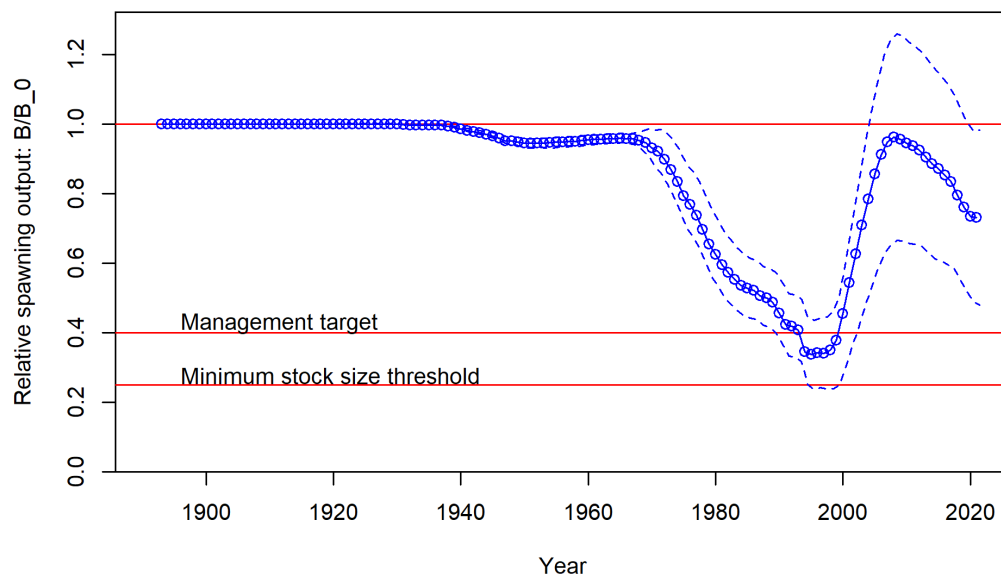


Figure 37: Estimated time series of fraction of unfished spawning output.

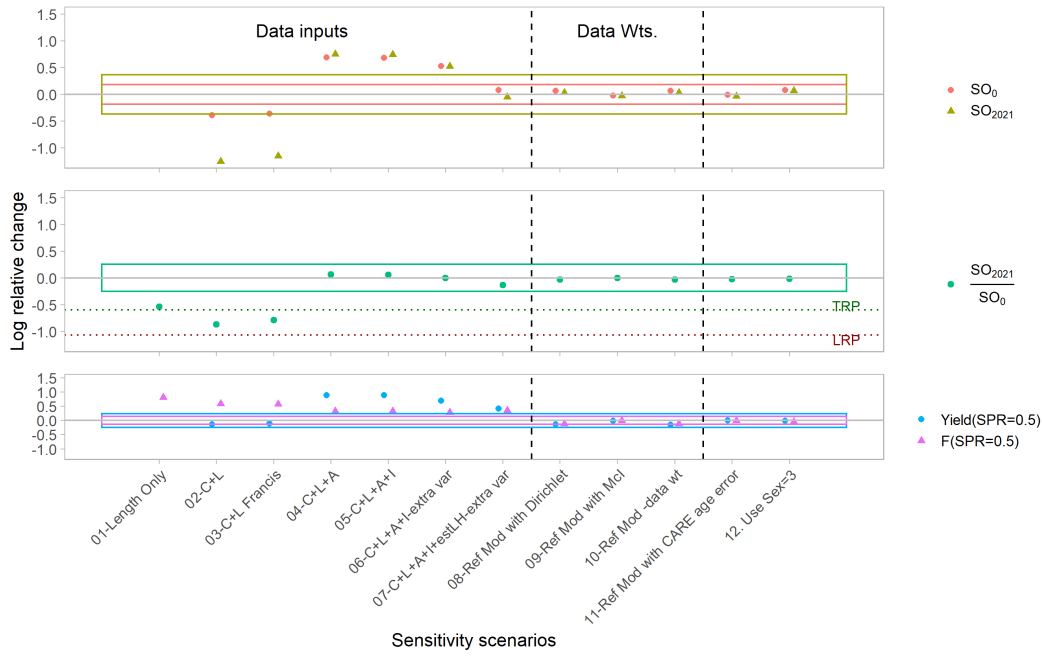


Figure 38: Log relative change ($\log((\text{Model_sensi}-\text{Model_ref})/\text{Model_ref}))$ in data treatment for 5 derived quantities. Colored boxes indicate 95 percent confidence interval of the reference model.

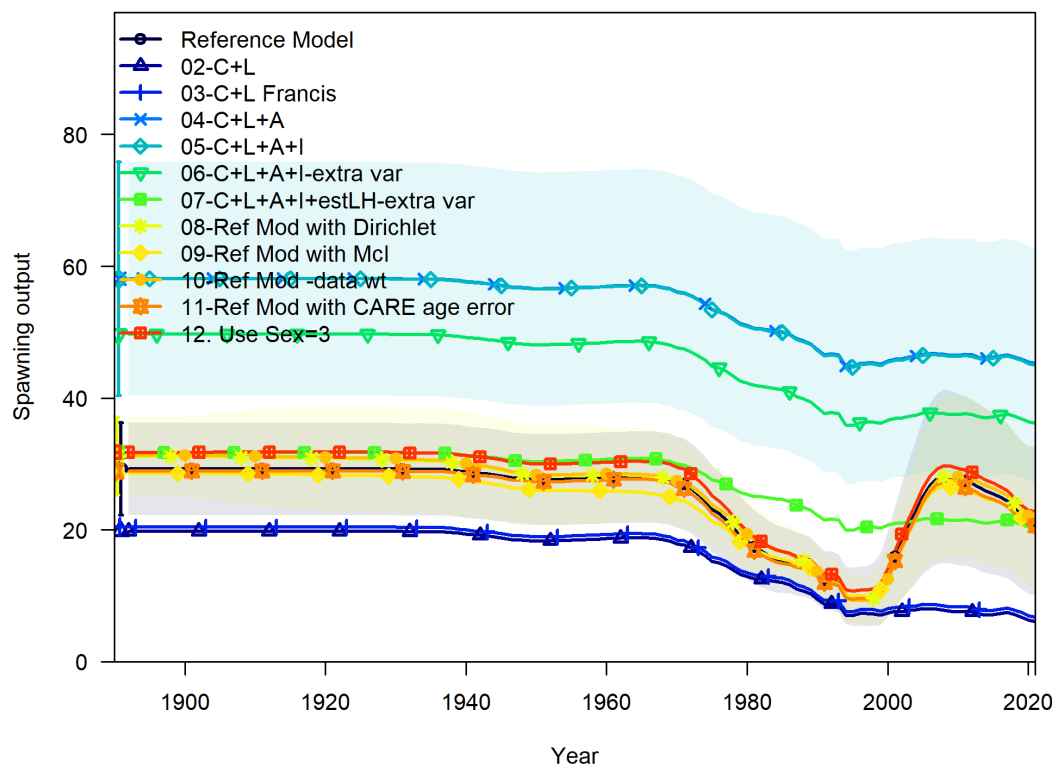


Figure 39: Spawning output (in millions of eggs) time series by data treatment compared to the reference model.

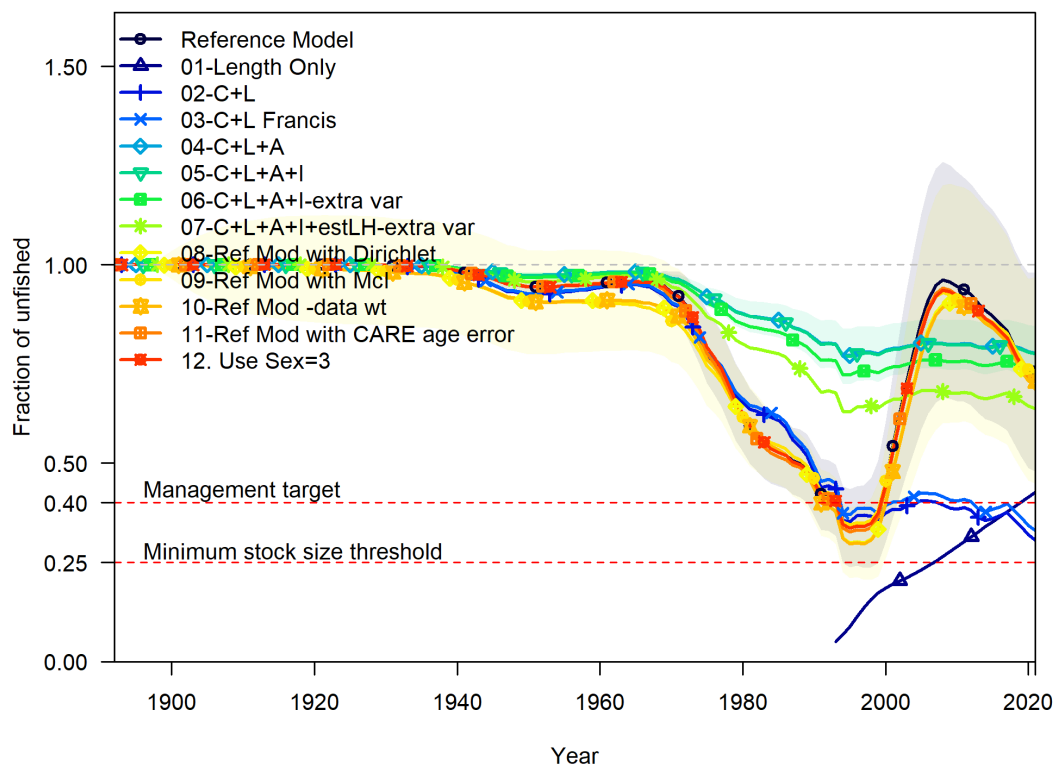


Figure 40: Relative spawning output time series by data treatment compared to the reference model. Missing scenarios mean the spawning output was too large to show.

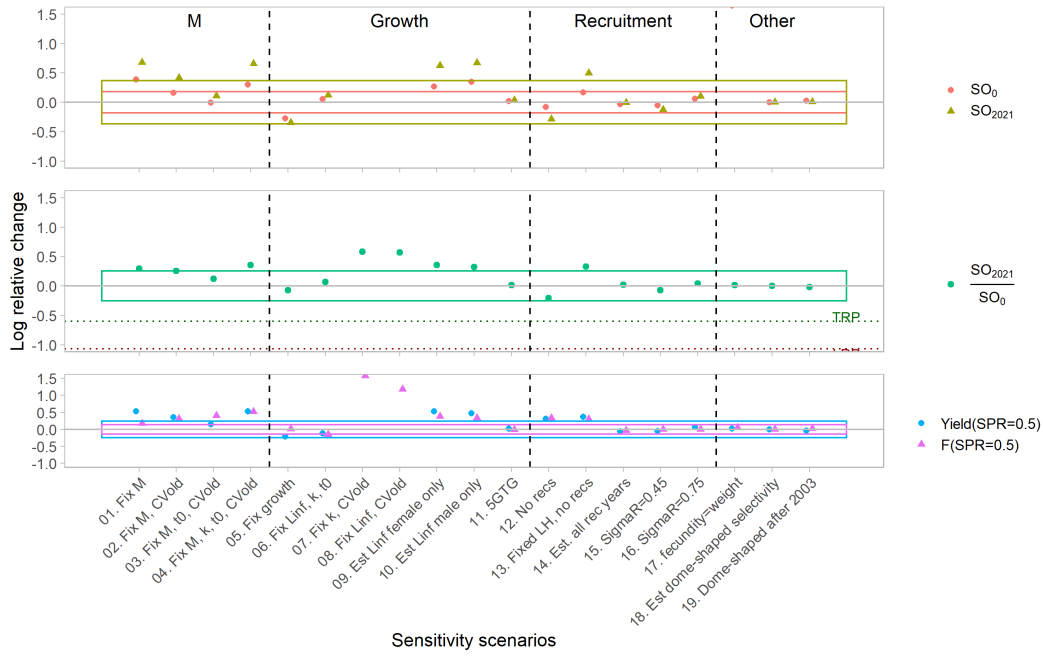


Figure 41: Log relative change ($\log((\text{Model_sensi}-\text{Model_ref})/\text{Model_ref})$) in model specification scenario for 5 derived quantities. Colored boxes indicate 95 percent confidence interval of the reference model.

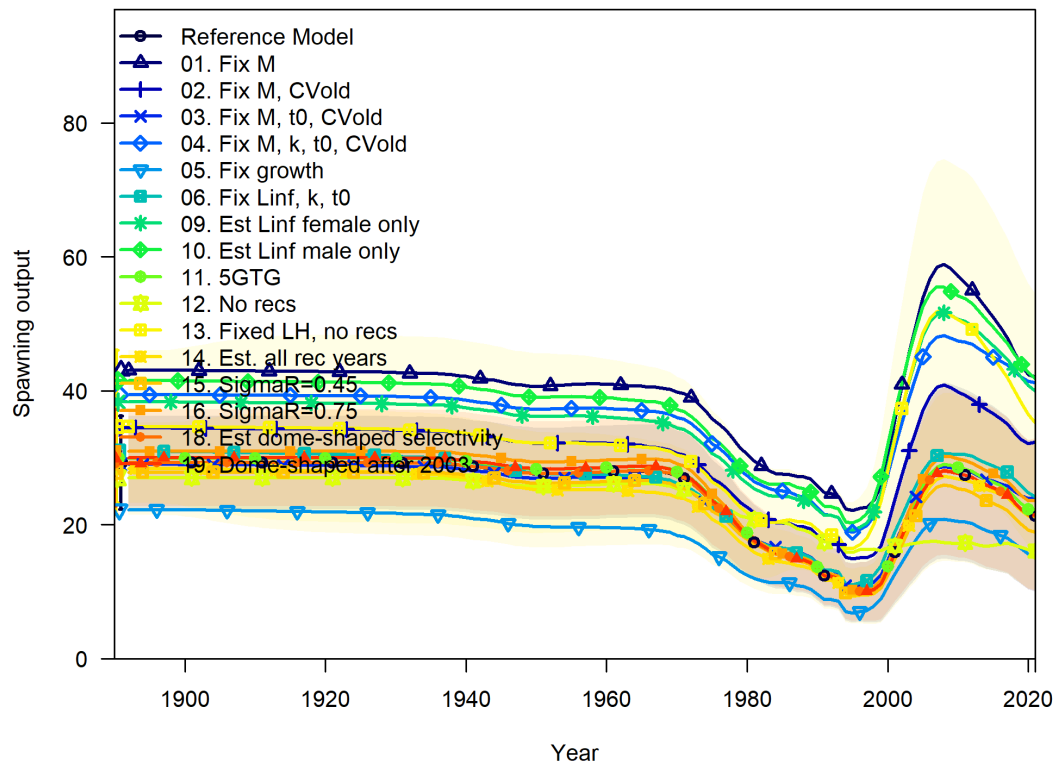


Figure 42: Spawning output (in millions of eggs) time series by model specification scenario compared to the reference model. Missing scenarios mean the spawning output was too large to show.

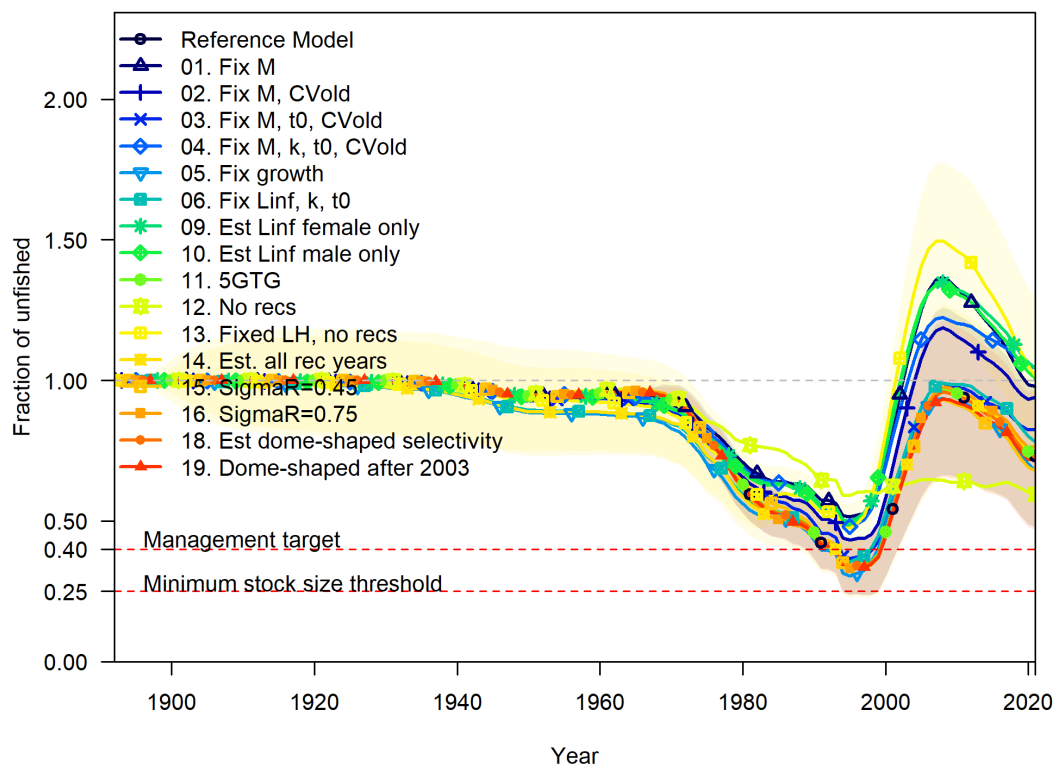


Figure 43: Relative spawning output time series by model specification scenario compared to the reference model.

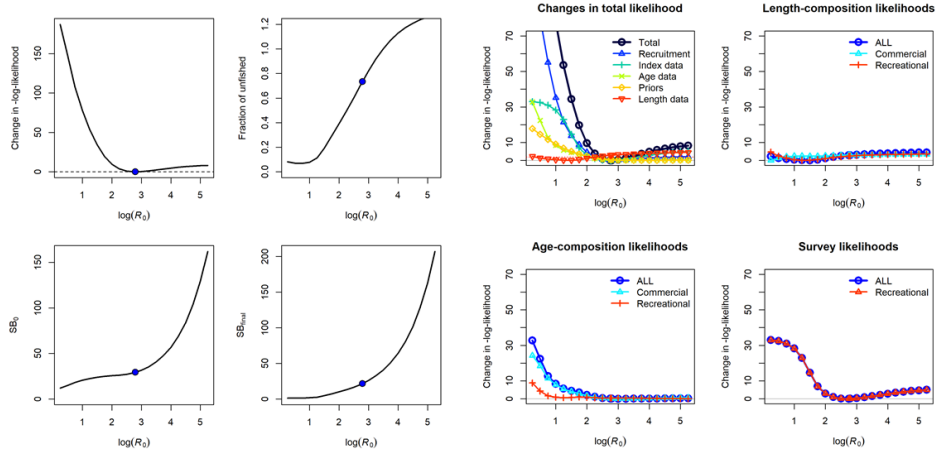


Figure 44: $\ln(R_0)$ likelihood profile (change in the negative log-likelihood across a range of $\ln(R_0)$ values) and derived quantities (left four figures) and likelihood component contributions (right three figures). Red line in the top left most figure indicates the significance level in likelihood difference.

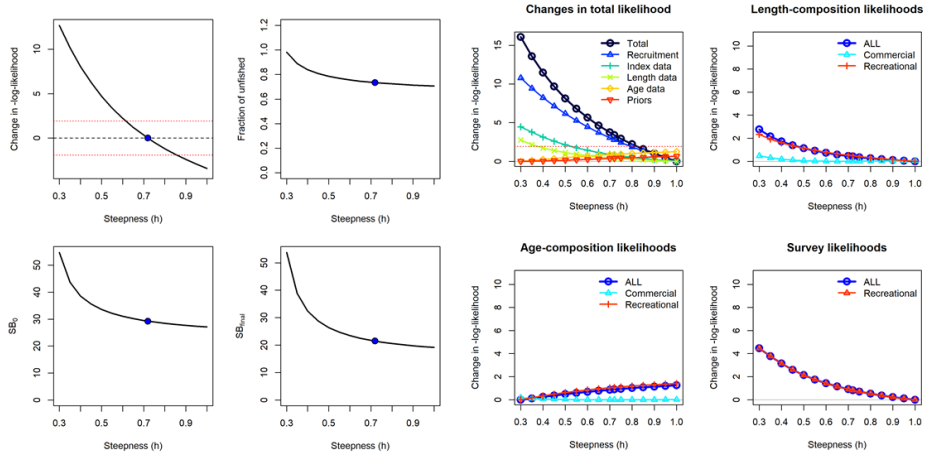


Figure 45: Steepness likelihood profile (change in the negative log-likelihood across a range of steepness values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

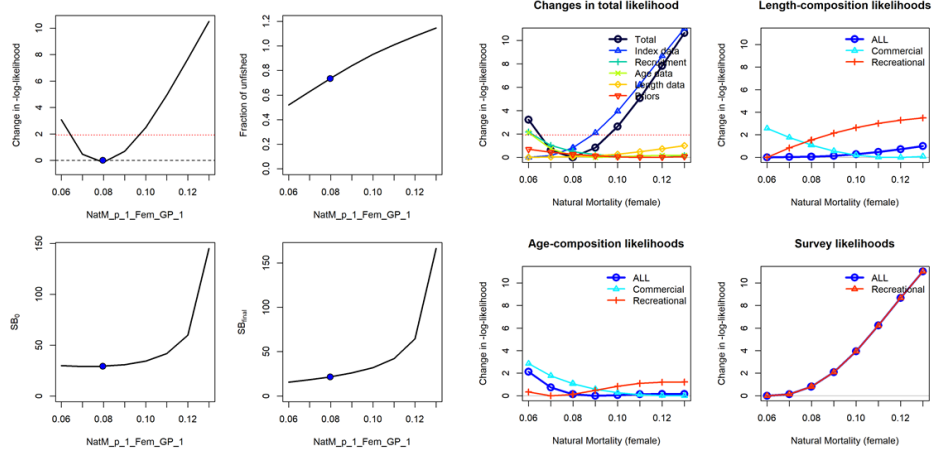


Figure 46: Female M likelihood profile (change in the negative log-likelihood across a range of M values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

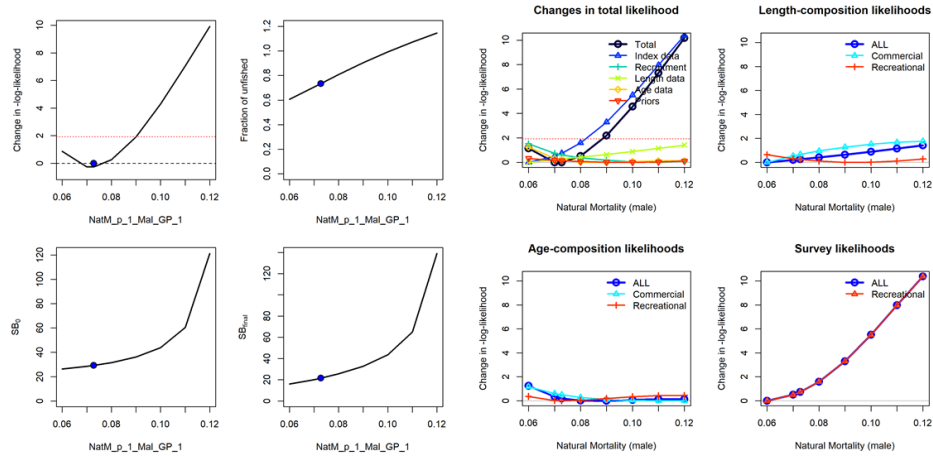


Figure 47: Male M likelihood profile (change in the negative log-likelihood across a range of M values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

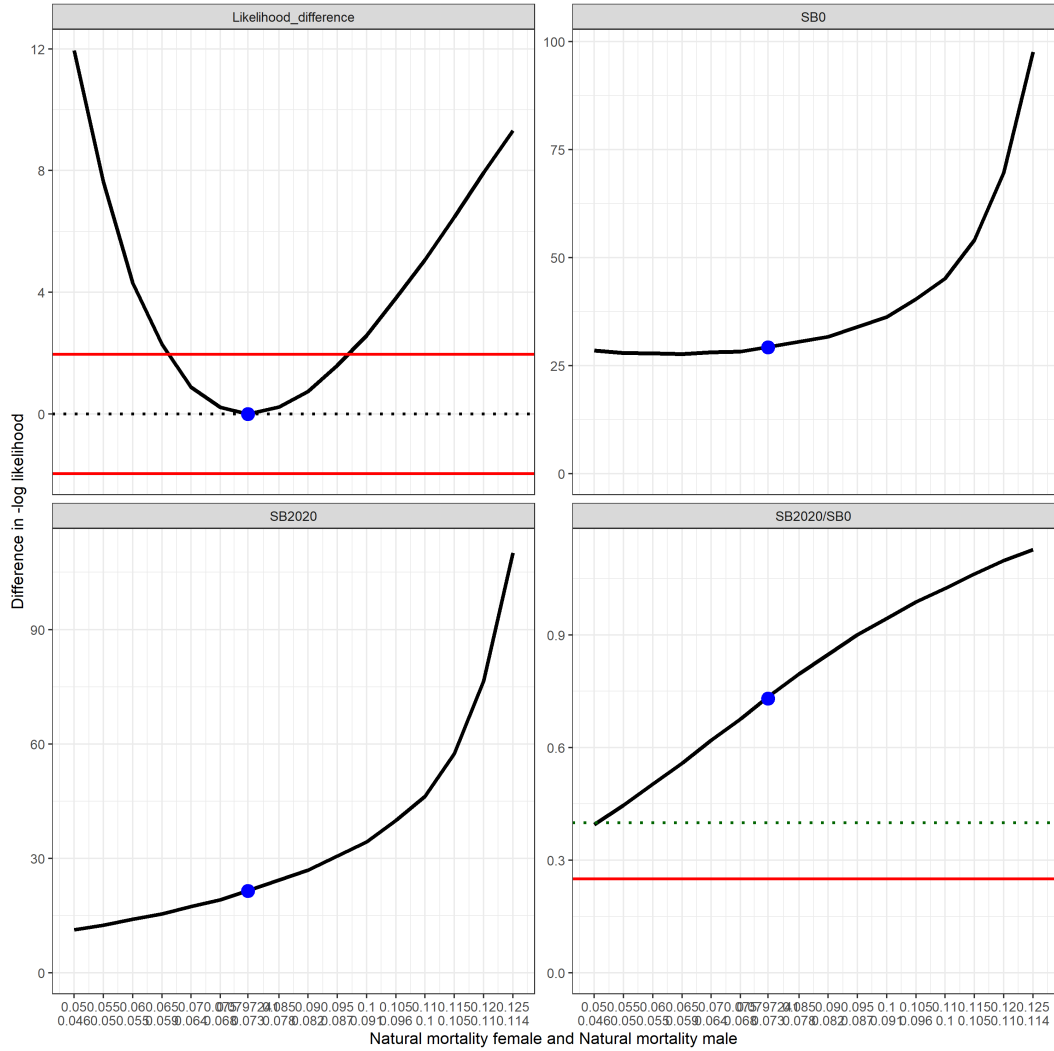


Figure 48: Female and male M multi-parameter likelihood profile and derived quantities. Red lines in the top left figure indicate significantly similar values compared to the reference model. Broken and solid lines in the bottom right figure indicate target and limit reference points, respectively.

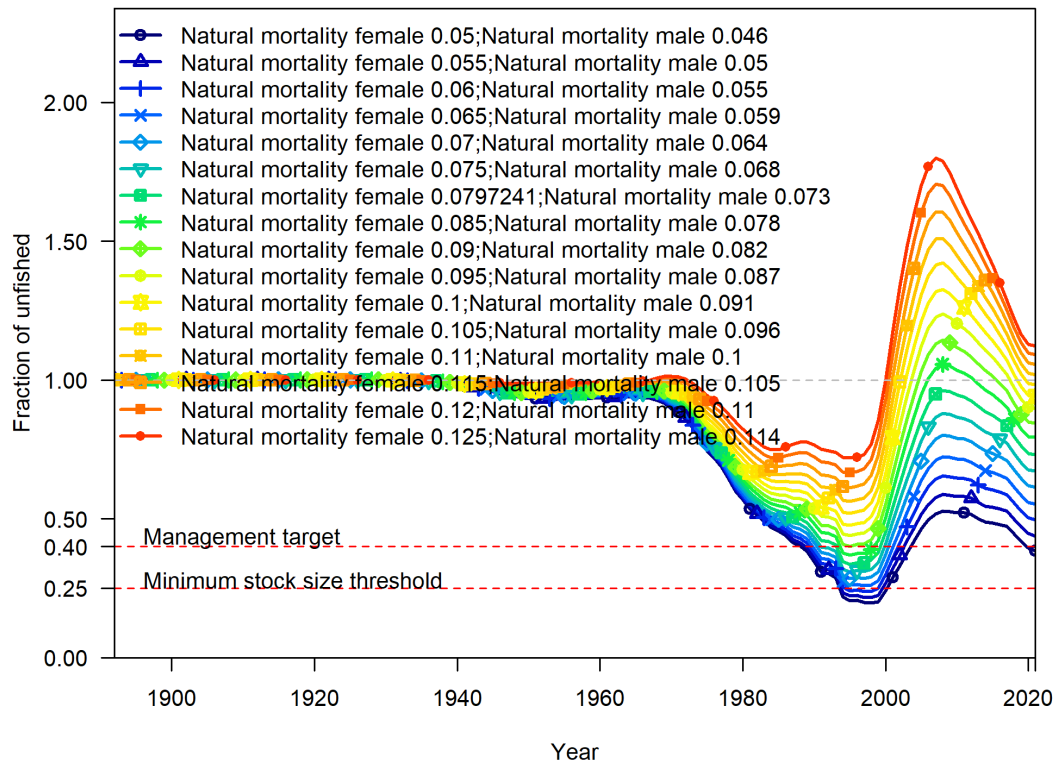


Figure 49: Relative stock status time series from the female and male M multi-parameter likelihood profile. Broken lines indicate target and limit reference points.

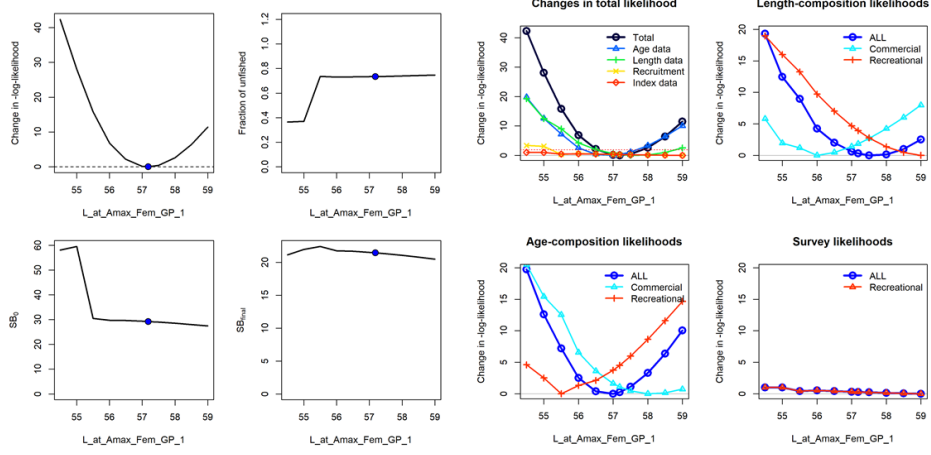


Figure 50: Female L_{inf} likelihood profile (change in the negative log-likelihood across a range of L_{inf} values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

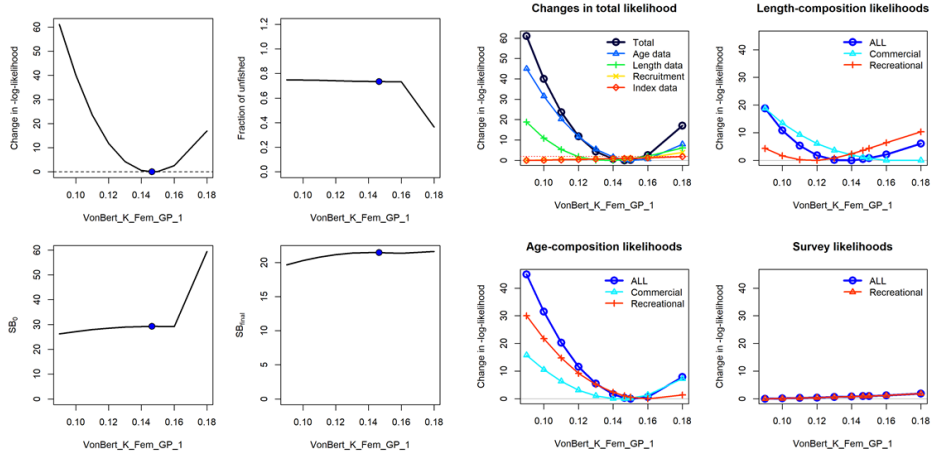


Figure 51: Female k likelihood profile (change in the negative log-likelihood across a range of k values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

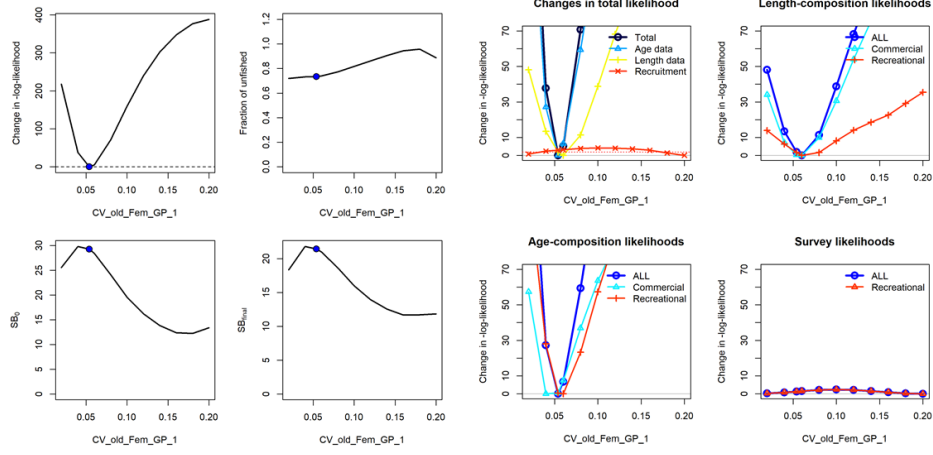


Figure 52: Female variability at maximum age likelihood profile (change in the negative log-likelihood across a range of CV at maximum age values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

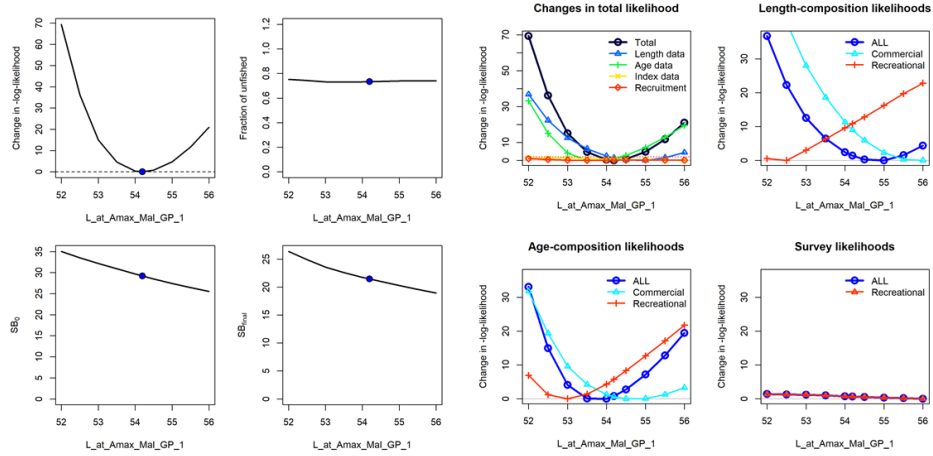


Figure 53: Male L_{inf} likelihood profile (change in the negative log-likelihood across a range of L_{inf} values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

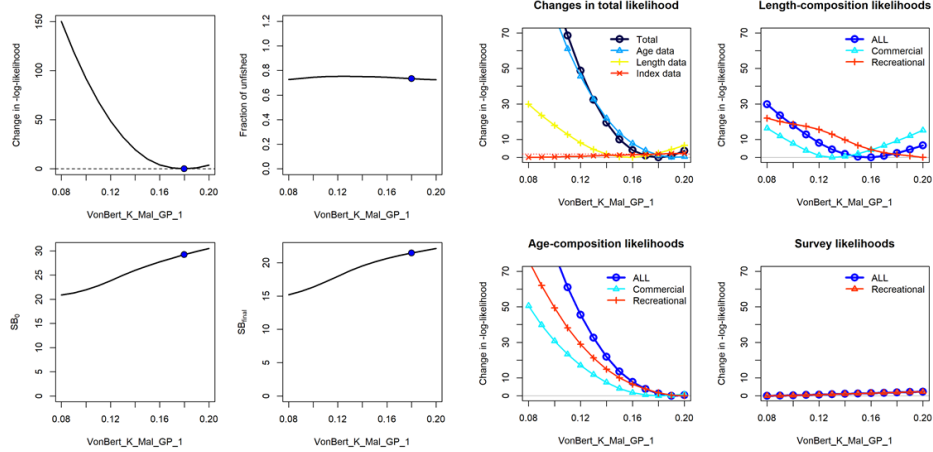


Figure 54: Male k likelihood profile (change in the negative log-likelihood across a range of k values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

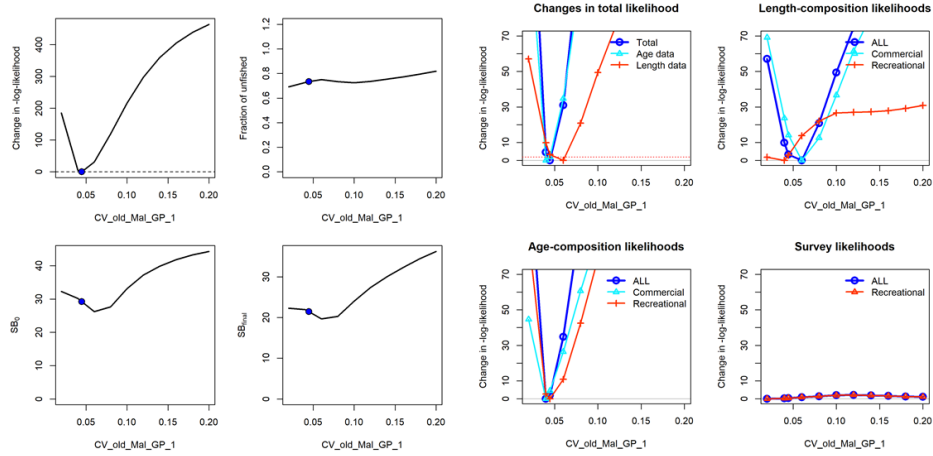


Figure 55: Male variability at maximum age likelihood profile (change in the negative log-likelihood across a range of CV at maximum age values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

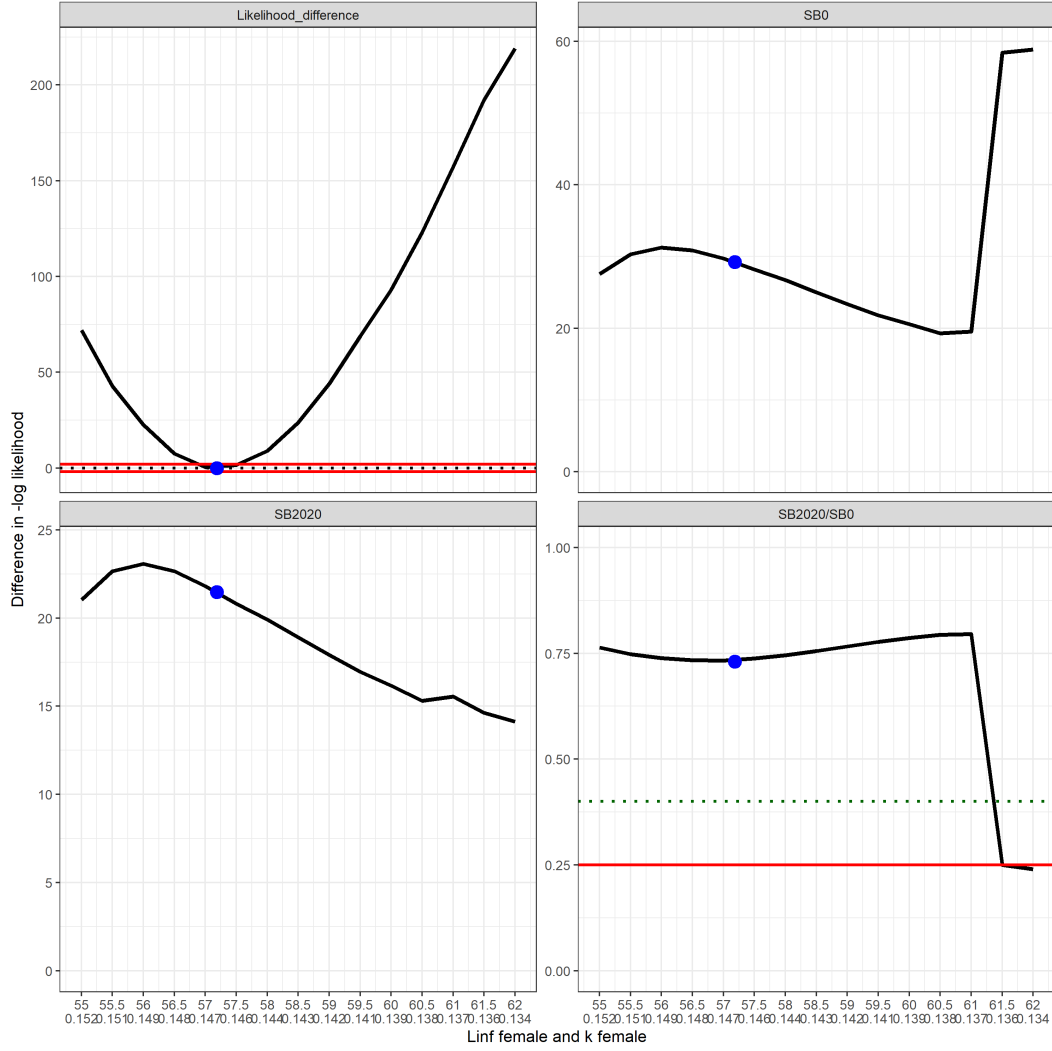


Figure 56: Female L_{inf} and k multi-parameter likelihood profile and derived quantities. Red lines in the top left figure indicate significantly similar values compared to the reference model. Broken and solid lines in the bottom right figure indicate target and limit reference points, respectively.

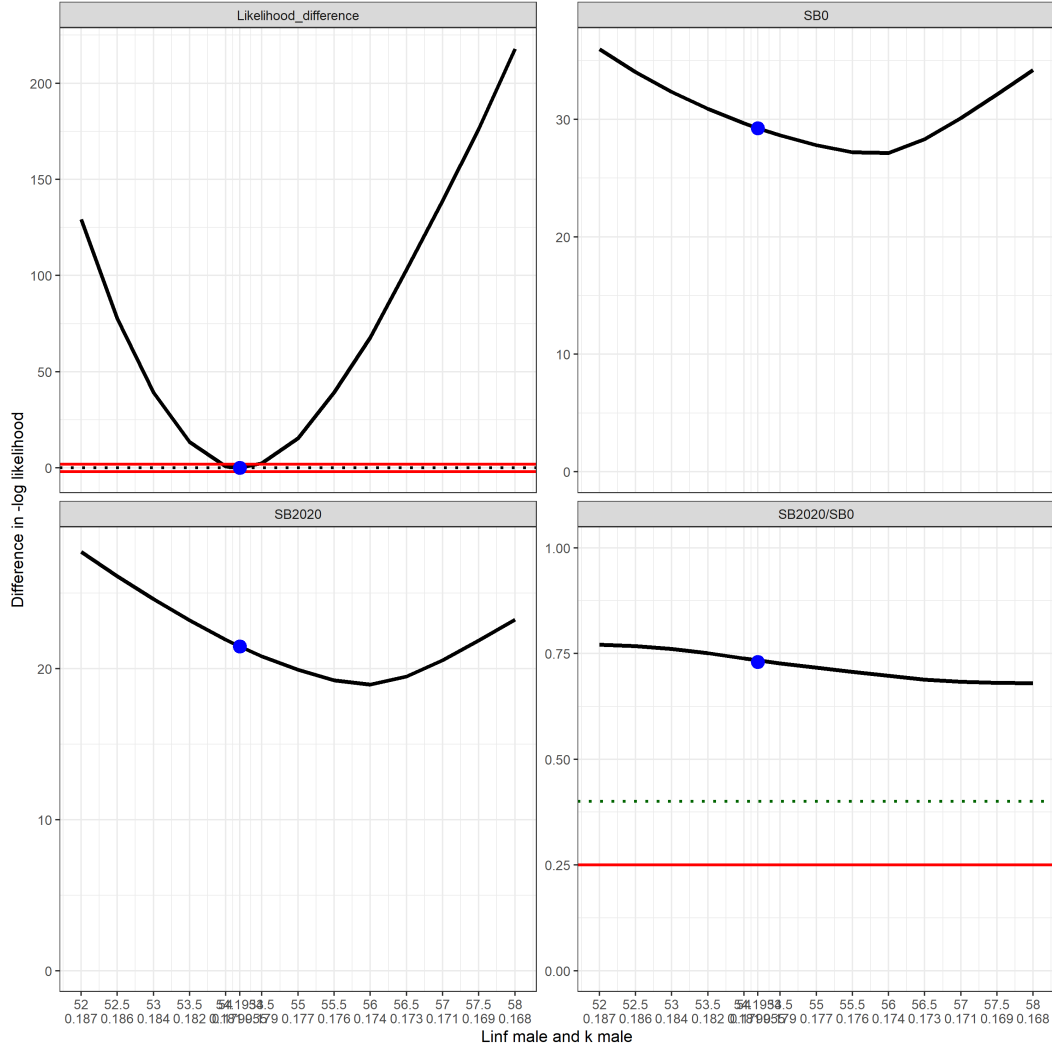


Figure 57: Male L_{inf} and k multi-parameter likelihood profile and derived quantities. Red lines in the top left figure indicate significantly similar values compared to the reference model. Broken and solid lines in the bottom right figure indicate target and limit reference points, respectively.

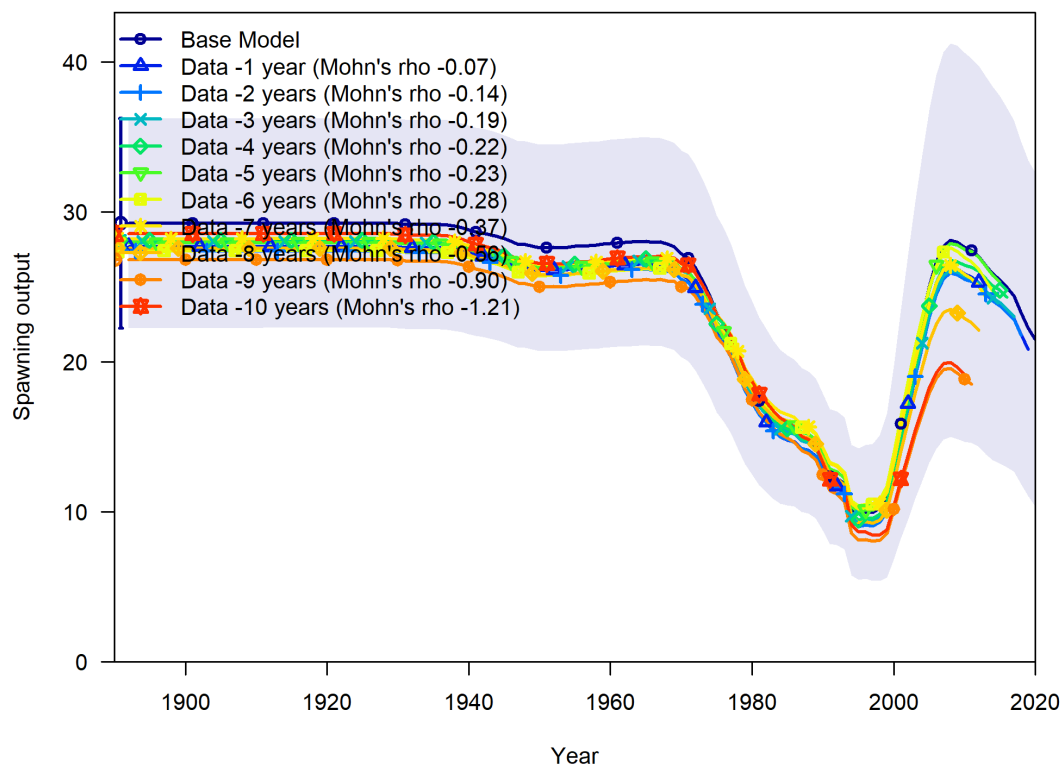


Figure 58: Change in the estimate of spawning output when the most recent 10 years of data area removed sequentially.

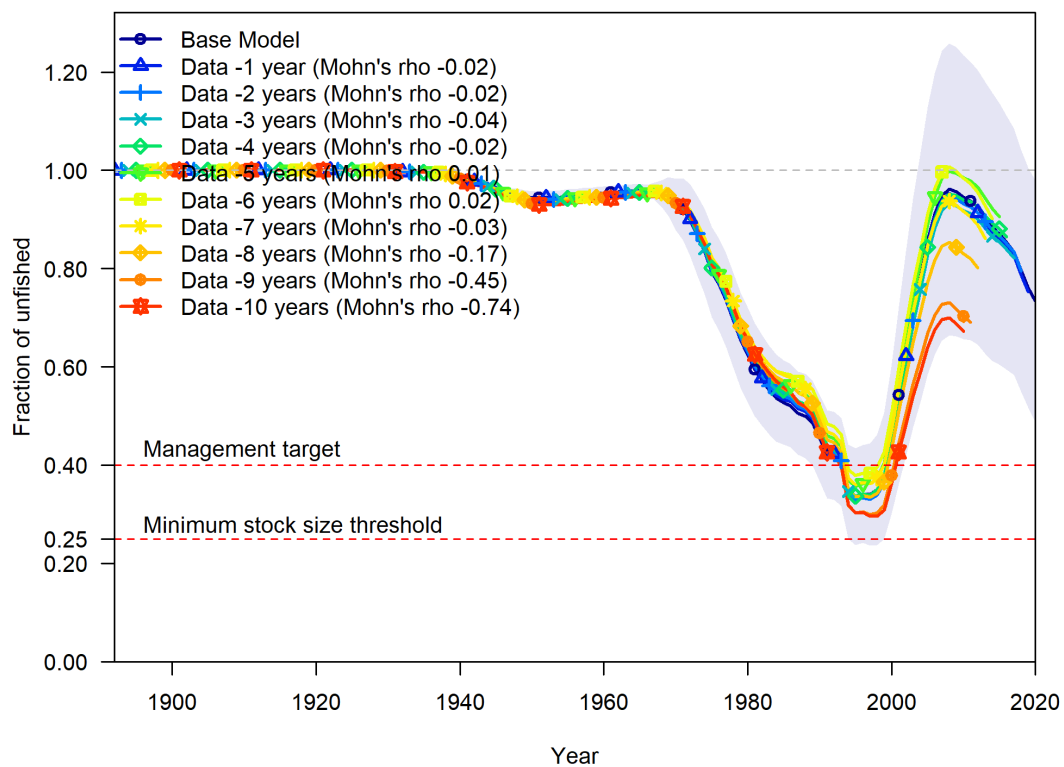


Figure 59: Change in the estimate of fraction unfished when the most recent 10 years of data area removed sequentially.

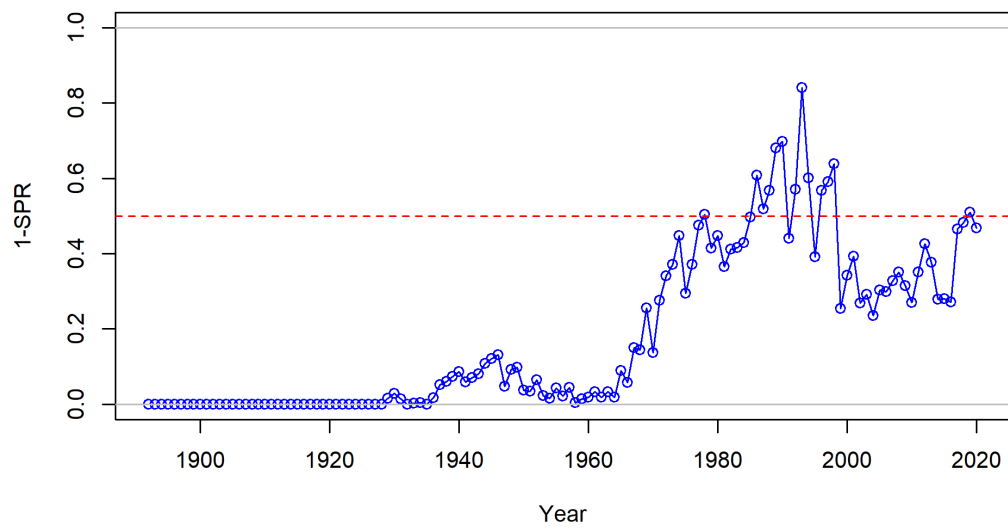


Figure 60: Estimated 1 - relative spawning ratio (SPR) by year.

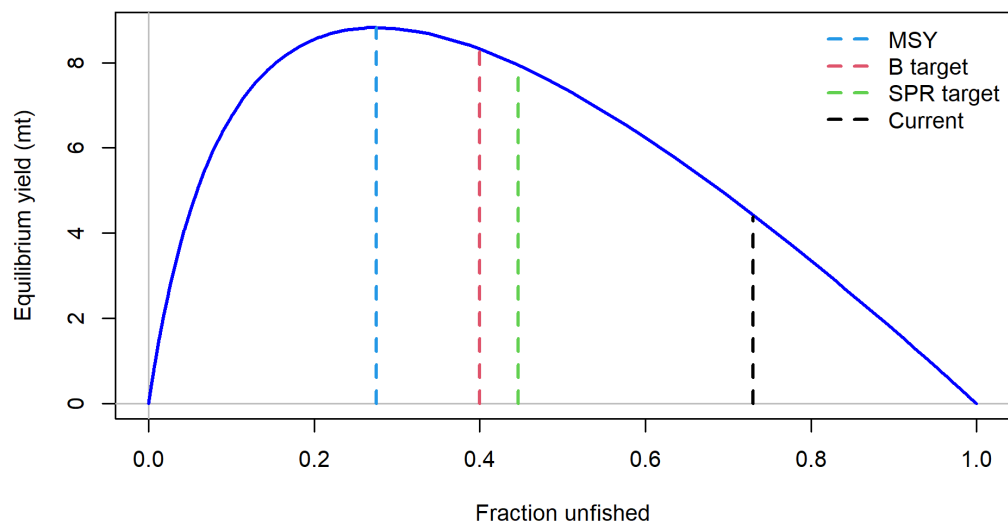


Figure 61: Equilibrium yield curve for the reference model. Values are based on the 2020 fishery selectivities and with steepness fixed at 0.72.

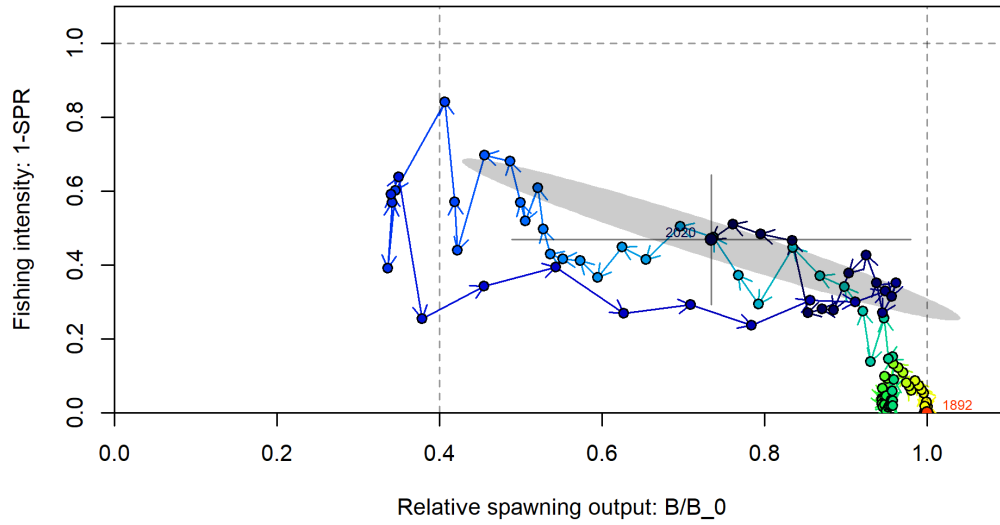


Figure 62: Phase plot of the relative biomass (also referred to as fraction unfished) versus the SPR ratio where each point represents the biomass ratio at the start of the year and the relative fishing intensity in that same year. Lines through the final point show the 95 percent intervals based on the asymptotic uncertainty for each dimension. The shaded ellipse is a 95 percent region which accounts for the estimated correlations between the biomass ratio and SPR ratio.

8 Appendix A: Detailed Fit to Length Composition Data

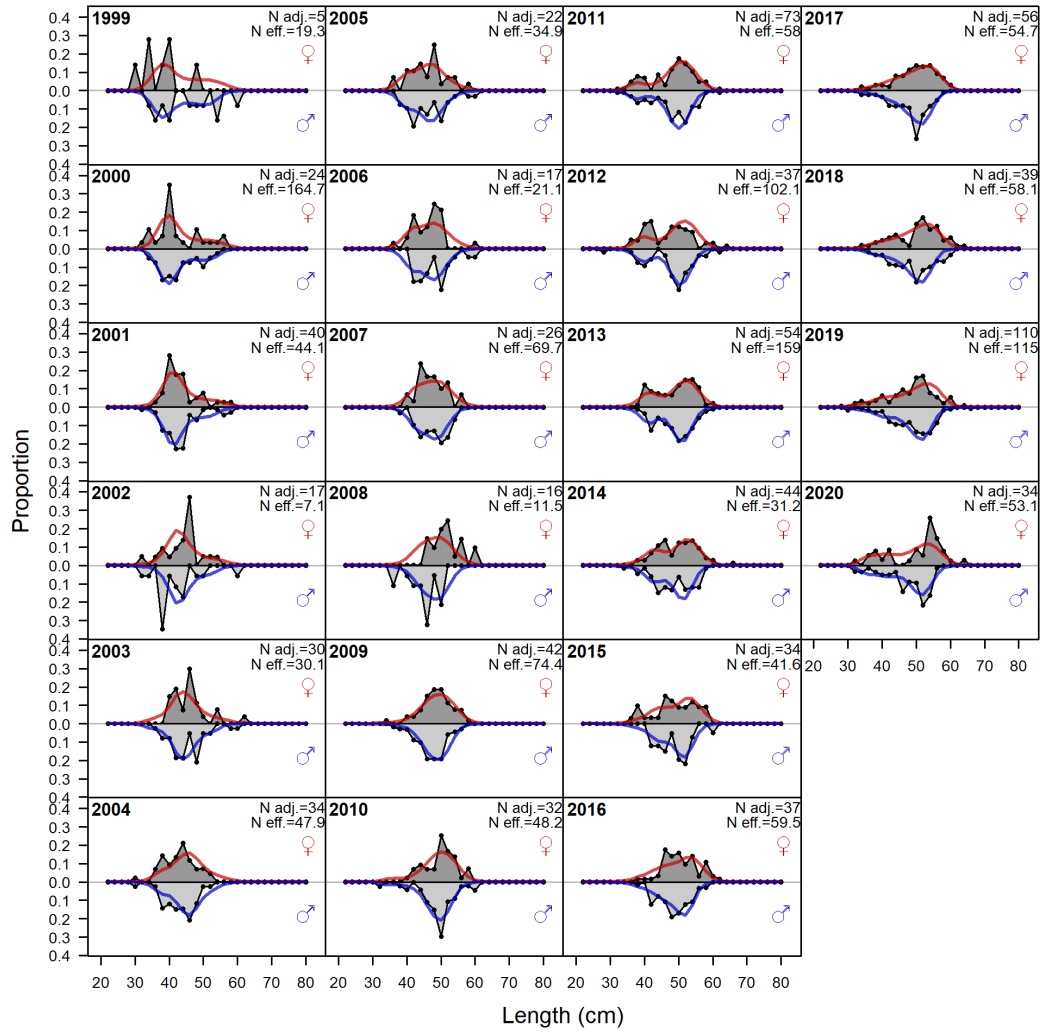


Figure 63: Length comps, whole catch, Commercial. 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method..

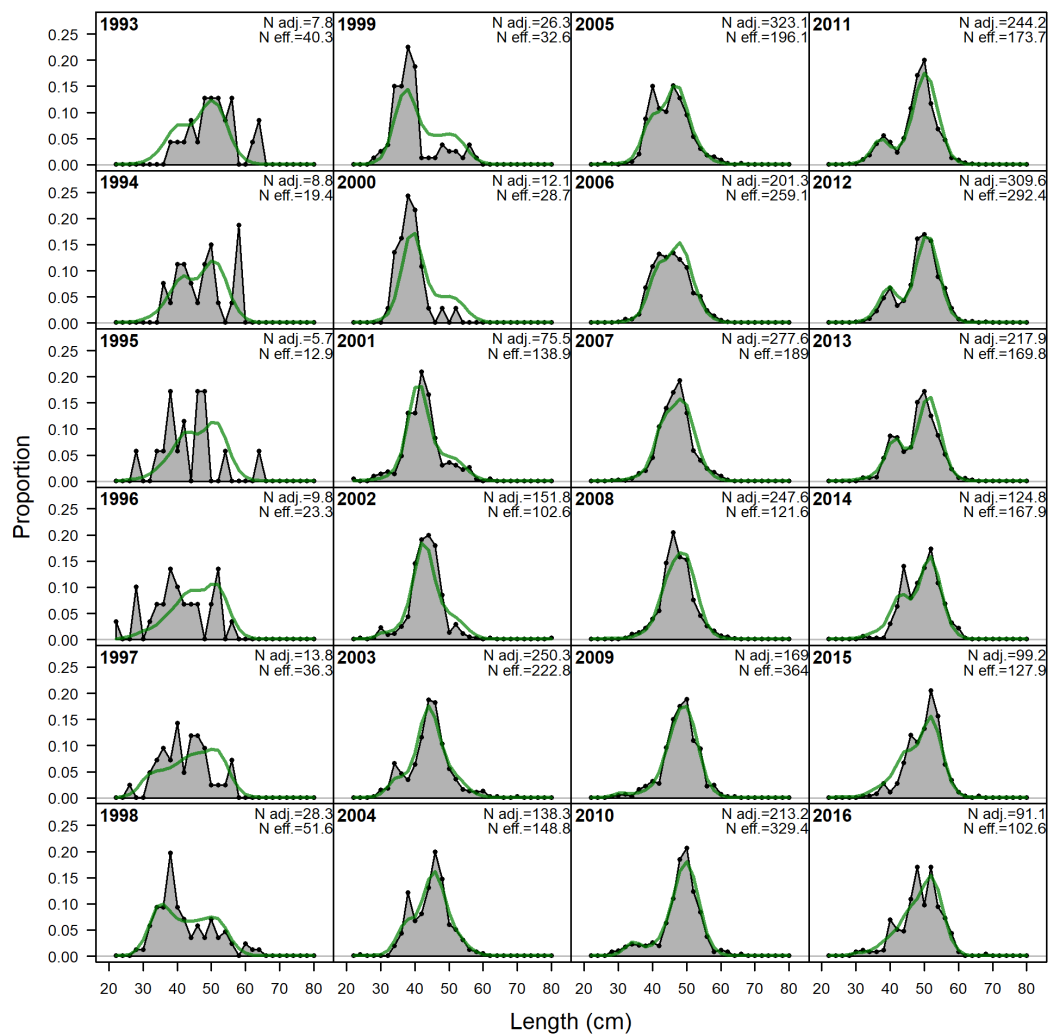
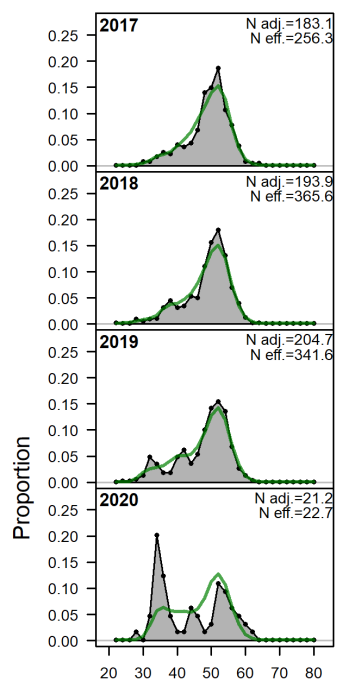


Figure 64: Length comps, whole catch, Recreational (plot 1 of 2): 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method..



Length (cm)

Figure 65: Length comps, whole catch, Recreational (plot 2 of 2).

9 Appendix B: Fit to Conditional-Age-at-Length Composition Data

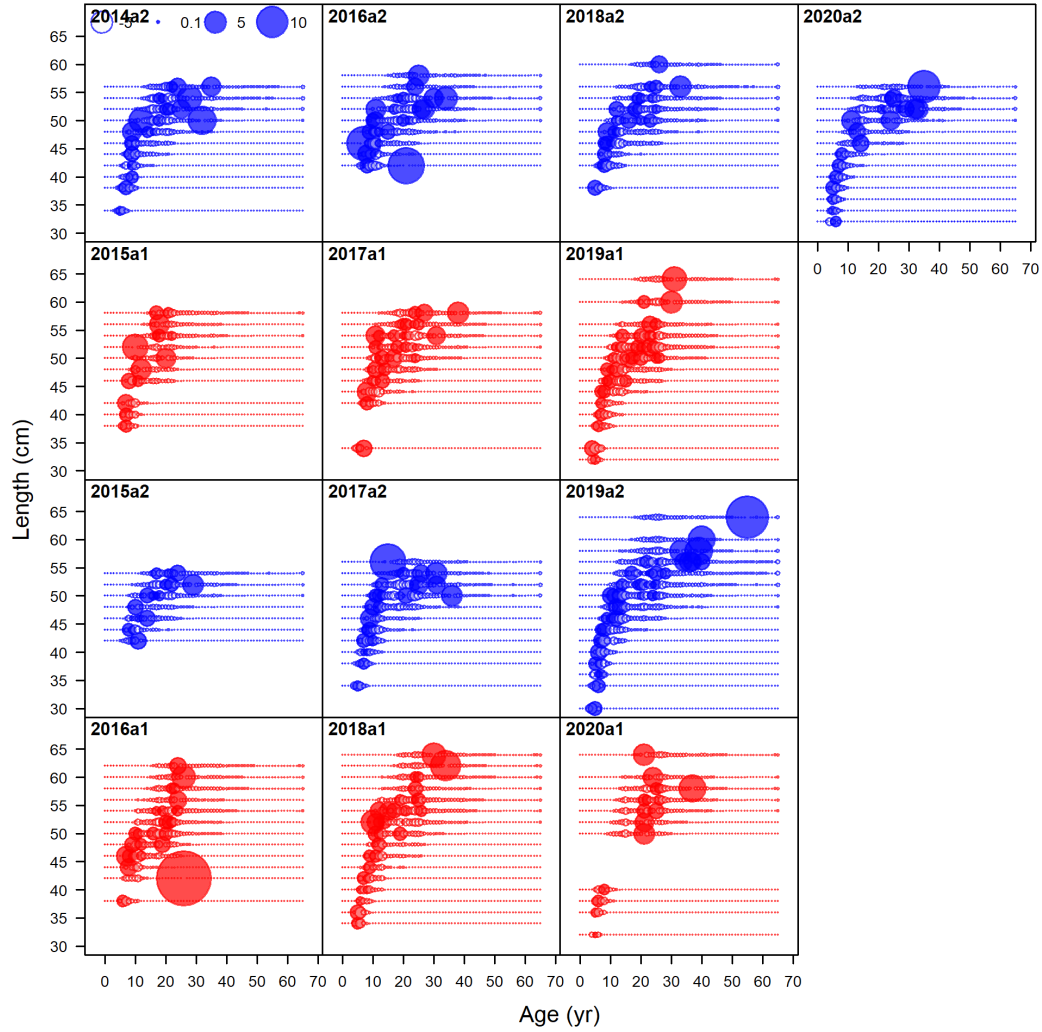


Figure 66: Pearson residuals for the commercial fleet (max=30.56) (plot 1 of 4) (plot 2 of 4).

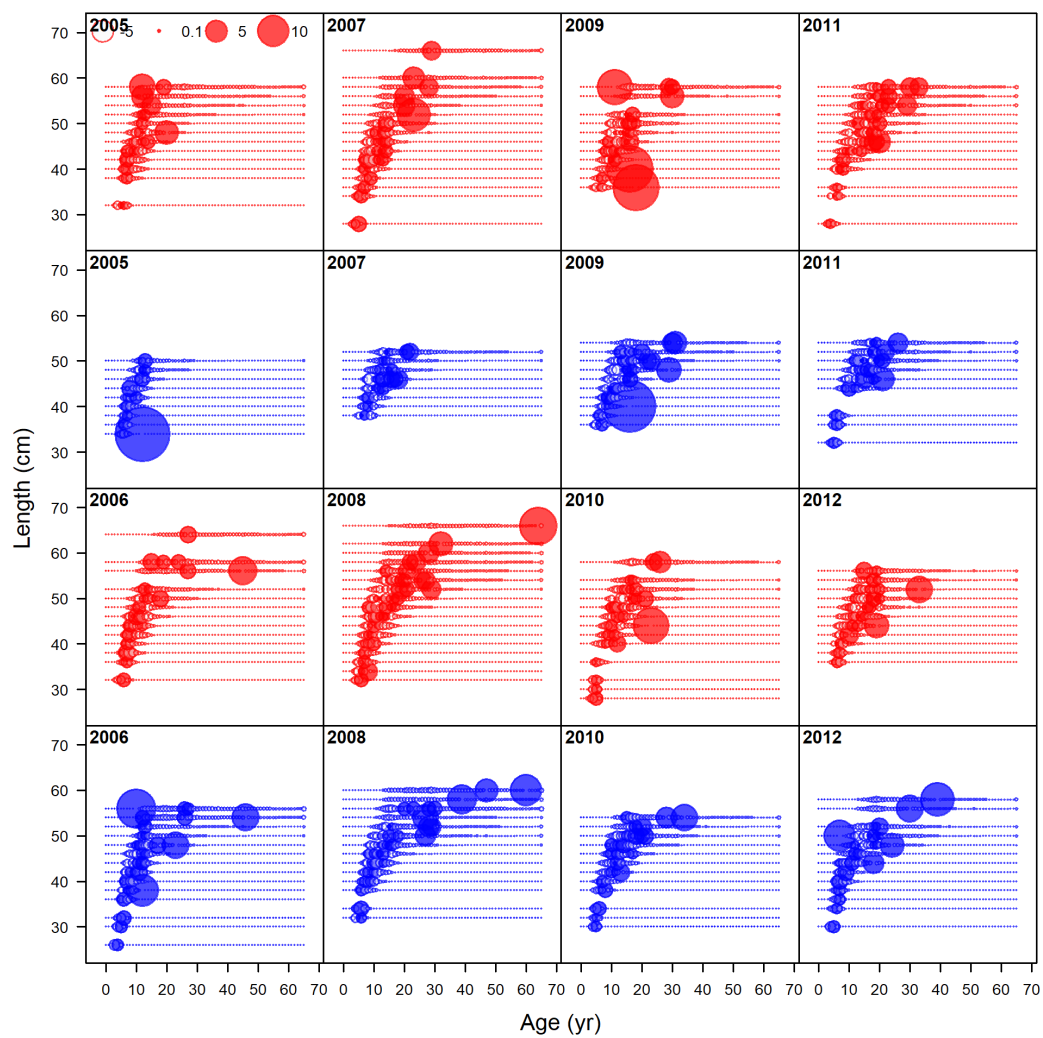


Figure 67: Pearson residuals for the recreational (max=30.63) (plot 1 of 3).

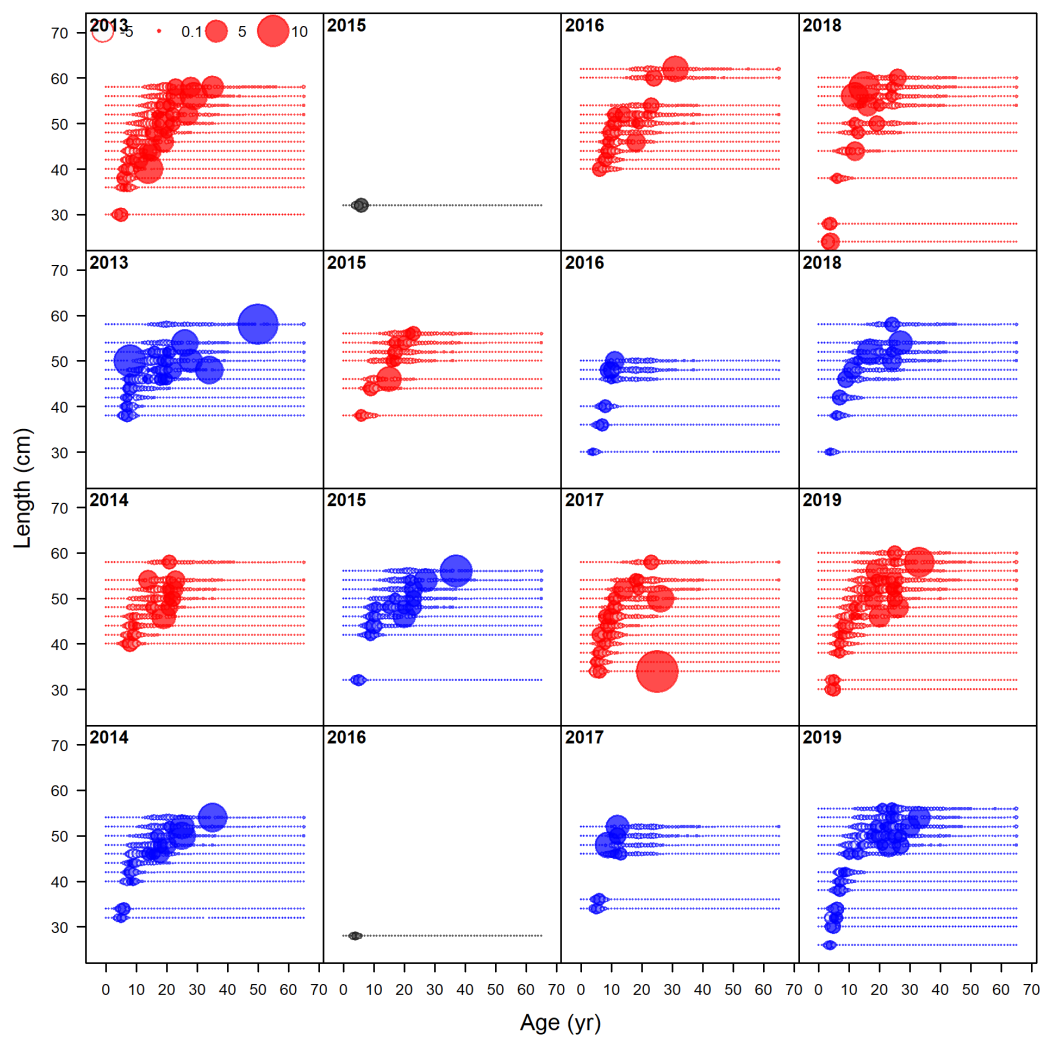


Figure 68: Pearson residuals for the recreational fleet (max=30.63) (plot 1 of 3) (plot 2 of 3).

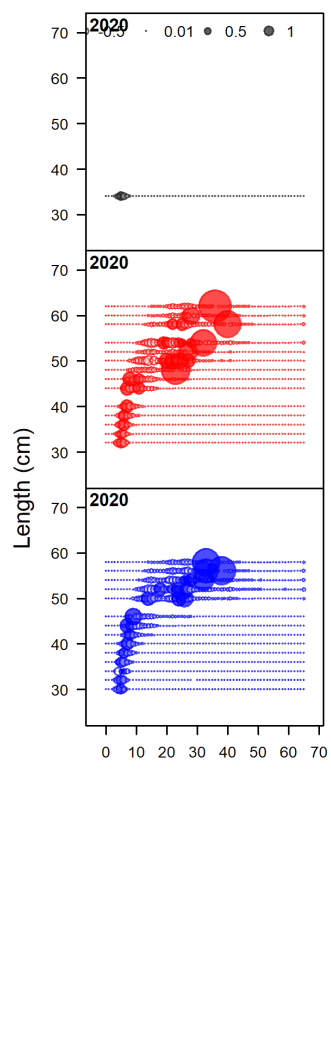


Figure 69: Pearson residuals for the recreational fleet (max=30.63) (plot 1 of 3) (plot 2 of 3) (plot 3 of 3).

10 Appendix C: Fit to Conditional-Age-at-Length Composition Data

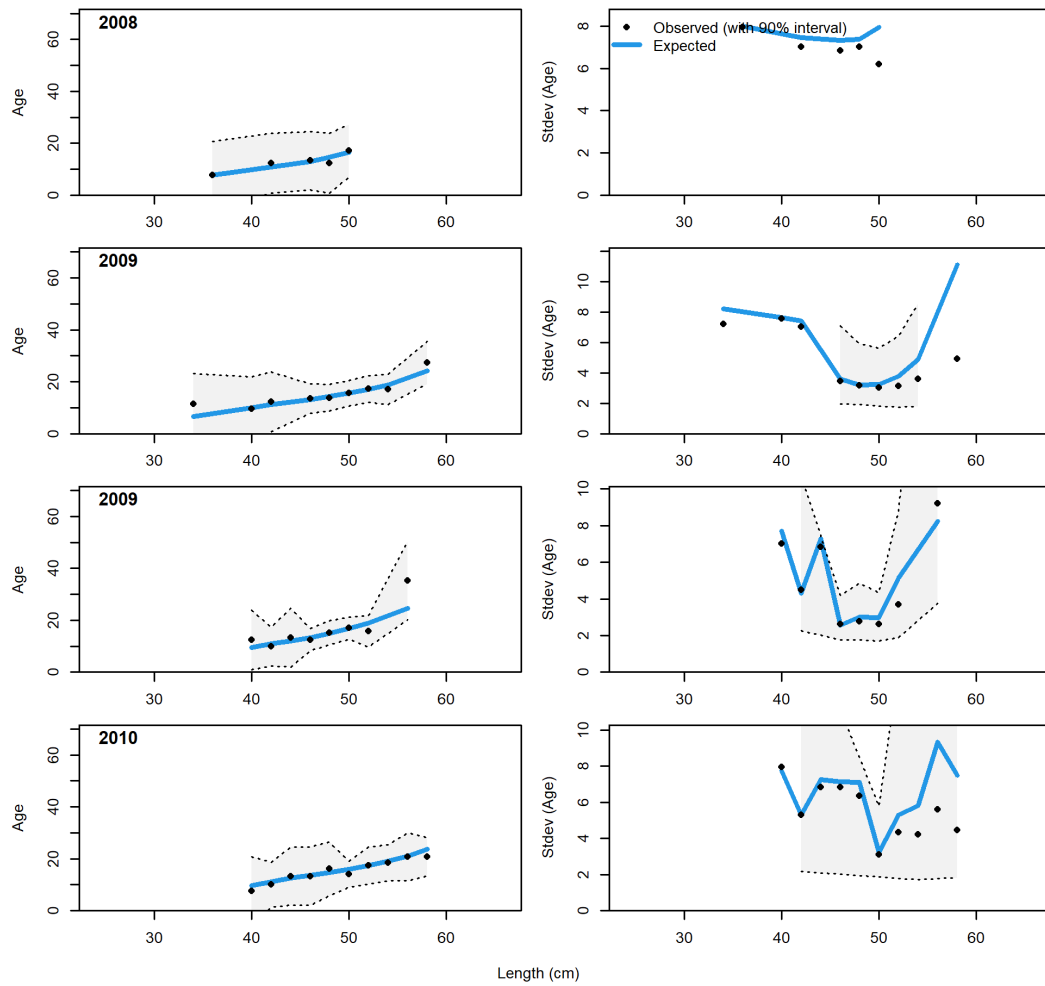


Figure 70: Commercial conditional AAL plot (plot 1 of 8) showing mean age (left panel) and standard deviation (right panel). Shaded areas are 90 percent CIs.

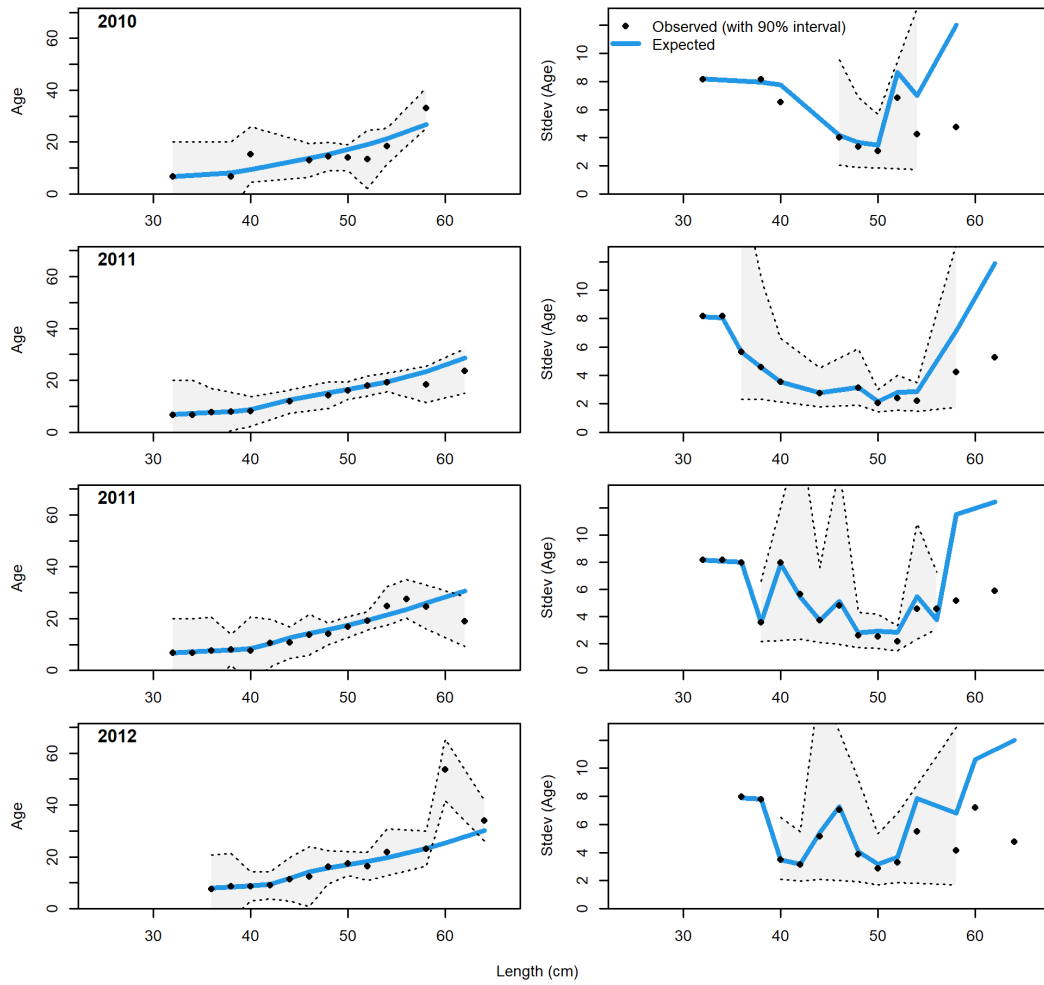


Figure 71: Commerical conditional AAL plot (plot 2 of 8).

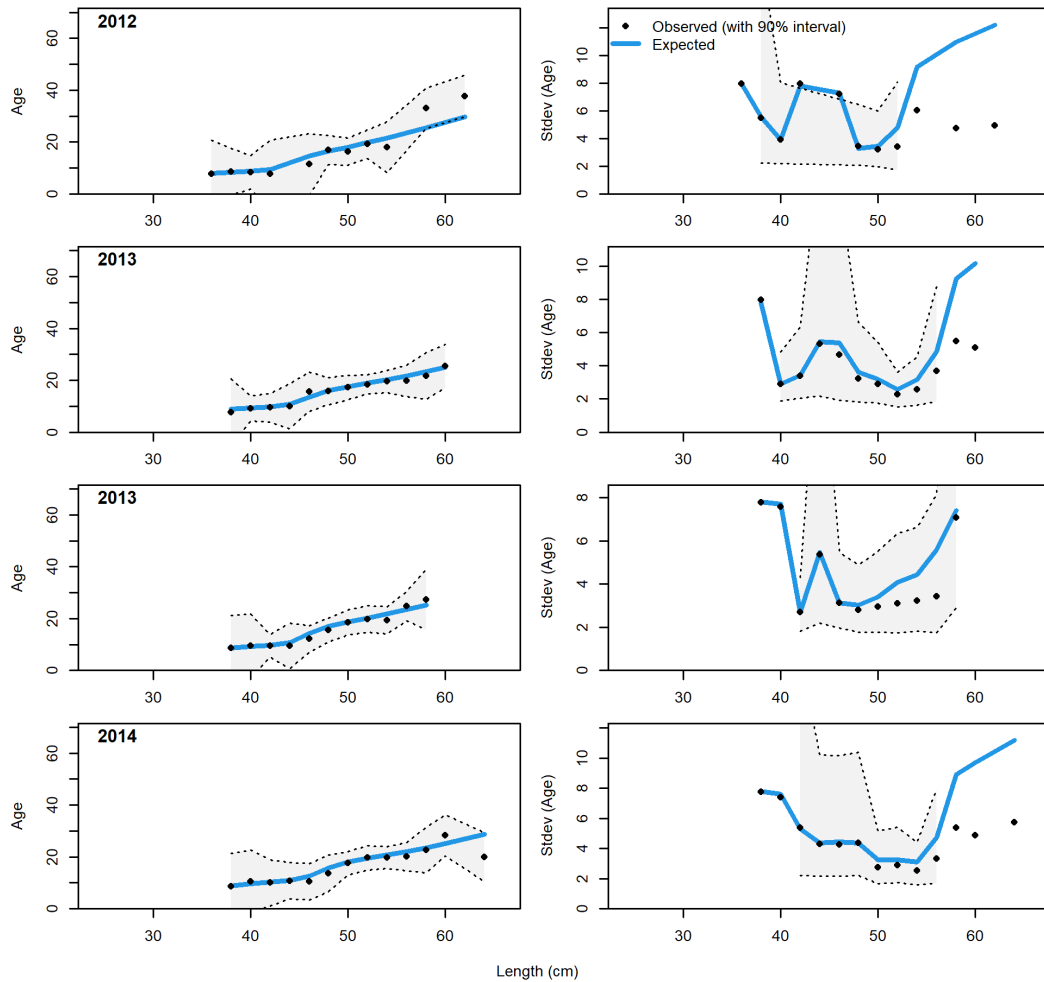


Figure 72: Commerical conditional AAL plot (plot 3 of 8).

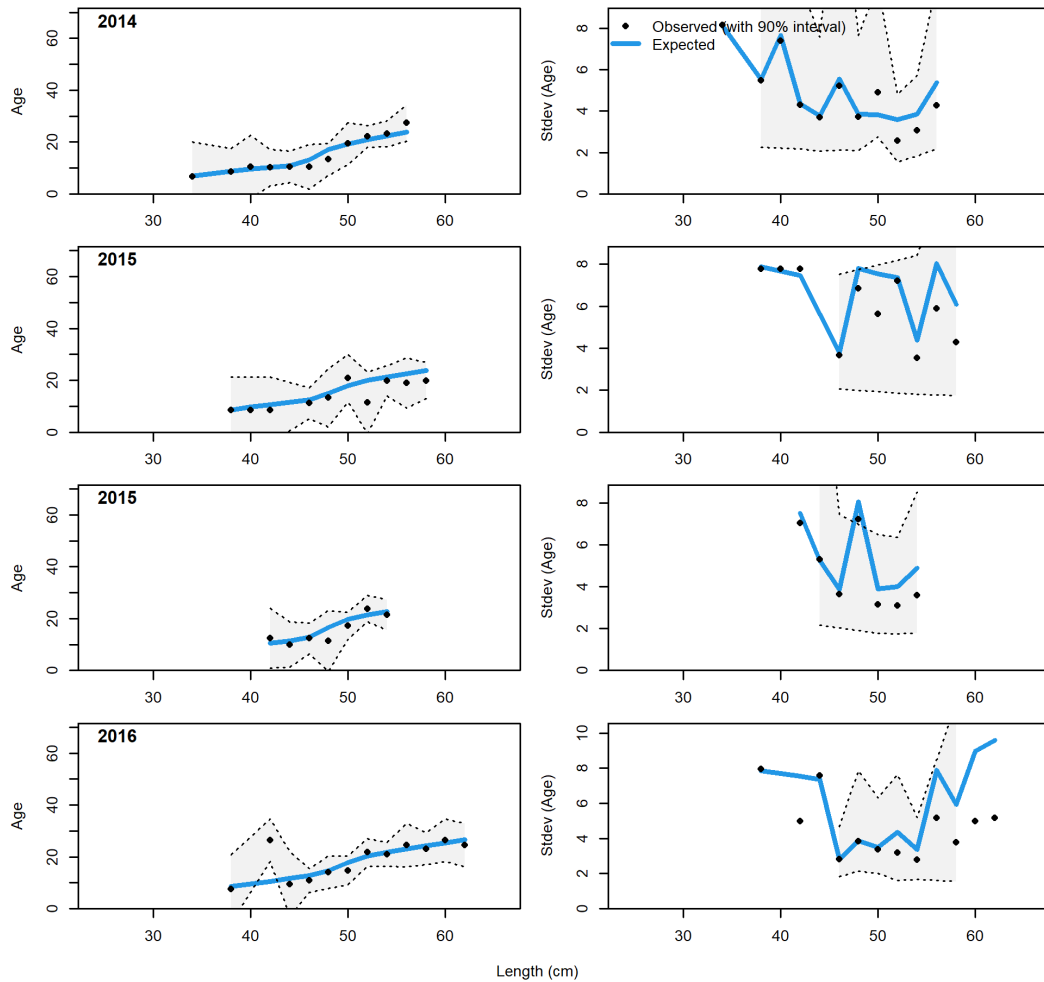


Figure 73: Commerical conditional AAL plot (plot 4 of 8).

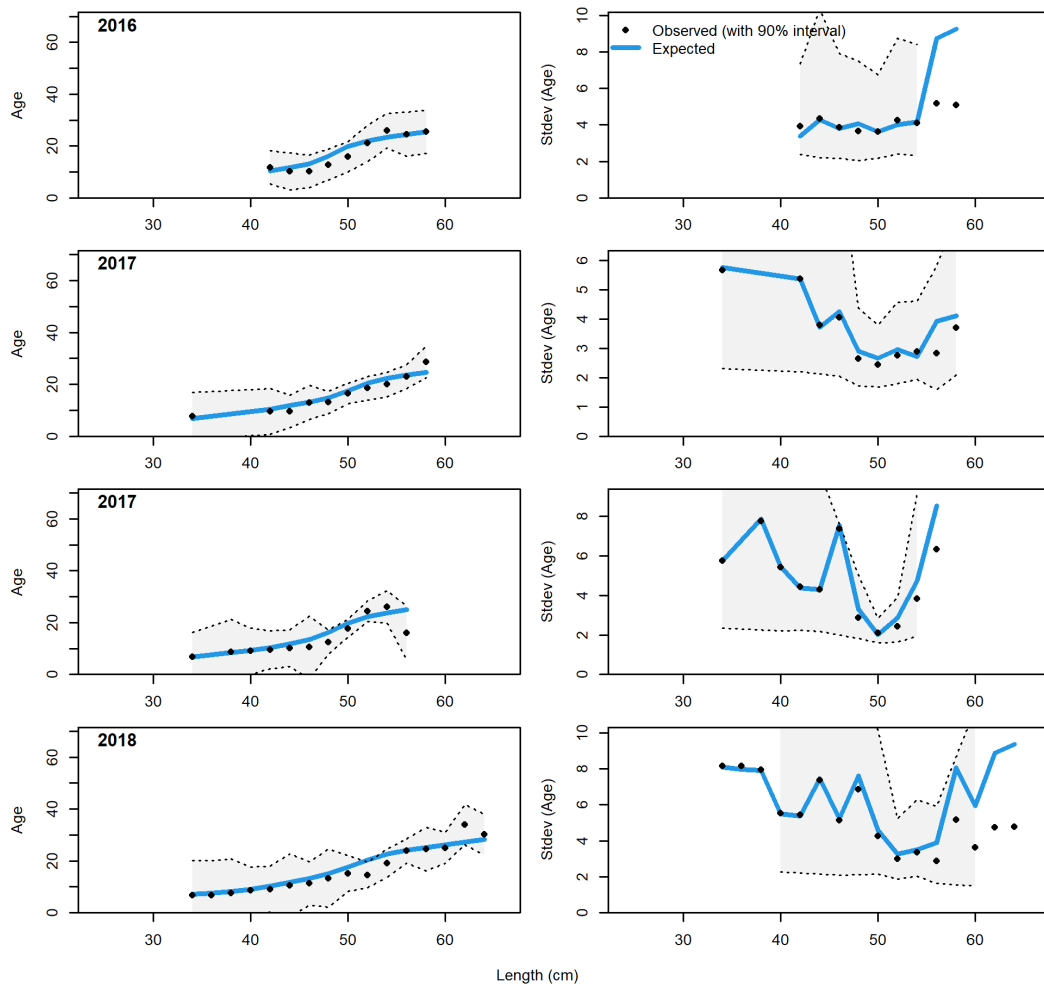


Figure 74: Commerical conditional AAL plot (plot 5 of 8).

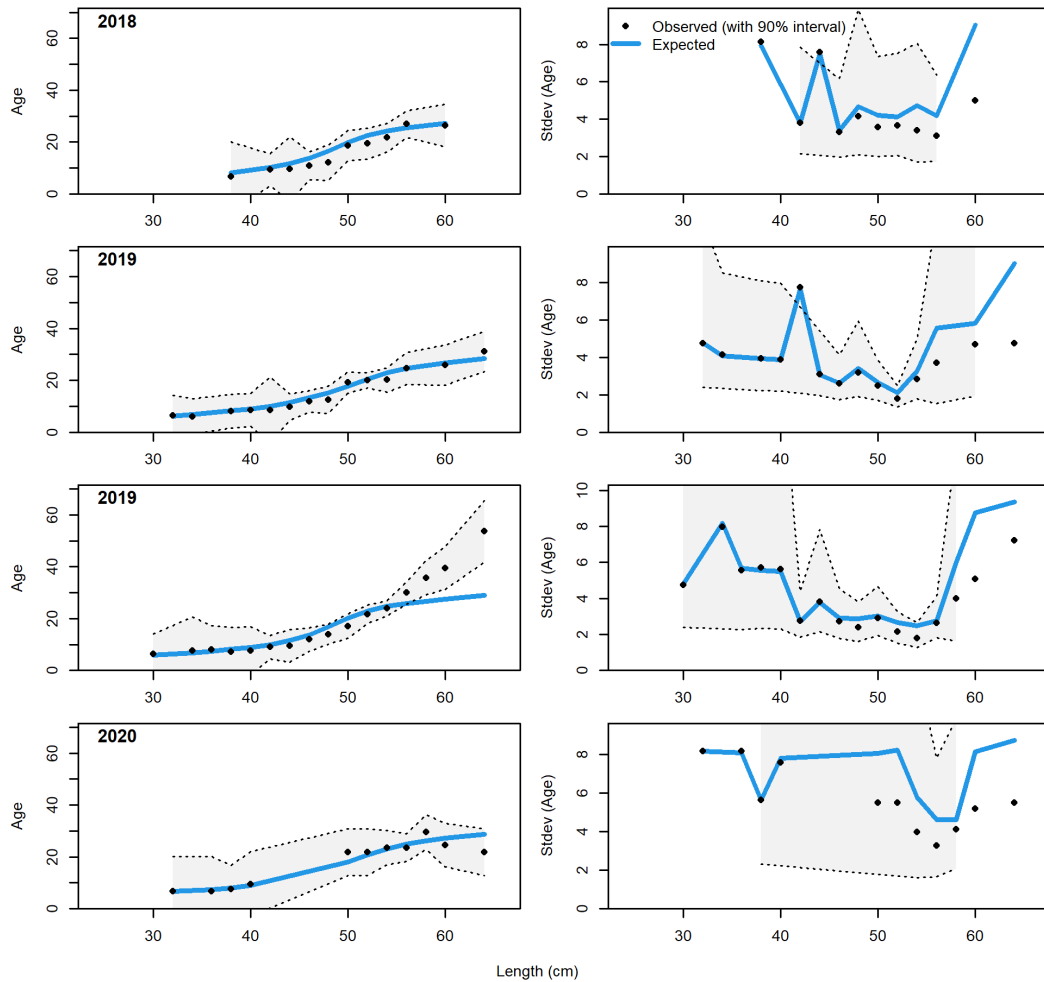


Figure 75: Commerical conditional AAL plot (plot 6 of 8).

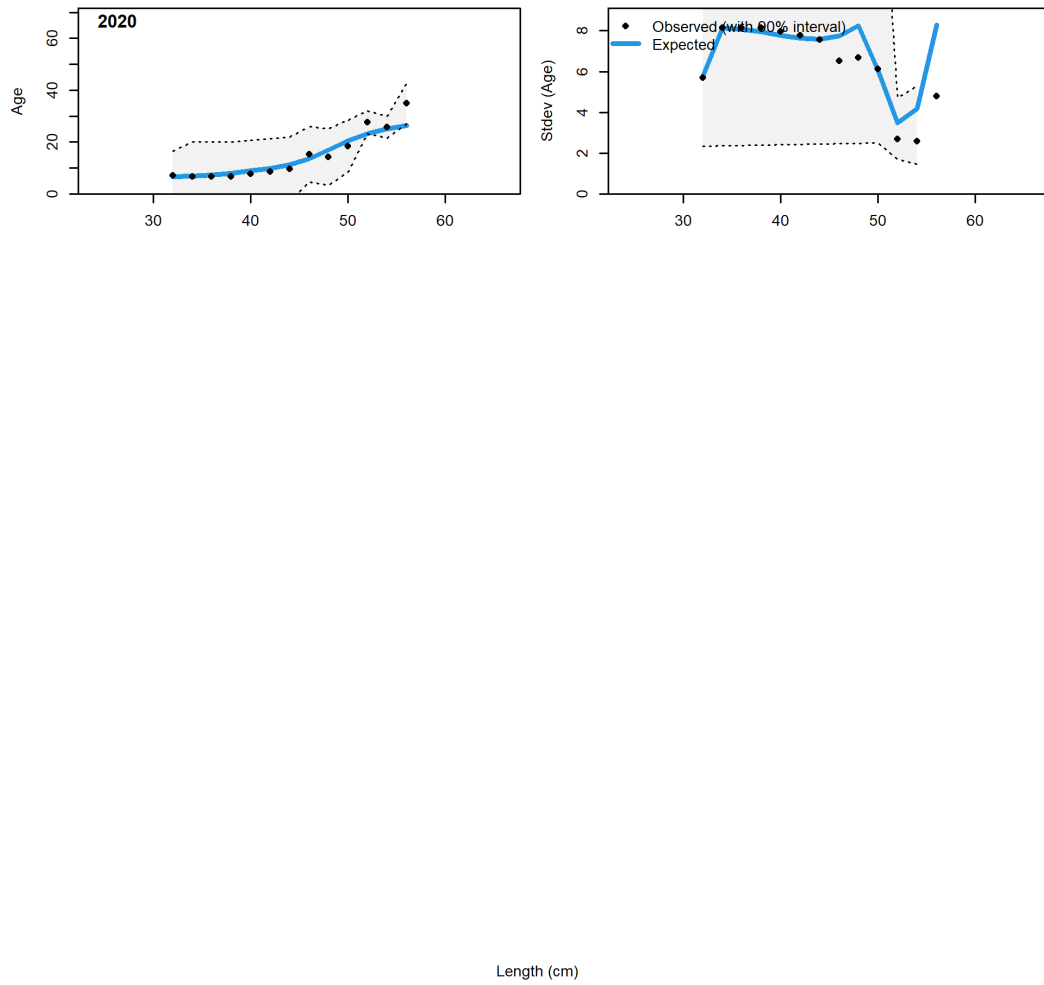


Figure 76: Commerical conditional AAL plot (plot 7 of 8).

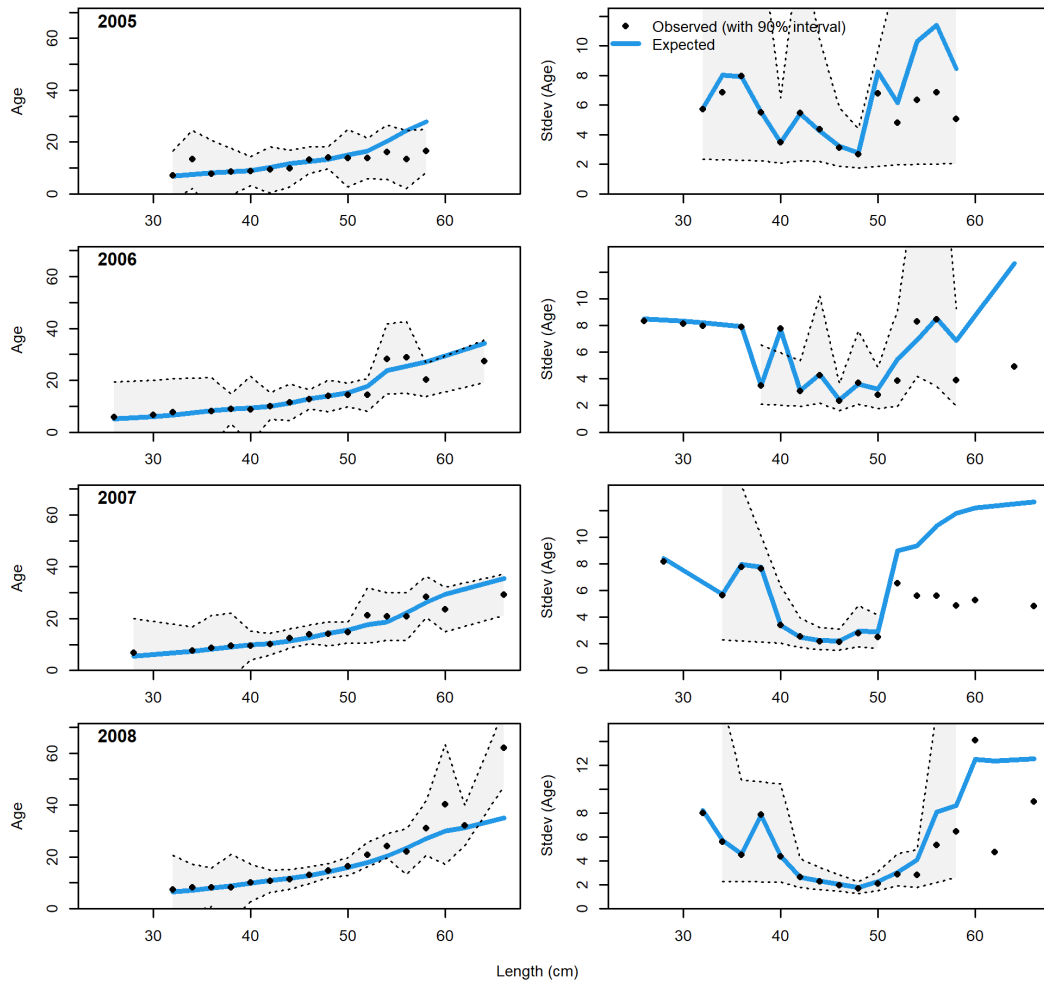


Figure 77: Commerical conditional AAL plot (plot 8 of 8).

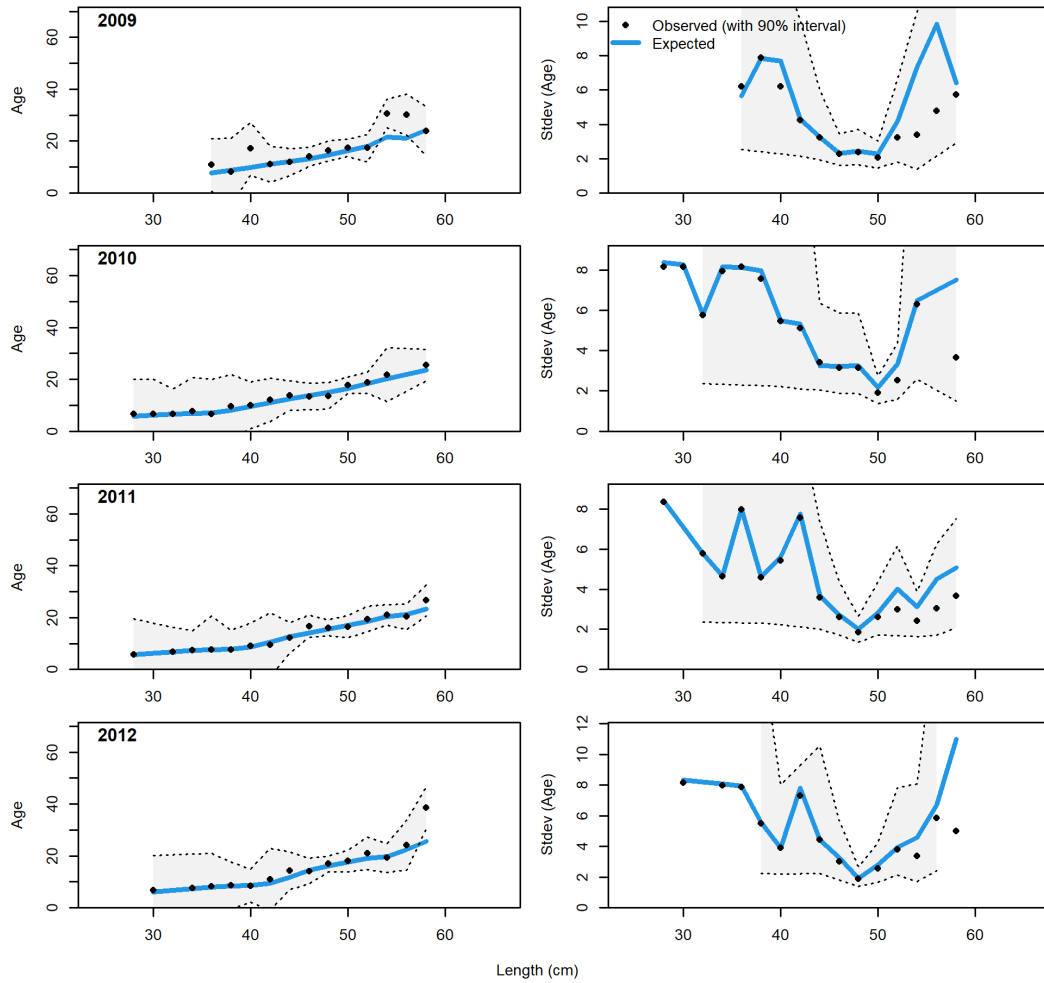


Figure 78: Recreational conditional AAL plot (plot 1 of 4) showing mean age (left panel) and standard deviation (right panel). Shaded areas are 90 percent CIs).

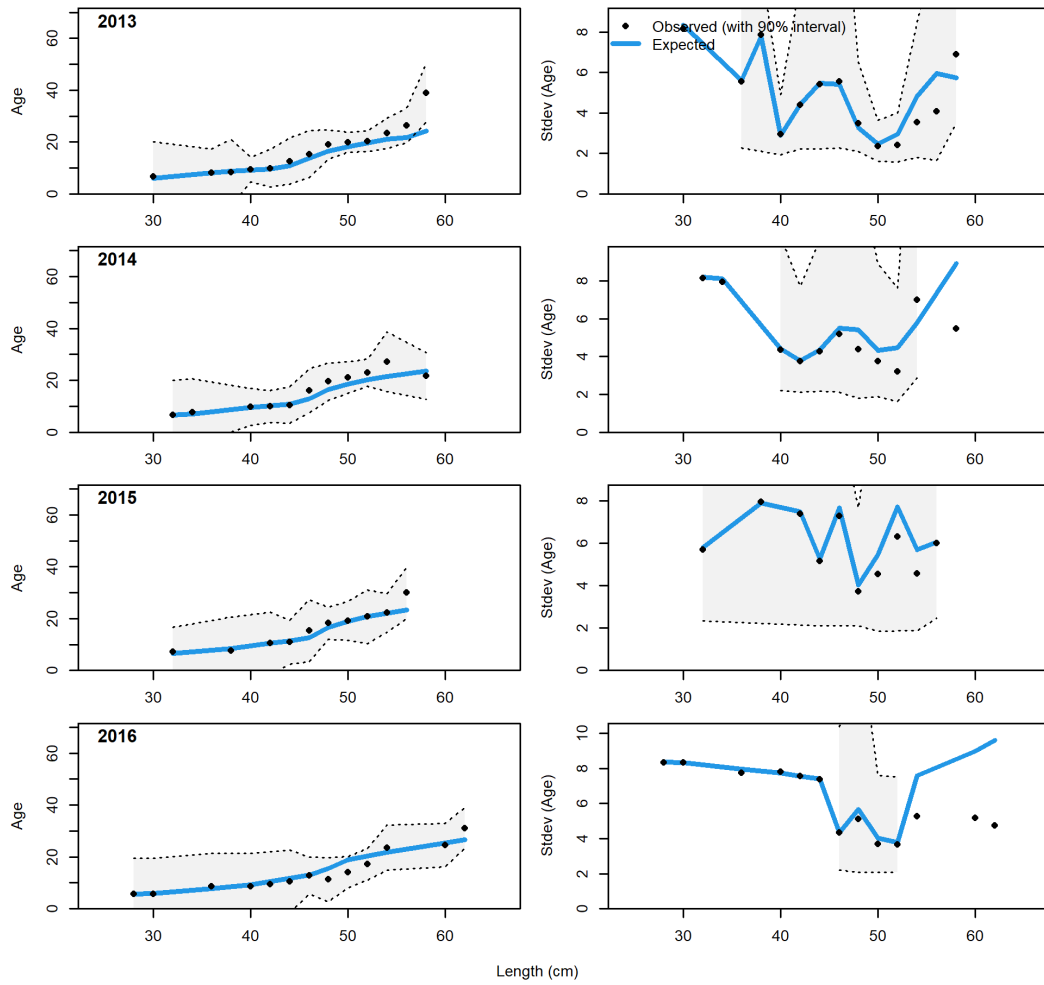


Figure 79: Recreational conditional AAL plot (plot 2 of 4).

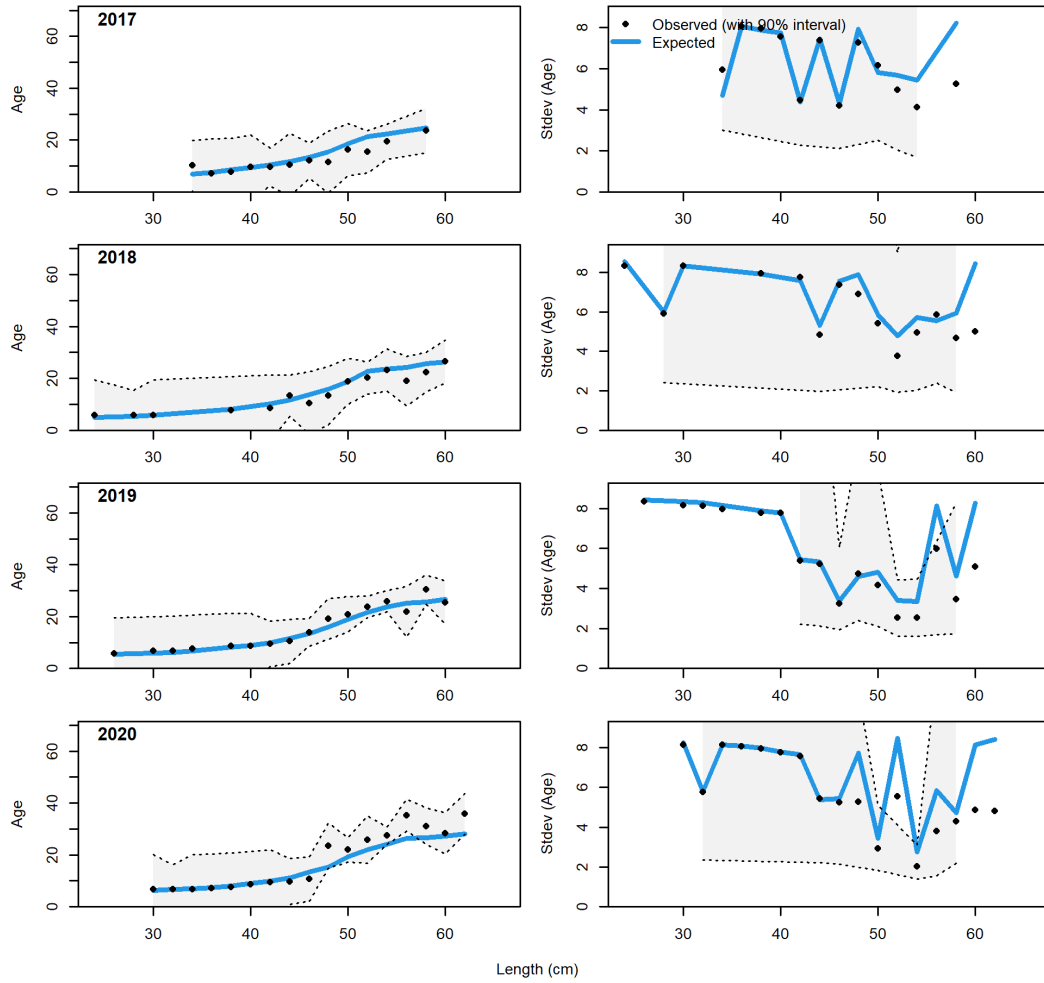


Figure 80: Recreational conditional AAL plot (plot 3 of 4).

11 Appendix D: Numbers at Age Plot

11.1 Females

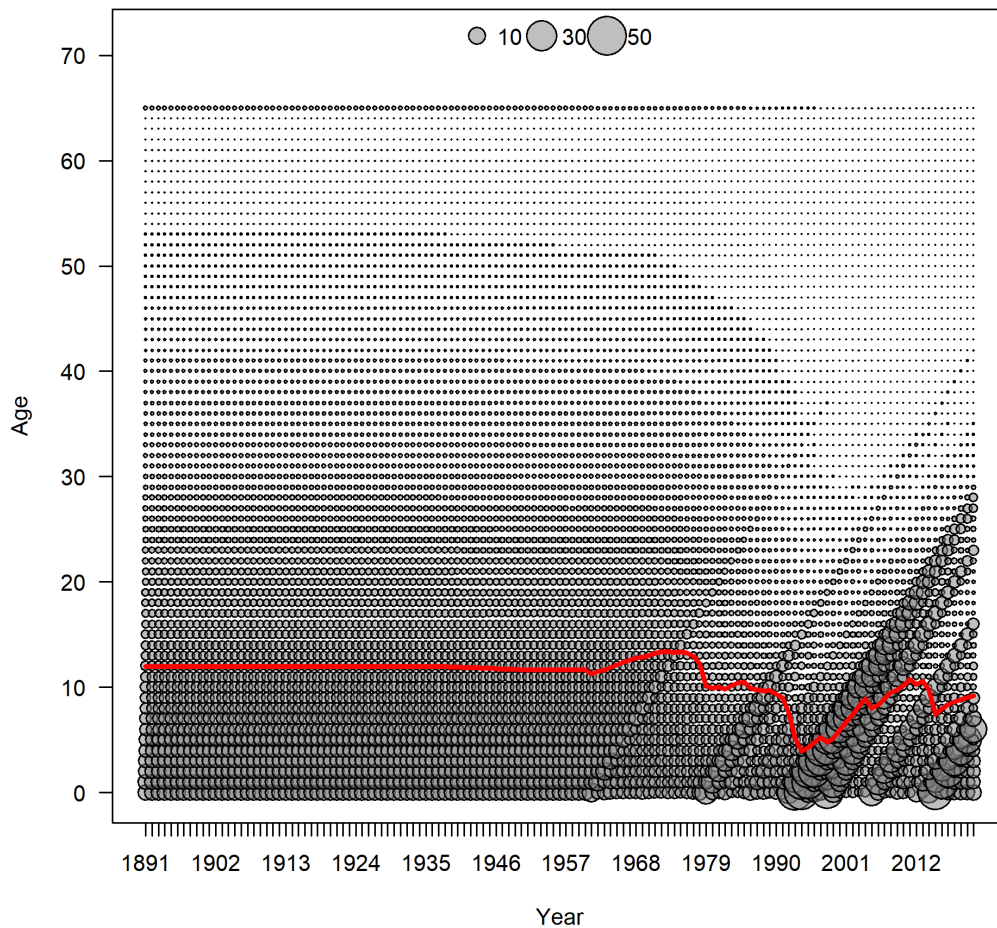


Figure 81: Female vermilion rockfish mean age over time.

11.2 Males

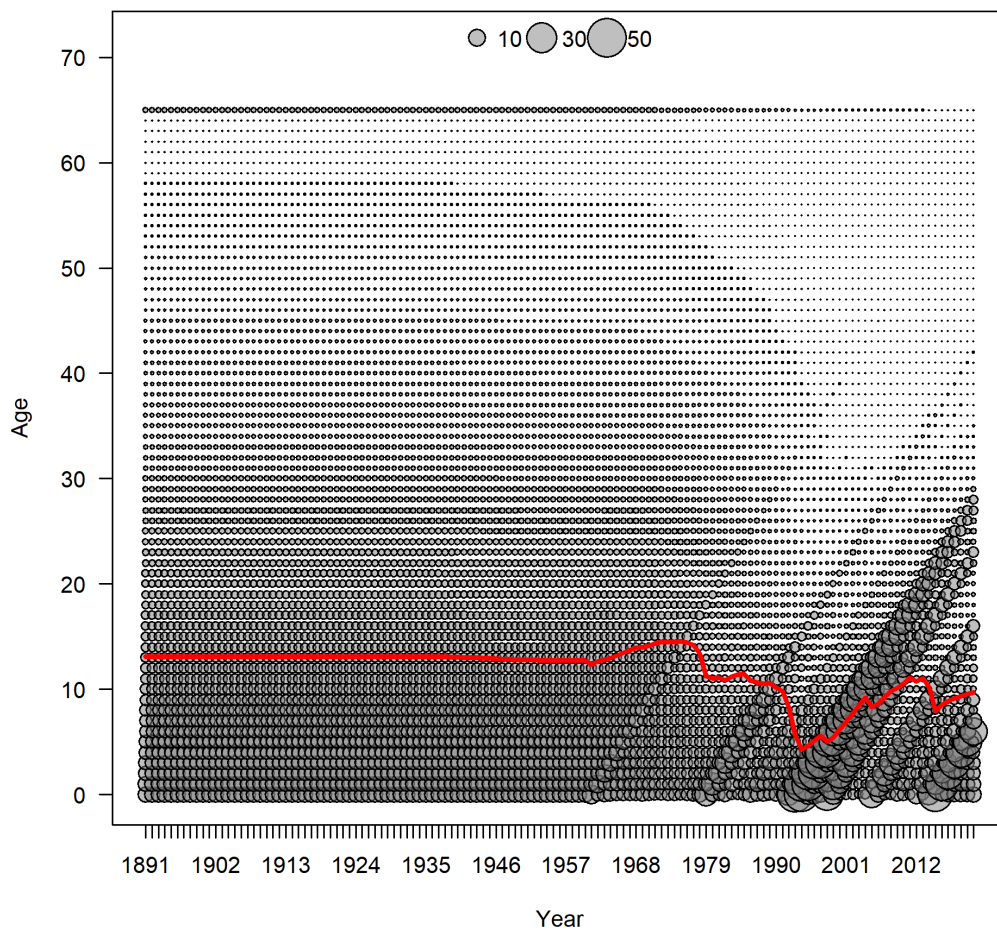


Figure 82: Male vermilion rockfish mean age over time.

12 Appendix E: Numbers at Length Plot

12.1 Females

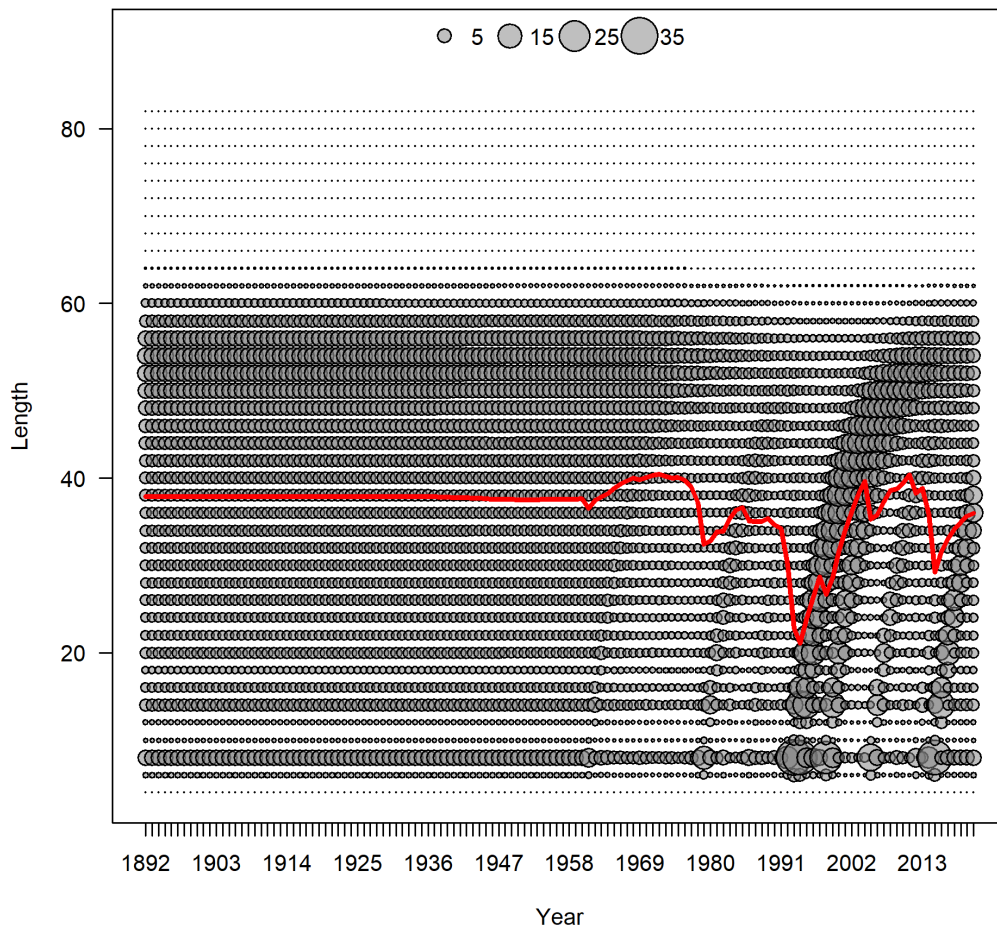


Figure 83: Female vermilion rockfish mean length (cm) over time.

12.2 Males

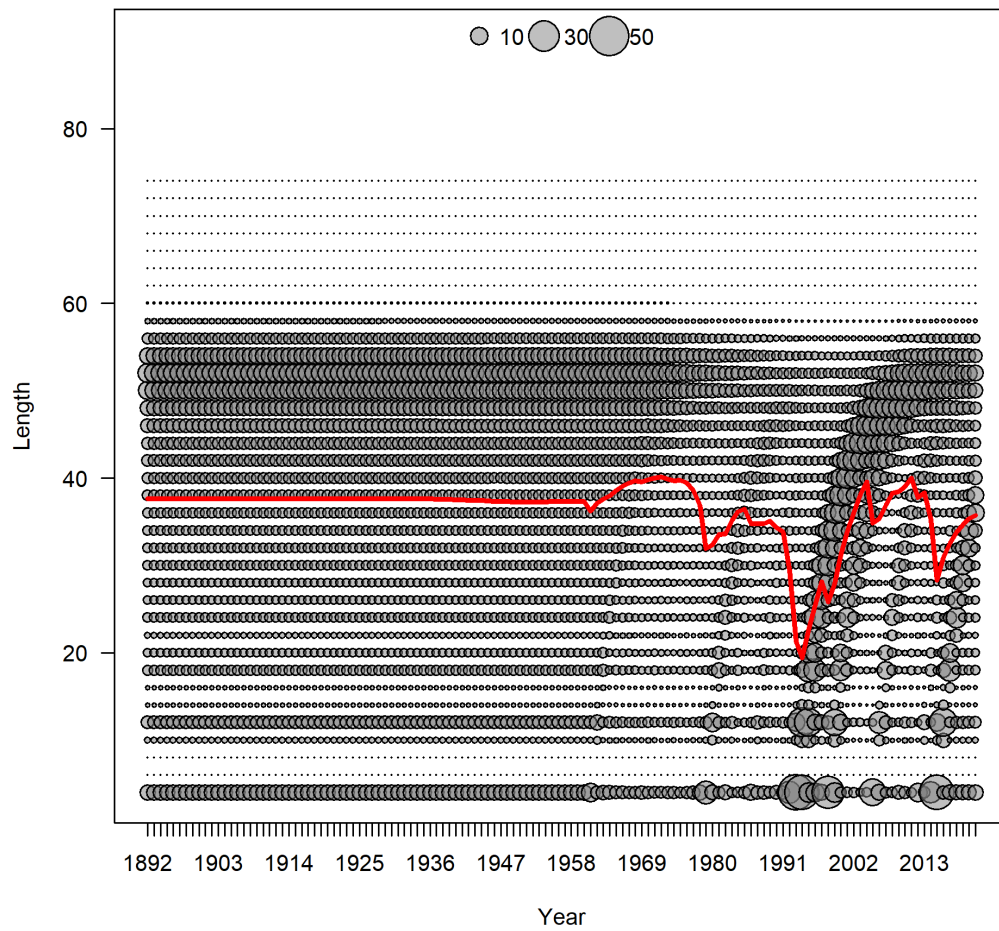


Figure 84: Male vermilion rockfish mean length over time.