September 2026 Eastern Bering Sea Pacific cod Alternative Assessment Model Evaluations and Explorations

Authors: Steven Barbeaux, Pete Hulson, and Ingrid Spies

- Link to Github repository Stock Synthesis model files and supporting figures

1.0 Plus-group Sensitivity Analysis

Introduction

This analysis evaluates reduction of the plus-group age for Eastern Bering Sea Pacific cod (*Gadus macrocephalus*; Barbeaux et al. 2024). The currently accepted plus-group age is 20. This analysis provides model performance results based on reducing the plus-group age from 20 to 10. Model 24.1 uses an age-20 plus group, although recent Bering Sea fishery and survey collections contained Pacific cod only through age 14. In addition, the tinyVAST-estimated bottom-trawl survey age composition used in the model applies an age-12 plus group because relatively few age-13 and age-14 fish occur in the survey data (Barbeaux et al. 2024).

The age-20 plus group in Model 24.1 is a remnant of earlier assessments, when Pacific cod were erroneously assigned substantially older ages. This analysis provides the first formal reevaluation of the retained age-20 plus group. This sensitivity analysis examines how reducing the plus-group age to better reflect the observed age structure of the population affects model fit, parameter estimates, uncertainty, and management reference points.

Methods

The data inputs for Model 24.1 were updated through 2025. The terminal plus group was then reduced from age 20 to age 10 in two-year increments, resulting in models with plus groups at ages 20, 18, 16, 14, 12, and 10 (Table 1.1). Changes in model likelihood, parameter estimates, and key derived quantities were evaluated across configurations.

Results

Model results were generally stable when the plus-group age was reduced from 20 to 14, but progressively larger changes occurred at ages 12 and 10 (Table 1.1). Total objective-function values were nearly identical for the plus-group ages 14 through 20 models, ranging from 366.31 to 366.57. The age-12 model had a slightly higher objective function of 367.55, whereas the age-10 model increased to 382.73. The deterioration in the age-10 model was primarily attributable to the length-composition likelihood, which increased by 19.08 likelihood units relative to the age-20 model, although age-composition and survey likelihood components improved slightly. The degradation in fit can mainly be attributable to the fits to the larger size bins as seen in the Pearson's residuals (Figure 1.1).

Table 1.1 Model-specific r4ss materials for the Eastern Bering Sea Pacific cod plus-group sensitivity analysis. Each link opens the model directory containing r4ss summaries generated from Stock Synthesis 3 (SS3) inputs and outputs and the associated diagnostic figures. Model names identify terminal plus-group age; 14+, for example, aggregates fish ages 14 and older.

Model	SS3/r4ss directory	Linked material	Destination
20+	MODEL26.1.20	r4ss summaries and diagnostic figures	Open MODEL26.1.20 outputs
18+	MODEL26.1.18	r4ss summaries and diagnostic figures	Open MODEL26.1.18 outputs
16+	MODEL26.1.16	r4ss summaries and diagnostic figures	Open MODEL26.1.16 outputs
14+	MODEL26.1.14	r4ss summaries and diagnostic figures	Open MODEL26.1.14 outputs
12+	MODEL26.1.12	r4ss summaries and diagnostic figures	Open MODEL26.1.12 outputs
10+	MODEL26.1.10	r4ss summaries and diagnostic figures	Open MODEL26.1.10 outputs

Results

Model results were generally stable when the plus-group age was reduced from 20 to 14, but progressively larger changes occurred at ages 12 and 10 (Table 1.2). Total objective-function values were nearly identical for the plus-group ages 14 through 20 models, ranging from 366.31 to 366.57. The age-12 model had a slightly higher objective function of 367.55, whereas the age-10 model increased to 382.73. The deterioration in the age-10 model was primarily attributable to the length-composition likelihood, which increased by 19.08 likelihood units relative to the age-20 model, although age-composition and survey likelihood components improved slightly. The degradation in fit can mainly be attributable to the fits to the larger size bins as seen in the Pearson's residuals (Figure 1.1).

Table 1.2 Negative log-likelihood (NLL) results and active parameter counts for six otherwise comparable Eastern Bering Sea Pacific cod models differing in terminal plus-group age. Model names identify the terminal plus group; for example, 14+ aggregates fish ages 14 and older. Delta NLL is each model's total NLL minus the 20+ model value, so smaller values indicate lower NLL. Length-composition, age-composition, and survey columns report selected NLL components. The shaded row identifies the recommended 14+ configuration. NLL values are rounded to one decimal because finer precision does not improve interpretation.

Model	Number of estimated parameters	Total NLL	Δ NLL vs. 20+	Length comp. NLL	Age comp. NLL	Survey NLL
20+	180	366.6	—	335.1	58.5	−58.2
18+	178	366.6	0	335.1	58.5	−58.2
16+	176	366.5	−0.1	335	58.5	−58.2
14+	174	366.3	−0.3	334.8	58.5	−58.2
12+	172	367.6	1	336.7	58	−58.6
10+	170	382.7	16.2	354.2	55.8	−59.7

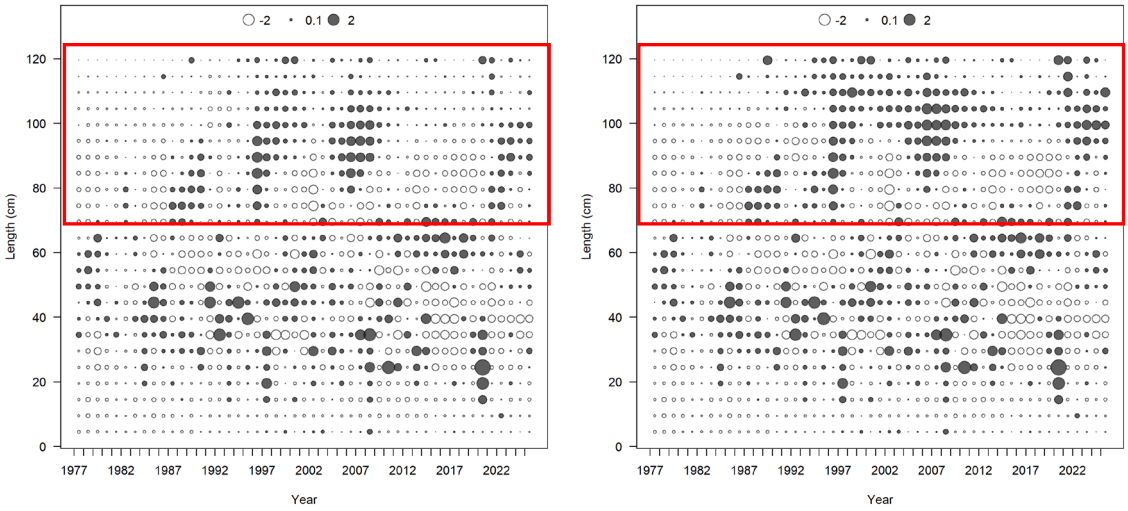

Figure 1.1 Pearson residuals for fishery length composition fits for 14+ age group (left) and 10+ age group (right) models showing higher residuals for the larger fish in the 10+ age group model. Red box indicates size bins with the greatest difference in residuals.

Estimated biological and fishery parameters were also similar among the plus-group age 14 through 20 models (Table 1.3). The age-12 model produced modest changes in recruitment scale, survey catchability, initial fishing mortality, and historical fishery selectivity. The age-10 model showed the largest departures, including an 8.7% reduction in estimated unfished recruitment, a 13.0% increase in survey catchability, and a 34.9% increase in initial fishing mortality relative to the age-20 model (Figure 1.2). The estimated 1977 fishery selectivity peak increased from 76.0 cm in the age-20 model to 79.8 cm in the age-10 model and was near its upper parameter bound. Estimated growth curves were nearly indistinguishable among the age-14 through age-20 models. For the 1977 cohort, size at age in the age-10 model was approximately 1.8% greater than the age-20 model at older ages (Figure 1.3), whereas differences for the age-12 model were approximately 0.25% and those for the age-14 through age-18 models were close to zero.

Table 1.3: Growth model parameters, catchability(q), initial F and peak fishery selectivity by plus group.

Plus group	L_{max} (cm)	von Bert. K	Richards	Ln(R_0)	R_0 Δ vs 20+	Survey Ln(q)	q Δ vs 20+	Initial F	1977 fishery peak (cm)
20+	111.04	0.118	1.462	13.331	—	0.019	—	0.1122	76.02
18+	111.01	0.118	1.462	13.331	0.01%	0.0189	−0.01%	0.1122	76.021
16+	110.97	0.118	1.462	13.331	0.08%	0.0179	−0.11%	0.1121	76.025
14+	110.83	0.119	1.461	13.331	0.05%	0.0183	−0.06%	0.1126	76.273
12+	110.92	0.12	1.451	13.314	−1.60%	0.04	2.13%	0.121	77.445
10+	110.55	0.13	1.382	13.24	−8.66%	0.1412	13.00%	0.1513	79.801

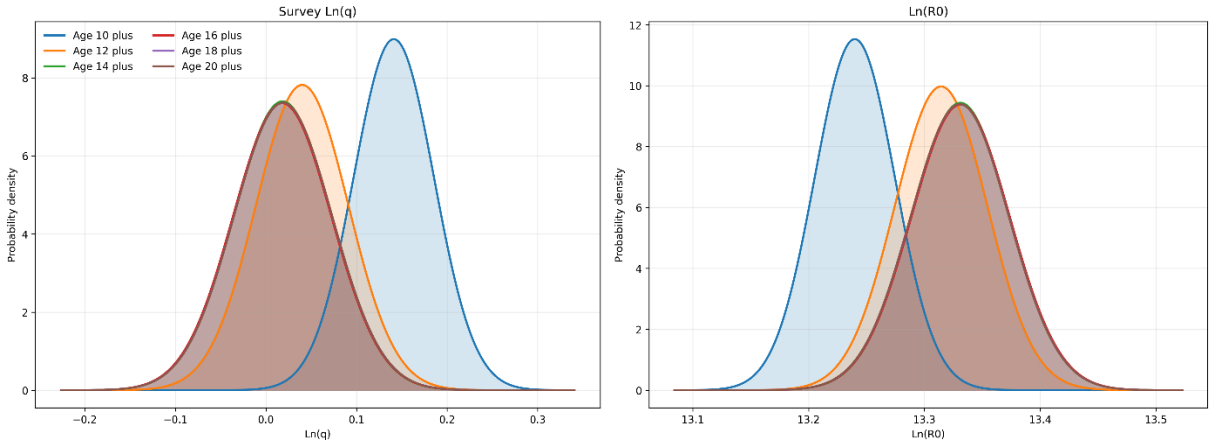

Figure 1.2 Density plots of log catchability (left) and log of virgin recruitment (R_0; right)

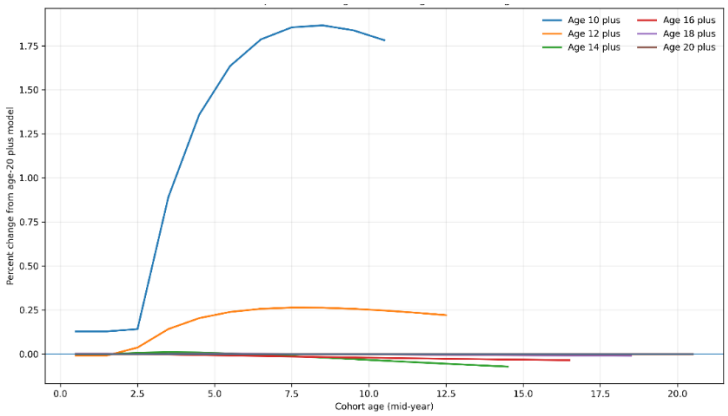

Figure 1.3: Percentage difference in size by plus group for 1977 cohort by age from the model with age 20 plus group.

Female spawning-biomass and recruitment trajectories retained the same general temporal patterns across all plus-group assumptions, but their estimated magnitudes declined as the plus-group age was reduced (Table 1.4; Figure 1.4). Approximate density distributions based on the reported estimates and standard deviations showed substantial overlap among the age-14 through age-20 models for unfished spawning biomass, 2025 spawning biomass, log survey catchability, and log unfished recruitment. In contrast, the age-10 model distributions were shifted toward lower spawning biomass and unfished recruitment and higher survey catchability, with the age-12 model generally intermediate (Figure 1.5). Overall, results indicate that plus-group ages of 14 or older produced stable model estimates, whereas use of an age-10 plus group materially affected model fit, parameter estimates, and estimated population scale.

Table 1.4: Derived quantities by plus group.

Plus group	Female unfished SSB	Female SSB_{1976}	Female SSB_{2025}	$Bratio_{2025}$	F_{2025}
20+	551.545 kt	167.712 kt	197.914 kt	0.3588	0.3516
18+	551.460 kt	167.719 kt	197.937 kt	0.3589	0.3515
16+	551.260 kt	167.906 kt	198.125 kt	0.3594	0.3512
14+	550.440 kt	167.746 kt	198.009 kt	0.3597	0.3513
12+	546.000 kt	159.351 kt	193.554 kt	0.3545	0.3596
10+	535.440 kt	133.419 kt	176.081 kt	0.3289	0.3941

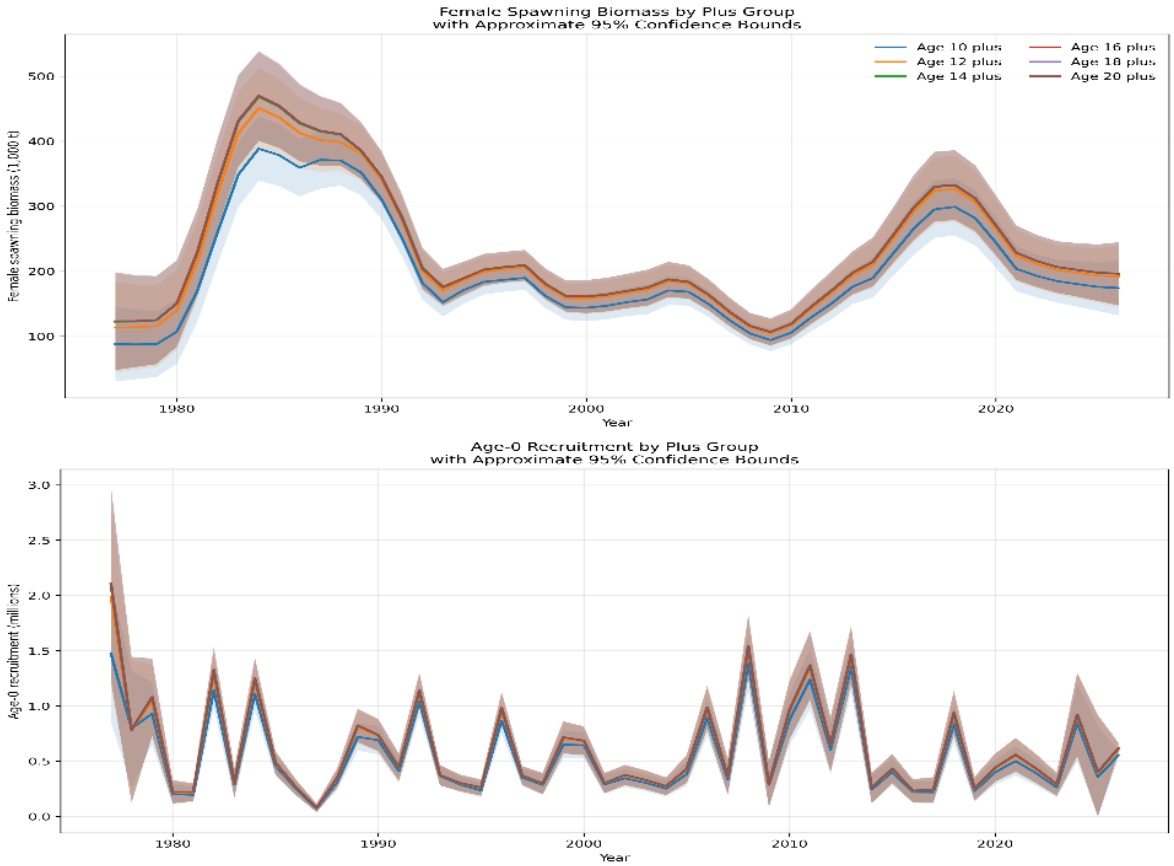

Figure 1.4: Female spawning biomass (top), and age-0 recruitment (bottom) by plus group

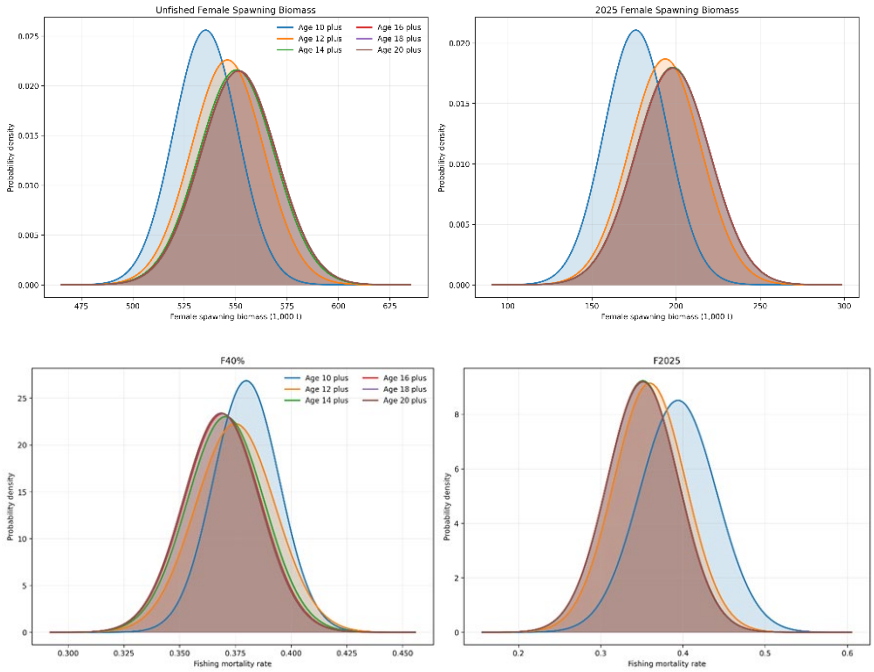

Figure 1.5: Density plot of unfished female spawning biomass (top left), 2025 female spawning biomass (top right), F40% (bottom left) and fishing mortality in 2025 (bottom right) by plus group.

Models with lower plus-group ages show lower uncertainty in estimated parameters and derived quantities (Figure 1.6). The lower uncertainty in key parameters and derived quantities for models with younger plus groups likely resulted from aggregating weakly or uninformed older ages and reducing covariance among older-aged abundance, initial conditions, catchability, and recruitment scale. This increase in conditional precision should not necessarily be interpreted as improved model performance, because the youngest plus-group model showed substantial changes in parameter estimates and a poorer overall fit.

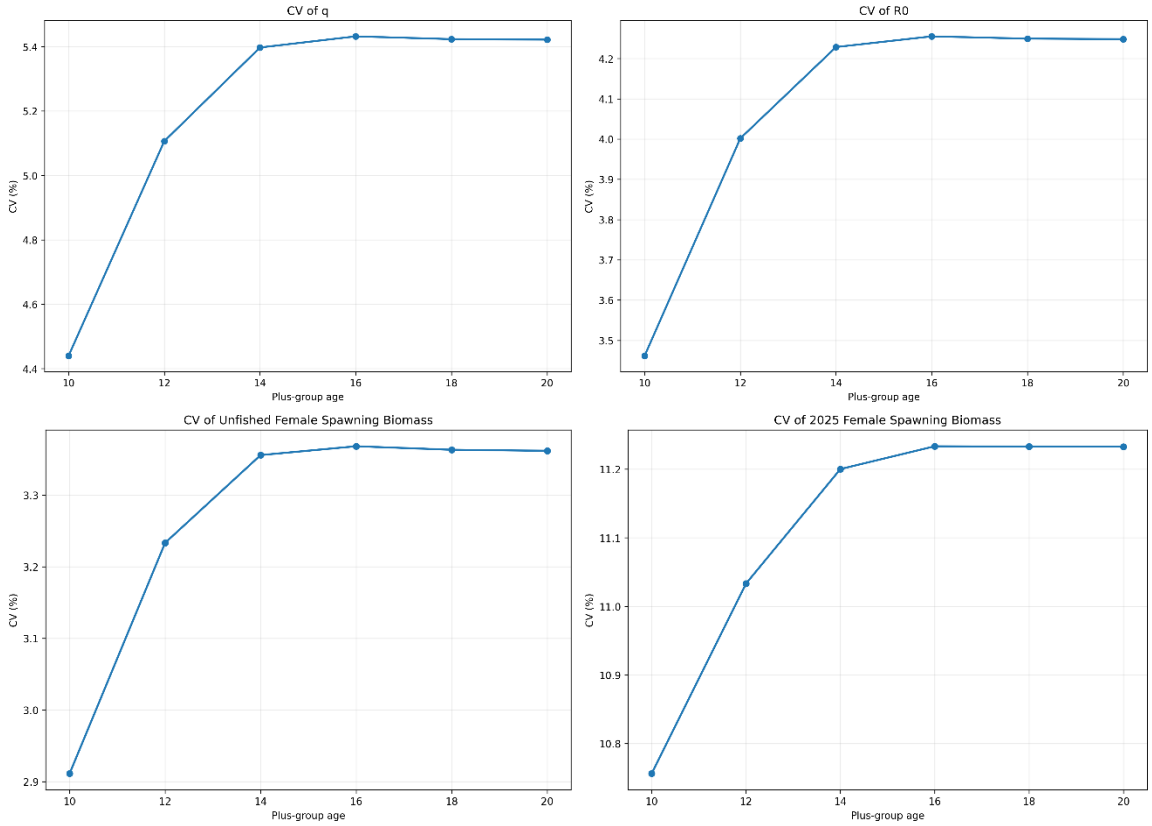

Figure 1.6: Coefficient of variation (CV) by plus-group age for catchability (q; top left), virgin recruitment (R_0; top right), female unfished spawning biomass (bottom left), and 2025 female spawning biomass (bottom right).

Recommendation

Changing the plus-group age from 20 to 14 had little effect on estimated biological and fishery parameters. Estimates of growth, recruitment, survey catchability, fishing mortality, and selectivity were nearly identical between the two models, and all differences were small relative to their estimated uncertainty. The largest changes among shared parameters were a slight decrease in maximum length, a small increase in the von Bertalanffy growth coefficient, and modest reductions in uncertainty for these growth parameters. The principal structural effect of adopting an age-14 plus group was the removal of six initial-age deviation parameters for ages 15–20 and the redistribution of less than 0.5% of the estimated initial abundance from the older age classes into the age-14 plus group. Thus, reducing the plus-group age improved model parsimony and changed the treatment of the oldest fish without materially affecting estimated population dynamics.

For the 2026 model, we recommend using an age-14 plus group because model results stabilized at plus-group ages of 14 and older. Reducing the plus-group age from 20 to 14 removed poorly informed older-age parameters while producing negligible changes in likelihood, growth, selectivity, spawning biomass, recruitment, catchability, uncertainty, and reference points. In contrast, further reductions to ages 12 and 10 produced progressively larger changes in parameter estimates and model fit. Therefore, the 2026 assessment should use an age-14 plus group.

2.0 Split-sex Model Exploration

The current Eastern Bering Sea Pacific cod assessment has historically modeled males and females as a combined population (Barbeaux et al. 2024). However, examination of sex composition data indicates that females grow faster than males and achieve higher asymptotic lengths (Figure 2.1).

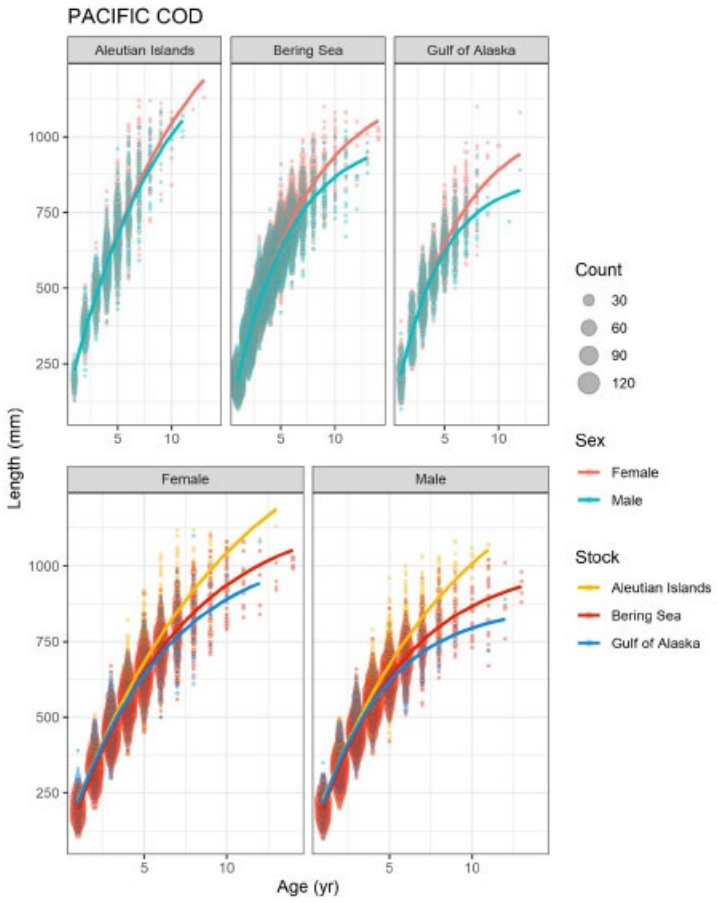

Figure 2.1: Observed length at age for samples from the Aleutian Islands, Bering Sea , and Gulf of Alaska (top) and by female on the left and males on the right (bottom) (Figure 29 from Matta et al. 2026)

In addition, the relative abundance of males and females varies with length in the bottom trawl survey (Matta et al. 2026) and the fishery, over time. In general, both the Eastern Bering Sea shelf bottom trawl survey and fishery sex composition are approximately balanced (50% male and 50% female) at lengths below 60 cm but the proportion of females in the population increases at larger sizes (Figure 2.2). Females comprise a clear majority of fish above approximately 70–80 cm, with the female proportion continuing to increase in the largest length classes.

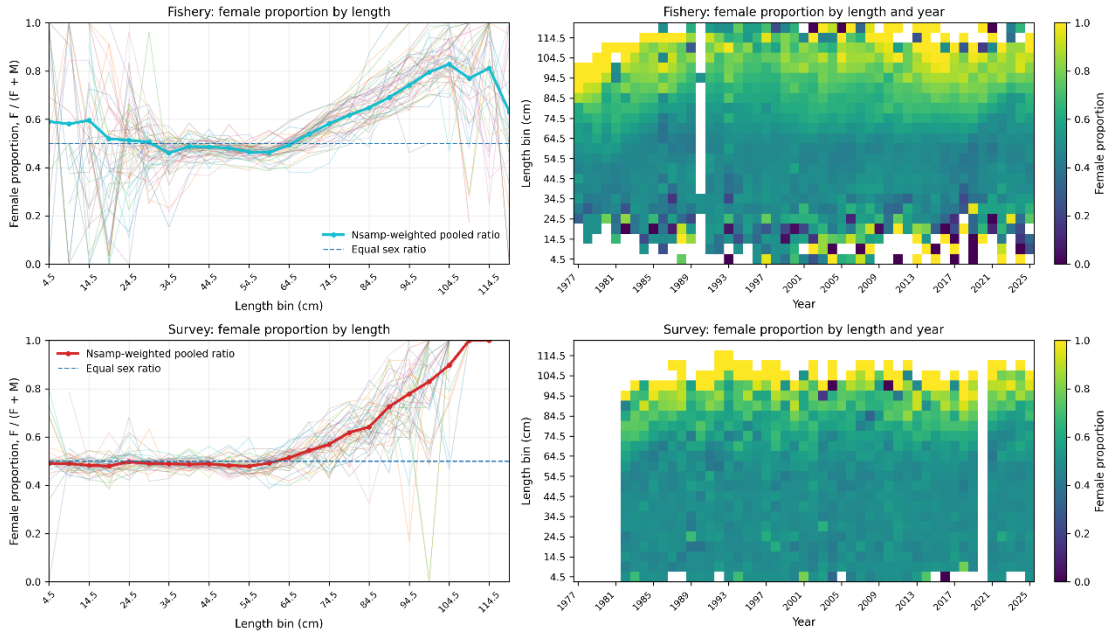

Figure 2.2: Female proportion by length (left) and length and year (right) for fishery (top) and Eastern Bering Sea shelf bottom trawl survey collections for 1977-2025 (bottom). Gray lines are annual data, colored lines are the overall weighted mean.

Survey observations also indicated age-dependent differences in sex composition (Figure 2.3). Sex ratios were approximately balanced at younger ages, whereas females generally became more prevalent among older fish. Although proportions at individual older ages were variable, the overall increase in female representation with both age and length suggests persistent differences in the population structure, growth, survival, or availability of males and females. These patterns provide additional motivation for evaluating a split-sex model in which sex-specific growth, mortality, and selectivity can be represented explicitly.

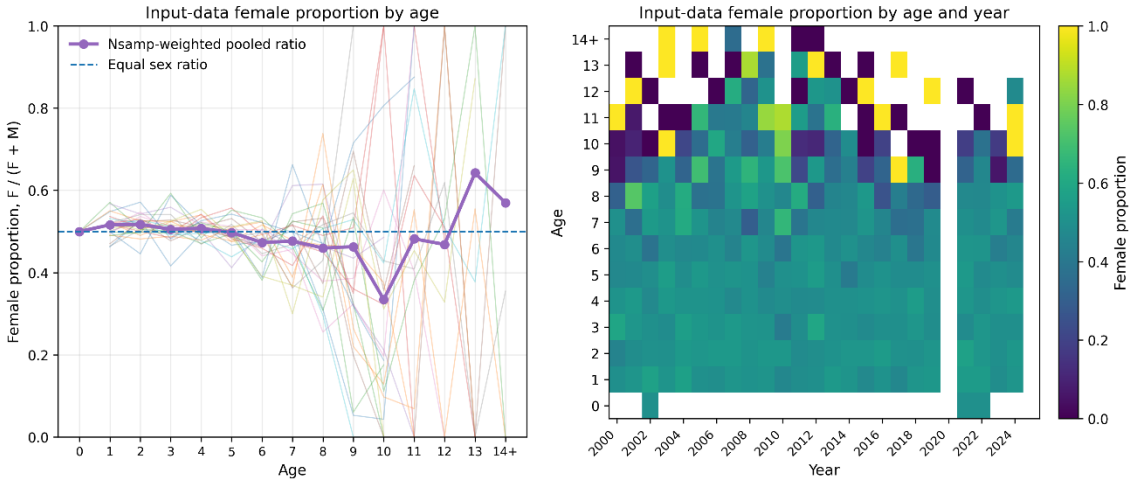

Figure 2.3: Female proportion by age (left) and age and year (right) for Eastern Bering Sea shelf bottom trawl survey collections for 2000-2024. Thin lines are annual data, the bolded line is the overall mean.

Similar length-dependent patterns are evident in both the trawl (Figure 2.4) and longline (Figure 2.5) fisheries. The proportion female is generally near 50% for fish between approximately 40 and 60 cm, a moderate increase in the proportion female at 70 cm, and a strong increase in the proportion female at 80 cm and above. The consistency of this pattern across the survey and two fisheries suggests that the predominance of females at larger sizes reflects an underlying difference in the size structure of males and females rather than an effect unique to a particular gear or sampling platform.

The data also indicate temporal variation in sex composition, particularly among the 60- and 70-cm length groups in the trawl fishery. The trawl fishery targets spawning aggregations in the winter and early spring. The variation in sex-ratios may reflect sex-specific differences in spatial distribution, availability, behavior, or vulnerability to fishing gear. Although evidence for comparable seasonal patterns in Pacific cod remains unavailable , temporal and spatial variation in spawning-season sex ratios has been documented for Atlantic cod (*Gadus morhua*). Morgan and Trippel (1996) observed both male- and female-dominated shoals off the northern Grand Bank and on the southern Scotian Shelf/Bay of Fundy. Male-dominated aggregations occurred consistently in shallower water and contained higher proportions of both males and females in spawning condition, whereas female-dominated aggregations contained a greater proportion of post-spawning (spent) females. Based on these observations, the authors hypothesized that male Atlantic cod may arrive at spawning areas before females, while females may move onto the spawning grounds to spawn and then return to deeper water after spawning is completed. Earlier arrival of males at Atlantic cod spawning grounds has also been reported in other regions, including Nova Scotia (McKenzie 1940) and the Baltic Sea (Chrzan 1950). An earlier arrival of males to the spawning grounds would explain the pattern observed in the Pacific cod trawl fishery data.

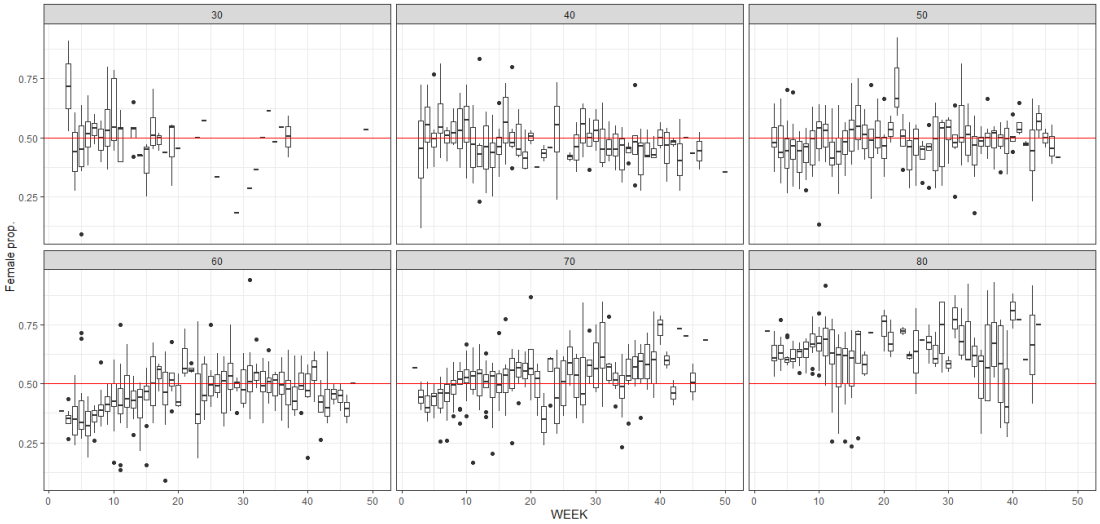

Figure 2.4: Female proportion in the Eastern Bering Sea trawl fishery by size bin (cm) and week of the year for 2010-2025. Note that the 30 cm bin includes all fish measured at 39 centimeters and below while the 80cm bin includes all fish measured at 80 cm and above.

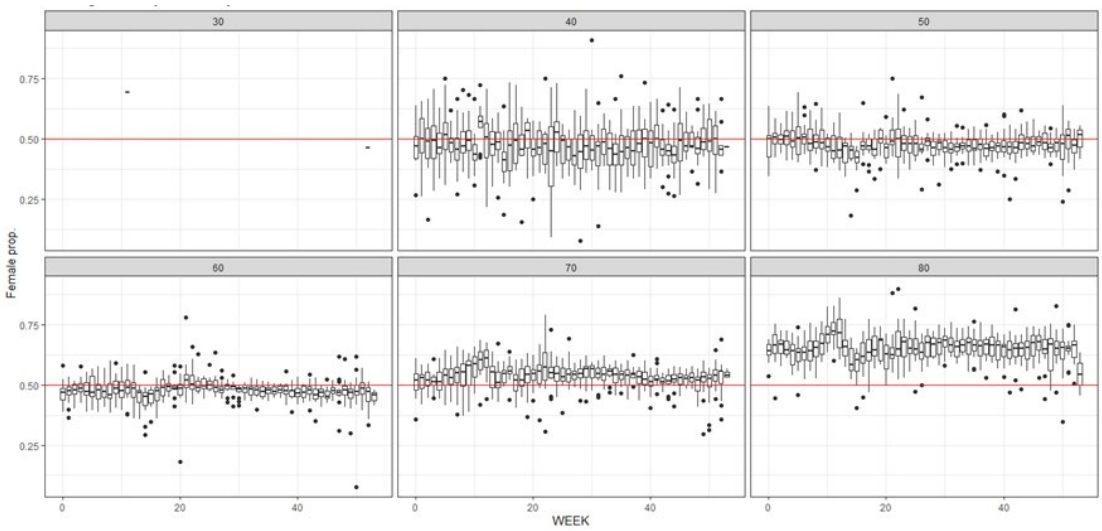

Figure 2.5: Female proportion in the Eastern Bering Sea longline fishery by size bin and week of the year for 2010-2025. Note that the 30 cm bin includes all fish measured at 39 centimeters and below while the 80cm bin includes all fish measured at 80 cm and above.

Combining sexes within a single population model may obscure these differences and require a single growth curve and selectivity pattern to represent observations generated by two potentially different components of the population. In particular, the scarcity of males in the largest length classes may be difficult to represent using a combined-sex growth model, while changes in the relative contribution of each sex could influence fitted length compositions and estimated selectivity. Because spawning biomass is determined primarily from the female component of the population, explicitly modeling females may also provide a more direct representation of the population quantity used to evaluate stock status.

Based on these observations, a split-sex Stock Synthesis model was developed and compared with the combined-sex model. The split-sex configuration estimated separate growth and selectivity relationships for males and females while retaining the same underlying data sources and general assessment structure. The evaluation focused on whether explicitly representing sex-specific population structure improved the fit to survey and fishery composition data, produced biologically reasonable parameter estimates, and materially affected estimated recruitment, spawning biomass, fishing mortality, and management reference points.

Methods

Two models were developed from the most recently accepted assessment model, Model 24.1 (Barbeaux et al. 2024). Model 24.1 uses model-based, combined-sex survey age-composition estimates produced by the Groundfish Assessment Program (GAP) of the Resource Assessment and Conservation Engineering (RACE) Division using tinyVAST (Barbeaux et al. 2024) as input. Producing these model-based estimates is time intensive, and the current analysis proceeded before split-sex model-based survey estimates became available for the current year's model exploration. Consequently, this analysis used design-based survey age-composition data in both the single-sex and split-sex models for consistency and to allow a direct comparison of results.

The single-sex model, Model 26.2, differs from Model 24.1 only in its use of design-based survey age-composition data, the inclusion of data through 2025, and the use of an age-14 plus group. The split-sex model, Model 26.3, builds on Model 26.2 by estimating sex-specific growth and fishery selectivity and by using split-sex design-based survey age compositions and split-sex fishery and survey length compositions. When the sex-specific observations in Model 26.3 were combined, the survey age compositions were effectively identical to those in Model 26.2 (Figure 2.6). Annual sample sizes, temporal coverage, age-error assignments, and combined age proportions were unchanged, with differences limited to numerical rounding. Recombined survey length compositions were also essentially unchanged, although year-specific input sample sizes differed between models. The mean age and lengths for the split sex data show older and larger females (Figure 2.7) with the single sex model means between the two sexes means.

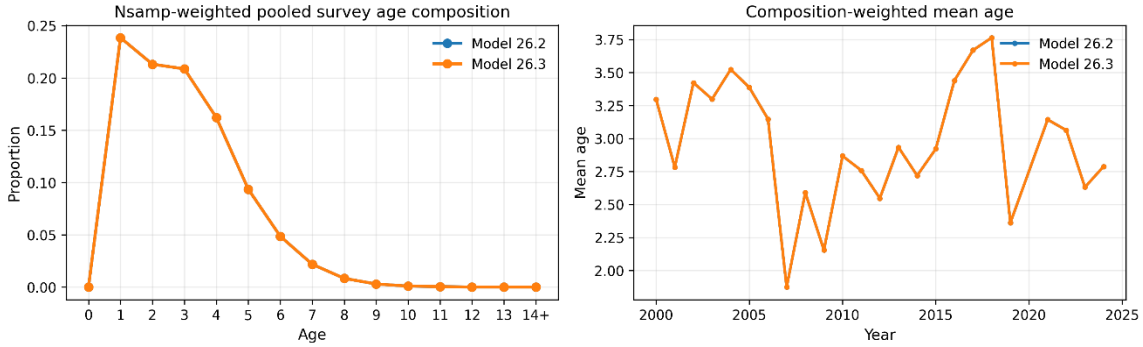

Figure 2.6 Eastern Bering Sea shelf bottom trawl survey age composition data for Model 26.2 and for pooled sexes for Model 26.3 examining sample size-weighted pooled age composition (left) and composition-weighted mean age (right).

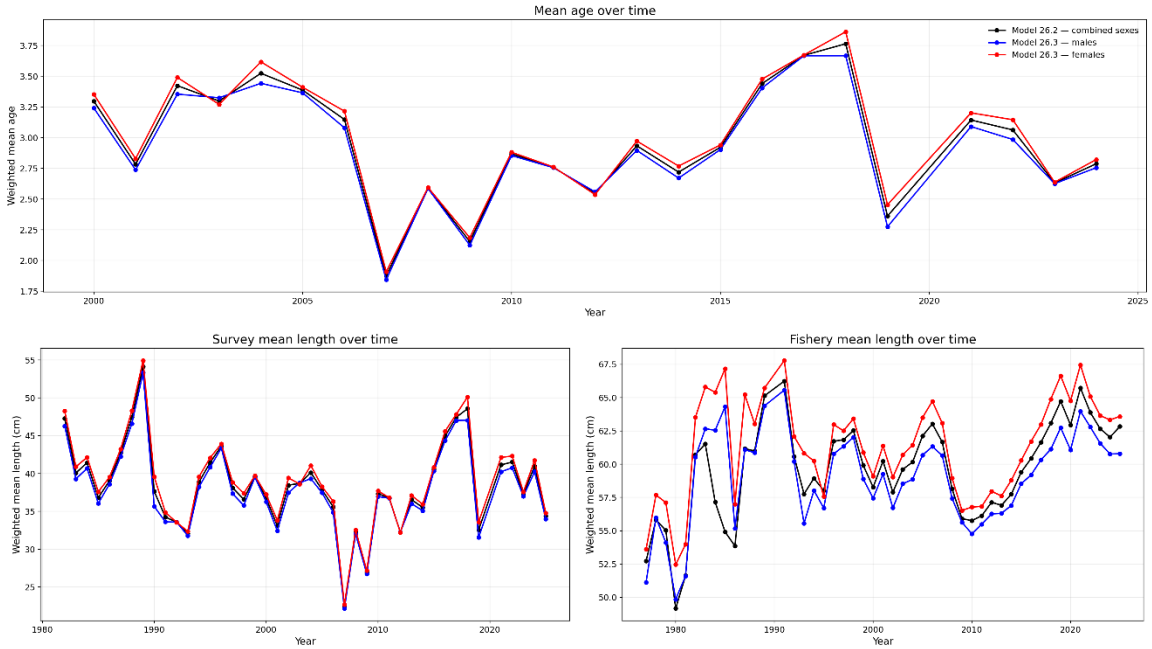

Figure 2.7: Mean age for the survey age composition data (top), mean length for survey length composition data (bottom left), and mean length for fishery age composition data (bottom right).

Both models input sample sizes for the fishery and survey age and length composition data were tuned iteratively using the *tune_comps()* function in the **r4ss** library until values remained stable for each.

Results

Because Models 26.2 and 26.3 use differently structured composition datasets, the differently structured composition datasets require comparison using common-scale residual diagnostics for evaluating overall fit. To that end we use observed-minus-expected mean length or age, coverage of the model's expected intervals, and standardized survey-index residuals (Table 2.1).

Model 26.2 fits the length and age combined-sex composition data well. Bias in the fishery mean length is essentially zero, and the typical annual discrepancy between observed and expected mean length is approximately 1.4 cm. Survey mean-length residuals are also small, although the positive mean residual indicates that observed survey fish are, on average, about 0.4 cm longer than predicted. Survey mean-age residuals are small, with the model tending to predict mean age approximately 0.15 years older than observed. The survey-index standard deviation of normalized residuals (SDNR) is 1.004, indicating that the residual variation is consistent with the assumed index uncertainty.

Model 26.3 provides a similarly good fit to the length and age split-sex composition data. Its fishery mean absolute residual is slightly lower than Model 26.2, although its fishery RMSE is slightly higher because several years have larger residuals. Model 26.3 provides a modestly better fit to the survey age compositions and a marginally lower survey-index RMSE. Its survey-index SDNR is also 1.004.

Table 2.1: Residual diagnostics for Model 26.2 and 26.3

Data component	Diagnostic	Model 26.2	Model 26.3
Fishery length	Mean residual	−0.08 cm	−0.38 cm
	Mean absolute residual	1.43 cm	1.38 cm
	RMSE	2.05	2.33
Survey length	Mean residual	+0.38 cm	+0.48 cm
	Mean absolute residual	1.18 cm	1.18 cm
	RMSE	1.62	1.69
Survey age	Mean residual	−0.151 years	−0.129 years
	Mean absolute residual	0.224 years	0.209 years
	RMSE	0.290	0.262
Survey biomass index	Log-scale RMSE	0.1518	0.1486
	SDNR	1.0044	1.0037

The common-scale diagnostics indicate comparable aggregate fit. The principal advantage of Model 26.3 is its ability to describe sex-specific length, growth, and selectivity patterns, whereas Model 26.2 has more internally consistent composition weights and achieves a comparable aggregate fit with less structural complexity. Fits were very similar with minor differences in mean age and mean length between models for most years (Figure 2.8).

The principal biological difference between models was the representation of sex-specific growth. Model 26.2 estimated a combined-sex maximum length of 111.8 cm. In Model 26.3, maximum length was estimated at 113.4 cm for females and 105.2 cm for males. The estimated von Bertalanffy K values were 0.129 for females and 0.120 for males, compared with 0.116 for the combined-sex model (Table 2.2). These differences produced increasing separation between female and male weight at age among older fish (Figure 2.9). The Model 26.2 growth curve effectively splits the difference between the male and female growth curves from Model 26.3.

Table 2.2 Growth parameters and standard error of the growth parameters (SE) for Model 26.2 and 26.3.

Growth parameter	Model 26.2 combined sex	SE	Model 26.3 female	SE	Model 26.3 male	SE
Lmin (cm)	13.95	0.32	14.03	0.32	14.30	0.31
Lmax (cm)	111.83	3.12	113.42	4.25	105.17	3.76
von Bertalanffy K	0.1158	0.0125	0.1286	0.0178	0.1197	0.0172
Richards parameter	1.4731	0.0709	1.3391	0.0937	1.5321	0.0997

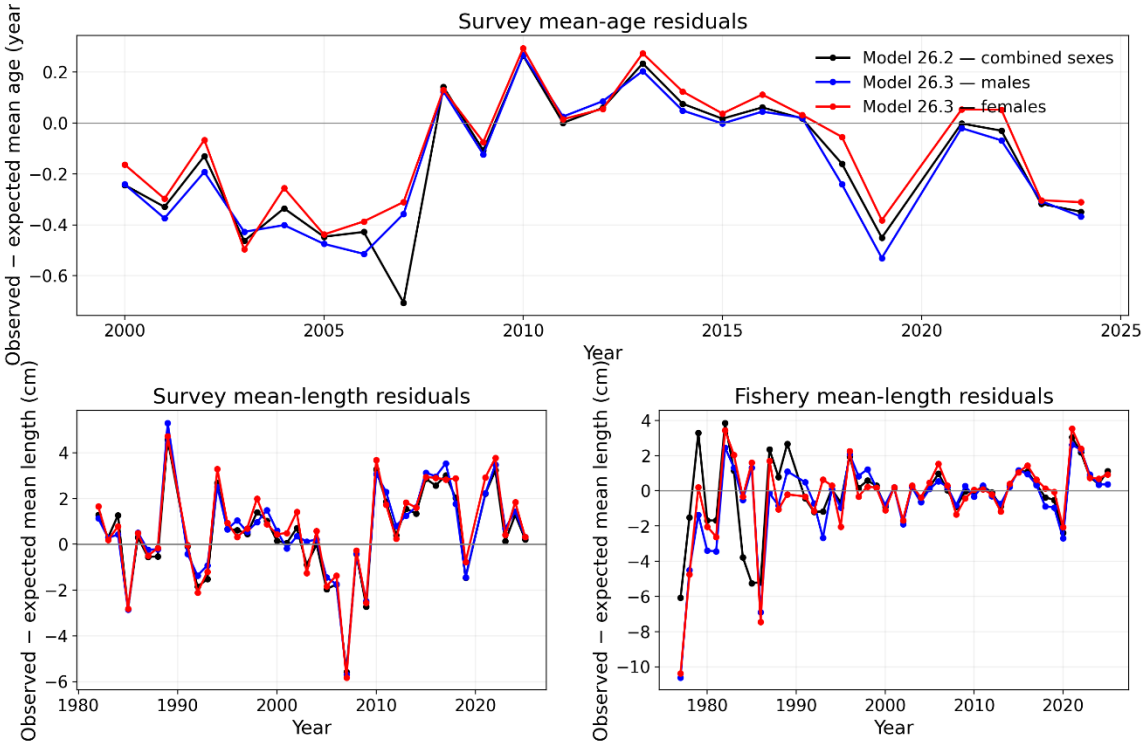

Figure 2.8: Residuals for mean age for the survey age composition fits (top), mean length for the survey length composition fits (bottom left), and mean length for the fishery length composition data fits (bottom right).

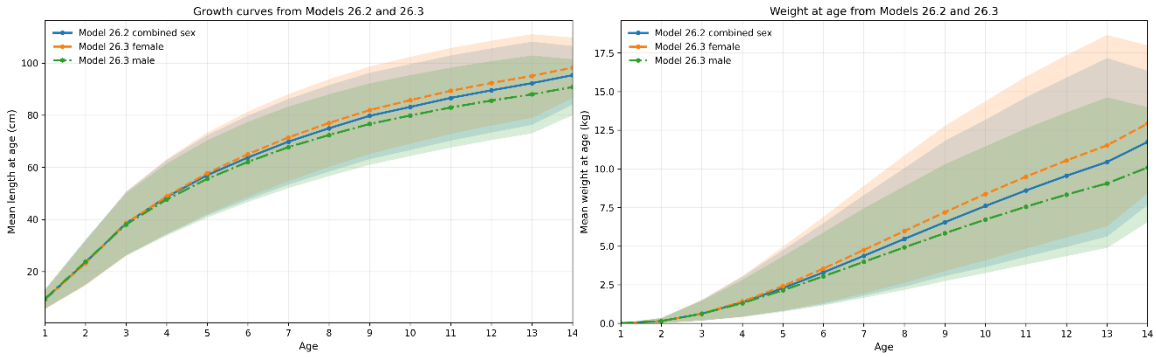

Figure 2.9: Mean length (cm; left) and weight (kg) at the beginning of the year (right) for Model 26.2 and 26.3.

Survey length selectivity was nearly identical among the combined-sex, female, and male curves. Fishery selectivity differed between sexes in Model 26.3. Male fishery selectivity approached 1.0, whereas female selectivity approached approximately 0.933. The uncertainty around the female scaling parameter included 1.0, indicating that the estimated reduction in maximum female vulnerability was not strongly distinguished from equal maximum vulnerability between sexes.

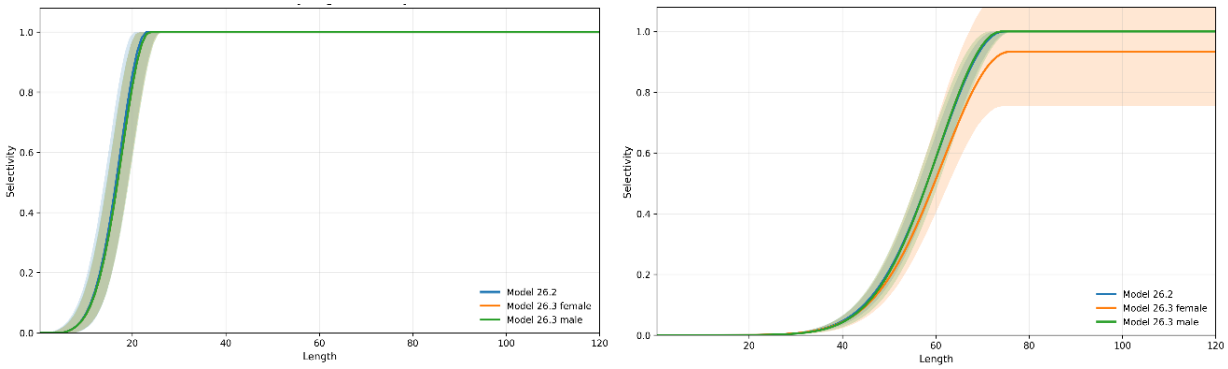

Figure 2.10 Model 26.2 combined sexes and Model 26.3 male and female survey selectivity (left), and fishery selectivity for 2025 (right)with approximate 95% confidence bounds.

Table 2.3: Key Parameters and derived quantities with standard error in parentheses for Model 26.2 and 26.3.

Quantity	Model 26.2	Model 26.3
Survey catchability, Q	1.0084 (0.0585)	1.0067 (0.0569)
Unfished recruitment, R_0	618,282 (28,344)	607,192 (26,965)
Fishery peak-selectivity parameter	74.49 cm (0.92)	♂ 74.08 cm (1.26)
		♀ 75.80 cm (1.34)
Survey peak-selectivity parameter	23.10 cm (1.32)	23.65 cm (1.19)
Unfished female spawning biomass	553.67 kt (19.95)	603.63 kt (21.78)
2025 female spawning biomass	200.76 kt (23.80)	216.66 kt (26.03)
$F_{40\%}$	0.3653 (0.0183)	0.4116 (0.0380)

Unfished recruitment (R_0) and survey catchability (q) were also similar between models (Table 2.3; Figure 2.11). Estimated unfished recruitment decreased by approximately 1.8% in Model 26.3 from

Model 26.2, and survey catchability differed by less than 0.2%. The estimated age-0 recruitment time series showed the same major year-class patterns under both model structures (Figure 2.12).

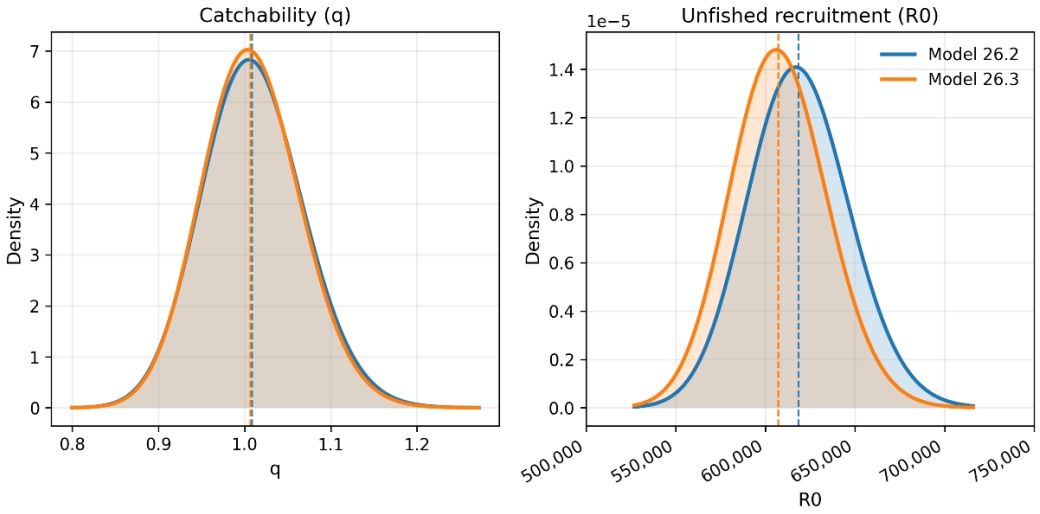

Figure 2.11: Model 26.2 and 26.3 Eastern Bering Sea shelf bottom trawl survey catchability (q; left) and unfished recruitment (R_0; right.

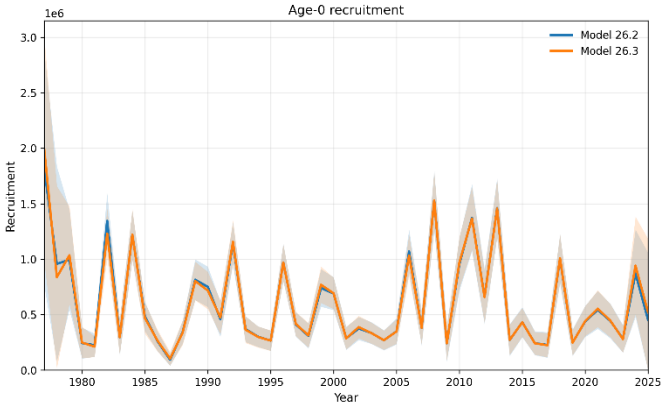

Figure 2.12: Time series of age-0 recruitment for Model 26.2 and 26.3.

Model 26.3 produced higher estimates of absolute female spawning biomass than the single-sex Model 26.2 (Figure 2.13). Unfished female spawning biomass was estimated at 603.6 kt in Model 26.3 compared with 553.7 kt in Model 26.2 (Figure 2.14), an increase of 9.0%. Female spawning biomass in 2025 was 216.7 kt in Model 26.3 and 200.8 kt in Model 26.2, while projected 2026 female spawning biomass was 210.5 and 194.9 kt, respectively.

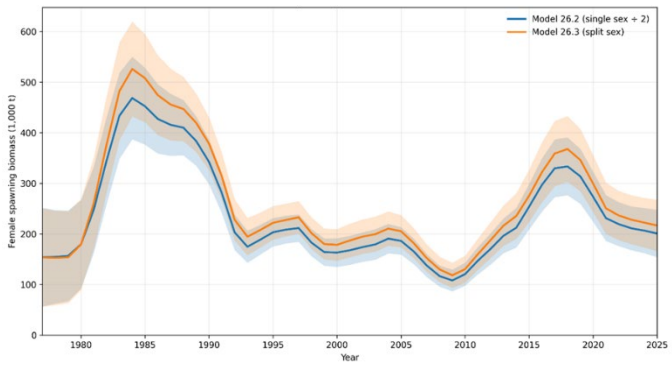

Figure 2.13 Female spawning biomass for Model 26.2 and Model 26.3.

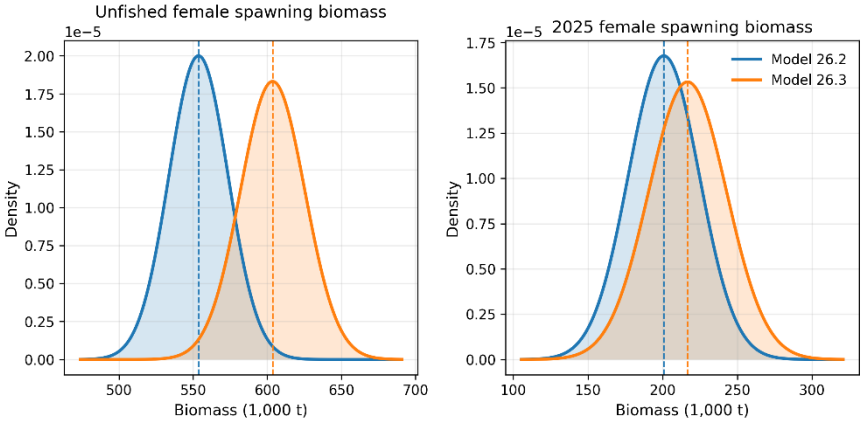

Figure 2.14: Density plots of unfished female spawning biomass (left) and 2025 female spawning biomass from Model 26.2 and 26.3.

Despite differences in absolute biomass, relative stock status was similar between models (Figure 2.15). The ratio of 2025 spawning biomass to unfished spawning biomass was 0.359 in Model 26.3 and 0.363 in Model 26.2. Similarly, $B_{2025}/B_{40\%}$ was 0.897 in Model 26.3 and 0.907 in Model 26.2. Both models therefore placed 2025 spawning biomass slightly below $B_{40\%}$.

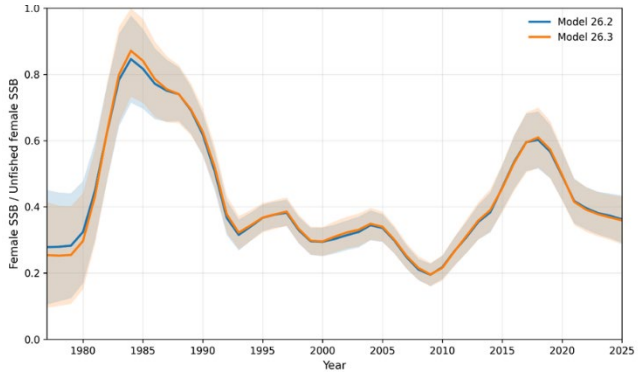

Figure 2.15 Spawning biomass ratio of annual female spawning biomass over unfished female spawning biomass for Model 26.2 and 26.3.

Fishing-mortality estimates were higher in the split-sex model (Figure 2.16 and Figure 2.17). Estimated F_{2025} increased from 0.350 in Model 26.2 to 0.382 in Model 26.3, and $F_{40\%}$ increased from 0.365 to 0.412.

However, fishing mortality relative to the model-specific reference point was slightly lower in Model 26.3: $F_{2025}/F_{40\%}$ was 0.928 compared with 0.959 in Model 26.2. Thus, both models indicated that fishing mortality in 2025 was below $F_{40\%}$.

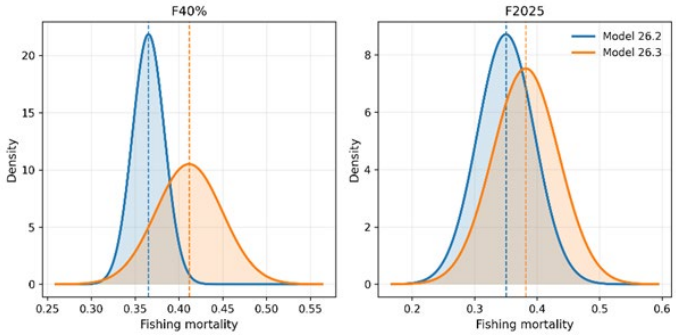

Figure 2.16: Density plots of $F_{40\%}$ (left) and F_{2025} (right)for Model 26.2 and Model 26.3.

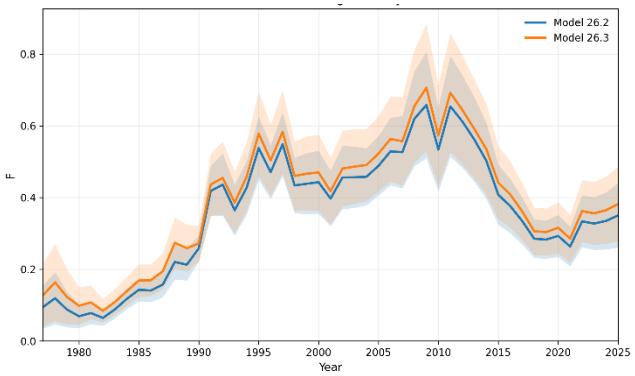

Figure 2.17: Annual fishing mortality for Model 26.2 and Model 26.3.

Management catch quantities were comparatively insensitive to model structure. Catch at $F_{40\%}$ was 175.9 kt in Model 26.2 and 174.9 kt in Model 26.3, a difference of less than 1%. The 2026 forecasted maximum ABC increased from 128.7 kt in Model 26.2 to 131.9 kt in Model 26.3 a difference of less than 2.5%. These differences were small relative to the differences in absolute biomass and fishing-mortality estimates.

Uncertainty in female spawning biomass was similar between models, but uncertainty in the fishing-mortality reference points increased under the split-sex structure. The standard error of $F_{40\%}$ increased from 0.018 in Model 26.2 to 0.038 in Model 26.3 (Table 2.3). Thus, the additional sex-specific structure changed the scale of the fishing-mortality reference points and reduced their precision without changing equilibrium yield or near-term catch advice.

The observed split-sex survey age-composition showed a weak relationship between model 26.3 derived fishing mortality and the observed female proportion among fish age 10 and older (r=0.19, p=0.39; Figure 2.19). In contrast, Model 26.3 estimated population showed a strong positive relationship (r=0.86, p<0.001; Figure 2.19 and Figure 2.20), with higher fishing mortality associated with a greater female proportion among older fish. This difference primarily reflects the limited information on older fish in the observed age compositions. The age-10+ observations from the design-based age composition data had a median implied effective sample size of less than one fish per year, resulting in

highly variable annual sex-ratio estimates with considerable uncertainty. The model-estimated numbers at age are much smoother because they integrate information from all data sources and years through the assumed population dynamics, including sex-specific growth, selectivity, mortality, and cohort survival. In particular, Model 26.3 estimates lower fishery vulnerability for larger females than for males, so periods of high fishing mortality produce a cumulative, model-implied increase in the proportion of females surviving to older ages. The observed data are therefore too sparse to independently confirm this pattern, while the strong modeled relationship partly reflects the estimated sex-specific selectivity and other structural assumptions of the model rather than a direct signal clearly present in the survey age-composition observations.

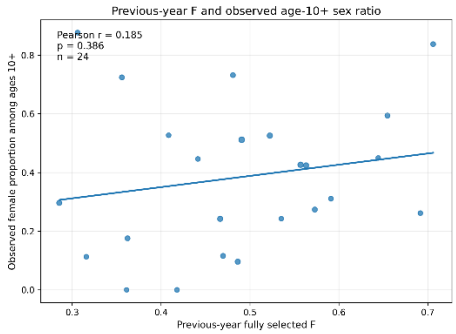

Figure 2.18: Previous-year F from Model 26.3 and observed age-10+ sex ratio from the design-based age composition data for 2000-2024.

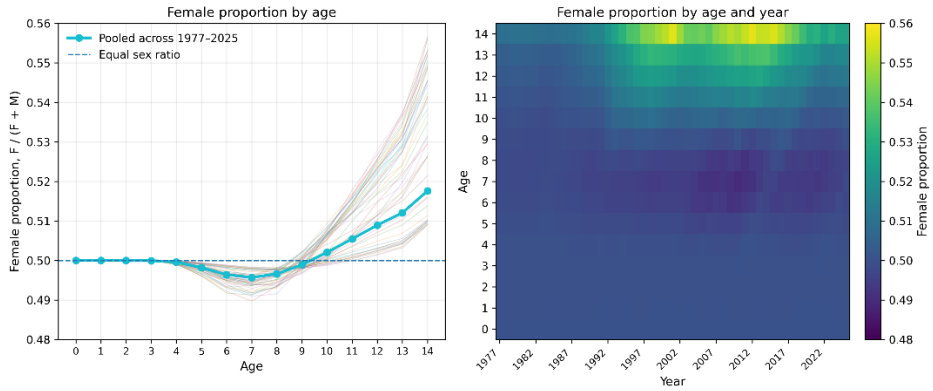

Figure 2.19: Model 26.3 modeled population sex ratios for 1977-2025.

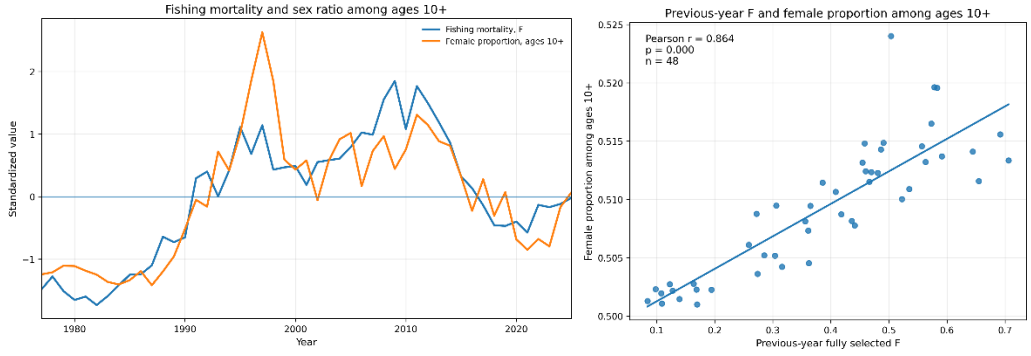

Figure 2.20: Model 26.3 standardized overall fishing mortality and sex ratio for ages 10+ (left) and ages 10+ female proportion plotted by previous-year fully selected fishing mortality.

Overall, the management conclusions were robust to the change from a single-sex to a split-sex model. Both models indicated that the stock was slightly below $B_{40\%}$, that fishing mortality was below $F_{40\%}$, and that similar catch levels were appropriate for 2026. Model 26.3 provided a more explicit representation of sex ratios over time, and sex-specific growth, weight at age, and fishery vulnerability, while Model 26.2 produced nearly the same management advice with fewer structural assumptions and a more precise estimate of $F_{40\%}$.

Recommendation

For the 2026 assessment cycle, we recommend retaining the single-sex model and continuing to use the survey age-composition estimates produced using tinyVAST. The single-sex model provides an adequate fit to the available data, is more parsimonious than the split-sex model, and produces nearly identical estimates of relative stock status and management quantities. Although the split-sex model provides a more explicit representation of sex-specific growth and fishery vulnerability, the additional complexity does not substantially change the resulting catch advice and increases uncertainty in some management reference points, particularly $F_{40\%}$.

On this basis, the available evidence supports retaining the single-sex formulation for 2026 as the primary assessment model for 2026. Nevertheless, the split-sex analysis demonstrates the potential value of explicitly accounting for sex-specific patterns in growth, selectivity, and fishery impacts. Further evaluation requires split-sex survey age compositions produced with the same model-based method. We therefore recommend requesting that the Groundfish Assessment Program produce split-sex survey age-composition estimates for the 2027 assessment cycle. Both single-sex and split-sex models should then be developed and evaluated using consistently derived survey inputs. This would allow a more direct assessment of whether the added biological realism of the split-sex model improves model performance, reduces residual patterns, or meaningfully changes estimates of stock status and management advice.

References

Barbeaux, S. J., Barnett, L., Hulson, P., Nielsen, J., Shotwell, S. K., Siddon, E., and Spies, I. 2024. Assessment of the Pacific cod stock in the Eastern Bering Sea. In Plan Team for the Groundfish Fisheries of the Bering Sea/Aleutian Islands (compiler), Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions, pp. 1–150. North Pacific Fishery Management Council, Anchorage, Alaska. https://www.npfmc.org/wp-content/PDFdocuments/SAFE/2024/EBSpcod.pdf

Chrzan, F. 1950. Investigations on the Baltic cod. Journal du Conseil International pour l'Exploration de la Mer, 16: 192–207 https://doi.org/10.1093/icesjms/16.2.192

Matta, M. E., Short, J. A., Brogan, J. D., and Chamberlin. D. W. 2026. Characteristics and reliability of groundfish age data produced by the Alaska Fisheries Science Center's Age and Growth Program: reflecting on 50 years of age determination. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-520, 222 p.

McKenzie, R. A. 1940. Nova Scotian autumn cod spawning. Journal of the Fisheries Research Board of Canada, 5: 105–120 https://doi.org/10.1139/f40-011

Morgan, M. J. and Trippel, E. A. 1996. Skewed sex ratios in spawning shoals of Atlantic cod (Gadus morhua). ICES Journal of Marine Science, 53: 820–826. https://doi.org/10.1006/jmsc.1996.0103