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Update of Base Case SSM and Investigation of Impacts of EU-Spain 3L Survey Data for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO

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Abstract

The Management Strategy Evaluation (MSE) for Greenland Halibut NAFO Subarea 2 and Divisions 3KLMNO is in review for 2023. To prepare, the SSM was run using the most recent survey indices and catch data to prepare for MSE simulations using updated SSM outputs. A suggestion was made to also investigate the impact of survey indices for EU-Spain Div. 3L, and whether or not their inclusion in the SSM impacts stock trends significantly. Two sensitivity models were run for the Greenland Halibut. One model included 3L data as a separate index, and another included 3L data in aggregate with the EU-Spain 3NO index. The base case model did not include 3L data from the EU-Spain survey. Outputs were compared between the sensitivity runs and the base case, and a retrospective analysis was done to further explore any disparities between models. Values of relative bias and Mohn's rho were derived to quantitatively compare retrospective fits. We concluded that EU-Spain 3L survey indices have little impact on parameter estimates and the overall stock trends.

Introduction

In preparation for the upcoming 2023 Management Strategy Evaluation (MSE) review of the Greenland halibut stock in NAFO Subarea 2 and Divisions 3KLMNO, assessment inputs were updated with survey data up to 2021. The state-space model (SSM) used for the assessment follows directly from Regular et al. (**2017**), but with updated Canadian and European survey indices and catches (see **Regular 2022** for details). However, there were additional considerations to include Div. 3L survey data in the assessment model. Previous model iterations had omitted 3L, but exploratory data analyses suggest these data may provide complementary information to the assessment model (**Regular 2022**). Whether these data change or improve the assessment is the question explored in this study.

We ran three assessment models with slightly different data inputs but identical structure. The base case follows previous iterations of the SSM, which used Canadian Fall 2J3K, Autumn 3LNO, and Spring 3LNO surveys, and EU-Spain 3NO and European 3M 0-1400m surveys; this model is referred to herein as the '3NO' model. One sensitivity run replaced the EU-Spain 3NO survey data with combined EU-Spain 3LNO survey data, which we refer to as the '3LNO' model. The second sensitivity run added the separated EU-Spain 3L survey data alongside the EU-Spain 3NO survey data, which we refer to as the '3NO+3L' model.

Methods

The SSM described in Regular et al. (**2017**) (formula replicated in **Appendix A**) has been updated using data listed in Regular (**2022**) (replicated in **Appendix B**). A similar update was conducted in 2020 (**Regular 2020**). For the 2020 update, various sensitivity runs were conducted to determine the most appropriate way to address potential biases introduced by partial coverage of deep strata by Canadian surveys. It was determined that data for ages 8+ should be excluded from the Canadian indices under such circumstances. Deep strata were not covered by the Canada Autumn 2J3K survey in 2018, 2019, and 2021 (**Rideout et al. 2022**); indices for ages 8+ were therefore excluded from the analyses presented here.

For this update, the potential utility of the EU-Spain survey of 3L is considered. The model runs were defined as follows:

a) **3NO (Base)**: Uses EU-Spain Div. 3N and 3O survey indices as an aggregate index. EU-Spain Div. 3L survey indices are excluded. This is identical to past base case SSM for Greenland halibut.
b) **3LNO**: Uses EU-Spain Div. 3L, 3N, and 3O survey indices as an aggregate index.
c) **3NO+3L**: Uses EU-Spain Div. 3N and 3O survey indices as an aggregate index, and EU-Spain Div. 3L survey indices as a separate index.

Outputs from three separate SSMs were generated, including survey, catchability, selectivity, and biomass trends, as well their associated residuals. A 7-year retrospective analysis (ranging from 2014 to 2020) was also performed to compare model estimates, and values of relative bias in biomass and Mohn's rho (**Mohn 1999**) were derived from biomass for each model. Relative bias is defined as

$$b_{y,m} = \left(B'_{y,m} - B_{y,m}\right)/B_{y,m},$$

where $B'_{y,m}$ is the biomass of the last year for year y's retrospective, $B_{y,m}$ is the biomass of year y from the full assessment model, and m indicates the sensitivity run. Mohn's rho is defined as the average relative bias for each model,

$$\rho_m = \frac{\Sigma_y b_{y,m}}{N},$$

where $N = 7$ is the number of retrospective years and is the same across models.

Results

Assessments of key stock quantities such as biomass and abundance were effectively the same across all three models (Figure 1). All other outputs showed little variation and residual patterns showed minimal changes between models. The 3NO model results deviated from the 3LNO and

3NO+3L models slightly due the exclusion of EU-Spain 3L survey indices altogether. Outputs compared across all models can be found in **Appendix C**. Retrospective diagnostics were also similar across all three models (Figure 2). While the 3NO+3L model had the lowest Mohn's rho, measures of relative bias in retrospective estimates between years were low (<0.07) and similar across models (Figure 3).

Discussion

Results from compared analyses of model retrospectives indicated that all models displayed a reasonable level of variability in biomass trends in recent years. Furthermore, despite some parameters estimates and stock trends from the models with 3L survey indices differing slightly from the model run without these indices (i.e. the 3NO base model), these differences were not substantive. Overall, the EU-Spain 3L survey indices were shown to have had little impact on Greenland halibut SSM results.

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Figures

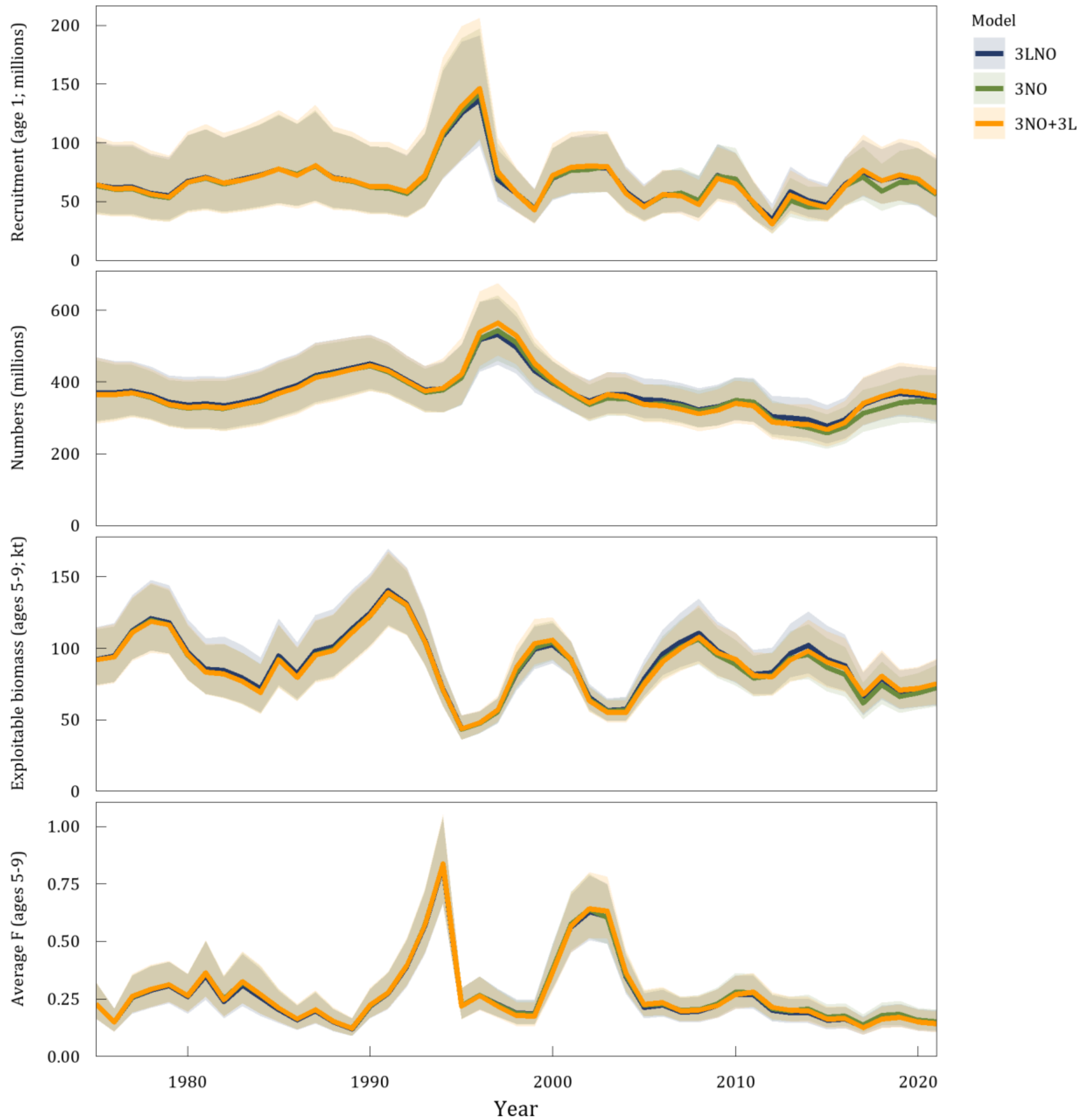

Figure 1. Estimates of recruitment (age 1), numbers, exploitable biomass (ages 5-9), and average F (ages 5-9), with 95% confidence intervals.

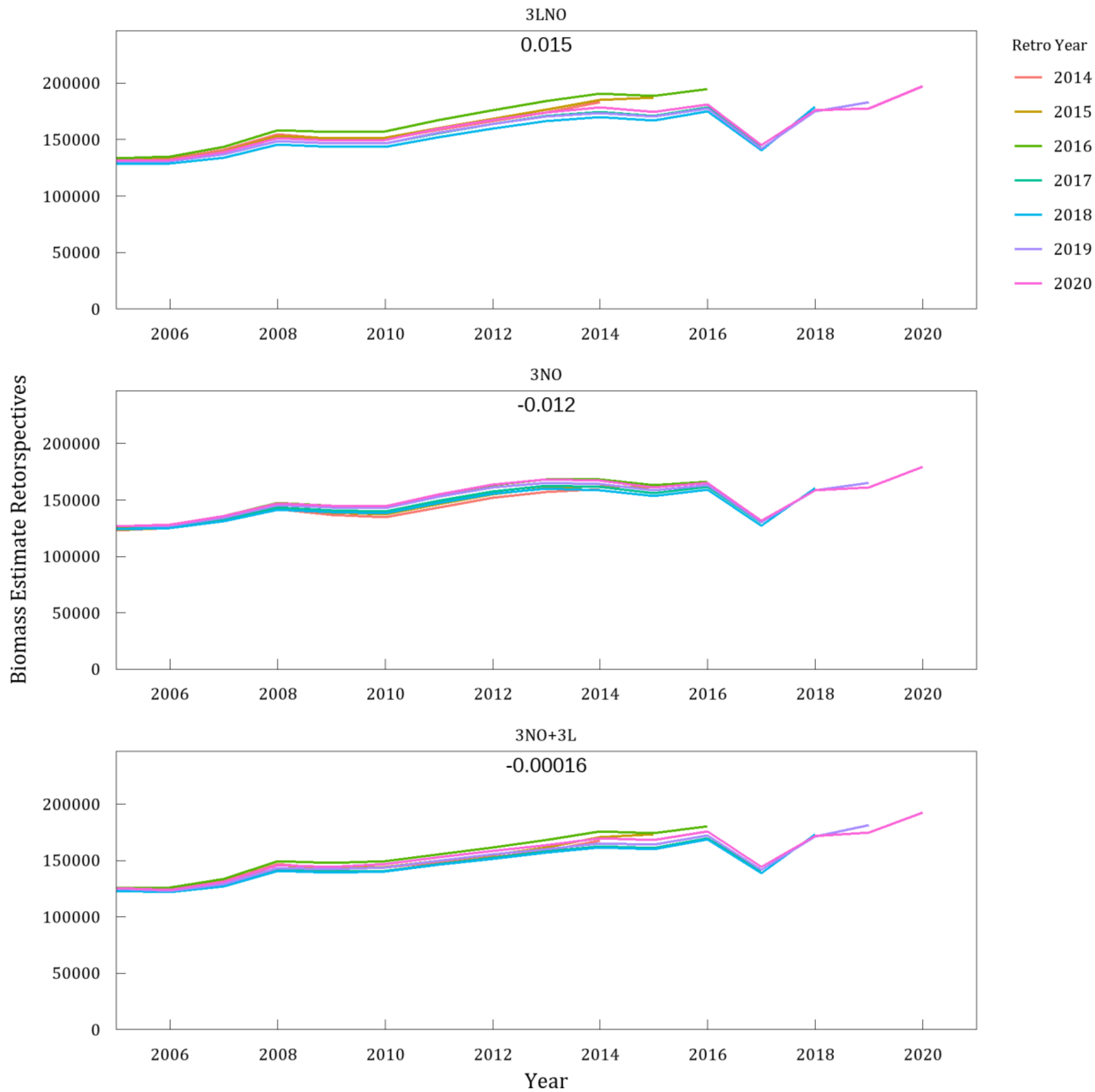

Figure 2. Retrospective patterns from SSM sensitivity tests examining the affect of Div. 3L survey indices on stock trends. Mohn's rho is indicated in each panel.

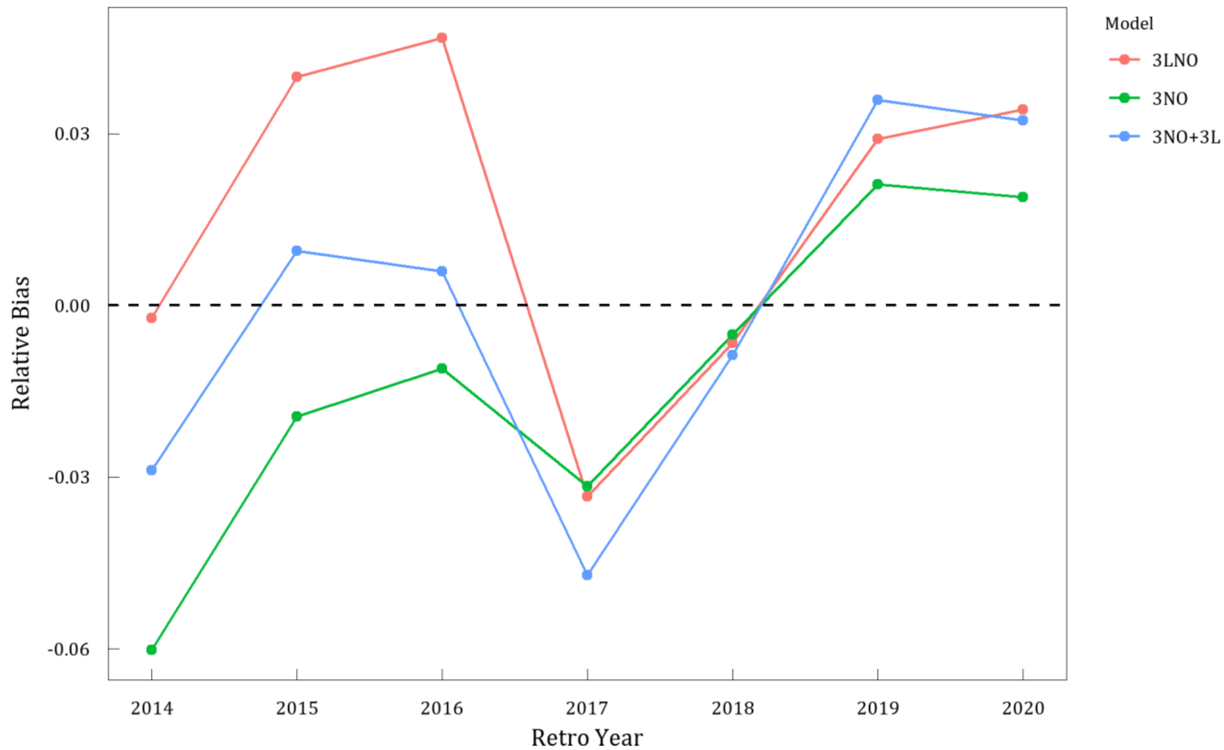

Figure 3. Relative bias of SSM retrospectives used to calculate Mohn's rho values.

Appendix A: Model description

The stock assessment model used here is similar to the state-space assessment model (SAM) by Nielsen and Berg (2014). State-space models contain two parts. The first part describes the process underlying the unobserved states of stock sizes and fishing moralities, which are related to indirect measurements modeled via observation equations. The process and observation equations used in this model are described below and associated fixed, random, and assumed parameters are listed in Table 1.

Process equations

Here a stochastic cohort model with a plus group was used to model the unobserved population states:

$$\log(N_{a,y}) = \begin{cases} \log(N_{a-1,y-1}) - Z_{a-1,y-1} + \delta_{a,y}, & a < A \\ \log\{N_{a-1,y-1}\exp(-Z_{a-1,y-1}) + N_{a,y-1}\exp(-Z_{a,y-1})\} + \delta_{a,y}, & a = A. \end{cases} \quad (1)$$

The ages are 1-10+ and years are 1975-2021. $Z_{a,y} = F_{a,y} + M_{a,y}$, where $M_{a,y} = 0.12$ is the base case assumption. Recruitment, $N_{1,1}, \ldots N_{1,Y}$, is treated as uncorrelated lognormal random variable,

$$\log(N_{1,y}) \overset{iid}{\sim} N(r, \sigma_r^2). \quad (2)$$

This seems reasonable because preliminary analyses with a year-class strength model did not indicate major temporal variation in recruitment. The numbers at age's 2-10+ in the first year are treated as unknown and free parameters to estimate. The process errors are assumed to have a normal distribution with zero mean but auto-correlated over ages and years because process errors should be more similar for fish that are close together in age and time. These errors are assumed to have a stationary distribution derived from a lag 1 autoregressive process in both age and year so that

$$Cov\{\delta_{a,y}, \delta_{a-j,y-k}\} = \frac{\sigma_\delta^2 \varphi_{\delta,\text{age}}^j \varphi_{\delta,\text{year}}^k}{(1-\varphi_{\delta,\text{age}}^2)(1-\varphi_{\delta,\text{year}}^2)}, \quad Corr\{\delta_{a,y}, \delta_{a-j,y-k}\} = \varphi_{\delta,\text{age}}^j \varphi_{\delta,\text{year}}^k. \quad (3)$$

Initial runs, however, indicated that patterns in auto-correlated process errors appeared to have the same effect as recruitment variation. Age and year auto-correlation ($\varphi_{\delta,\text{age}}$, and $\varphi_{\delta,\text{year}}$, respectively) in process errors were therefore fixed to be near zero (~0.00001), similar to a standard SAM, to minimize potential confounding with recruitment.

Catches are modeled using the Baranov catch equation,

$$C_{a,y} = N_{a,y}\{1 - \exp(-Z_{a,y})\}F_{a,y}/Z_{a,y} \quad (4)$$

and total predicted landings were calculated by summing the product of predicted catch numbers and catch weights across ages,

$$L_y = \sum_{a=1}^{A} C_{a,y} W_{a,y}. \quad (5)$$

Fishing moralities are modeled as a stochastic process similar to the δ process errors, with

$$Cov\{\log(F_{a,y}),\log(F_{a-j,y-k})\} = \frac{\sigma_F^2 \varphi_{F,\mathrm{age}}^j \varphi_{F,\mathrm{y}}^k}{(1-\varphi_{F,\mathrm{age}}^2)(1-\varphi_{F,\mathrm{year}}^2)}. \tag{6}$$

However, there are no commercial catches at ages 1 and 2 so the F's for these ages were fixed at zero for these ages. Greenland halibut are rarely reported as catch at age 3 and catches at age 4 tend to be much lower than older ages. Hence, $\varphi_{F,a}$ was fixed to be zero for ages 3 and 4 so that F's at these ages are correlated over years but not ages. $F_{3-4,1}$ are like free parameters. In summary, F's for ages 1 and 2 will be 0, F's for ages 3-4 are assumed to be independent across age but they are allowed to be autocorrelated across years, and F's for ages 5-10+ are allowed to be autocorrelated across age and year. The later age groups are commonly observed in the fishery and the F's they experience are expected to be similar for fish that are close together in age and time.

Observation equations

Survey data

The observation models are similar to the traditional approaches used for Northwest Atlantic fish stocks. Let $I_{s,a,y}$ denote the age-based abundance index for survey s. Let t be the midpoint of the survey dates which is expressed in a fraction of the year. The model predicted catch for survey s is

$$\log(I_{s,a,y}) = \log(q_{s,a}) + \log(N_{a,y}) - t_{s,y}Z_{a,y} + \varepsilon_{s,a,y}, \;\; \varepsilon_{s,a,y} \overset{iid}{\sim} N(0,\sigma_{s,a}^2). \tag{7}$$

The $-t_{s,y}Z_{a,y}$ term projects beginning-of-year log-abundance to the time of each survey. This model was used for all survey ages and years, including the plus group age for plus group survey indices. The $q_{s,a}$'s are time-invariant catchability parameters estimated independently for each survey and age. Survey variances were split out and self-weighted by age groups 1-3, 4-7, and 8-10+ in the base-case model. Weighting by survey and age group minimized some large residual patterns observed at younger ages in earlier versions of this model. The variance of each survey, $\sigma_{s,a}^2$, is not estimated freely because this type of index self-weighting can be unreliable, particularly when the lengths of different survey time-series vary substantially. Our modelling objective is for $\sigma_{s,a}^2$ to vary only when the data really warrant it. We achieve this goal using random effects. We model

$$\log\{\sigma_{s,a}\} = \log(\sigma_{main}) + \Delta_{s,a}, \;\; \Delta_{s,a} \overset{iid}{\sim} N(0,\sigma_{\Delta}^2) \tag{8}$$

Hence we estimate two parameters (σ_{main} and σ_{Δ}) and use random effect predictions for values of $\sigma_{s,a}^2$ used in equation (7). Predictions of $\Delta_{s,a}$ should be close to zero unless the data really warrant otherwise.

Similar to Cadigan (**2015**), indices with a zero value were assumed to be caused by low stock abundance in the survey area (i.e. they were not missed by mistake). It was therefore assumed that these zero's represent stock densities that are below a detection limit. Here a detection limit of 0.005 was used, which is half of the minimum positive value in the data series. The censored likelihood for a zero index is $L(I_{s,a,y}=0|\theta) = \Phi_N[\log\{0.005/E(I_{s,a,y})\}/\sigma_s]$, where Φ_N is the Normal cumulative probability distribution function. The log-likelihood for a zero will be close to zero if $E(I_{s,a,y}) \ll 0.005$ which is very different from substituting 0.005 for a zero index and using the above index observation equation for its distribution.

Catch data

Total landings and age compositions were treated separately. Logged observed total landings, L_y^{obs}, was modeled as a function of predicted total landings, L_y, from equation (5),

$$\log\left(L_y^{\text{obs}}\right) = \log\left(L_y\right) + \varepsilon_{L,y},\ \ \varepsilon_{L_y} \overset{iid}{\sim} N(0, \sigma_L^2). \qquad (9)$$

Here, σ_L^2 is fixed to 0.1 as the base case assumption.

Age compositions were modeled as multiplicative logistic normal with a censored component for zero's. For the age composition model, $X_{a,y}$ is set as the continuation-ratio logit of $P_{a,y} = C_{a,y}/C_y$, where C_y is obtained by summing $C_{a,y}$ from (4) across ages. Continuation-ratio logits are well suited to fitting age compositions since it fits to the probability of being at age a given that it is at least age a. So, by first calculating proportions from the predicted catch at age,

$$P_{a,y} = \frac{C_{a,y}}{\sum_{a=1}^{A} C_{y,a}},\ \ a = 1, \dots, A, \qquad (10)$$

and then calculating conditional probabilities

$$Prob(age = a | age \geq a) = \frac{P_{a,y}}{P_{a,y} + \dots + P_{A,y}} = \pi_{a,y}, \qquad (11)$$

the continuation-ratio logit is obtained by

$$X_{a,y} = \log\left(\frac{\pi_{a,y}}{1 - \pi_{a,y}}\right),\ \ a = 1, \dots, A - 1. \qquad (12)$$

Observed continuation-ratio logits, $X_{a,y}^{\text{obs}}$, are calculated from observed catch at age data, $C_{a,y}^{\text{obs}}$, using equations (10) - (12). Errors in predicted continuation-ratio logits are assumed to be normally distributed,

$$X_{a,y}^{\text{obs}} = X_{a,y} + \varepsilon_{X_{a,y}},\ \ \varepsilon_{X_{a,y}} \overset{iid}{\sim} N(0, \sigma_X^2). \qquad (13)$$

The censored component for zero's in the catch age composition involved replacing the zero's by 0.5 in the catch at age (i.e. half minimum non-zero value) and recomputing the age composition and continuation-ratio logits. The new values of proportions that were zero and associated new values for continuation-ratio logits are treated as upper bounds in a censored likelihood: $L(P = 0) = \Phi_N(\sigma_X)$. Note that replacing the zero catches with 0.5 at ages 3 and 4 did not affect the continuation-ratio logits at older ages. These logits are the same as in the original data with zero's.

Table 1. Descriptions of fixed, random and assumed model parameters.

Component	Type	Parameter	Description
Process	Fixed	$N_{2-10+,1}$	Numbers at age in year 1
		r	Mean log-recruitment
		σ_r^2	Variance of log-recruitment
		σ_δ^2	Process error variance parameter
		σ_F^2	F variance parameter
		$\varphi_{F,\text{ages 5-10+}}, \varphi_{F,\text{year}}$	Age (5-10+) and year correlation in F process
	Random	$\delta_{a,y}$	Cohort model process error
		$N_{1,y}$	Number of recruits
		$F_{3-10+,y}$	Fishing mortality for ages 3-10+
	Assumed	$F_{1-2,y}$	Fishing mortality for ages 1-2 (0)
		$M_{a,y}$	Natural mortality (0.12)
		$\varphi_{\delta,\text{age}}, \varphi_{\delta,\text{year}}$	Age and year correlation in process errors (~0.00001)
		$\varphi_{F,\text{ages 3-4}}$	Age (3-4) correlation in F process (0)
Observation	Random	$\Delta_{s,a}$	Deviations from mean survey observation error; estimates are coupled across ages 1-3, 4-7, and 8-10+
	Fixed	σ_{main}^2	Mean survey observation error
		σ_Δ^2	Survey observation error variance
		$q_{s,a}$	Survey index catchability parameter
		σ_X^2	Catch at age composition observation error
	Assumed	σ_L^2	Landings observation error (0.1)

Appendix B: Data

Table 2. Landings (kt) of Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO. The SCAA uses data since 1960 and the SSM uses data since 1975.

Year	Landings
1960	0.900
1961	0.700
1962	0.600
1963	2.000
1964	4.000
1965	10.000
1966	19.000
1967	27.000
1968	32.000
1969	37.000
1970	37.000
1971	25.000
1972	30.000
1973	29.000
1974	28.000
1975	28.814
1976	24.611
1977	32.048
1978	39.070
1979	34.104
1980	32.867
1981	30.754
1982	26.278
1983	27.861
1984	26.711
1985	20.347
1986	17.976
1987	32.442
1988	19.215
1989	20.034
1990	47.454
1991	65.008

Year	Landings
1992	63.193
1993	62.455
1994	51.029
1995	15.272
1996	18.840
1997	19.858
1998	19.946
1999	24.226
2000	34.177
2001	38.232
2002	34.062
2003	35.151
2004	25.486
2005	23.255
2006	23.531
2007	22.747
2008	21.180
2009	23.156
2010	26.174
2011	24.960
2012	22.978
2013	19.976
2014	21.433
2015	15.273
2016	14.875
2017	14.760
2018	16.630
2019	16.481
2020	16.307
2021	15.039

Table 3. Catch numbers at age estimates (000s) for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO.

Year	1	2	3	4	5	6	7	8	9	10+
1975	0	0	0	0	334	2,819	5,750	4,956	3,961	3,092
1976	0	0	0	0	17	610	3,231	5,413	3,769	3,448
1977	0	0	0	0	534	5,012	10,798	7,346	2,933	1,563
1978	0	0	0	0	2,982	8,415	8,970	7,576	2,865	3,008
1979	0	0	0	0	2,386	8,727	12,824	6,136	1,169	1,344
1980	0	0	0	0	209	2,086	9,150	9,679	5,398	5,049
1981	0	0	0	0	863	4,517	9,806	11,451	4,307	1,400
1982	0	0	0	0	269	2,299	6,319	5,763	3,542	2,890
1983	0	0	0	0	701	3,557	9,800	7,514	2,295	1,258
1984	0	0	0	0	902	2,324	5,844	7,682	4,087	2,098
1985	0	0	0	0	1,983	5,309	5,913	3,500	1,380	943
1986	0	0	0	0	280	2,240	6,411	5,091	1,469	1,042
1987	0	0	0	0	137	1,902	11,004	8,935	2,835	2,092
1988	0	0	0	0	296	3,186	8,136	4,380	1,288	1,007
1989	0	0	0	0	181	1,988	7,480	4,273	1,482	1,688
1990	0	0	0	95	1,102	6,758	12,632	7,557	4,072	5,533
1991	0	0	0	220	2,862	7,756	13,152	10,796	7,145	7,782
1992	0	0	0	1,064	4,180	10,922	20,639	12,205	4,332	4,242
1993	0	0	0	1,010	9,570	15,928	17,716	11,918	4,642	4,438
1994	0	0	0	5,395	16,500	15,815	11,142	6,739	3,081	2,871
1995	0	0	0	323	1,352	2,342	3,201	2,130	1,183	1,610
1996	0	0	0	190	1,659	5,197	6,387	1,914	956	1,405
1997	0	0	0	335	1,903	4,169	7,544	3,215	1,139	1,498
1998	0	0	0	552	3,575	5,407	5,787	3,653	1,435	1,222
1999	0	0	0	297	2,149	5,625	8,611	3,793	1,659	1,568
2000	0	0	0	271	2,029	12,583	21,175	3,299	973	1,332
2001	0	0	0	448	2,239	12,163	22,122	5,154	1,010	1,368
2002	0	0	37	479	1,662	7,239	17,581	6,607	1,244	1,450
2003	0	0	203	1,279	4,491	10,723	16,764	6,385	1,614	1,111
2004	0	0	17	897	4,062	8,236	10,542	4,126	1,307	1,164
2005	0	0	40	534	1,652	5,999	10,313	3,996	1,410	912
2006	0	0	10	216	1,869	6,450	12,144	4,902	1,089	627
2007	0	0	0	88	570	3,732	11,912	5,414	1,230	785
2008	0	0	0	29	448	3,312	10,697	5,558	1,453	595
2009	0	0	0	61	476	3,121	8,801	7,276	1,949	846
2010	0	0	0	146	825	5,077	11,202	6,171	2,134	841
2011	0	0	430	690	1,385	4,101	7,257	3,953	1,255	715

Year	1	2	3	4	5	6	7	8	9	10+
2012	0	0	1,216	706	1,982	3,422	7,618	5,529	1,992	1,143
2013	0	0	125	460	1,744	3,873	3,997	3,255	787	330
2014	0	0	119	259	1,007	3,041	3,583	4,626	910	288
2015	0	0	59	89	429	1,237	4,037	5,546	1,571	331
2016	0	0	39	116	445	1,294	2,457	6,072	1,399	445
2017	0	0	0	2	38	442	2,688	4,623	2,922	1,671
2018	0	0	0	117	516	1,582	2,671	4,587	2,923	830
2019	0	0	0	221	752	2,038	3,168	4,288	2,605	947
2020	0	1	20	283	1,276	3,286	2,391	2,913	2,059	1,251
2021	0	7	39	211	819	3,749	3,692	2,527	2,204	983

Table 4. Catch weight-at-age estimates (kg) for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO.

Year	1	2	3	4	5	6	7	8	9	10+
1975	0.00	0.00	0.13	0.24	0.61	0.76	0.95	1.19	1.58	2.85
1976	0.00	0.00	0.13	0.24	0.61	0.76	0.95	1.19	1.58	2.51
1977	0.00	0.00	0.13	0.24	0.61	0.76	0.95	1.19	1.58	2.70
1978	0.00	0.00	0.13	0.24	0.61	0.76	0.95	1.19	1.58	2.91
1979	0.00	0.00	0.13	0.24	0.61	0.76	0.95	1.19	1.58	3.44
1980	0.00	0.00	0.13	0.24	0.51	0.66	0.87	1.05	1.15	1.40
1981	0.00	0.00	0.13	0.24	0.39	0.60	0.79	0.98	1.24	2.40
1982	0.00	0.00	0.13	0.24	0.52	0.68	0.89	1.13	1.40	2.58
1983	0.00	0.00	0.13	0.24	0.41	0.63	0.86	1.18	1.65	3.38
1984	0.00	0.00	0.13	0.24	0.38	0.58	0.83	1.10	1.46	2.75
1985	0.00	0.00	0.13	0.24	0.57	0.75	0.94	1.24	1.69	3.19
1986	0.00	0.00	0.13	0.24	0.35	0.58	0.81	1.10	1.58	3.31
1987	0.00	0.00	0.13	0.24	0.36	0.59	0.84	1.16	1.59	3.44
1988	0.00	0.00	0.13	0.24	0.36	0.57	0.80	1.16	1.66	3.49
1989	0.00	0.00	0.13	0.24	0.40	0.56	0.77	1.08	1.66	3.10
1990	0.00	0.00	0.09	0.18	0.34	0.55	0.77	1.12	1.61	3.01
1991	0.00	0.00	0.13	0.24	0.38	0.59	0.83	1.23	1.81	3.38
1992	0.00	0.00	0.17	0.29	0.43	0.58	0.79	1.23	1.82	3.46
1993	0.00	0.00	0.13	0.23	0.37	0.55	0.81	1.21	1.73	3.23
1994	0.00	0.00	0.08	0.20	0.33	0.51	0.79	1.18	1.70	3.29
1995	0.00	0.00	0.08	0.29	0.36	0.53	0.81	1.20	1.76	3.75
1996	0.00	0.00	0.16	0.24	0.36	0.54	0.83	1.27	1.80	3.41
1997	0.00	0.00	0.12	0.21	0.34	0.49	0.77	1.16	1.73	3.30
1998	0.00	0.00	0.12	0.23	0.37	0.54	0.81	1.20	1.75	3.17
1999	0.00	0.00	0.18	0.25	0.36	0.53	0.82	1.25	1.68	3.19
2000	0.00	0.00	0.00	0.25	0.35	0.52	0.79	1.19	1.77	3.12
2001	0.00	0.00	0.00	0.25	0.38	0.57	0.83	1.17	1.79	3.18
2002	0.00	0.00	0.22	0.25	0.37	0.56	0.84	1.19	1.76	3.00
2003	0.00	0.00	0.19	0.25	0.39	0.56	0.82	1.20	1.65	2.87
2004	0.00	0.00	0.18	0.25	0.38	0.54	0.81	1.20	1.63	2.91
2005	0.00	0.00	0.25	0.30	0.40	0.56	0.85	1.25	1.69	2.78
2006	0.00	0.00	0.13	0.27	0.40	0.60	0.81	1.09	1.50	2.36
2007	0.00	0.00	0.00	0.28	0.39	0.58	0.83	1.14	1.50	2.41
2008	0.00	0.00	0.00	0.28	0.40	0.62	0.89	1.20	1.60	2.44

Year	1	2	3	4	5	6	7	8	9	10+
2009	0.00	0.00	0.00	0.28	0.39	0.60	0.86	1.16	1.61	2.43
2010	0.00	0.00	0.00	0.25	0.35	0.57	0.84	1.21	1.65	2.45
2011	0.00	0.00	0.13	0.21	0.31	0.53	0.85	1.25	1.75	2.63
2012	0.00	0.00	0.17	0.24	0.30	0.57	0.89	1.28	1.75	2.73
2013	0.00	0.00	0.14	0.27	0.42	0.63	0.87	1.25	1.83	2.87
2014	0.00	0.00	0.15	0.24	0.40	0.62	0.89	1.31	1.92	2.96
2015	0.00	0.00	0.16	0.24	0.41	0.63	0.89	1.22	1.76	2.93
2016	0.00	0.00	0.22	0.31	0.47	0.67	0.90	1.28	1.82	2.71
2017	0.00	0.00	0.00	0.26	0.31	0.52	0.71	1.08	1.37	2.03
2018	0.00	0.00	0.00	0.30	0.42	0.62	0.88	1.25	1.79	2.75
2019	0.00	0.00	0.19	0.28	0.41	0.60	0.85	1.19	1.73	2.65
2020	0.00	0.08	0.24	0.28	0.41	0.63	0.87	1.23	1.80	2.90
2021	0.09	0.12	0.24	0.32	0.41	0.60	0.85	1.18	1.64	2.64

Table 5. Stratified estimates of mean weight per tow (kg) and mean numbers per tow from Canadian and EU research vessel surveys.

Year	Canada Autumn 2J3K	Canada Autumn 3LNO	Canada Spring 3LNO	EU-Spain 3L	EU-Spain 3LNO	EU-Spain 3NO	EU 3M 0-1400m	EU 3M 0-700m
1995								13.52
1996	22.66	2.58	1.53					14.42
1997	25.89	2.73	2.46			7.73		20.01
1998	24.82	3.97	4.65			11.73		30.13
1999	32.48	2.82	2.83			12.00		26.37
2000	25.17	2.37	3.04			9.48		21.08
2001	23.67	2.06	1.40			8.17		17.25
2002	14.78	1.42	0.72			2.64		15.05
2003	15.95	1.62	1.46	14.64	7.98	5.10		7.73
2004	18.17	1.68	1.15	12.29	6.93	3.68	23.33	
2005	21.24	2.47	1.67			3.39	16.71	
2006	27.02	2.43		15.48	7.83	3.03	19.17	
2007	29.12	2.38	3.03	16.64	9.14	3.98	25.10	
2008		2.87	2.10	24.40	14.11	7.66	32.35	
2009	19.99	1.57	0.68	20.78	17.15	14.78	29.44	
2010	19.92	1.59	1.68	23.41	18.25	14.80	22.13	
2011	26.74	2.21	1.06	14.61	9.99	7.09	26.15	
2012	23.50	1.71	1.94	14.67	10.18	7.37	19.20	
2013	29.79	2.53	0.73	17.31	10.03	5.46	19.11	
2014	33.34		0.66	24.09	13.12	6.24	23.92	
2015	22.29	0.87		23.90	15.04	9.49	47.52	
2016	18.54	1.31	0.66	21.26	13.60	8.80	28.30	
2017	15.10	1.25		34.83	23.64	16.63	42.66	
2018	17.05	1.89	1.88	21.75	13.22	7.88	29.80	
2019	16.28	1.87	1.45	29.69	16.87	8.82	16.89	
2020	15.84	2.71					13.23	
2021	21.15					8.09	16.31	

Table 6. Stratified estimates of mean number per tow at age from Canadian and EU research vessel surveys.

Year	0	1	2	3	4	5	6	7	8	9	10+
Canada Autumn 2J3K											
1996	5.18	103.83	49.99	33.64	10.28	6.60	2.55	0.88	0.20	0.19	0.10
1997	2.30	29.55	63.09	43.89	21.84	10.67	5.13	2.11	0.68	0.21	0.13
1998	1.59	25.33	26.23	32.20	22.23	11.11	4.68	2.18	0.60	0.14	0.13
1999	6.46	15.99	34.42	24.07	28.28	20.04	10.53	3.81	0.70	0.14	0.13
2000	3.30	38.10	23.18	16.83	13.73	14.54	7.72	2.28	0.53	0.07	0.06
2001	8.94	46.30	23.34	17.42	14.53	10.33	7.91	3.59	0.73	0.12	0.06
2002	8.75	42.85	25.48	13.09	9.95	6.31	2.07	0.76	0.20	0.04	0.02
2003	10.44	47.57	27.90	12.14	9.92	6.63	2.43	0.94	0.28	0.04	0.04
2004	4.39	33.77	34.54	14.24	13.01	9.41	2.81	1.26	0.38	0.09	0.05
2005	5.31	16.57	17.09	8.75	14.36	11.41	7.22	4.16	0.70	0.12	0.09
2006	3.95	33.80	18.90	8.97	18.44	13.67	9.52	4.45	1.21	0.19	0.07
2007	2.21	32.61	14.51	12.81	18.77	9.57	10.35	6.17	2.14	0.34	0.15
2009	5.52	50.91	19.26	11.47	8.47	9.96	5.40	3.61	1.40	0.25	0.13
2010	20.28	47.17	36.27	14.72	9.61	6.88	3.96	2.31	1.07	0.19	0.15
2011	4.81	43.75	41.89	20.97	18.79	10.32	5.50	3.15	1.26	0.33	0.22
2012	5.15	12.28	9.61	11.27	11.86	10.96	9.03	4.30	1.69	0.29	0.22
2013	2.81	23.47	12.19	6.98	6.97	10.98	9.14	7.98	3.97	0.51	0.24
2014	3.10	22.08	30.41	11.39	4.54	7.96	7.38	8.92	6.62	0.97	0.30
2015	0.50	17.17	13.98	15.14	7.77	6.82	4.18	3.91	3.92	0.65	0.24
2016	10.58	29.65	19.47	10.81	8.15	4.83	4.89	3.01	2.09	0.51	0.21
2017	6.43	30.57	22.75	10.20	8.76	5.72	2.63	1.26	0.96	0.36	0.20
2018	1.70	14.18	17.04	17.21	8.62	7.00	5.04	2.02	1.03	0.45	0.20
2019	26.62	16.52	19.53	19.17	12.12	8.82	3.65	1.38	0.41	0.15	0.13
2020	3.57	24.36	25.32	13.55	8.29	6.24	4.29	1.26	0.62	0.35	0.28
2021	10.95	23.70	29.21	18.98	7.82	4.81	5.77	3.29	0.88	0.35	0.22
Canada Autumn 3LNO											
1996	0.26	5.41	5.07	3.94	1.45	1.04	0.41	0.08	0.00	0.00	0.00
1997	0.25	1.27	3.45	4.53	3.61	1.73	0.49	0.10	0.04	0.00	0.00
1998	0.06	0.56	1.81	1.87	2.94	4.07	1.49	0.31	0.08	0.01	0.00
1999	0.22	0.04	0.62	0.73	1.04	1.97	1.67	0.39	0.04	0.01	0.01
2000	0.12	1.66	1.34	0.40	0.77	1.17	1.41	0.45	0.04	0.01	0.00
2001	0.51	1.36	0.67	0.64	1.42	0.77	1.17	0.62	0.05	0.01	0.00

Year	0	1	2	3	4	5	6	7	8	9	10+
2002	0.14	1.29	0.94	1.10	1.03	0.93	0.39	0.16	0.04	0.00	0.00
2003	0.18	1.83	1.11	1.57	1.94	0.93	0.28	0.05	0.02	0.00	0.00
2004	0.05	1.13	1.40	1.51	1.55	1.20	0.25	0.08	0.01	0.00	0.00
2005	0.08	0.55	0.93	0.44	1.81	1.48	1.06	0.47	0.06	0.01	0.00
2006	0.16	0.86	0.50	0.11	0.68	1.34	1.36	0.59	0.13	0.01	0.00
2007	0.09	0.83	0.47	0.27	0.81	0.61	1.24	0.75	0.21	0.02	0.02
2008	0.25	0.95	0.28	0.82	1.13	0.90	1.00	0.76	0.44	0.04	0.00
2009	0.23	2.11	0.23	0.41	0.47	0.87	0.61	0.30	0.14	0.03	0.01
2010	0.44	1.70	0.47	0.84	0.66	0.70	0.66	0.31	0.11	0.02	0.01
2011	0.33	1.30	4.13	1.20	2.02	0.93	0.67	0.32	0.06	0.02	0.01
2012	0.33	0.62	0.20	0.45	1.18	0.93	0.70	0.27	0.08	0.01	0.01
2013	0.08	2.67	0.95	0.37	0.38	1.00	1.01	0.61	0.26	0.01	0.02
2015	0.05	0.78	0.60	0.33	0.31	0.25	0.34	0.17	0.10	0.01	0.01
2016	0.98	1.30	0.44	0.56	0.50	0.63	0.38	0.21	0.09	0.03	0.01
2017	0.16	2.60	0.86	1.32	0.55	0.57	0.34	0.16	0.09	0.02	0.01
2018	0.00	3.13	1.81	1.64	0.94	1.14	0.71	0.22	0.06	0.02	0.00
2019	0.16	3.22	1.96	2.00	1.64	0.99	0.49	0.14	0.03	0.03	0.00
2020	0.00	4.74	2.59	1.54	2.00	1.51	0.79	0.23	0.10	0.04	0.02
Canada Spring 3LNO											
1996	0.00	1.62	4.25	4.60	2.19	0.83	0.28	0.06	0.00	0.00	0.00
1997	0.00	1.16	3.92	5.16	3.23	1.46	0.51	0.10	0.01	0.00	0.00
1998	0.00	0.24	0.86	3.97	6.33	5.06	1.26	0.33	0.07	0.01	0.00
1999	0.00	0.30	0.56	1.19	2.03	3.43	1.08	0.24	0.05	0.01	0.00
2000	0.02	0.79	1.07	1.07	1.51	1.95	2.04	0.56	0.03	0.01	0.01
2001	0.00	0.57	0.72	0.75	0.68	0.79	0.69	0.24	0.02	0.00	0.00
2002	0.00	0.65	0.58	0.61	0.59	0.61	0.21	0.05	0.01	0.00	0.00
2003	0.00	0.93	2.15	1.68	1.58	1.05	0.21	0.05	0.01	0.00	0.00
2004	0.00	0.68	0.58	1.21	1.21	1.19	0.26	0.04	0.02	0.00	0.00
2005	0.00	0.35	0.31	1.09	0.95	1.37	0.82	0.21	0.02	0.00	0.00
2007	0.00	1.60	0.52	0.80	0.40	1.40	1.49	1.12	0.18	0.02	0.00
2008	0.00	0.44	0.77	0.96	0.71	1.25	0.75	0.64	0.28	0.02	0.01
2009	0.00	0.27	0.22	0.19	0.39	0.45	0.26	0.13	0.07	0.01	0.00
2010	0.00	0.77	0.66	0.52	0.40	0.84	1.08	0.35	0.14	0.02	0.02
2011	0.00	1.98	1.41	0.93	0.65	0.62	0.29	0.16	0.10	0.01	0.00
2012	0.02	0.32	0.80	2.48	1.40	1.16	0.50	0.18	0.06	0.02	0.01
2013	0.00	1.28	0.68	0.05	0.38	0.61	0.23	0.11	0.04	0.00	0.00

Year	0	1	2	3	4	5	6	7	8	9	10+
2014	0.00	1.62	1.19	0.32	0.20	0.24	0.24	0.14	0.06	0.01	0.00
2016	0.08	0.42	0.56	0.37	0.46	0.30	0.20	0.08	0.05	0.01	0.01
2018	0.00	3.05	4.40	1.90	1.37	0.90	0.64	0.10	0.09	0.02	0.01
2019	0.00	4.52	2.10	1.79	1.41	0.89	0.28	0.18	0.05	0.02	0.01
EU 3M 0-700m											
1995		12.41	2.54	2.23	1.91	2.66	5.10	3.77	2.12	1.31	0.35
1996		5.84	7.97	2.41	3.04	4.20	5.82	2.49	1.62	0.42	0.16
1997		3.33	3.78	6.00	6.50	7.11	8.46	4.99	2.15	0.66	0.31
1998		2.74	2.13	7.68	11.00	12.33	11.30	7.84	2.62	0.75	0.26
1999		1.06	0.70	3.01	10.47	13.41	12.58	5.55	1.82	0.35	0.12
2000		3.75	0.29	0.60	2.16	7.09	14.10	5.40	2.32	0.45	0.17
2001		8.03	1.43	1.81	0.99	2.79	7.79	6.63	3.21	0.18	0.05
2002		4.08	2.94	2.79	1.67	3.79	5.59	5.73	1.28	0.13	0.09
2003		2.20	1.00	0.61	1.51	2.48	2.94	1.93	0.47	0.13	0.12
EU 3M 0-1400m											
2004		1.40	2.19	2.92	1.54	6.80	9.16	4.95	1.46	0.73	1.11
2005		0.36	0.53	2.09	1.73	5.28	6.79	3.42	0.98	0.26	0.88
2006		0.45	0.26	0.44	0.91	5.85	8.56	4.68	1.39	0.42	0.90
2007		0.25	0.05	0.39	0.29	3.84	9.09	8.57	2.88	0.72	1.20
2008		0.13	0.07	0.10	0.16	2.03	9.00	12.53	3.18	1.14	1.90
2009		0.05	0.01	0.03	0.08	1.13	6.80	11.43	3.54	0.93	2.16
2010		0.03	0.01	0.02	0.11	2.00	6.01	7.83	2.50	0.98	1.63
2011		0.00	0.00	0.01	0.09	1.85	6.70	8.49	2.56	1.11	2.34
2012		0.00	0.01	0.04	0.16	2.42	5.78	5.00	1.92	0.75	1.78
2013		0.00	0.00	0.01	0.32	2.11	7.03	4.52	1.64	0.53	1.81
2014		0.02	0.00	0.01	0.16	2.78	8.04	6.87	1.62	0.45	1.53
2015		0.03	0.01	0.01	0.12	2.54	14.85	14.04	4.61	1.67	3.07
2016		0.17	0.02	0.01	0.01	0.58	4.88	9.24	3.94	1.47	2.21
2017		0.76	0.03	0.02	0.30	4.19	11.50	12.69	4.82	2.11	3.41
2018		0.30	0.19	0.21	0.12	2.13	5.99	7.17	3.09	1.58	4.30
2019		0.37	0.23	0.20	0.62	3.05	4.42	3.43	1.32	0.90	1.93
2020		0.05	0.12	0.31	0.51	2.77	4.71	2.32	0.72	0.67	1.48
2021		0.02	0.00	0.03	0.39	2.55	6.00	3.11	1.03	0.68	1.80
EU-Spain 3NO											
1997	0.00	9.92	5.52	3.49	3.81	2.24	1.97	1.22	0.60	0.07	0.15
1998	0.00	1.71	5.24	9.08	8.47	5.06	2.77	1.10	0.66	0.21	0.20

Year	0	1	2	3	4	5	6	7	8	9	10+
1999	0.15	4.38	4.80	7.21	9.31	6.29	2.92	0.77	0.49	0.23	0.24
2000	0.00	2.92	0.49	0.80	1.39	3.84	4.42	2.56	0.71	0.28	0.34
2001	0.00	8.87	5.90	1.18	1.07	2.84	3.96	1.56	0.22	0.06	0.25
2002	0.00	2.86	0.63	1.01	0.68	1.12	0.91	0.43	0.22	0.02	0.08
2003	0.00	3.52	2.37	1.67	1.89	1.56	0.89	0.77	0.26	0.06	0.15
2004	0.00	1.20	6.85	2.05	2.03	1.22	0.84	0.51	0.21	0.05	0.10
2005	0.00	1.07	0.96	1.80	1.03	1.31	1.44	0.68	0.19	0.08	0.16
2006	0.00	2.29	1.11	0.40	1.54	1.37	0.81	0.52	0.22	0.05	0.08
2007	0.00	1.83	0.65	0.51	0.33	1.50	1.41	1.03	0.29	0.10	0.17
2008	0.00	0.64	1.01	0.92	0.71	0.96	2.78	2.57	0.76	0.41	0.36
2009	0.00	0.57	3.03	2.13	2.54	2.66	4.86	5.58	0.83	0.35	0.49
2010	0.00	0.38	2.26	0.96	0.75	3.50	5.72	5.29	1.27	0.40	0.63
2011	0.00	2.26	1.34	0.50	0.64	0.98	2.07	2.18	0.45	0.23	0.48
2012	0.00	0.09	1.83	1.36	0.45	1.11	1.73	2.03	0.54	0.41	0.68
2013	0.00	0.28	0.46	0.23	0.82	1.19	1.50	1.23	0.34	0.21	0.59
2014	0.00	0.53	1.32	0.26	0.15	0.55	1.70	1.79	0.46	0.21	0.69
2015	0.00	0.95	0.63	0.21	0.22	0.48	1.85	3.46	0.96	0.45	0.80
2016	0.00	1.13	0.57	0.36	0.47	0.53	1.94	2.66	0.94	0.23	0.84
2017	0.00	3.45	1.70	0.90	1.12	2.43	4.48	4.72	1.71	0.52	1.07
2018	0.00	2.45	2.09	1.01	0.84	1.70	1.96	1.68	0.98	0.30	0.52
2019	0.00	3.39	4.27	4.17	2.82	2.66	2.02	1.28	0.65	0.24	0.81
2021	0.00	2.40	6.89	1.48	1.11	2.26	2.52	1.31	0.39	0.28	0.73
EU-Spain 3LNO											
2003	0.00	4.25	6.17	4.53	4.32	3.08	1.45	0.88	0.27	0.06	0.19
2004	0.03	3.21	5.56	3.99	5.28	3.93	1.40	0.49	0.17	0.05	0.11
2006	0.00	4.64	2.19	1.00	2.98	4.77	2.96	1.21	0.27	0.06	0.14
2007	0.00	3.31	0.93	1.16	0.69	4.64	4.14	2.14	0.42	0.15	0.21
2008	0.00	1.84	0.98	2.61	1.18	3.03	5.84	4.65	1.08	0.44	0.50
2009	0.00	3.10	2.59	1.70	2.68	4.33	6.15	5.69	1.13	0.40	0.55
2010	0.00	0.74	2.73	1.45	1.56	5.15	6.69	4.97	1.50	0.57	0.87
2011	0.01	3.05	1.53	0.97	1.01	1.85	3.30	2.40	0.77	0.37	0.66
2012	0.00	1.25	2.32	3.93	1.18	2.18	3.14	2.26	0.60	0.42	0.69
2013	0.00	5.09	0.98	0.57	1.86	3.29	3.49	2.07	0.44	0.29	0.65
2014	0.00	3.53	4.56	1.30	0.63	3.05	3.80	3.25	0.95	0.45	0.92
2015	0.00	1.16	2.16	1.17	1.13	1.49	4.57	3.58	1.63	0.51	1.14
2016	0.01	2.10	2.18	2.02	1.80	1.84	2.74	3.18	1.63	0.39	1.29

Year	0	1	2	3	4	5	6	7	8	9	10+
2017	0.00	5.39	4.18	6.55	5.72	7.00	6.14	4.86	2.11	0.70	1.46
2018	0.00	17.21	6.51	3.53	2.69	3.66	2.92	2.03	1.25	0.45	1.04
2019	0.01	8.86	6.79	10.60	5.50	6.09	4.31	2.12	0.90	0.33	1.29
EU-Spain 3L											
2003	0.00	6.02	13.08	10.52	11.29	7.44	3.01	1.03	0.31	0.05	0.30
2004	0.07	6.71	3.37	7.10	9.68	9.42	2.31	0.46	0.15	0.06	0.12
2006	0.00	8.39	3.86	2.25	3.29	11.21	7.03	2.34	0.41	0.07	0.25
2007	0.00	5.45	1.27	2.17	0.77	9.06	8.40	4.06	0.59	0.22	0.26
2008	0.00	3.76	0.61	5.70	1.63	6.58	10.95	7.81	1.53	0.42	0.73
2009	0.00	7.08	1.49	1.16	2.50	7.53	8.19	5.76	1.61	0.38	0.69
2010	0.00	1.27	3.47	2.10	3.30	7.33	8.07	4.50	1.66	0.83	1.23
2011	0.03	4.49	1.58	1.78	1.55	3.50	5.20	2.34	1.44	0.68	0.94
2012	0.00	3.14	2.56	8.57	2.39	4.09	5.62	2.28	0.66	0.40	0.70
2013	0.00	12.87	1.70	1.10	3.95	6.10	6.83	3.25	0.65	0.37	0.78
2014	0.01	8.43	9.93	2.55	1.43	7.29	6.88	5.44	1.82	0.84	1.27
2015	0.00	1.51	4.73	2.59	2.63	2.99	8.88	3.89	2.63	0.62	1.68
2016	0.03	3.64	4.04	5.12	4.03	4.41	3.82	3.76	3.01	0.61	1.96
2017	0.00	8.30	5.58	17.59	14.60	14.28	8.32	4.67	2.70	0.91	2.12
2018	0.00	41.53	14.20	6.70	4.90	6.74	4.61	2.45	1.76	0.64	1.88
2019	0.02	17.91	8.99	22.64	9.46	12.70	6.55	3.44	1.34	0.44	2.06

Appendix C: Model Ouputs

Tables

Table 7. Key parameter estimates from each sensitivity test. See Table 1 for parameter descriptions.

Parameter	3NO	3LNO	3NO+3L
$\sigma_{\text{Canada Autumn 2J3K, 1-3}}$	0.27	0.29	0.29
$\sigma_{\text{Canada Autumn 2J3K, 4-7}}$	0.30	0.30	0.32
$\sigma_{\text{Canada Autumn 2J3K, 8-10}}$	0.43	0.42	0.45
$\sigma_{\text{Canada Autumn 3LNO, 1-3}}$	0.70	0.69	0.68
$\sigma_{\text{Canada Autumn 3LNO, 4-7}}$	0.39	0.38	0.39
$\sigma_{\text{Canada Autumn 3LNO, 8-10}}$	0.62	0.63	0.65
$\sigma_{\text{Canada Spring 3LNO, 1-3}}$	0.71	0.70	0.68
$\sigma_{\text{Canada Spring 3LNO, 4-7}}$	0.53	0.54	0.52
$\sigma_{\text{Canada Spring 3LNO, 8-10}}$	0.67	0.67	0.66
$\sigma_{\text{EU-Spain 3NO, 1-3}}$	0.80	NA	0.79
$\sigma_{\text{EU-Spain 3NO, 4-7}}$	0.60	NA	0.58
$\sigma_{\text{EU-Spain 3NO, 8-10}}$	0.43	NA	0.40
$\sigma_{\text{EU 3M, 1-3}}$	1.49	1.49	1.48
$\sigma_{\text{EU 3M, 4-7}}$	0.56	0.55	0.55
$\sigma_{\text{EU 3M, 8-10}}$	0.39	0.39	0.40
σ_{main}	0.57	0.54	0.56
σ_{Δ}	0.37	0.37	0.35
σ_{X}	0.19	0.19	0.19
σ_{r}	0.31	0.29	0.32
r	11.07	11.09	11.09
σ_{F}	0.21	0.20	0.20
σ_{δ}	0.14	0.15	0.16
$\varphi_{F,y}$	0.97	0.98	0.98
$\varphi_{F,a}$	0.50	0.50	0.50
$\sigma_{\text{EU-Spain 3LNO, 1-3}}$	NA	0.61	NA
$\sigma_{\text{EU-Spain 3LNO, 4-7}}$	NA	0.50	NA
$\sigma_{\text{EU-Spain 3LNO, 8-10}}$	NA	0.35	NA
$\sigma_{\text{EU-Spain 3L, 1-3}}$	NA	NA	0.74
$\sigma_{\text{EU-Spain 3L, 4-7}}$	NA	NA	0.48
$\sigma_{\text{EU-Spain 3L, 8-10}}$	NA	NA	0.38

Table 8. Estimates of recruitment (age 1; millions) from each sensitivity test.

Year	3NO	3LNO	3NO+3L
1975	63.3	64.5	64.4
1976	60.6	61.9	61.1
1977	60.9	62.3	61.5
1978	55.4	57.0	56.4
1979	53.3	55.0	53.9
1980	66.3	67.3	66.6
1981	69.7	70.6	70.4
1982	65.0	66.0	65.6
1983	68.5	69.3	68.5
1984	72.3	72.9	72.5
1985	77.6	77.7	77.5
1986	73.1	73.4	72.4
1987	80.3	80.2	80.7
1988	69.7	70.1	70.0
1989	67.1	67.7	67.8
1990	62.4	63.0	62.8
1991	61.6	62.3	62.8
1992	56.9	57.9	58.3
1993	70.4	71.0	72.1
1994	107.4	105.9	109.7
1995	127.8	125.4	131.3
1996	142.1	136.6	146.0
1997	73.3	68.8	75.5
1998	57.0	56.7	56.8
1999	43.7	43.8	43.2
2000	70.4	69.8	72.3
2001	77.0	77.0	79.1
2002	77.4	79.3	80.1
2003	79.6	78.6	79.6
2004	56.7	58.5	56.8
2005	45.6	47.1	45.5
2006	54.8	55.7	55.8
2007	57.5	56.2	54.9
2008	51.2	51.1	47.7
2009	71.8	72.4	69.8

Year	3NO	3LNO	3NO+3L
2010	69.4	66.9	65.5
2011	48.0	48.3	48.8
2012	31.3	34.7	31.3
2013	51.1	58.3	55.3
2014	45.5	50.8	49.1
2015	45.3	47.1	45.0
2016	63.2	64.9	63.4
2017	70.6	74.8	76.9
2018	58.8	67.6	68.0
2019	66.5	71.8	72.8
2020	67.0	66.4	69.4
2021	55.8	56.0	57.1

Table 9. Estimates of exploitable biomass (ages 5-9; Kt) from each sensitivity test.

Year	3NO	3LNO	3NO+3L
1975	91.7	92.3	91.8
1976	93.9	94.7	93.9
1977	111.4	112.4	111.0
1978	119.4	120.6	118.8
1979	116.2	117.8	116.3
1980	95.1	97.0	95.4
1981	83.3	85.2	83.5
1982	82.0	84.4	81.9
1983	76.8	79.2	76.7
1984	69.6	71.9	69.1
1985	92.2	94.8	91.8
1986	79.7	82.0	79.5
1987	95.4	97.8	95.2
1988	99.1	101.2	98.4
1989	111.6	113.4	111.2
1990	122.9	124.7	122.8
1991	138.5	140.4	138.8
1992	129.7	131.2	130.3
1993	104.5	105.8	105.1
1994	70.8	71.6	71.0
1995	43.5	43.9	43.6
1996	47.5	47.7	47.9
1997	55.7	55.4	56.9
1998	83.3	82.3	86.4
1999	100.5	99.2	103.3
2000	104.2	102.6	105.8
2001	91.6	91.7	91.9
2002	64.1	65.6	63.5
2003	56.0	56.4	55.3
2004	56.5	57.2	55.3
2005	75.4	78.3	74.9
2006	92.4	95.8	90.6
2007	100.9	104.4	99.9
2008	106.6	110.7	107.8
2009	95.0	98.2	96.9

Year	3NO	3LNO	3NO+3L
2010	88.5	91.6	92.4
2011	79.2	81.7	80.7
2012	81.0	83.0	80.0
2013	93.0	96.5	91.8
2014	95.6	102.0	98.1
2015	86.4	92.5	90.1
2016	81.6	87.7	86.2
2017	61.7	66.3	67.7
2018	74.3	79.0	80.4
2019	66.0	69.6	70.5
2020	68.5	71.1	71.7
2021	72.2	74.2	75.3

Table 10. Estimates of average F (ages 5-9; Kt) from each sensitivity test.

Year	3NO	3LNO	3NO+3L
1975	0.2	0.2	0.2
1976	0.2	0.1	0.2
1977	0.3	0.3	0.3
1978	0.3	0.3	0.3
1979	0.3	0.3	0.3
1980	0.3	0.3	0.3
1981	0.4	0.4	0.4
1982	0.2	0.2	0.2
1983	0.3	0.3	0.3
1984	0.3	0.3	0.3
1985	0.2	0.2	0.2
1986	0.2	0.2	0.2
1987	0.2	0.2	0.2
1988	0.2	0.2	0.2
1989	0.1	0.1	0.1
1990	0.2	0.2	0.2
1991	0.3	0.3	0.3
1992	0.4	0.4	0.4
1993	0.6	0.6	0.6
1994	0.8	0.8	0.8
1995	0.2	0.2	0.2
1996	0.3	0.3	0.3
1997	0.2	0.2	0.2
1998	0.2	0.2	0.2
1999	0.2	0.2	0.2
2000	0.4	0.4	0.4
2001	0.6	0.6	0.6
2002	0.6	0.6	0.6
2003	0.6	0.6	0.6
2004	0.4	0.3	0.4
2005	0.2	0.2	0.2
2006	0.2	0.2	0.2
2007	0.2	0.2	0.2
2008	0.2	0.2	0.2
2009	0.2	0.2	0.2

Year	3NO	3LNO	3NO+3L
2010	0.3	0.3	0.3
2011	0.3	0.3	0.3
2012	0.2	0.2	0.2
2013	0.2	0.2	0.2
2014	0.2	0.2	0.2
2015	0.2	0.2	0.2
2016	0.2	0.2	0.2
2017	0.1	0.1	0.1
2018	0.2	0.2	0.2
2019	0.2	0.2	0.2
2020	0.2	0.2	0.2
2021	0.2	0.1	0.1

Figures

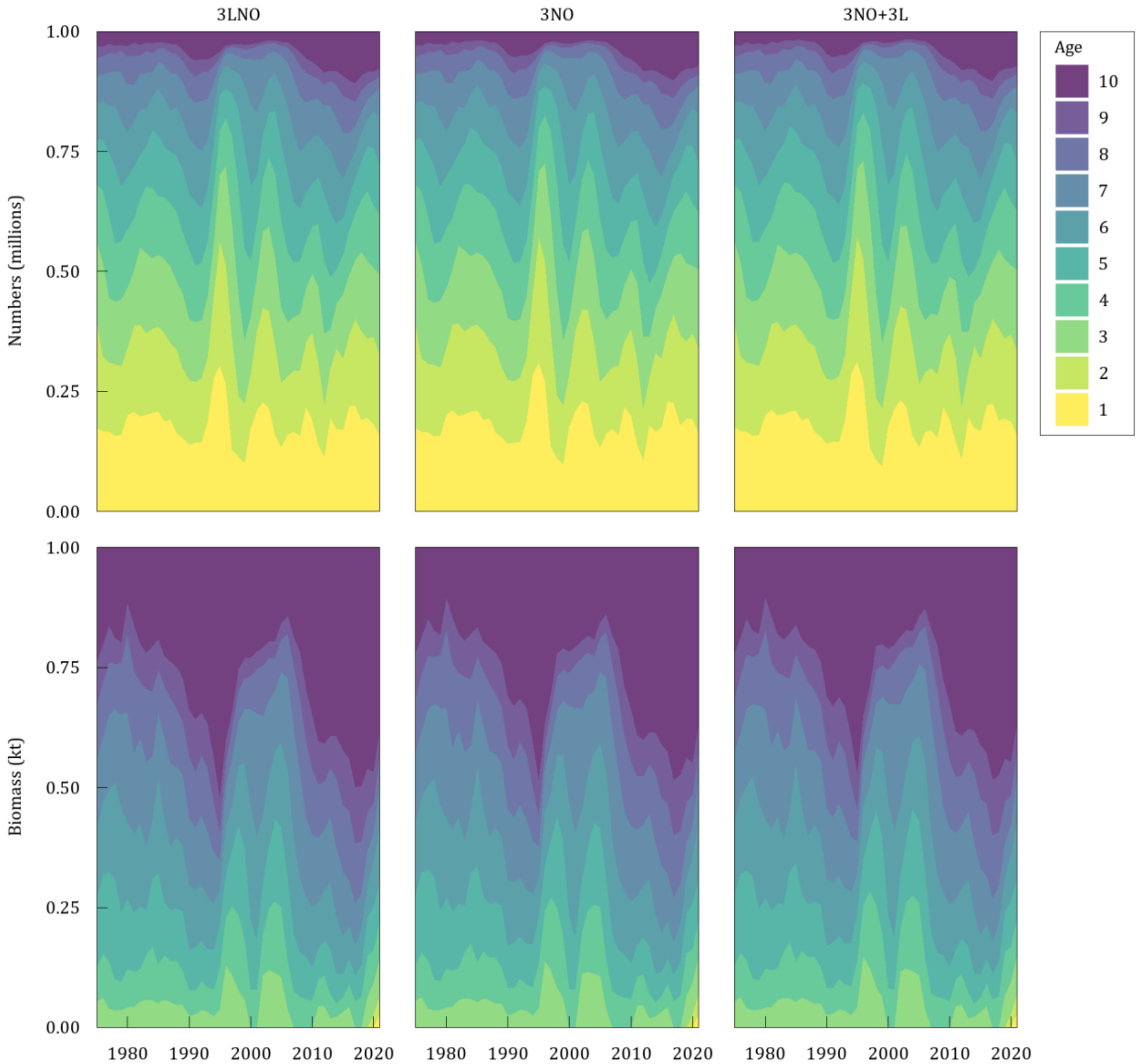

Figure 4. Stock abundance and biomass proportion at age.

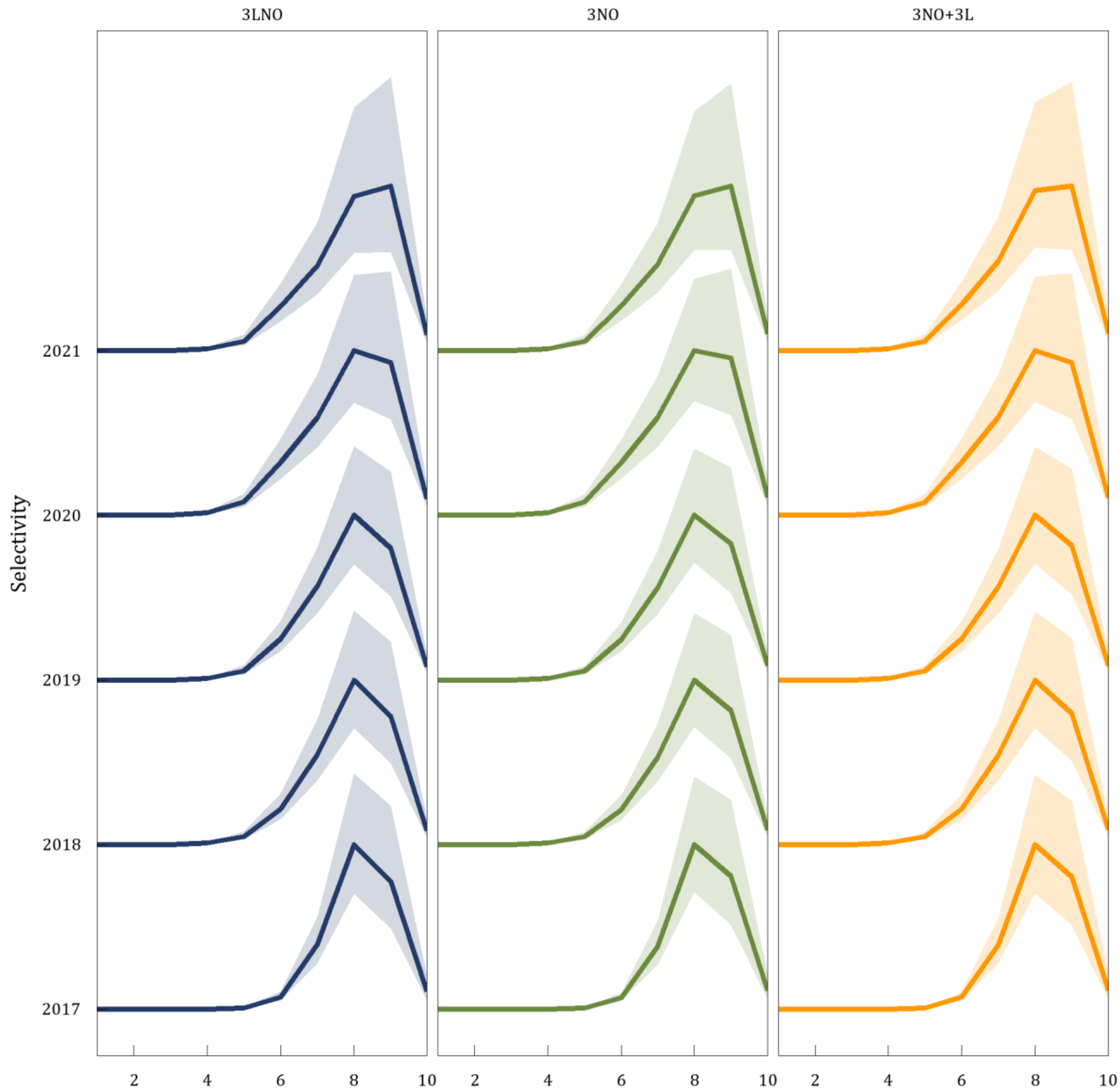

Figure 5. Selectivity curves from the most recent five years.

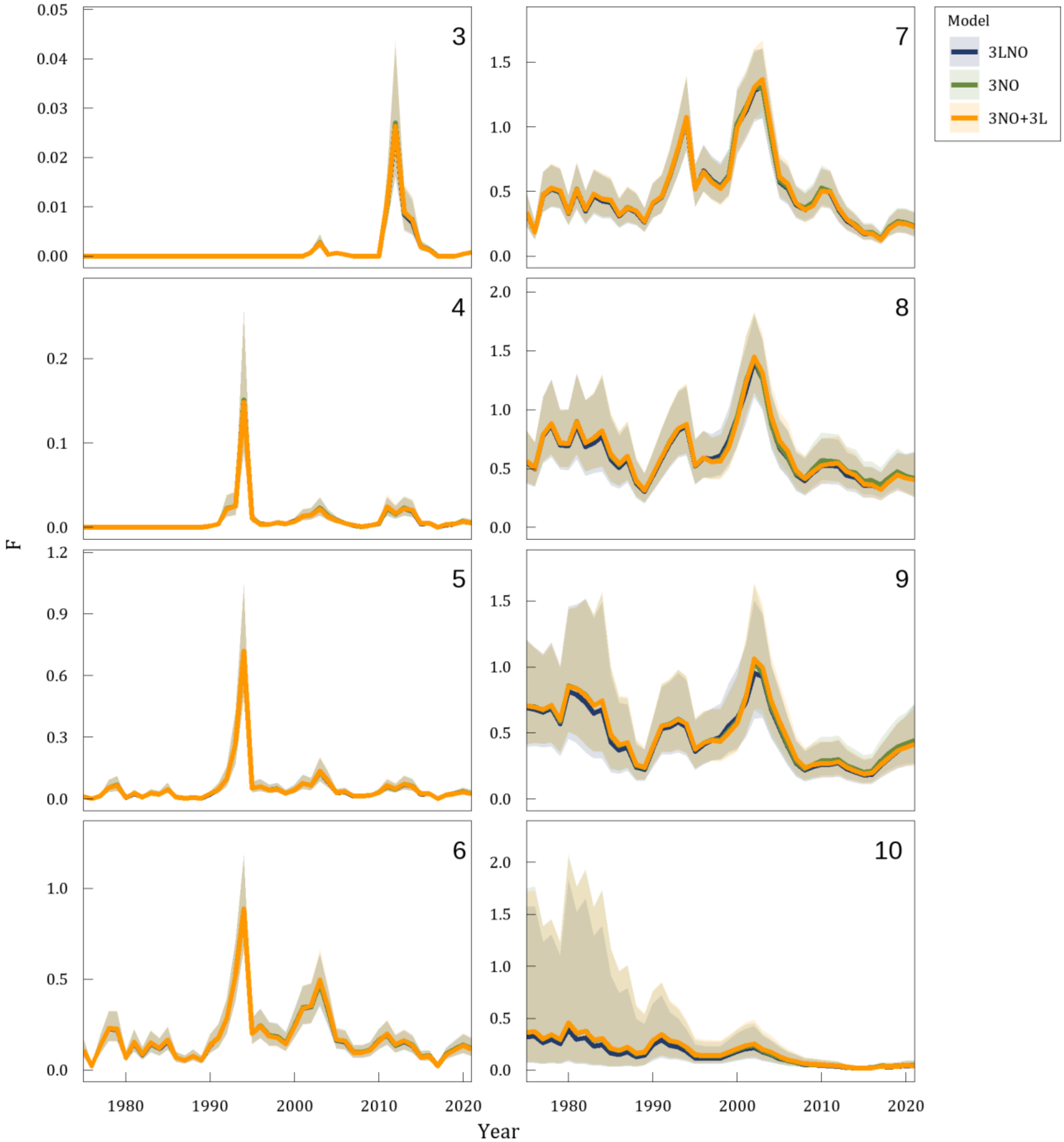

Figure 6. Fishing mortality at age.

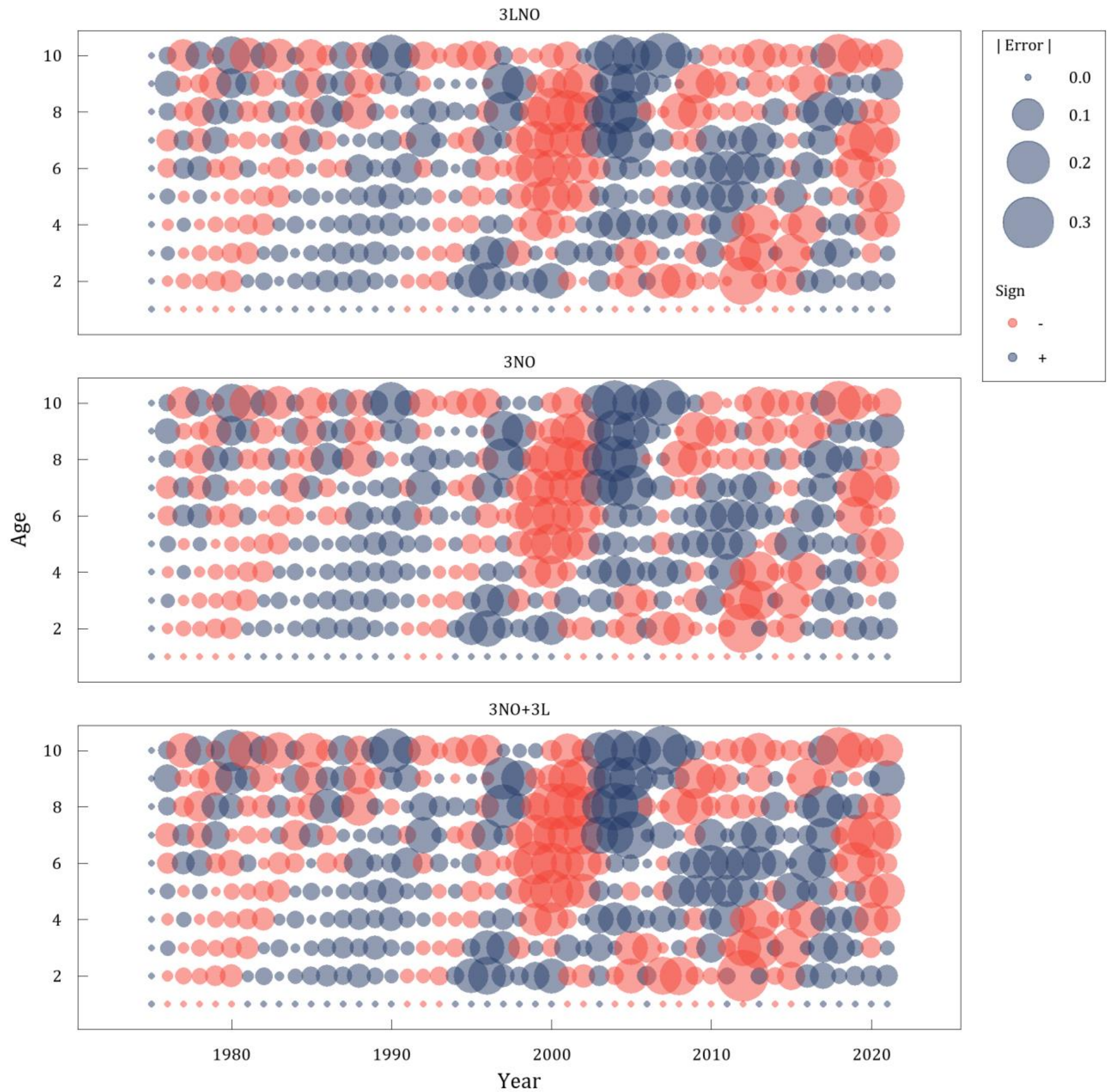

Figure 7. Matrix plot of predicted process errors.

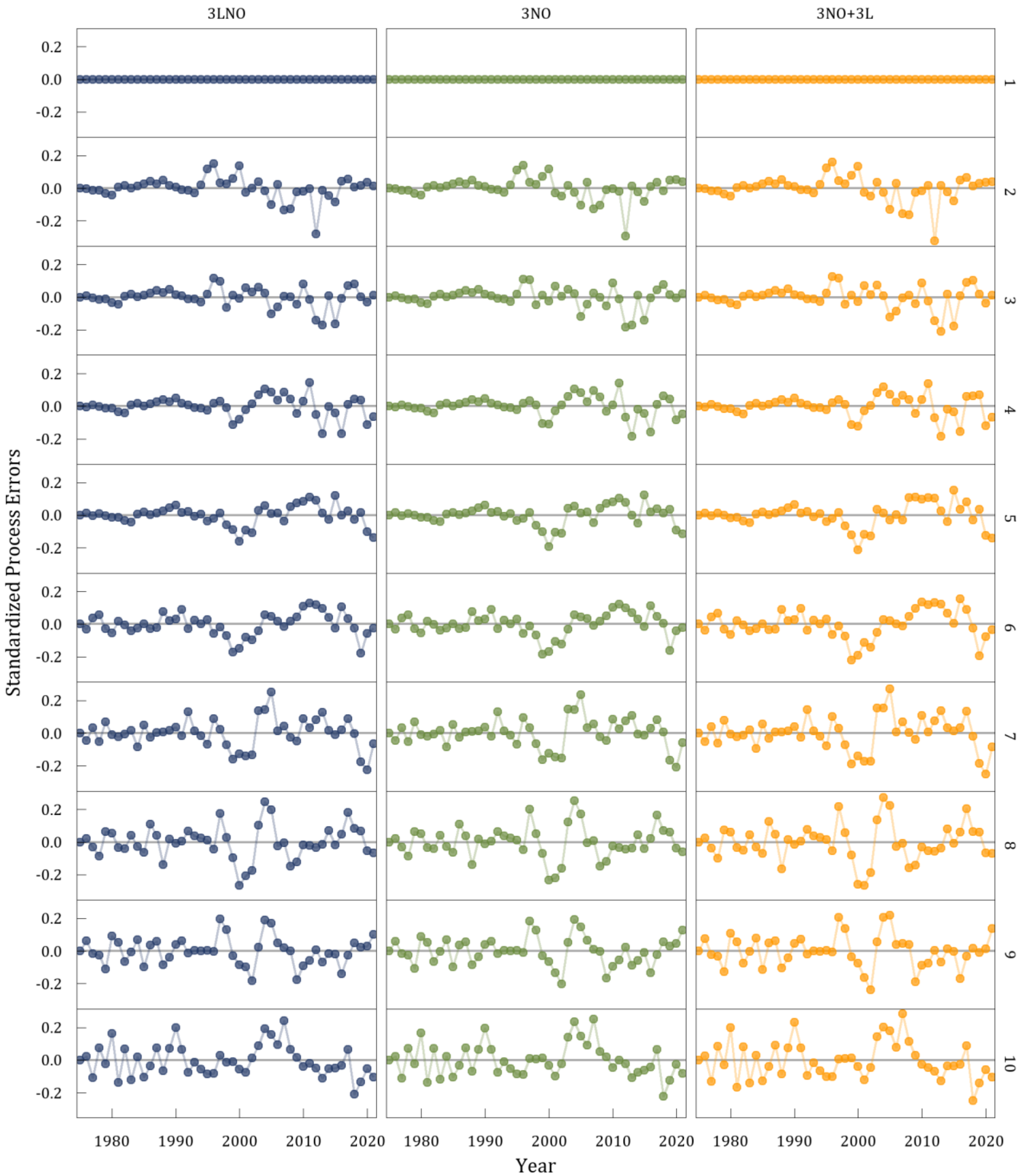

Figure 8. Predicted process error at age.

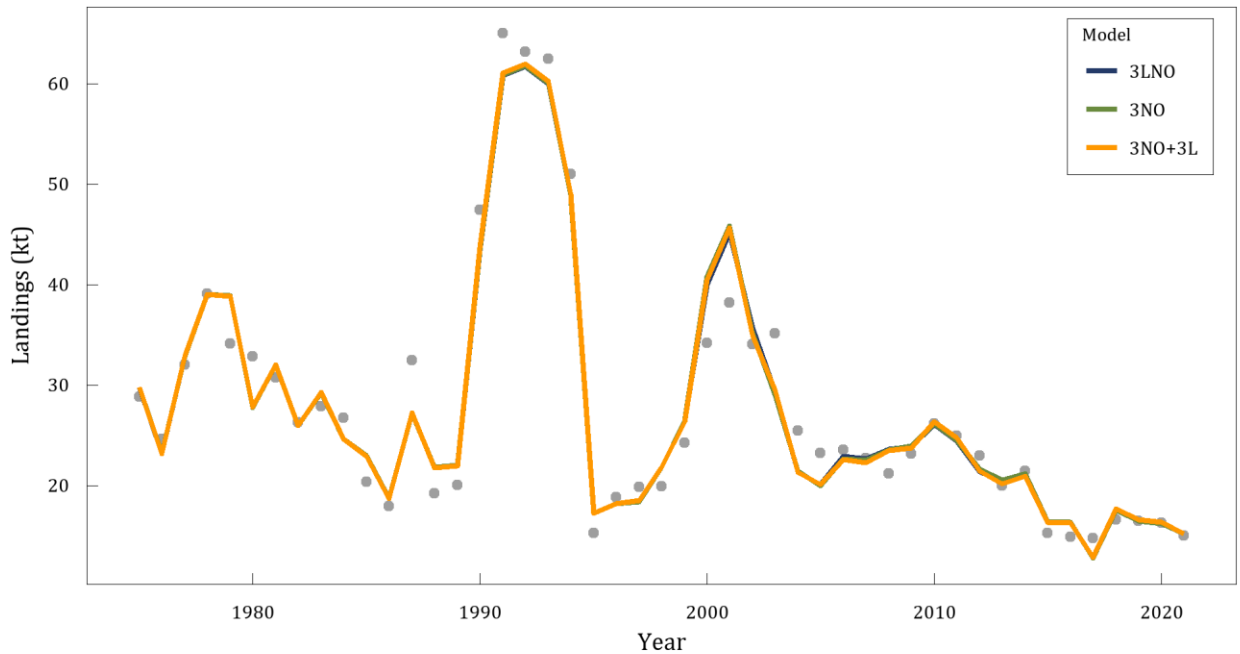

Figure 9. Observed and predicted landings (kt).

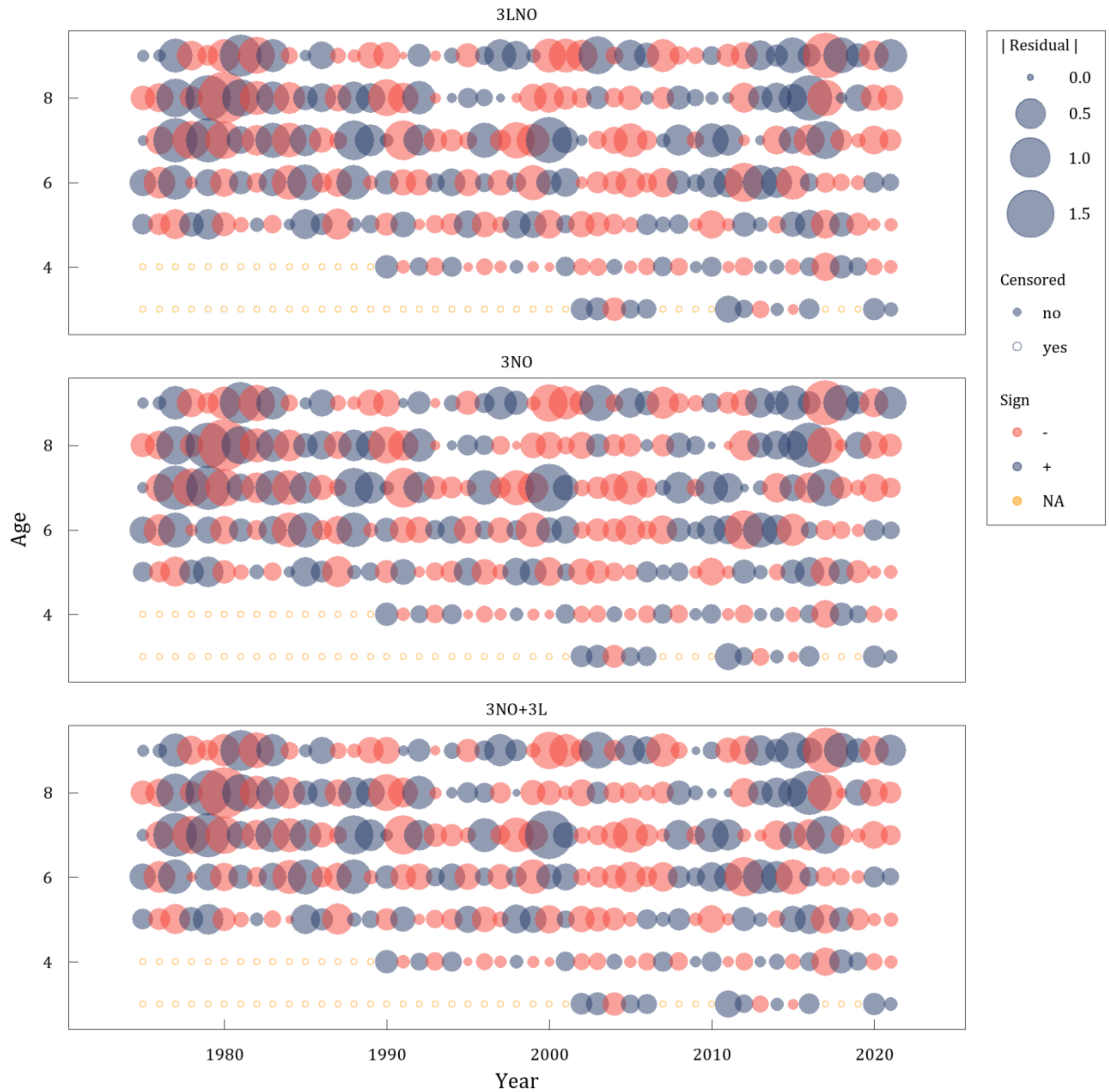

Figure 10. Matrix plot of standardized residuals for catch at age continuation ratio logits (observed minus predicted).

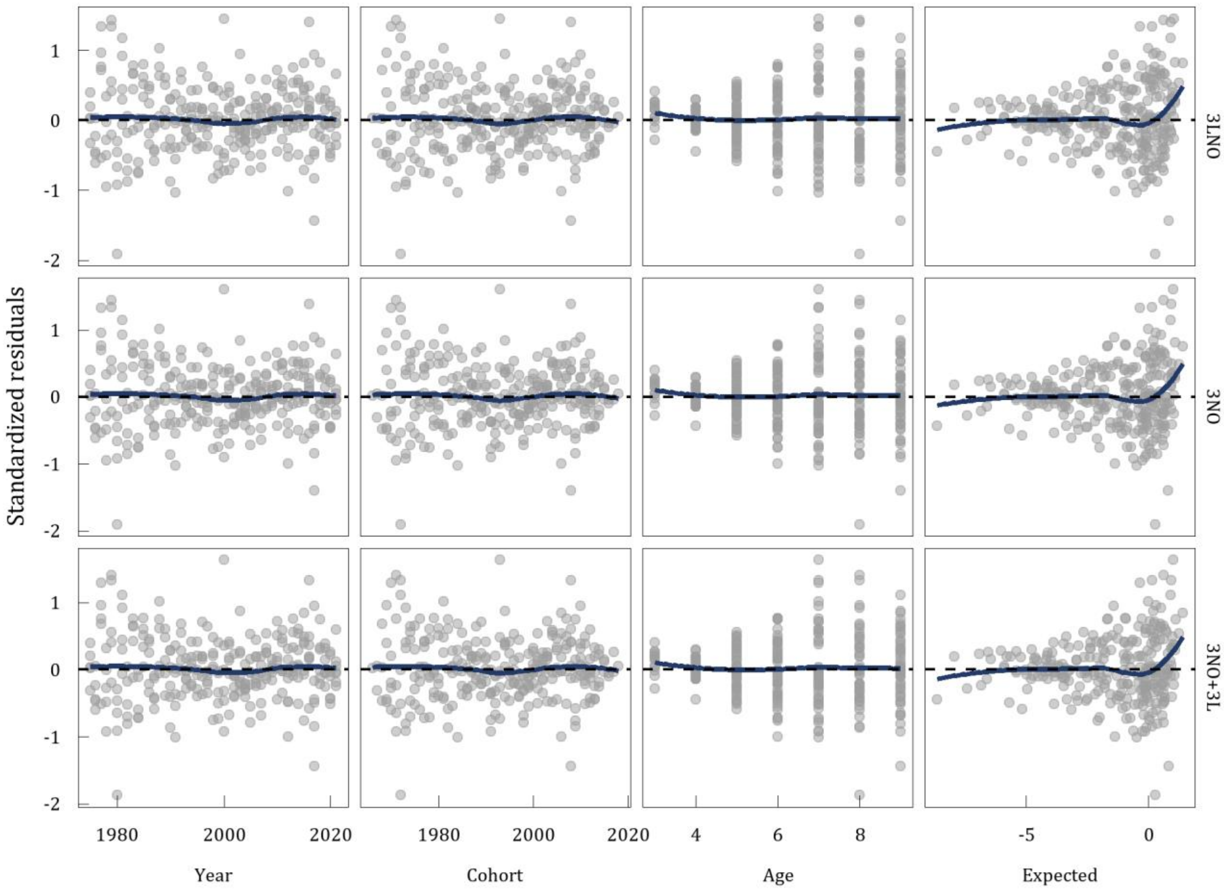

Figure 11. Standardized residuals for catch at age continuation ratio logits versus year, cohort, age, and predicted value.

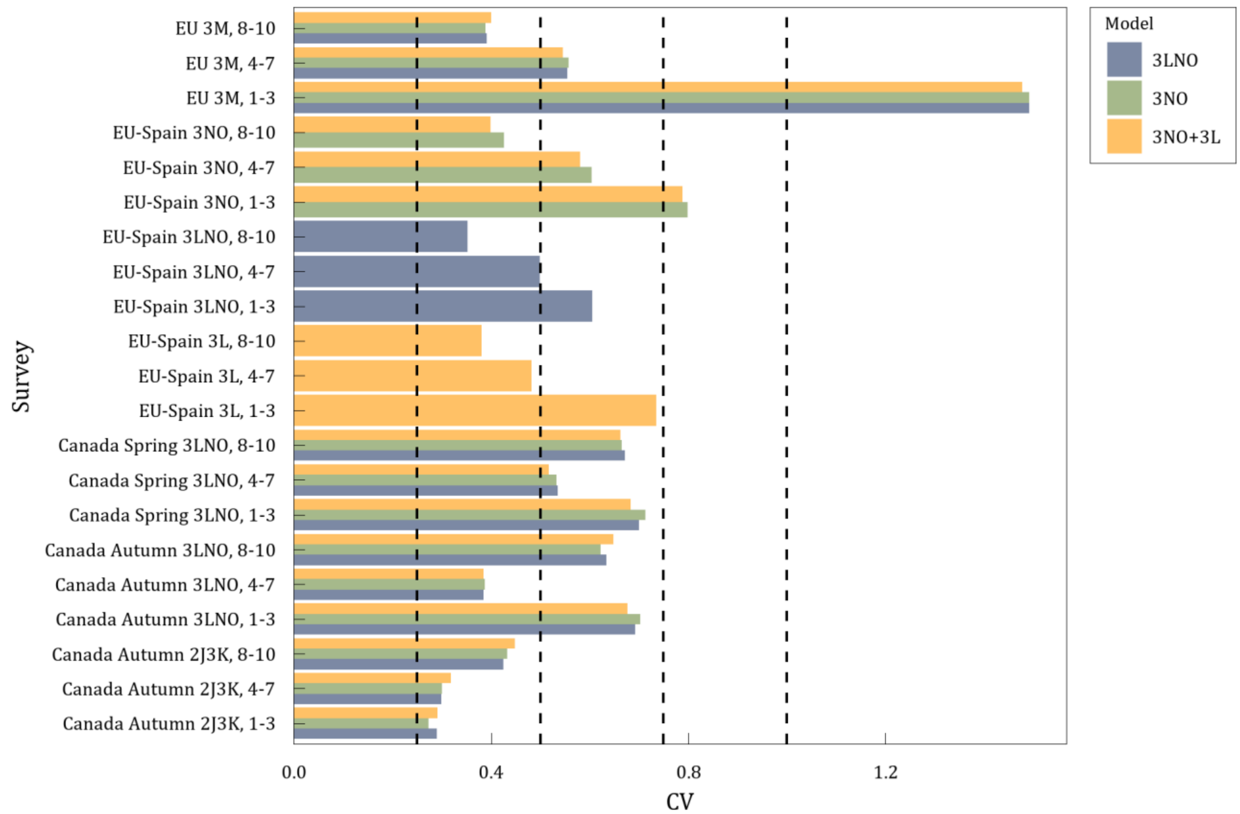

Figure 12. Estimates of survey CV. Age ranges follow the survey name.

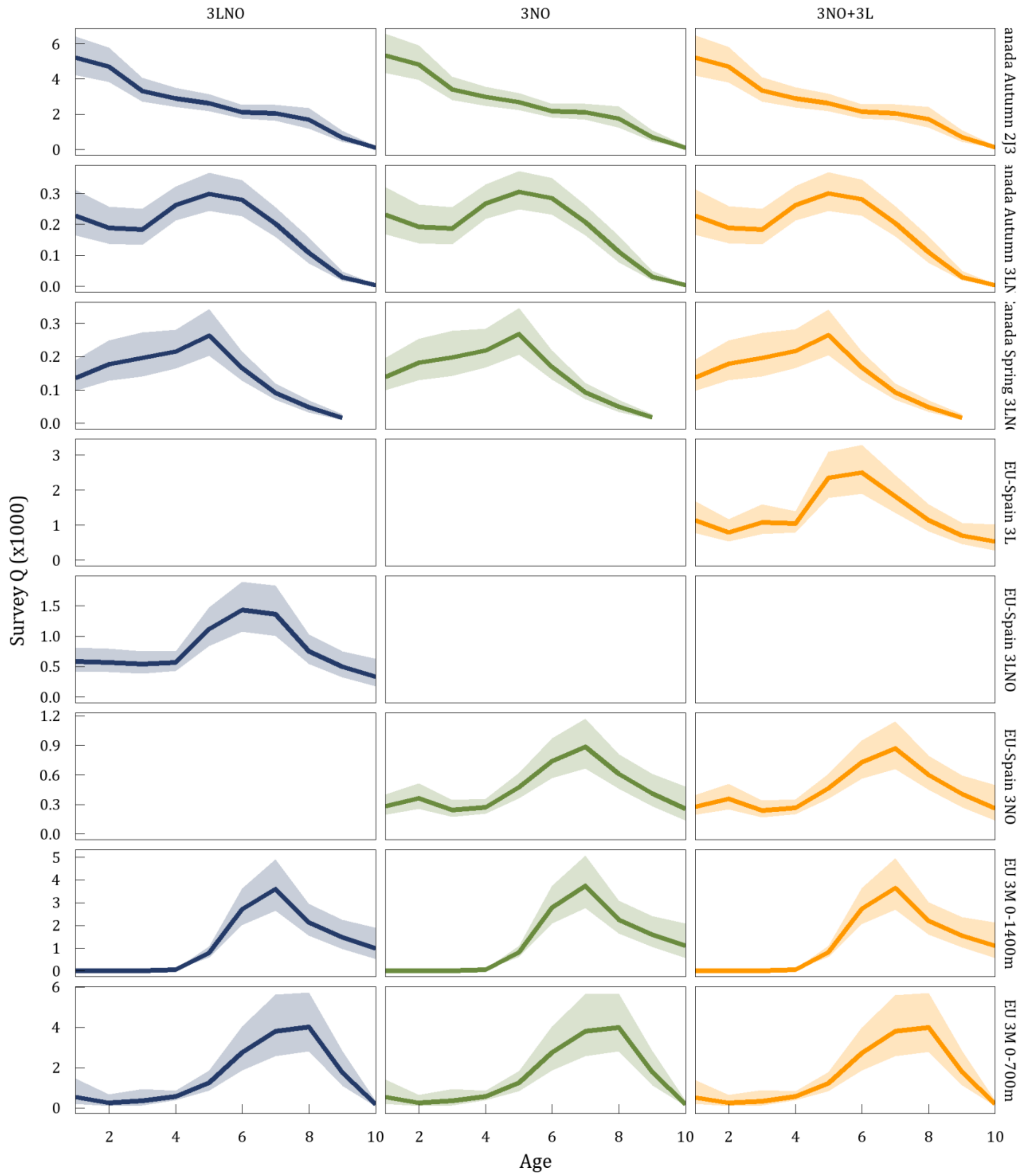

Figure 13. Age patterns in survey catchability parameters, with 95% confidence intervals.

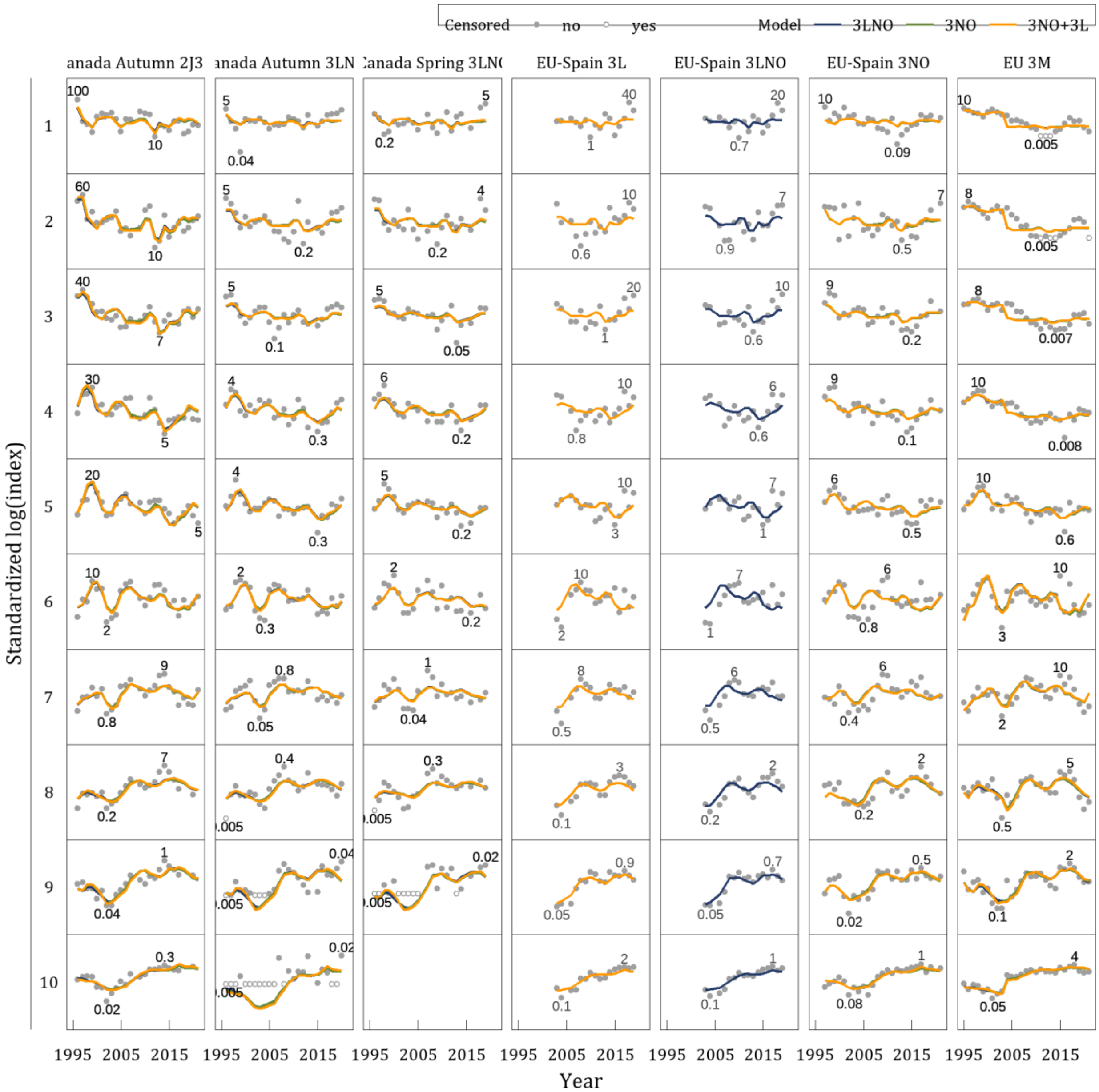

Figure 14. Observed and predicted survey indices at age. Log(index) standardized by survey and age. Min and max observed index values are indicated.

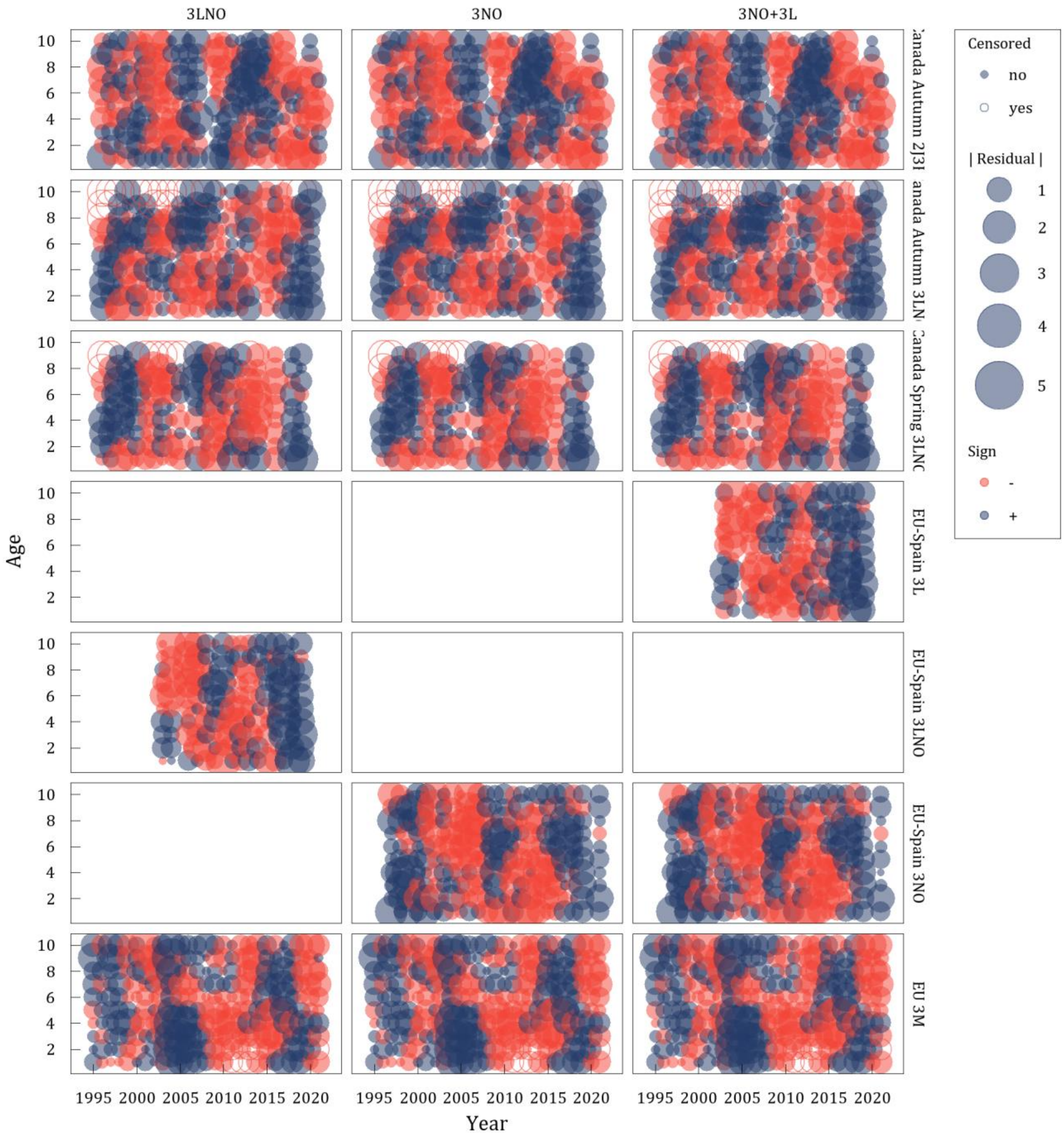

Figure 15. Matrix plot of standardized residuals for index at age by survey.

Appendix D: Session info

This version of the document was generated on 2023-06-03 11:59:58 using the R markdown template for SCR documents from **NAFOdown**.

The computational environment that was used to generate this version is as follows:

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#> Running under: Windows 10 x64 (build 19044)
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#> [2] LC_CTYPE=English_United States.utf8
#> [3] LC_MONETARY=English_United States.utf8
#> [4] LC_NUMERIC=C
#> [5] LC_TIME=English_United States.utf8
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e
#>
#> other attached packages:
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000
#>  [4] RcppEigen_0.3.3.9.3  TMB_1.9.4            tibble_3.2.1
#>  [7] tidyr_1.3.0          dplyr_1.1.1          flextable_0.9.1
#> [10] ggpubr_0.6.0         ggplot2_3.4.2        NAFOdown_0.0.1.900
0
#>
#> loaded via a namespace (and not attached):
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3
#>  [4] tools_4.2.2             backports_1.4.1         utf8_1.2.3
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#> [10] withr_2.5.0             tidyselect_1.2.0        curl_5.0.0
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era_0.1.1
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