Application of the Woods Hole Assessment Model to Black Sea Bass

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Summary

The Woods Hole Assessment Model (WHAM) software package is maintained and developed at the Northeast Fisheries Science Center to enable state-space stock assessments, i.e. where processes such as the annual transitions in numbers-at-age (survival), natural mortality, selectivity, and catchability are treated as time- and, in some cases, age-varying random effects.

The current proposed model for management uses the Multi-WHAM version of WHAM (Miller, 2023) and models northern and souther components of the stock simultaneously. It includes movement of the northern stock to and from the southern region, VAST and Recreational CPA indices in the north and south, commercial and recreational fleets in the north and south and age composition observations for all fleets and indices. Process errors in recruitment, survival, and fleet and index selectivity are estimated.

The proposed model exhibits no retrospective patterns in fishing mortality or SSB and OSA residuals appear adequate for most of the data components.

1 Introduction

Black sea bass is currently assessed using ASAP, the Age-Structured Assessment Program (Legault and Restrepo, 1998; Miller and Legault, 2015). ASAP is a statistical catch-at-age (SCAA) model which estimates all model parameters as fixed effects.

We fit a series of models using the multi-stock, multi-region extension of WHAM for black sea bass (https://github.com/timjmiller/wham/tree/lab, Miller, 2023).

2 Methods

All code used for model fits along with results summaries can be found at https://github.com/kcurti/BSB.2023.RT.Modeling.

2.1 Early runs

The development of the multi-stock, multi-area version of WHAM was driven primarily by the needs of black sea bass and NEUS stocks of Atlantic cod. Because this extension to WHAM represents a major change to the code used to configure and estimate models, we compared results from fits of separate ASAP models and separate fits using the standard WHAM model for each region, and simultaneous fits of the regional components in the new extension of WHAM without any movement (Figure 1). All WHAM fits assume no random effects and estimate annual recruitment parameters as fixed effects. Estimates fro the latter fit and those from fits using the standard WHAM model provide identical results, but ASAP fits provide small differences in estimates for the northern component.

2.2 Model configurations

The first 18 runs that used updated and new observations included either separate indices for all surveys or fall and spring VAST indices that combined all surveys other than the recreational CPA (Table 1). Many of these runs explored alternative selectivity and age composition assumptions to reduce patterns observed in the OSA residuals for age composition observations. We then found that the age composition for fall FAST and NEAMAP indices were incorrectly calculated. Then from Run 19 onward we only used the spring VAST and Recreational CPA indices.

From Run 19-27 we still had issues reducing patterns in OSA residuals and sometimes large patterns in retrospective patterns for the northern component. We then decided to iterate among alternative assumptions about selectivity and age composition models with the northern and southern components separately to resolve diagnostic problems more efficiently. These analyses resulted in different age composition model assumptions for different fleets and indices and the use of selectivity random effects for the northern fleets and indices (Table 2).

Runs 28-34 largely used these same assumptions . For these last runs with movement, more realistic assumptions about movement and more appropriate usage of the estimates from the stock synthesis runs (Fay and McNamee, 2023). Runs 31 and 32 assumed temporal random effects on the movement rate from the north to the south and Beverton-Holt stock recruit relationships for both the north and south components, respectively, but did not prove to be reliable. Run 33 investigated bottom temperature effects on recruitment, and we found evidence of an effect on northern recruitment. Run 34 then relaxed an assumption common to many earlier runs about the estimated uncertainty in the Recreational CPA indices and allowed a scalar to be estimated in the model.

2.3 Seasonality and movement

The WHAM model assumes 11 intervals within each calendar year: 5 monthly time intervals from Jan 1 to May 31, a spawning season from June 1 to July 31, and 5 monthly intervals from August 1 to December 31. All southern fish are assumed to never move to the northern region. Northern fish are all in the northern region during the spawning period. A proportion p_1 of northern fish can move to the south each month during the last 5 months of the year, but no movement is allows from the south to the north during this period. For the first 4 months of the year a proportion p_2 of northern fish in the south can move back to the north, but no movement from the north to south is allowed during this period. In the fifth month any northern fish still in the south are assumed to move back to the north for the subsequent spawning period. We configured survival and movement to occur sequentially in each interval. Each of the two proportions are assumed constant across intervals, age, and year.

The monthly movement matrices are

$$\mathbf{p}_1 = \begin{bmatrix} 1-p_1 & p_1 \\ 0 & 1 \end{bmatrix}$$

for the portion of the year after spawning and

$$\mathbf{p}_2 = \begin{bmatrix} 1 & 0 \\ p_2 & 1-p_2 \end{bmatrix}$$

for the portion of the year before spawning.

2.3.1 Prior distribution for movement rates

The Stock Synthesis model has 2 seasons (6 months each) where a proportion P_1 of the northern component moves to the south in one season and some proportion P_2 move back to the south in the second season (Fay and McNamee, 2023). The movement matrices for each season is

$$\mathbf{P}_1 = \begin{bmatrix} 1-P_1 & P_1 \\ 0 & 1 \end{bmatrix}$$

and

$$\mathbf{P}_2 = \begin{bmatrix} 1 & 0 \\ P_2 & 1-P_2 \end{bmatrix}.$$

We approximate the monthly movement matrices as the roots $\mathbf{P}_1$ and $\mathbf{P}_2$ defined by the number of months of movement for each season (5 and 4, respectively): $\mathbf{p}_1 = \mathbf{P}_1^{\frac{1}{5}}$ and $\mathbf{p}_2 = \mathbf{P}_2^{\frac{1}{4}}$. Given the proportion parameter, the eigen decomposition of the matricies can be used to define the roots

$$\mathbf{P}_1^{1/5} = \mathbf{V}_1 \mathbf{D}_1^{\frac{1}{5}} \mathbf{V}_1^{-1}$$

$$\mathbf{P}_2^{1/4} = \mathbf{V}_2 \mathbf{D}_2^{\frac{1}{4}} \mathbf{V}_2^{-1}$$

where $\mathbf{V}_i$ and $\mathbf{D}_i$ are the matrix of eigenvectors (columnwise) and the diagonal matrix of corresponding eigenvalues of $\mathbf{P}_i$ for parameter P_i. Note, for diagonal matrices, $\mathbf{D}_i^k$ is equal to the diagonal matrix with the elements raised to the power k.

We used a parametric bootstrap approach to determine an appropriate standard deviation for the prior distribution for the movement parameters. The actual SS parameter estimates $x_1 = -1.44$ and $x_2 = 1.94$ are transformations of $P_1 = 0.11$ and $P_2 = 0.78$ such that

$$P_i = \frac{1}{1 + 2e^{-x_i}}$$

In WHAM a logit transformation is used

$$p_i = \frac{1}{1 + e^{-y_i}}.$$

We simulated 1000 values from a normal distribution with mean and standard deviation defined by the SS parameter estimate and standard error $\tilde{x}_i \sim N(x_i, SE(x_i))$. For each simulated value we constructed $\mathbf{P}_i$, took the appropriate root and calculated inverse logit for $\tilde{y}_i$. We calculated the mean and standard deviation of the values y_i. The mean values did not differ meaningfully from the transformation of the original estimates ($y_1 = -3.79$ and $y_2 = -0.79$) and the standard deviation was approximately 0.2 for both parameters.

2.4 Initial abundance at age

With the movement configuration, the northern origin fish (ages 2+) can occur in the southern region on January 1. Estimating initial numbers at age as separate parameters can be challenging even in single-stock models. To avoid challenges with estimating initial numbers at age in each region for the northern component in the two stock model, we used the equilibrium assumption described in Miller (2023). Using this assumption two parameters are estimated for each regional component: an initial recruitment and an equilibrium full F across all fleets.

2.5 Recruitment and Survival

For the northern population abundance at age 1 on January 1 (recruitment) is only allowed in the northern region, but given the monthly movement described above, older individuals that previously recruited in the northern region may occur in the southern region on January 1. Therefore, a model with survival random effects will model the transitions (survival/movement) of abundances at age of northern origin fish in each region. All of the initial runs assumed variance parameters for these random effects to be the same for northern origin fish occurring in both regions on January 1. The base model assumes very small variance for the transitions of northern fish in the southern region, which is essentially the same as the deterministic transition assumptions of a statistical catch at age model. We also allow 2DAR1 correlation for recruitment and survival for both the northern and southern components. Variance and correlation parameters for the recruitment and survival random effects are different for the northern and southern components.

2.6 Uncertainty recreational CPA index observations

The CVs provided by the analyses for the recreational catch per angler (RecCPA) ranged between 0.02 and 0.06 which the working group felt did not capture the true uncertainty in the index with regard to its relationship to stock abundance. In many of the initial runs as well as the base model we allowed a scalar multiple of the standard deviation of the log aggregate index to be estimated for these indices in the northern and southern regions. Models that successfully estimated these scalars indicated standard deviations for these surveys to be approximately 5 times the input value and this value was fixed in many preliminary runs to avoid dealing with convergence problems. However, the base model successfully estimated these scalars. The model estimates are negligibly affected by estimating these scalars, but we felt estimating these parameters allowed uncertainty in model output to be more properly conveyed.

2.7 Bottom Temperature effects on recruitment

We have bottom temperature observations for the northern and southern regions from 1963 to 2021 and estimated standard errors of those observations. We assumed AR1 models for the latent bottom temperature covariates in each region. We fit models with the bottom temperature covariate observations in the model, but without effects on recruitment. This is the null model which can be compared with models with effects on recruitment using AIC because the observations included in each model are the same. We also fit a model with effects of the regional bottom temperatures on the respective stock components. The hypothesis is that bottom temperature affects overwinter survival of fish where the fish turn from age 0 to age 1 on January 1.

We assume the covariate in year y affects recruitment in the same years because the covariate observations are from months January to March. The fish are technically already 1 year old, but there are no observations of these individuals until later in the year except possibly in fishery catches which are accumulated over the whole year. Expected log-recruitment is a linear function of log-recruitment at the previous time step and bottom temperature

$$\log R_y = \mu_R + \beta x_y + \epsilon_y$$

Comparison of the base model to one with the bottom temperature effect on natural mortality at age 1 might be of interest in the future.

2.8 Dead End Runs

We attenmpted a few further extensions of the base model. First we fit models that assumed Beverton-Holt stock recruit relationships for the north and south components. Although this fit converged nominally, the α and β parameters tended toward infinity (equivalent to steepness tending toward 1). We also fit a model with AR1 annual random effects in the movement rates from the north to the south for the northern stock component. This run did not converge.

2.9 Jitter analysis

For this analysis we simulated fixed effects parameter vectors from a normal distribution with mean equal to the optimized values and covariance equal to the hessian-based covariance matrix. From refitting the model starting at 16 different simulated parameter vectors, we found 3 cases with a lower (~2 units) marginal negative log likelihood (Figure 3). The gradients at these optimized values were satisfactory and there was no difference in parameter value among the 3 lower optimizations. In 1 of the 16 iterations, the model did not optimized satisfactorily, and in the other 12 iterations, the optimized marginal negative log-likelihood and parameter estimates were identical to the original fit. The parameters with estimates that differed most between the 2 optimization results were those associated with age composition observation dispersion parameters.

Given the revised model fit with the lower marginal NLL, we used the same jittering method with 100 simulated parameter values as starting values (Figure 4). Three of the fits failed to complete, and none of these iterations resulted in lower marginal NLLs than that from the revised model estimates. Three of the fits minimized to greater marginal NLLs, but the gradients indicate lack of convergence.

2.10 Self tests

We performed a simulation self-test where new observations were simulated conditional on all random effects estimated in the base model and the same proposed base model configuration was fit to each of the simulated data sets.

The maximum absolute gradient was greater than 1×10^{-6} for all of the simulated data sets. This appeared to be attributable to the estimation of the scalar for the standard errors of the log transformed Rec CPA indices (Figure XX).

Nearly all models converged poorly which . At least one of these scalars nearly always tended to 0. However, even for these fits with poor convergence, the SSB estimates appeared to be reliable (Figure XX). When we redid the self-tests fixing those parameters at the estimated values, the convergence was much improved.

2.11 Reference points

For equilibrium per recruit calculations, the current assessment uses the average by age of the most recent 5 years for maturity, SSB weight, catch weight, fleet selectivity, and natural mortality. The current assessment also uses the average of recruitment for years after 1999. We use these same configurations for the proposed base model. However, in this model, WHAM can calculate SPR-based reference points internally so as to propagate uncertainty in any estimated parameters into the derived reference points.

2.12 Projections

The same options in the basic single stock WHAM model are available in the multi-stock extension. To demonstrate the the projection capability, we configured a three year projection with catch set to 10kmt in 2022 and fishing at F_{40} in the subsequent two years.

Models for random effects on the bottom temperature covariate, recruitment, survival are used to predict bottom temperature and abundance at age in the projection years.

3 Results

4 Conclusions

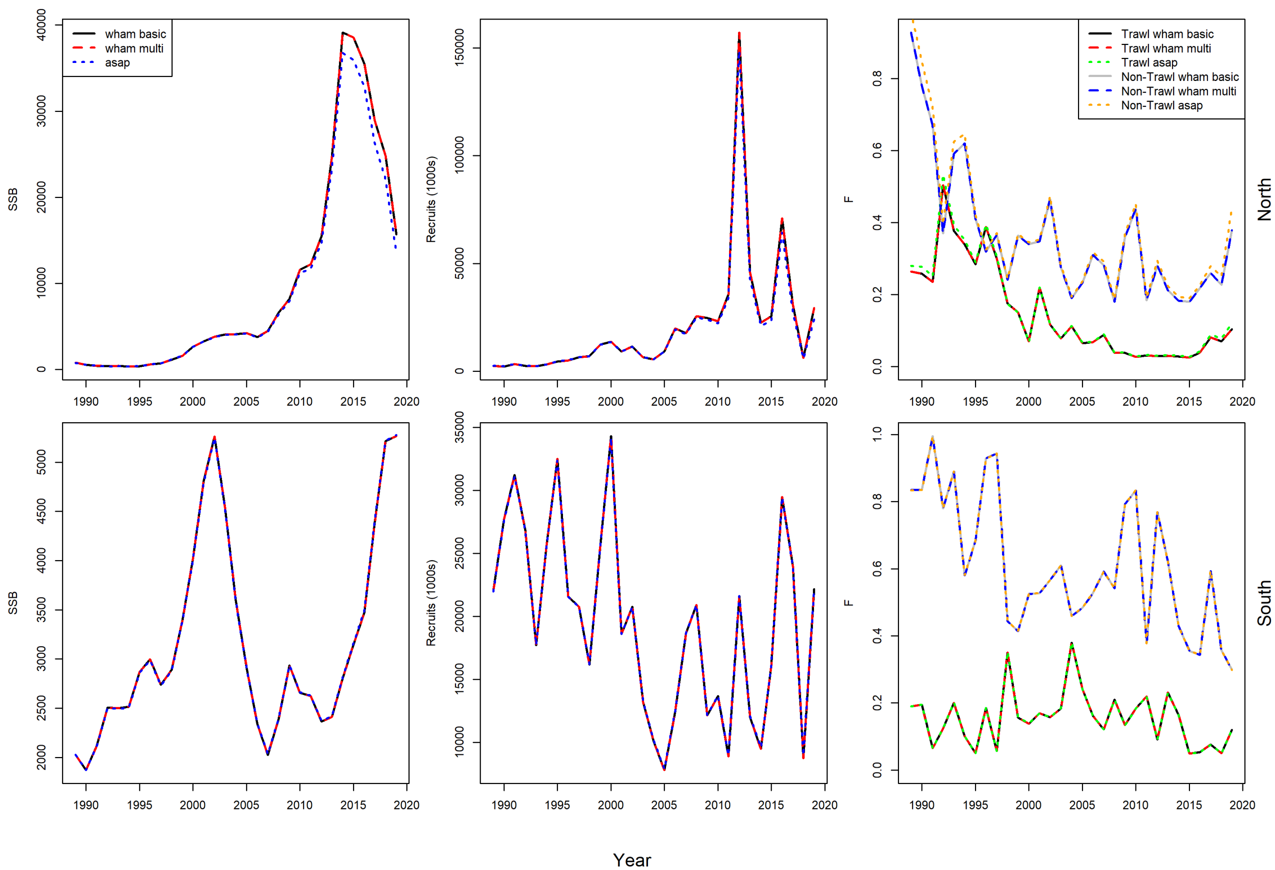

Figure 1: Comparison of recruitment, spawning stock biomass, and fishing mortality estimates from fitted models in ASAP3, the basic version of WHAM, and the multi-stock extension of WHAM to each regional component, separately, using ASAP3 model input files from the most recent management track assessment.

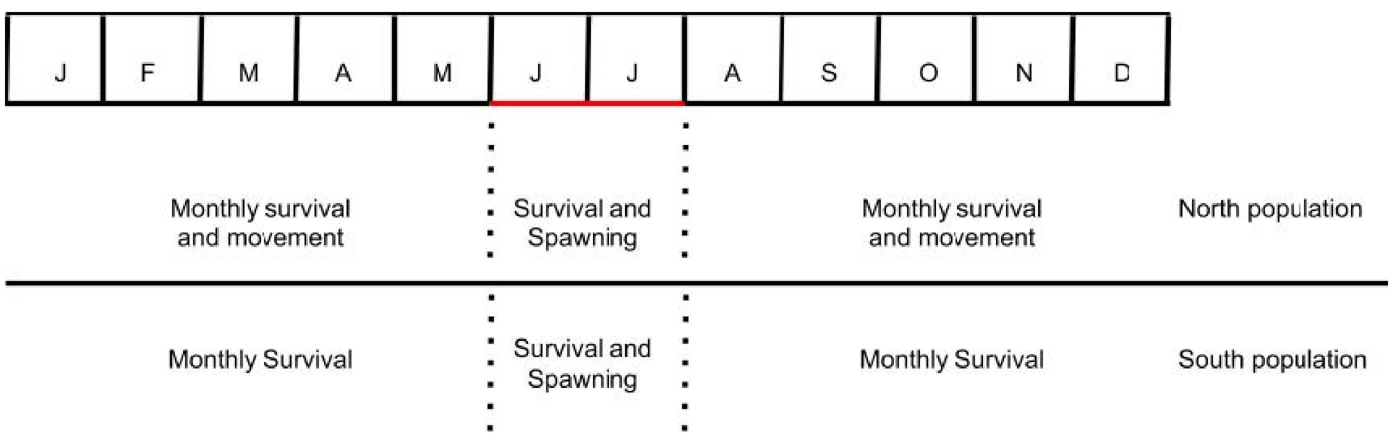

Figure 2: Diagram of intervals within the year and configuation of the dynamics of each component of the BSB population.

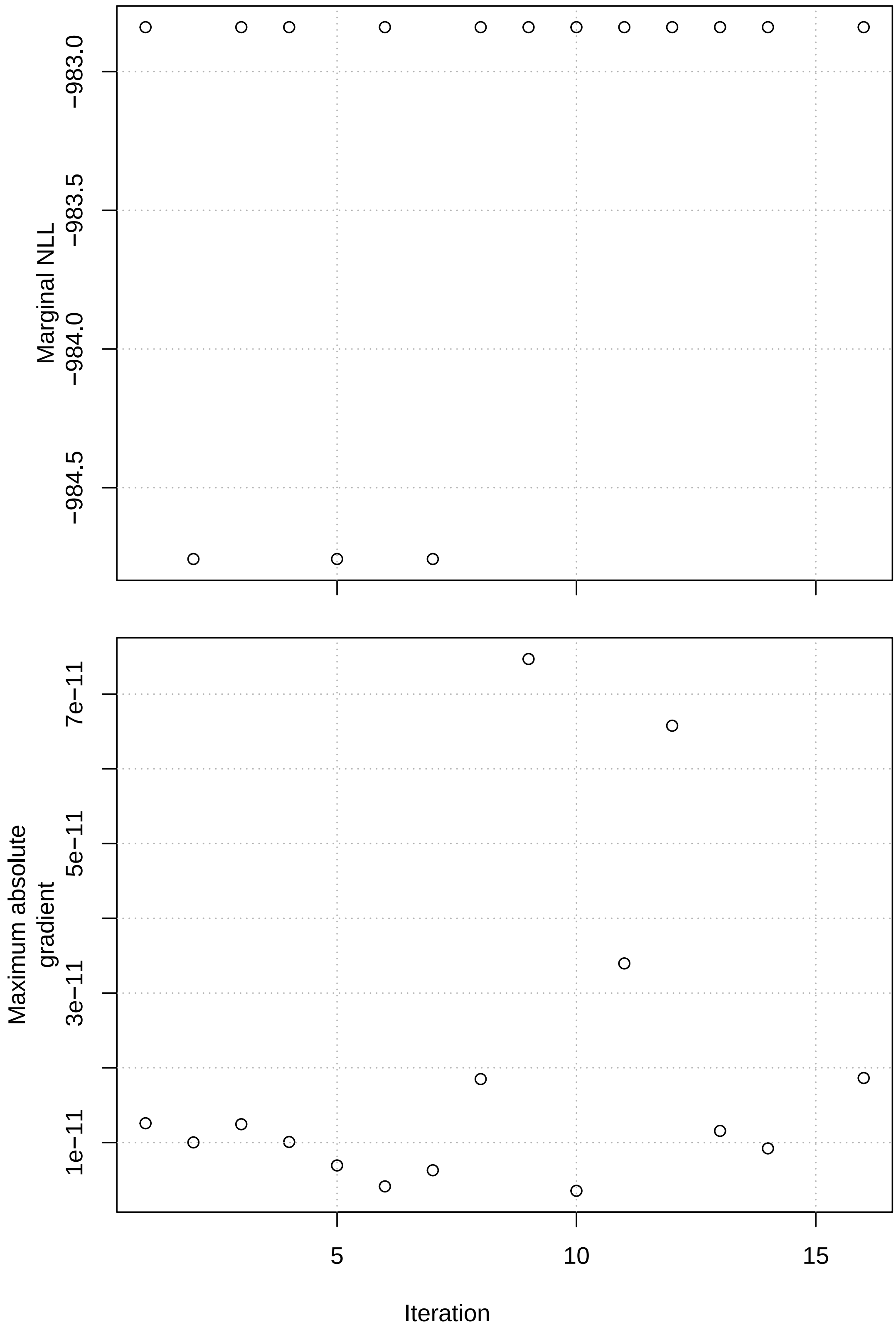

Figure 3: Marginal negative log-likelihood and maximum absolute value of gradients for each of 16 jitter iterations.

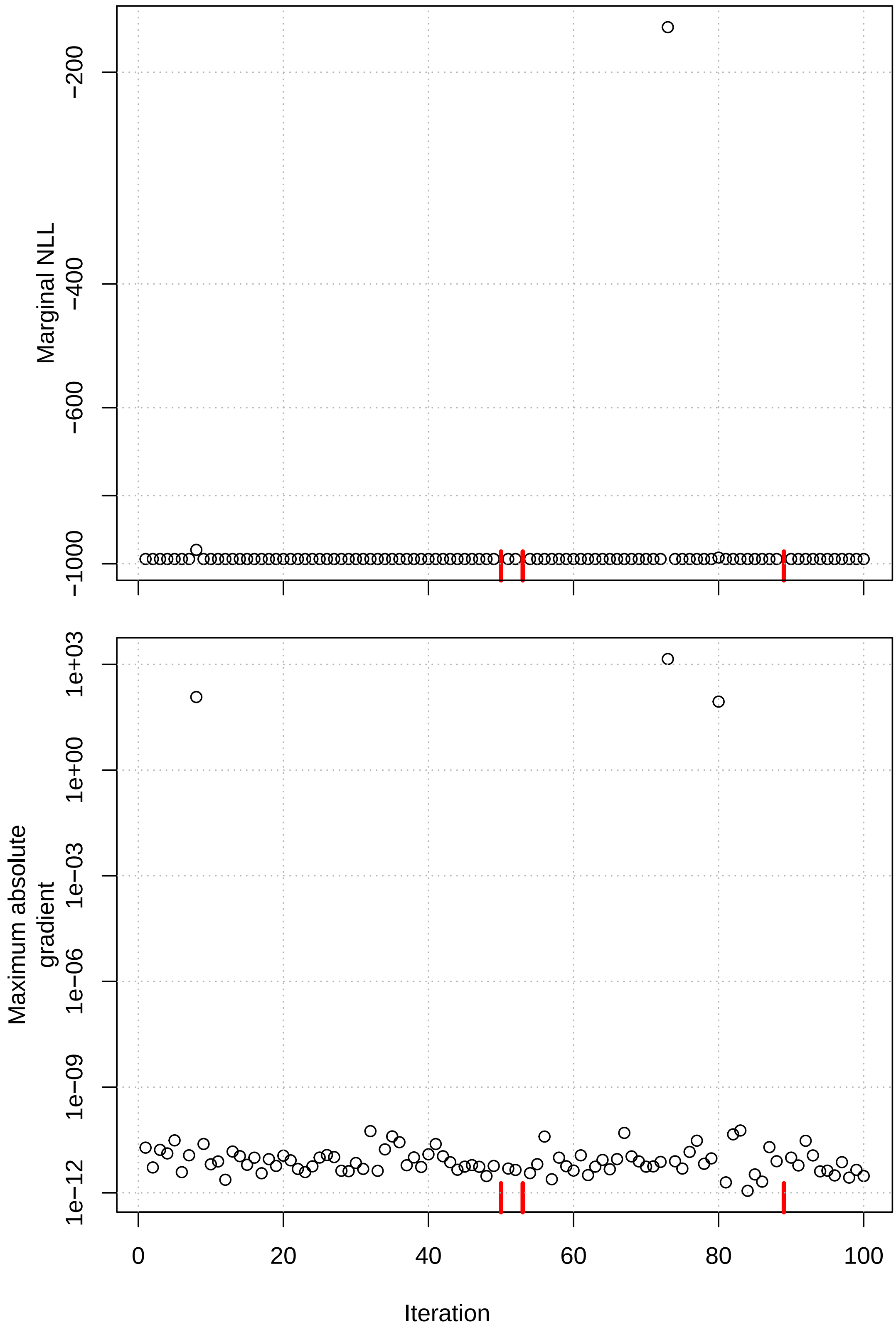

Figure 4: Marginal negative log-likelihood and maximum absolute value of gradients for each of 100 jitter iterations from revised Run 34 fit. Red rug lines indicate fits that failed to complete.

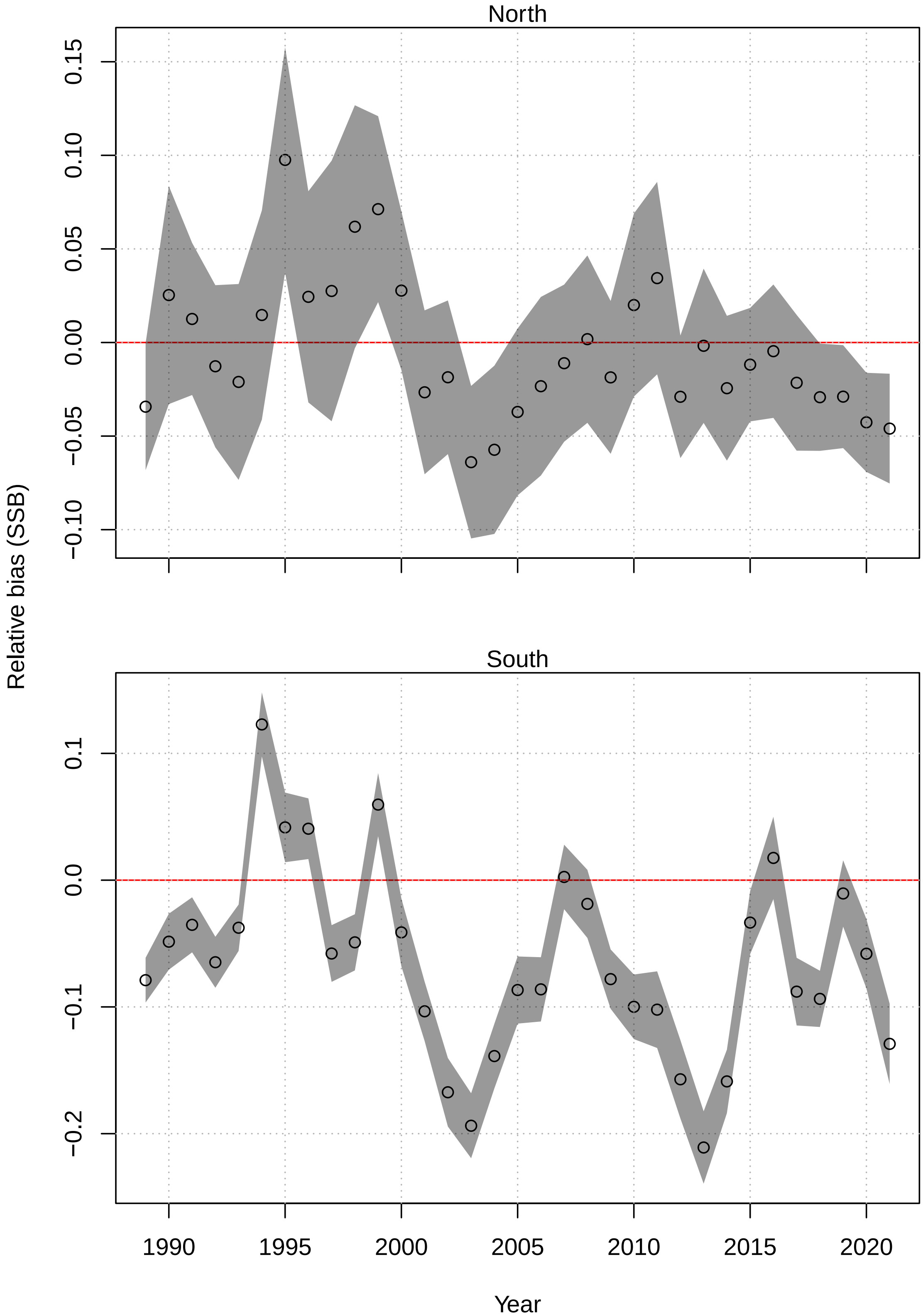

Figure 5: Relative bias of SSB estimates from conditional self test simulations.

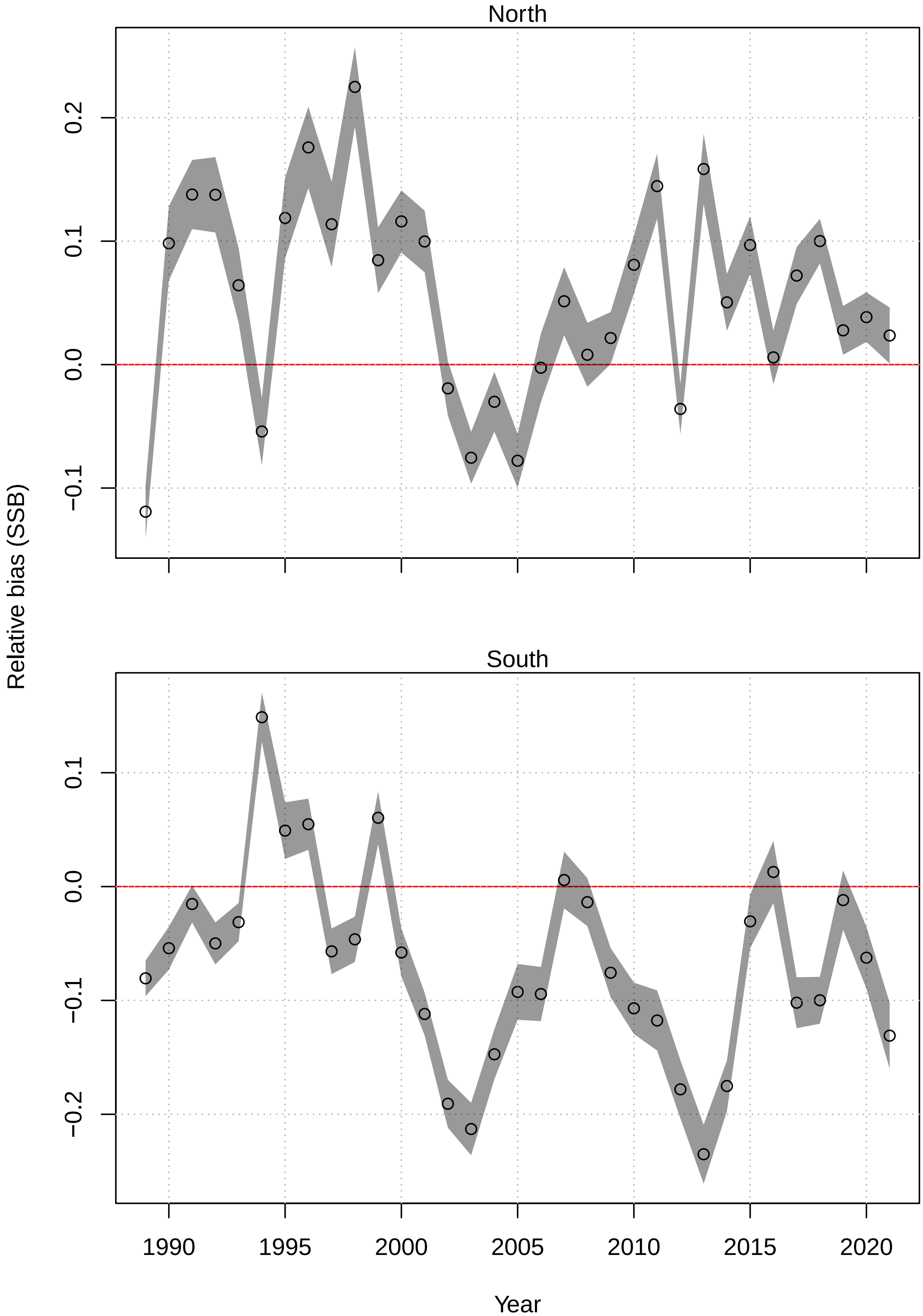

Figure 6: Relative bias of SSB estimates from conditional self test simulations with Rec CPA uncertainty scalar fixed at estimated values.

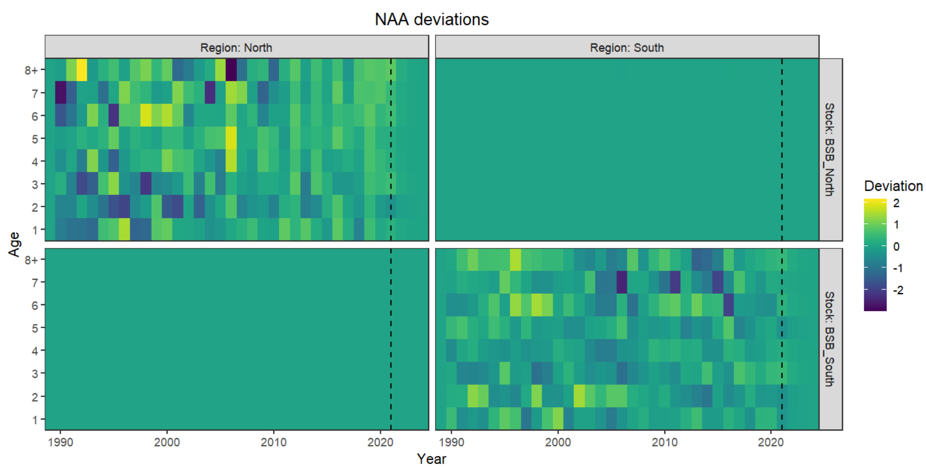

Figure 7: Estimated survival deviations from the proposed base model.

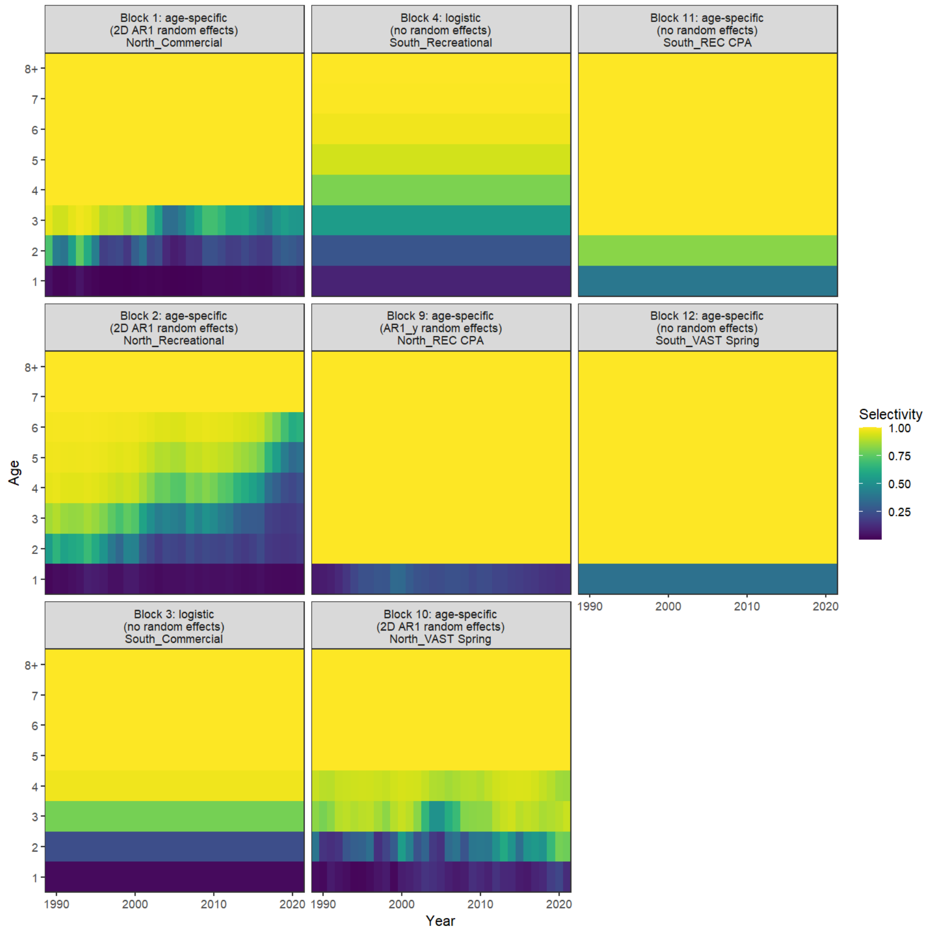

Figure 8: Estimated selectivity for indices and fleets from the proposed base model.

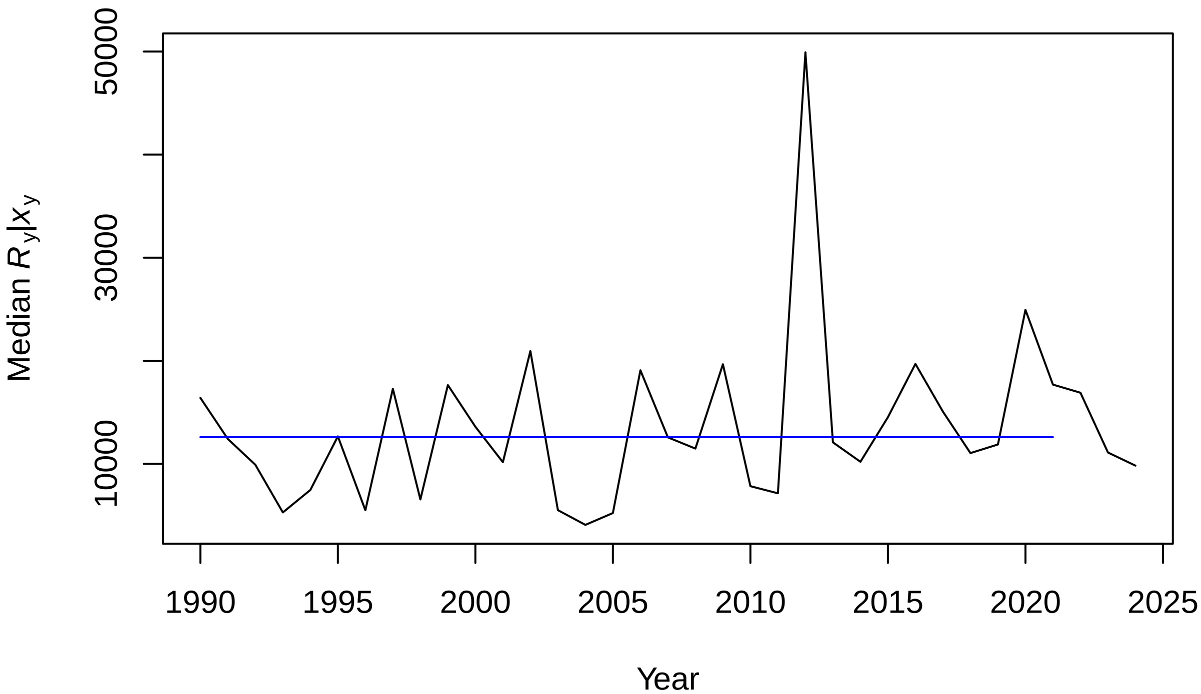

Figure 9: Median recruitment with and without temperature (x) effects.

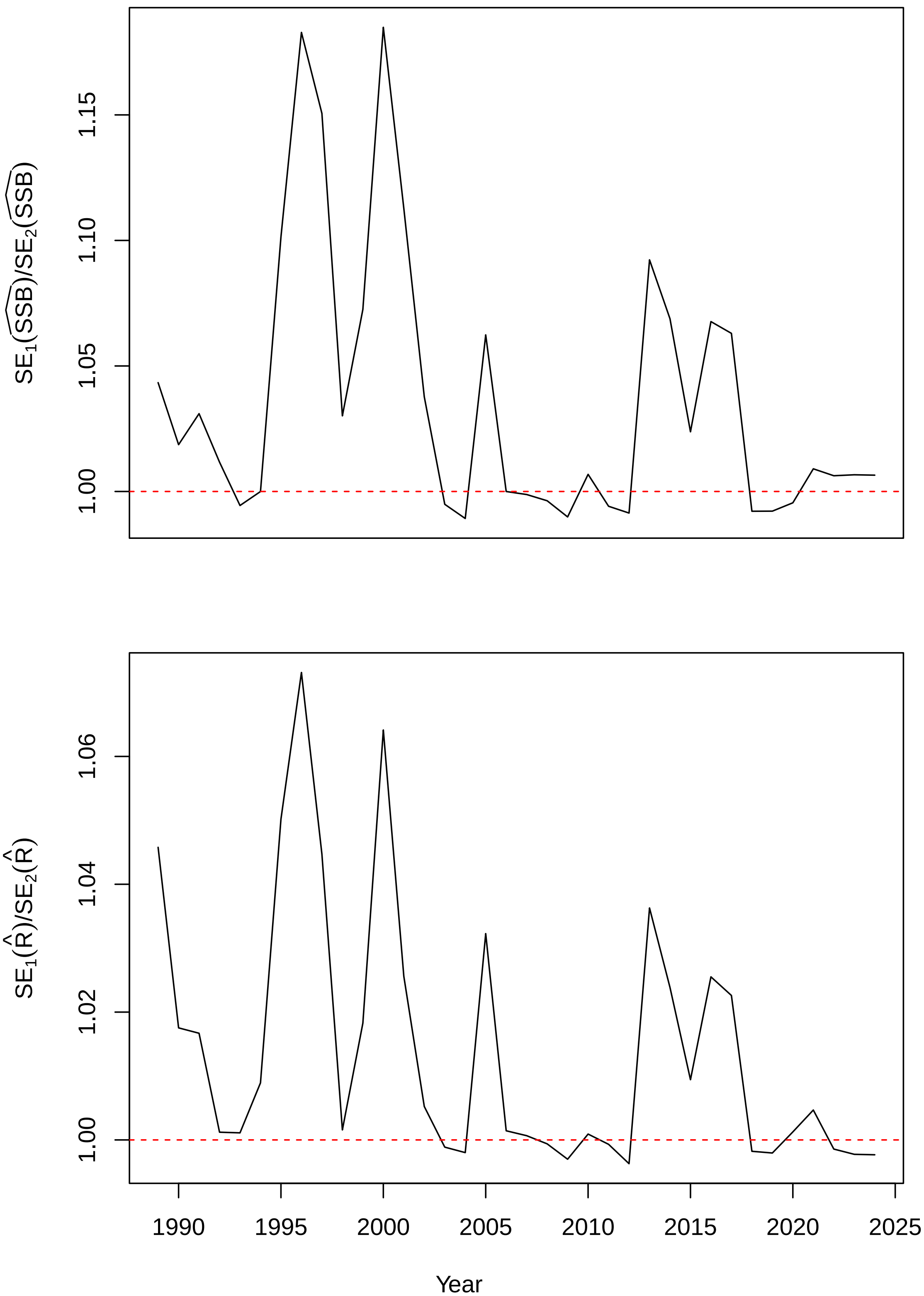

Figure 10: Ratio of standard errors of Northern component SSB (top) and recruitment (bottom) for fitted models with (SE_1) and without (SE_2) the scalar of the Recreational CPA index standard errors estimated.

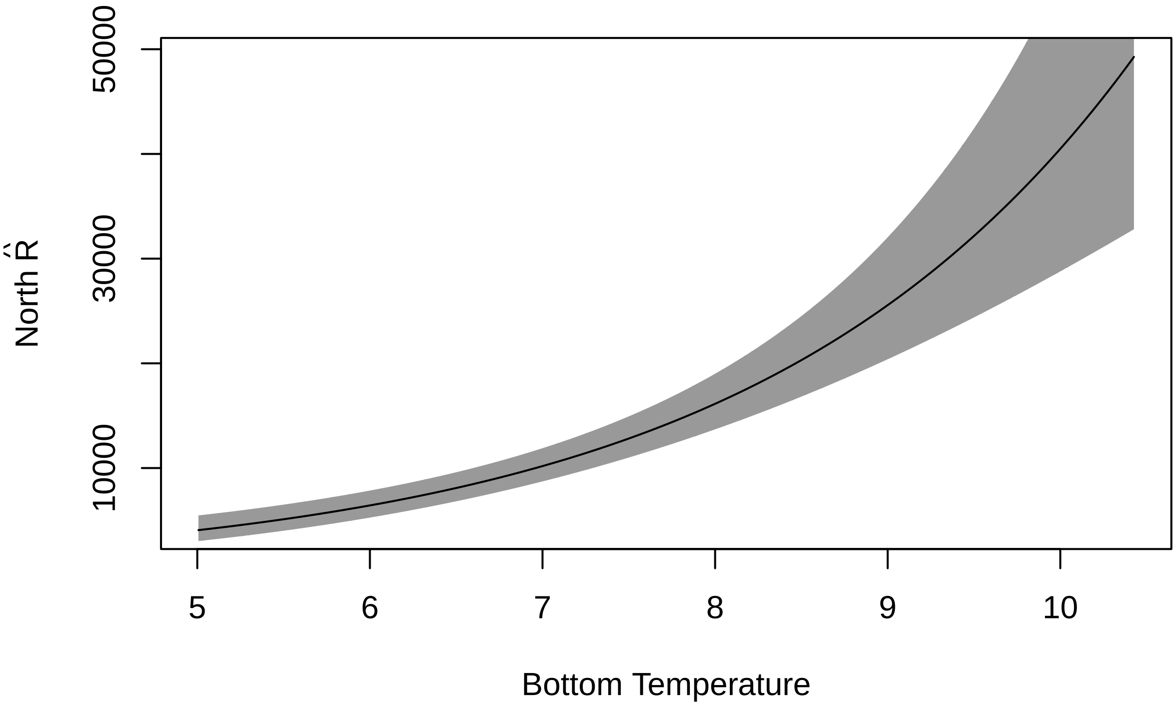

Figure 11: Expected recruitment for the northern component of the black sea bass stock as a function of bottom temperature

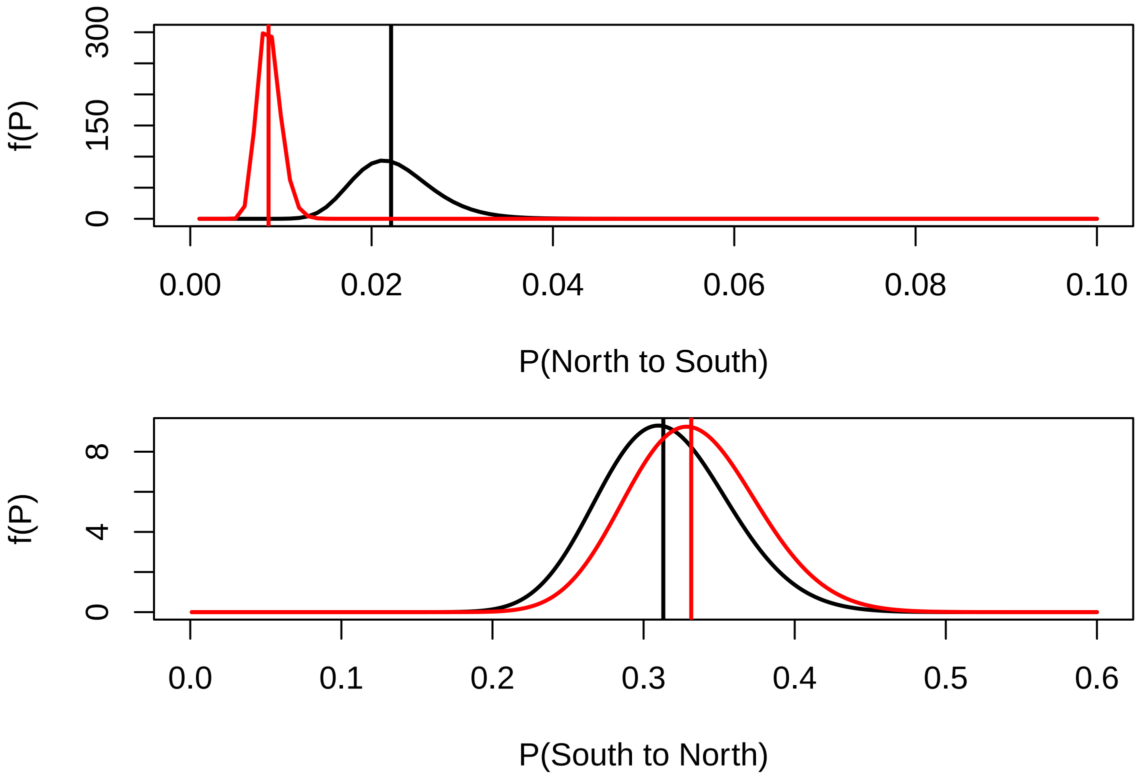

Figure 12: Prior (black) and posterior (red) distributions of movement of northern component stock from north to south (top) and south to north (bottom)

Table 1: WHAM runs with description and comments.

Run	Description	Comments
1	RE on recruitment and survival (iid). All indices with selectivities not flat topped at 2+ reexamined. Fleet selectivity (blocks, logistic) left as is.	Results in domed selectivity for several indices.
2	Like Run 1, but removed blocking for recreational fleet and assumed iid time varying random effects on logistic parameters.	Does not converge. Variance of RE went to zero implying time-varying selectivity was not supported by data.
3	Like Run 1, but estimated scalar multiplier for Rec CPA indices for north and south	Estimated multipliers were about 10 and 7 times for north and south input CVs.
4	Like Run 3, but exchange all indices (other than Rec CPA) for VAST indices	Use bridge run 9 dat files
5	Like Run 3, but remove all indices other than NEFSC, Rec CPA and NEAMAP	Use bridge run 6 dat files
6	Like Run 3, but exchange all indices (other than Rec CPA) for VAST indices (spring AND FALL)	Use bridge run 8 dat files
7	Like Run 6, but switch age comp ll for all fleets, indices to logistic-normal-miss0	re-examine selectivity for all indices
8	Like Run 7, but assume movement from north to south and north to south for north pop during non spawning seasons at rates from synthesis model.	Had to fix CVs for Rec CPA indices and sigma for North 2+ survival at values from Run 7.
9	Like Run 8, but use priors for movement with mean and sigma from synthesis model	Had to fix sigma for North 2+ survival like Run 8 and had to fix CVs for Rec CPA back to original smaller values.
10	Like Run 9, but try estimating ar1 time-varying north-south movement	Does not coverge
11	Like Run 8, but include time-varying selectivity for VAST indices	Better AIC than Run 8
12	Like Run 11, but try to estimate AR1 correlations for survival deviations	Does not coverge
13	Like Run 11, but try to estimate M	Does not coverge
14	Like Run 11, but use priors for movement rates instead of fixed	Does not coverge
15	Like Run 8, but make selectivity logistic for everything	Does not coverge
16	like Run 8, but simplify selectivities. Put selblock 5 back to logistic, simplify age-specific selectivities for Vast indices. Make Rec CPA logistic.	
17	like Run 16, but use Dirichlet	
18	Like Run 17, but set max age of fall VAST in North to age 1.	
19	Just spring VAST and rec CPA as indices. Use Dirichlet.	An error was found error in fall VAST and NEAMAP age comps. Only Spring VAST and Rec CPA indices used from this run on.

Table 1: WHAM runs with description and comments. *(continued)*

Run	Description	Comments
20	Like Run 19, but use Dirichlet-multinomial.	Expanded input sample sizes to 1000. Initially tried logistic normal with and without AR1 assumption, but those did not converge. OSA residuals look same as 19.
21	Like Run 20, but use ar1 time-varying selectivity for north vast index.	when used also for south vast index, did not converge
22	like Run 19, but just "rec" NAA re, D-M age comp, and get to time-varying selectivity for all indices.	
23	like Run 22, but include survival RE.	Tried 2dar1 correlation even with just North. there becomes a scale problem. Reverted back to none-time-varying selectivity but ar1 with age to keep the number of fixed effects down.
24	Like Run 23, but trying time-varying movement rate for north-south.	Retro for north SSB is not good
25	Like Run 24, but dirichlet instead of D-M.	
26	Like Run 25, but try rounded age comp. Not advised.	Does not coverge
27	Like Run 25, but try time-varying selectivity on fleets.	Does not coverge
28	Use selectivity and age comp based on examinations of separate runs for north and south in North.Runs and South.Runs	Big changes in selectivity and age comp model assumptions
29	Run 28, but include movement (fixed parameters).	Has projections.
30	Run 29, but use priors for movement parameters instead of fixed values.	Fine tune variance parameters for populations. I.e., North population in the south is set to be SCAA. 2dar1 now converges for north and south. Has projections. SSB40 now just uses avg recruitment from years 2000 onward.
31	Run 30, but estimate AR1 on north to south movement rate for north pop	Does not coverge
32	Run 30, but estimate B-H SR curves for North and South Populations	Steepness goes to 1 for both components
33	Run 30, but estimate temperature effects on north recruitment.	Also fits here with no effect (but temp included), temp effect on both north and south, but temp effect on NORTH is best.
34	Run 33, but Estimate log Rec CPA index sd scalars.	Proposed base model

Table 2: Configuration of Age composition likelihood, mean selectivity model, and selectivity random effects for each age composition data component in Run 34.

Data component	Age Composition Likelihood	Mean Selectivity model	Random effects configuration
North Commercial	Dirichlet-Multinomial	age-specific (flat-topped at ages $>$ 3)	2D-AR1 (age and year)
North Recreational	Logistic-normal (0s as missing)	age-specific (flat-topped at ages $>$ 6)	2D-AR1 (age and year)
South Commercial	Logistic-normal (AR1, 0s as missing)	logistic	None
South Recreational	Logistic-normal (AR1, 0s as missing)	logistic	None
North Recreational CPA	Logistic-normal (0s as missing)	age-specific (flat-topped at ages $>$ 1)	AR1 (year)
North VAST	Dirichlet-Multinomial	age-specific (flat-topped at ages $>$ 4)	2D-AR1 (age and year)
South Recreational CPA	Logistic-normal (AR1, 0s as missing)	age-specific (flat-topped at ages $>$ 2)	None
South VAST	Logistic-normal (AR1, 0s as missing)	age-specific (flat-topped at ages $>$ 1)	None

Table 3: Comparison of AIC and estimates of standard deviation of recruitment for models without any temperature effects on recruitment, with just effects on the northern component, and with effects on both components for Run 33.

	AIC	North $\widehat{\sigma}_R$
No effect	-1556.58	-0.10
North temperature effect	-1567.42	-0.33
Both temperature effects	-1566.87	-0.33

Table 4: Parameter estimates, standard errors, and confidence intervals. Rounded to 3 decimal places.

	Estimate	Std. Error	95% CI lower	95% CI upper
BSB North mean log(R) intercept	6.009	0.899	4.247	7.770
BSB North in North NAA σ (age 1)	0.718	0.101	0.545	0.945
BSB North in North NAA σ (ages 2-8+)	0.807	0.047	0.721	0.904
BSB North in South NAA σ (age 1)	0.718	0.101	0.545	0.945
BSB North in North NAA AR1 ρ age	0.091	0.094	-0.095	0.271
BSB North in North NAA AR1 ρ year	0.256	0.079	0.096	0.404
BSB South Mean Recruitment	21252.124	4468.181	14074.738	32089.604
BSB South in North NAA σ (age 1)	0.518	0.079	0.384	0.700
BSB South in North NAA σ (ages 2-8+)	0.614	0.070	0.490	0.769
BSB South in South NAA σ (age 1)	0.518	0.079	0.384	0.700
BSB South in South NAA σ (ages 2-8+)	0.614	0.070	0.490	0.769
BSB South in North NAA AR1 ρ age	-0.108	0.114	-0.323	0.118
BSB South in North NAA AR1 ρ year	0.318	0.101	0.109	0.501
BSB South in South NAA AR1 ρ age	-0.108	0.114	-0.323	0.118
BSB South in South NAA AR1 ρ year	0.318	0.101	0.109	0.501
North REC CPA fully selected q	1.020×10^{-4}	1.502×10^{-5}	7.641×10^{-5}	1.361×10^{-4}
North VAST Spring fully selected q	0.016	0.002	0.012	0.021
South REC CPA fully selected q	1.521×10^{-4}	2.024×10^{-5}	1.171×10^{-4}	1.974×10^{-4}
South VAST Spring fully selected q	0.015	0.002	0.011	0.019
Block 1: North Commercial Mean Selectivity for age 1	0.019	0.015	0.004	0.088
Block 1: North Commercial Mean Selectivity for age 2	0.326	0.173	0.094	0.694
Block 1: North Commercial Mean Selectivity for age 3	0.814	0.128	0.455	0.958
Block 1: North Commercial Mean Selectivity for age 4	1.000			
Block 1: North Commercial Mean Selectivity for age 5	1.000			
Block 1: North Commercial Mean Selectivity for age 6	1.000			
Block 1: North Commercial Mean Selectivity for age 7	1.000			
Block 1: North Commercial Mean Selectivity for age 8+	1.000			
Block 2: North Recreational Mean Selectivity for age 1	0.029	0.026	0.005	0.153
Block 2: North Recreational Mean Selectivity for age 2	0.325	0.199	0.075	0.740
Block 2: North Recreational Mean Selectivity for age 3	0.558	0.226	0.173	0.884
Block 2: North Recreational Mean Selectivity for age 4	0.787	0.157	0.371	0.959
Block 2: North Recreational Mean Selectivity for age 5	0.888	0.097	0.542	0.981
Block 2: North Recreational Mean Selectivity for age 6	0.950	0.050	0.709	0.993

Table 4: Parameter estimates, standard errors, and confidence intervals. Rounded to 3 decimal places. *(continued)*

	Estimate	Std. Error	95% CI lower	95% CI upper
Block 2: North Recreational Mean Selectivity for age 7	1.000			
Block 2: North Recreational Mean Selectivity for age 8+	1.000			
Block 3: South Commercial a_{50}	2.465	0.124	2.229	2.713
Block 3: South Commercial 1/slope (increasing)	0.401	0.034	0.340	0.472
Block 4: South Recreational a_{50}	2.843	0.233	2.405	3.314
Block 4: South Recreational 1/slope (increasing)	0.822	0.101	0.645	1.042
Block 9: North REC CPA Mean Selectivity for age 1	0.158	0.067	0.065	0.336
Block 9: North REC CPA Mean Selectivity for age 2	1.000			
Block 9: North REC CPA Mean Selectivity for age 3	1.000			
Block 9: North REC CPA Mean Selectivity for age 4	1.000			
Block 9: North REC CPA Mean Selectivity for age 5	1.000			
Block 9: North REC CPA Mean Selectivity for age 6	1.000			
Block 9: North REC CPA Mean Selectivity for age 7	1.000			
Block 9: North REC CPA Mean Selectivity for age 8+	1.000			
Block 10: North VAST Spring Mean Selectivity for age 1	0.073	0.027	0.035	0.148
Block 10: North VAST Spring Mean Selectivity for age 2	0.403	0.092	0.242	0.589
Block 10: North VAST Spring Mean Selectivity for age 3	0.893	0.060	0.710	0.966
Block 10: North VAST Spring Mean Selectivity for age 4	0.926	0.039	0.804	0.975
Block 10: North VAST Spring Mean Selectivity for age 5	1.000			
Block 10: North VAST Spring Mean Selectivity for age 6	1.000			
Block 10: North VAST Spring Mean Selectivity for age 7	1.000			
Block 10: North VAST Spring Mean Selectivity for age 8+	1.000			
Block 11: South REC CPA Selectivity for age 1	0.399	0.070	0.273	0.541
Block 11: South REC CPA Selectivity for age 2	0.824	0.076	0.626	0.929
Block 11: South REC CPA Selectivity for age 3	1.000			
Block 11: South REC CPA Selectivity for age 4	1.000			
Block 11: South REC CPA Selectivity for age 5	1.000			
Block 11: South REC CPA Selectivity for age 6	1.000			
Block 11: South REC CPA Selectivity for age 7	1.000			
Block 11: South REC CPA Selectivity for age 8+	1.000			
Block 12: South VAST Spring Selectivity for age 1	0.370	0.080	0.231	0.535
Block 12: South VAST Spring Selectivity for age 2	1.000			
Block 12: South VAST Spring Selectivity for age 3	1.000			

Table 4: Parameter estimates, standard errors, and confidence intervals. Rounded to 3 decimal places. *(continued)*

	Estimate	Std. Error	95% CI lower	95% CI upper
Block 12: South VAST Spring Selectivity for age 4	1.000			
Block 12: South VAST Spring Selectivity for age 5	1.000			
Block 12: South VAST Spring Selectivity for age 6	1.000			
Block 12: South VAST Spring Selectivity for age 7	1.000			
Block 12: South VAST Spring Selectivity for age 8+	1.000			
Block 1: North Commercial Selectivity RE σ	0.406	0.116	0.233	0.710
Block 1: North Commercial Selectivity RE AR1 ρ (age)	0.479	0.138	0.339	0.940
Block 1: North Commercial Selectivity RE AR1 ρ (year)	0.590	0.082	0.582	0.967
Block 2: North Recreational Selectivity RE σ	0.208	0.030	0.156	0.277
Block 2: North Recreational Selectivity RE AR1 ρ (age)	0.519	0.063	0.650	0.910
Block 2: North Recreational Selectivity RE AR1 ρ (year)	0.733	0.024	0.874	0.983
Block 9: North REC CPA Selectivity RE σ	0.257	0.067	0.154	0.428
Block 9: North REC CPA Selectivity RE AR1 ρ (year)	0.659	0.077	0.543	0.988
Block 10: North VAST Spring Selectivity RE σ	0.745	0.151	0.501	1.109
Block 10: North VAST Spring Selectivity RE AR1 ρ (age)	0.116	0.249	-0.276	0.635
Block 10: North VAST Spring Selectivity RE AR1 ρ (year)	0.341	0.168	0.182	0.845
North Commercial in North age comp, Dirichlet-multinomial: dispersion (ϕ)	54.899	7.007	42.749	70.503
North Recreational in North age comp, logistic-normal: σ	2.832	0.337	2.243	3.576
South Commercial in South age comp, logistic-normal: σ	33.924	3.453	27.789	41.413
South Commercial in South age comp, logistic-normal: ρ	0.719	0.061	0.585	0.823
South Recreational in South age comp, logistic-normal: σ	27.914	4.330	20.596	37.831
South Recreational in South age comp, logistic-normal: ρ	0.910	0.027	0.842	0.951
North REC CPA in North age comp, logistic-normal: σ	4.301	0.395	3.592	5.149
North VAST Spring in North age comp, Dirichlet-multinomial: dispersion (ϕ)	28.550	3.233	22.868	35.644
South REC CPA in South age comp, logistic-normal: σ	27.466	4.520	19.893	37.921
South REC CPA in South age comp, logistic-normal: ρ	0.927	0.024	0.864	0.962
South VAST Spring in South age comp, logistic-normal: σ	48.175	3.878	41.143	56.408
South VAST Spring in South age comp, logistic-normal: ρ	0.661	0.057	0.542	0.762
stock BSB North μ from North to South (intercept)	0.009	0.001	0.006	0.011
stock BSB North μ from South to North (intercept)	0.332	0.043	0.253	0.421
North REC CPA log-index observation SD scalar	4.736	1.433	2.618	8.569
South REC CPA log-index observation SD scalar	5.306	1.270	3.319	8.482
Ecov North BT: μ	6.803	0.190	6.431	7.175
Ecov North BT: σ	1.131	0.109	0.937	1.367

Table 4: Parameter estimates, standard errors, and confidence intervals. Rounded to 3 decimal places. *(continued)*

	Estimate	Std. Error	95% CI lower	95% CI upper
Ecov North BT: AR1 ρ	0.290	0.121	0.040	0.506
Ecov South BT: μ	7.606	0.148	7.316	7.895
Ecov South BT: σ	1.017	0.092	0.852	1.215
Ecov South BT: AR1 ρ	0.149	0.124	-0.099	0.380
BSB North Recruitment Ecov: North BT β_1	0.460	0.117	0.232	0.688

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