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Update of Base Case SSM for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO

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Abstract

Here an update of the state-space model (SSM) developed for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO is presented. This model was developed in 2017 to support a management strategy evaluation (MSE) for this stock. The primary purpose of this update is to assess whether the stock is following the trends projected from the base case operating model from the 2017 MSE process. Unfortunately, a series of technical issues complicated this comparison. In particular, concerns were express regarding the potential impacts of incomplete survey and catch data on the model. There were also concerns regarding the validity of the SSM simulations conducted in 2017. A series of sensitivity tests were run to assess the potential consequences the incomplete data and results from these tests were compared to projections from reviewed and revised SSM simulations. Current SSM estimates are broadly consistent with the revised projections, indicating that there are few signs that the stock is deviating from the expected trajectory while being managed using the current HCR.

Introduction

The Greenland Halibut stock in NAFO Subarea 2 and Divisions 3KLMNO has been managed using a harvest control rule (HCR) since 2010. Since 2017, TACs have been set based on a HCR adopted in 2017 (NAFO, **2017**). This rule was tested using operating models derived from two core assessment model formulations: 1) a statistical-catch-at-age (SCAA) model, and 2) a state-space model (SSM). Here an update of the SSM is presented. This model is described in Regular et al. (**2017**) and here in **Apendix A**. In short, the SSM is a variation of the northern cod assessment model (NCAM) developed by Cadigan (**2015**) that follows the style of the state-space assessment model (SAM) developed by Nielsen and Berg (**2014**). The core of this model is similar to other age-structured assessment models since the population dynamics involve a basic cohort model with a plus group and it fits catch using the Baranov catch equation. Key features and settings include:

- Natural mortality fixed at M = 0.12.
- Variation between reported landings and their model predicted values (σ_L) = 0.1.
- Plus group = 10.
- Starting year for the survey data = 1995.
- Starting year for the landings data = 1975.
- Zeros in mean catch at age from the survey indices and catch at age from catch statistics were replaced with 0.005 and 0.5, respectively, and these values were treated as an upper limit in the likelihood. This predicates that zero observations are not true zeros, rather they are below the detection limit of the sampling programs.
- Like all state-space models, this model attempts to differentiate process error and observation error.
- Fishing mortality is modeled as an autoregressive process with autocorrelation assumed across both ages and years. In other words, Greenland halibut of similar ages and periods are assumed to experience similar levels of fishing mortality.
- Recruitment was modeled as a random effect as there was no clear sign of a stock-recruitment relationship.
- Catch at age proportions were modeled using continuation ratio logits.

The purpose of the update of the SSM is to determine whether the most recent estimates of key management quantities are consistent with past assessment results and if they fall within the probability envelopes from the base case SSM projections produced through the management strategy evaluation process of 2017. Specifically, SC agreed to conduct the following check to determine whether exceptional circumstances are occurring:

"A comparison of assessment model outputs for recruitment, exploitable biomass, and fishing mortality with operating model projections (base case) will also be taken into account qualitatively. Notwithstanding some technical issues regarding the comparison of the simulated distributions against updated assessments, it was agreed that SC will compare the estimated median of the assessment with the 95% Confidence Interval from the base case of SSM and SCAA for the above quantities. Expert judgement will determine whether Exceptional Circumstances are occurring" (NAFO, **2018**).

Though this is the ultimate goal of the update, the most recent data to be used by the model must be evaluated and deemed reasonable for use. Several logistical constraints, however, meant that some of the survey and catch data inputs were incomplete. This has led to some concerns regarding the utility of the survey and catch data. A lack of documentation regarding the probability envelopes produced from the SSM simulations may also limit the ability of SC to conduct the above-mentioned comparison. These issues are summarized below.

Survey data issues

Concerns have been raised regarding the potential impacts of the strata missed during the Canadian survey of Divs. 2J3K in the fall of 2018 and 2019 on the age-structured models used to assess this stock. Analyses of the survey data revealed that the oldest ages (roughly 8+) are the most affected by the missed strata (Regular et al., **2020**; Rideout, **2020**). The potential impacts of these missing data on metrics such as recruitment, exploitable biomass, and average F are unknown and, as such, sensitivity tests are presented here to evaluate the consequences of using or excluding these data.

Catch data issues

Concerns were also raised regarding the commercial catch at age data. Otoliths from much of the commercial catch could not be read because of constraints imposed by the COVID-19 situation.

Consequently, the necessary age-length-keys (ALK) could not be constructed to process the catch data. An ALK from 2018 was therefore "borrowed" to construct catch numbers and weights at age in 2019, however, this imputed key may introduce bias in the estimates. In an attempt to minimize the potential bias, an alternate vector of catch numbers and weights at age was constructed using an average key based on keys from 2015 to 2018. Details of the 2019 catch at age analysis are presented in Ings (Ings, **2020**). Despite these efforts, the magnitude of the bias introduced by the "borrowed" keys is unknown as are its effects on key management quantities. Sensitivity tests were therefore run to evaluate different catch at age options.

SSM projection issues

At the June meeting of 2019, piecemeal documentation regarding the confidence intervals around projected survey indices precluded the use of the SSM output for evaluating exceptional circumstances (NAFO, **2019**). A thorough review of the code behind the SSM MSE simulations has since been conducted and several issues have been identified and resolved (Varkey et al., **2020**). Current SSM estimates are compared with the projections from the revised projections to determine whether the stock is deviating from the expected trajectory.

Methods

The data used in this update are listed in **Apendix B**. Given the above-mentioned data limitations, the following sensitivity tests were run:

a) **Base**: Includes all commercial data and survey CAA data, except for indices of ages 8-10+ from the Fall survey of 2J3K in 2018 and 2019
b) **S1**: As a) **Base**, but including all survey ages (1 to 10+)
c) **S2**: As a) **Base**, but excluding the 2019 survey CAA data
d) **S3**: As a) **Base**, but excluding the 2018 and 2019 survey CAA data
e) **S4**: As a) **Base**, but excluding the 2019 commercial proportions-at-age
f) **S5**: As a) **Base**, but including the alternative 2019 CAA commercial data

A retrospective analysis was also conducted to assess the consistency of the model estimates.

Results

- Trends in key management quantities are comparable for the **Base**, **S1**, **S4** and **S5** options, however recruitment and total abundance is higher in recent years when the 2018 or the 2018 and 2019 2J3K data are excluded (**S2** and **S3**; **Figure 1**).
- Uncertainty in recent F estimates is increased slightly when the 2019 catch proportions at age are excluded (**S4**; **Figures 3, 4**).
- Process error for age 2 is higher in the **S2** and **S3** cases than the **Base** and **S1** options (**Figure 6**).
- The 2J3K survey is an important data series for the model and it has the highest weighting (lowest CV) for the 1-3 and 4-7 age groups; indices of ages 8-10+ from this survey, however, are relatively noisy (**Figure 10**).
- Model fit to the indices of ages 1 and 2 from the Canada Fall 3LNO survey is improved when the incomplete 2J3K survey data are excluded (**S2** and **S3**; **Figure 12**).
- Recent estimates of exploitable biomass and average F from all sensitivity tests fall within the 95% confidence intervals from the revised SSM MSE simulations (**Figure 14**). Recent estimates of

recruitment and abundance fall outside the 95% confidence intervals when the 2J3K survey data are excluded from the model (**S2**, **S3**; **Figure 14**).

- Parameter estimates and derived quantities are consistent as data are retrospectively excluded from the model **Apendix C**.

Discussion

Data issues

Interpretation: In the absence of recent estimates of Greenland halibut from the Canadian Fall 2J3K survey, the model increases the number of ages 1 and 2 to improve the fit to the Canadian Fall 3LNO survey. However, this increase has little impact on biomass estimates as mean weights of ages 1 and 2 tends to be less than 0.01 kg. There is also an slight increase in uncertainty around the shape of commercial selectivity when the most recent catch proportions at age are excluded.

Conclusion: It is difficult to justify the complete exclusion of the 2018 and 2019 2J3K data as the potential impacts of the missed strata on MNPT estimates are relatively minor for most age groups (Regular et al., **2020**; Rideout, **2020**). Moreover, this is an important index to the model, particularly for ages 1-7. The values excluded in the **Base** run may be justified on principle, however, it could be argued that the independent estimation of survey variance for ages 8-10+ allows the model to account for more noisy observations. In short, while recent MNPT estimates of ages 7+ from the 2J3K survey have a negligible impact on the assessment model, there is a noticeable impact of ignoring information from this survey. Likewise, there is a slight impact of ignoring the latest estimate of catch proportions at age, however, it is unknown whether the impact of ignoring these data is greater than the impact of using estimates based on burrowed ALKs.

Consistency

The retrospective analysis indicates that the model estimates are stable in recent years, including those obtained in 2017 (terminal year = 2016) when this model was first utilized as part of the MSE process. Unfortunately, the issues identified with the initial MSE simulations make comparisons with current estimates moot. Following guidance from documents produced during the 2017 MSE process, the SSM simulation code was modified in an attempt to generate the intended projection results (Varkey et al., **2020**). Current SSM estimates are broadly consistent with these results, indicating that there are few signs that the stock is deviating from the expected trajectory while being managed using the current HCR.

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Tables

Table 1. Key parameter estimates from each sensitivity test. See Table 5 for parameter descriptions.

Parameter	Base	S1	S2	S3	S4	S5
$\sigma_{\text{Canada Fall 2J3K},1-3}$	0.30	0.30	0.29	0.25	0.30	0.30
$\sigma_{\text{Canada Fall 2J3K},4-7}$	0.30	0.30	0.30	0.31	0.30	0.30
$\sigma_{\text{Canada Fall 2J3K},8-10}$	0.45	0.45	0.44	0.45	0.45	0.45
$\sigma_{\text{Canada Fall 3LNO},1-3}$	0.67	0.67	0.65	0.63	0.67	0.67
$\sigma_{\text{Canada Fall 3LNO},4-7}$	0.38	0.38	0.38	0.38	0.38	0.38
$\sigma_{\text{Canada Fall 3LNO},8-10}$	0.61	0.60	0.60	0.61	0.61	0.61
$\sigma_{\text{Canada Spring 3LNO},1-3}$	0.71	0.71	0.68	0.65	0.71	0.70
$\sigma_{\text{Canada Spring 3LNO},4-7}$	0.53	0.53	0.53	0.52	0.53	0.53
$\sigma_{\text{Canada Spring 3LNO},8-10}$	0.65	0.66	0.65	0.65	0.66	0.66
$\sigma_{\text{EU 3NO},1-3}$	0.80	0.80	0.79	0.79	0.80	0.80
$\sigma_{\text{EU 3NO},4-7}$	0.61	0.61	0.61	0.61	0.61	0.61
$\sigma_{\text{EU 3NO},8-10}$	0.43	0.44	0.43	0.43	0.43	0.43
$\sigma_{\text{EU 3M},1-3}$	1.48	1.48	1.47	1.46	1.47	1.47
$\sigma_{\text{EU 3M},4-7}$	0.56	0.57	0.56	0.56	0.57	0.56
$\sigma_{\text{EU 3M},8-10}$	0.38	0.38	0.38	0.38	0.38	0.38
σ_{main}	0.57	0.57	0.56	0.56	0.57	0.57
σ_{Δ}	0.37	0.37	0.36	0.36	0.37	0.36
σ_{X}	0.19	0.19	0.19	0.19	0.19	0.19
σ_{r}	0.32	0.32	0.34	0.37	0.32	0.32
r	11.10	11.10	11.11	11.12	11.10	11.10
σ_{F}	0.21	0.21	0.21	0.20	0.21	0.21
σ_{δ}	0.15	0.15	0.15	0.15	0.15	0.15
$\varphi_{F,y}$	0.98	0.98	0.98	0.98	0.98	0.97
$\varphi_{F,a}$	0.50	0.50	0.50	0.50	0.50	0.50

Table 2. Estimates of recruitment (age 1; millions) from each sensitivity test.

Year	Base	S1	S2	S3	S4	S5
1975	64.27	64.33	64.85	65.00	64.18	64.15
1976	61.33	61.41	61.62	61.48	61.31	61.25
1977	61.71	61.81	62.02	61.88	61.68	61.57
1978	56.07	56.16	56.12	55.54	56.01	55.96
1979	53.90	54.00	53.71	52.99	53.92	53.76
1980	67.17	67.32	67.82	68.17	67.16	67.07
1981	70.88	71.00	71.92	72.73	70.83	70.78
1982	65.92	66.03	66.61	66.99	65.89	65.87
1983	69.50	69.63	70.31	71.00	69.55	69.48
1984	73.59	73.69	74.80	75.97	73.65	73.56
1985	79.02	79.11	80.62	82.35	79.11	79.06
1986	74.28	74.36	75.27	76.45	74.43	74.35
1987	81.80	81.88	83.65	85.60	81.81	81.73
1988	70.69	70.74	71.59	72.36	70.72	70.68
1989	67.97	68.02	68.69	69.16	67.95	67.91
1990	62.95	62.95	63.17	63.22	62.96	62.92
1991	62.02	61.99	62.32	62.35	61.91	61.91
1992	57.11	57.05	57.19	56.79	57.08	57.01
1993	71.10	71.02	71.96	72.62	71.07	71.00
1994	110.14	110.02	113.84	117.82	110.17	110.12
1995	132.81	132.63	137.21	139.57	132.87	132.93
1996	141.88	141.69	145.64	150.19	141.82	141.75
1997	74.66	74.56	74.77	72.25	74.67	74.68
1998	56.56	56.49	55.80	54.48	56.56	56.43
1999	44.04	43.98	42.90	40.90	44.07	43.96
2000	72.68	72.58	72.59	71.11	72.67	72.60
2001	77.85	77.74	77.77	76.25	77.84	77.75
2002	78.39	78.29	78.37	76.73	78.41	78.35
2003	80.53	80.42	80.90	79.97	80.51	80.46
2004	57.37	57.30	56.93	55.48	57.36	57.27
2005	46.74	46.68	45.83	43.35	46.76	46.70
2006	55.47	55.39	55.09	53.99	55.45	55.38
2007	58.49	58.41	58.34	57.91	58.47	58.37
2008	52.58	52.52	51.91	50.85	52.61	52.48
2009	73.96	73.86	73.94	75.56	73.90	73.67

Year	Base	S1	S2	S3	S4	S5
2010	72.23	72.11	72.94	75.12	72.15	72.00
2011	48.48	48.38	48.56	49.20	48.40	48.34
2012	32.38	32.30	31.57	30.19	32.35	32.30
2013	52.77	52.68	52.86	52.99	52.77	52.64
2014	47.20	47.13	46.73	45.12	47.20	47.00
2015	47.34	47.27	46.44	44.24	47.47	47.50
2016	67.01	66.91	67.42	65.08	66.89	65.98
2017	78.26	78.16	78.97	90.15	78.54	79.76
2018	64.49	64.42	69.68	120.03	64.58	64.75
2019	66.23	66.17	111.01	120.24	66.31	66.50

Table 3. Estimates of exploitable biomass (ages 5-9; Kt) from each sensitivity test.

Year	Base	S1	S2	S3	S4	S5
1975	91.67	91.80	91.69	91.64	91.63	91.60
1976	93.94	94.11	93.98	93.90	93.84	93.79
1977	111.48	111.68	111.44	111.33	111.44	111.31
1978	119.50	119.71	119.45	119.34	119.51	119.32
1979	116.45	116.73	116.60	116.47	116.36	116.22
1980	95.49	95.79	95.69	95.53	95.44	95.26
1981	83.55	83.87	83.71	83.52	83.42	83.30
1982	82.33	82.71	82.42	82.13	82.23	82.03
1983	77.04	77.47	77.09	76.76	76.94	76.74
1984	69.82	70.27	69.87	69.60	69.77	69.52
1985	92.49	93.05	92.69	92.54	92.40	92.15
1986	80.02	80.54	80.22	80.12	79.96	79.75
1987	95.66	96.27	95.98	95.94	95.62	95.41
1988	99.29	99.89	99.56	99.65	99.28	99.09
1989	111.93	112.51	112.38	112.65	112.00	111.82
1990	123.23	123.81	123.77	124.06	123.35	123.18
1991	138.82	139.49	139.54	139.86	138.93	138.74
1992	129.82	130.44	130.45	130.63	129.88	129.74
1993	104.53	105.08	104.93	104.94	104.59	104.44
1994	70.60	71.02	70.70	70.59	70.65	70.52
1995	43.08	43.34	42.99	42.87	43.09	42.98
1996	46.81	46.94	46.64	46.55	46.76	46.70
1997	55.08	55.18	55.09	54.95	55.02	54.96
1998	83.11	83.19	83.39	83.40	83.00	82.93
1999	100.52	100.55	100.70	100.59	100.42	100.32
2000	103.73	103.73	103.65	103.54	103.63	103.54
2001	91.00	91.02	90.79	90.56	90.94	90.83
2002	63.51	63.55	63.16	63.07	63.49	63.39
2003	55.51	55.53	55.30	55.26	55.44	55.40
2004	56.85	56.86	56.73	56.49	56.79	56.72
2005	75.59	75.67	75.54	74.95	75.54	75.42
2006	91.83	91.99	91.72	90.87	91.79	91.61
2007	100.02	100.25	99.95	98.91	99.97	99.74
2008	105.42	105.70	105.21	104.17	105.35	105.07
2009	93.88	94.14	93.44	92.72	93.80	93.57

Year	Base	S1	S2	S3	S4	S5
2010	87.16	87.36	86.86	86.36	87.04	86.87
2011	77.96	78.15	77.76	77.13	77.90	77.73
2012	79.81	80.00	79.69	78.78	79.78	79.58
2013	91.65	91.88	91.55	90.37	91.62	91.39
2014	93.79	94.04	93.65	92.34	93.80	93.52
2015	84.54	84.67	84.23	83.21	84.58	84.29
2016	80.08	79.91	79.59	78.94	80.14	79.89
2017	60.70	60.05	60.49	60.26	60.76	60.60
2018	74.09	72.32	74.36	73.90	74.02	73.70
2019	67.85	65.22	69.24	68.86	67.14	68.86

Table 4. Estimates of average F (ages 5-9; Kt) from each sensitivity test.

Year	Base	S1	S2	S3	S4	S5
1975	0.23	0.23	0.23	0.23	0.23	0.23
1976	0.15	0.15	0.15	0.15	0.15	0.15
1977	0.26	0.26	0.26	0.26	0.26	0.26
1978	0.29	0.29	0.29	0.29	0.29	0.29
1979	0.31	0.31	0.31	0.31	0.31	0.31
1980	0.27	0.26	0.26	0.27	0.27	0.27
1981	0.36	0.36	0.36	0.36	0.36	0.36
1982	0.25	0.25	0.25	0.25	0.25	0.25
1983	0.32	0.32	0.32	0.32	0.32	0.32
1984	0.27	0.27	0.27	0.27	0.27	0.27
1985	0.21	0.21	0.21	0.21	0.21	0.21
1986	0.16	0.16	0.16	0.16	0.16	0.16
1987	0.20	0.20	0.20	0.20	0.20	0.20
1988	0.15	0.15	0.15	0.15	0.15	0.15
1989	0.12	0.12	0.12	0.12	0.12	0.12
1990	0.22	0.22	0.22	0.22	0.22	0.22
1991	0.28	0.28	0.28	0.28	0.28	0.28
1992	0.40	0.40	0.40	0.40	0.40	0.40
1993	0.57	0.57	0.57	0.58	0.57	0.58
1994	0.84	0.84	0.84	0.85	0.84	0.84
1995	0.22	0.22	0.22	0.22	0.22	0.22
1996	0.27	0.27	0.27	0.27	0.27	0.27
1997	0.23	0.23	0.23	0.23	0.23	0.23
1998	0.19	0.18	0.18	0.18	0.19	0.19
1999	0.18	0.18	0.18	0.18	0.18	0.18
2000	0.38	0.38	0.38	0.38	0.38	0.38
2001	0.58	0.58	0.58	0.58	0.58	0.58
2002	0.65	0.65	0.65	0.65	0.65	0.65
2003	0.61	0.61	0.61	0.61	0.61	0.61
2004	0.35	0.35	0.35	0.35	0.35	0.35
2005	0.22	0.22	0.22	0.23	0.22	0.22
2006	0.23	0.23	0.23	0.24	0.23	0.23
2007	0.20	0.20	0.20	0.20	0.20	0.20
2008	0.21	0.20	0.21	0.21	0.21	0.21
2009	0.23	0.23	0.23	0.23	0.23	0.23

Year	Base	S1	S2	S3	S4	S5
2010	0.29	0.28	0.29	0.29	0.29	0.29
2011	0.28	0.28	0.28	0.28	0.28	0.28
2012	0.21	0.21	0.21	0.21	0.21	0.21
2013	0.20	0.20	0.20	0.21	0.20	0.20
2014	0.21	0.21	0.21	0.21	0.21	0.21
2015	0.17	0.17	0.17	0.18	0.17	0.17
2016	0.18	0.18	0.18	0.18	0.18	0.18
2017	0.14	0.14	0.14	0.14	0.14	0.14
2018	0.17	0.18	0.17	0.17	0.17	0.18
2019	0.18	0.19	0.17	0.17	0.19	0.17

Figures

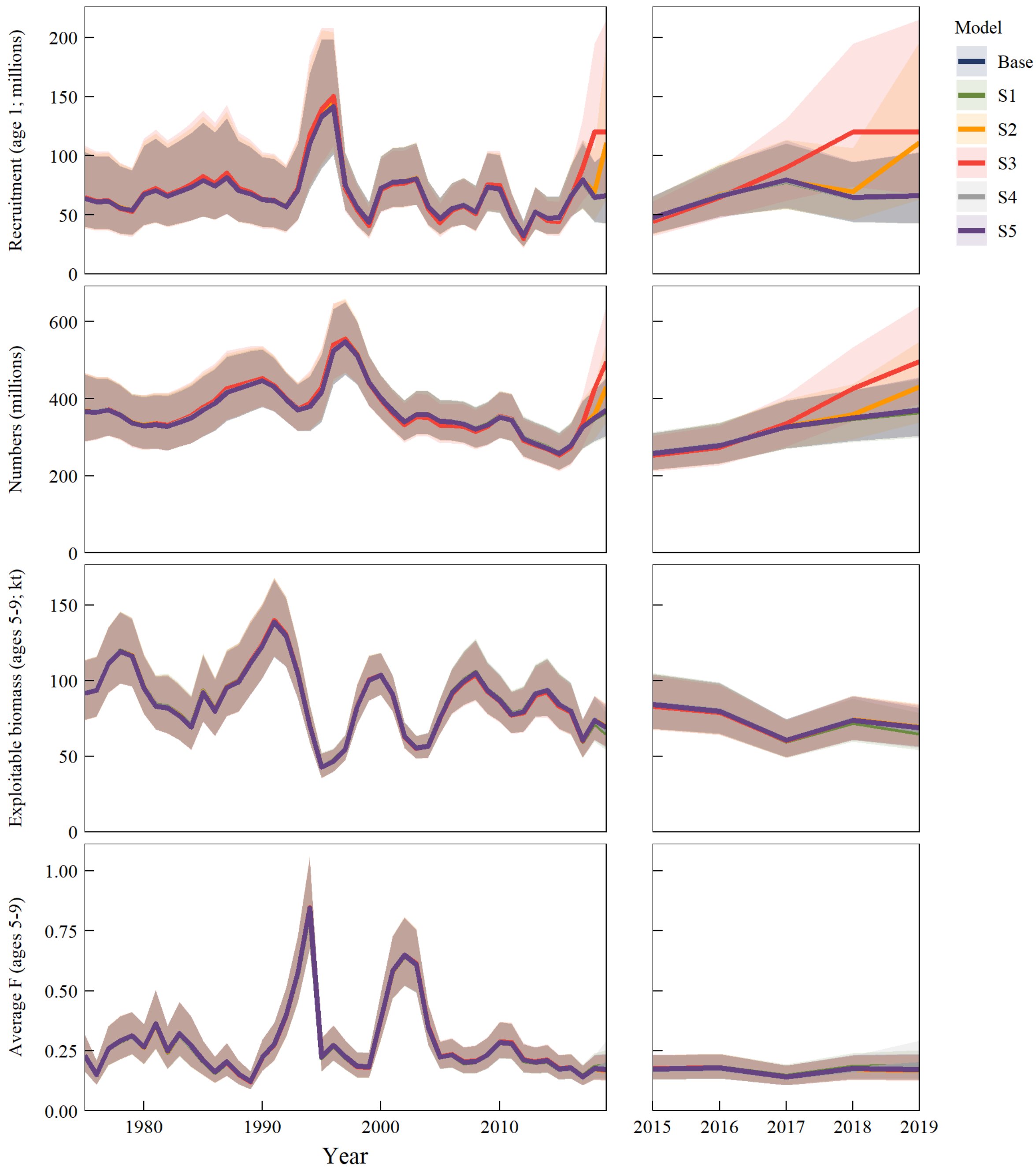


Figure 1. Estimates of recruitment (age 1), numbers, exploitable biomass (ages 5-9), and average F (ages 5-9), with 95% confidence intervals, for the whole time-series (left) and from the last 5 years (right).

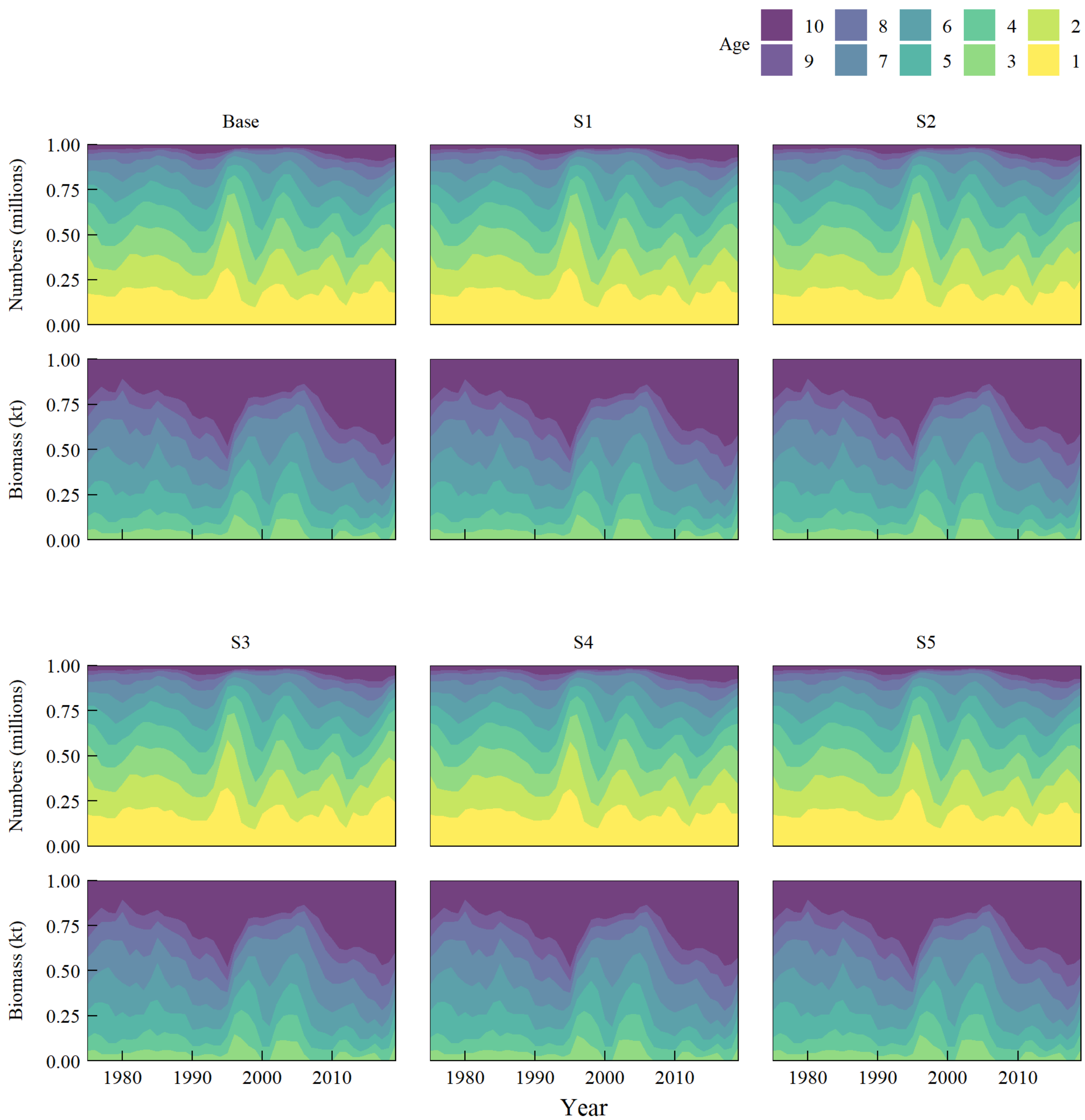


Figure 2. Stock abundance and biomass proportion at age.

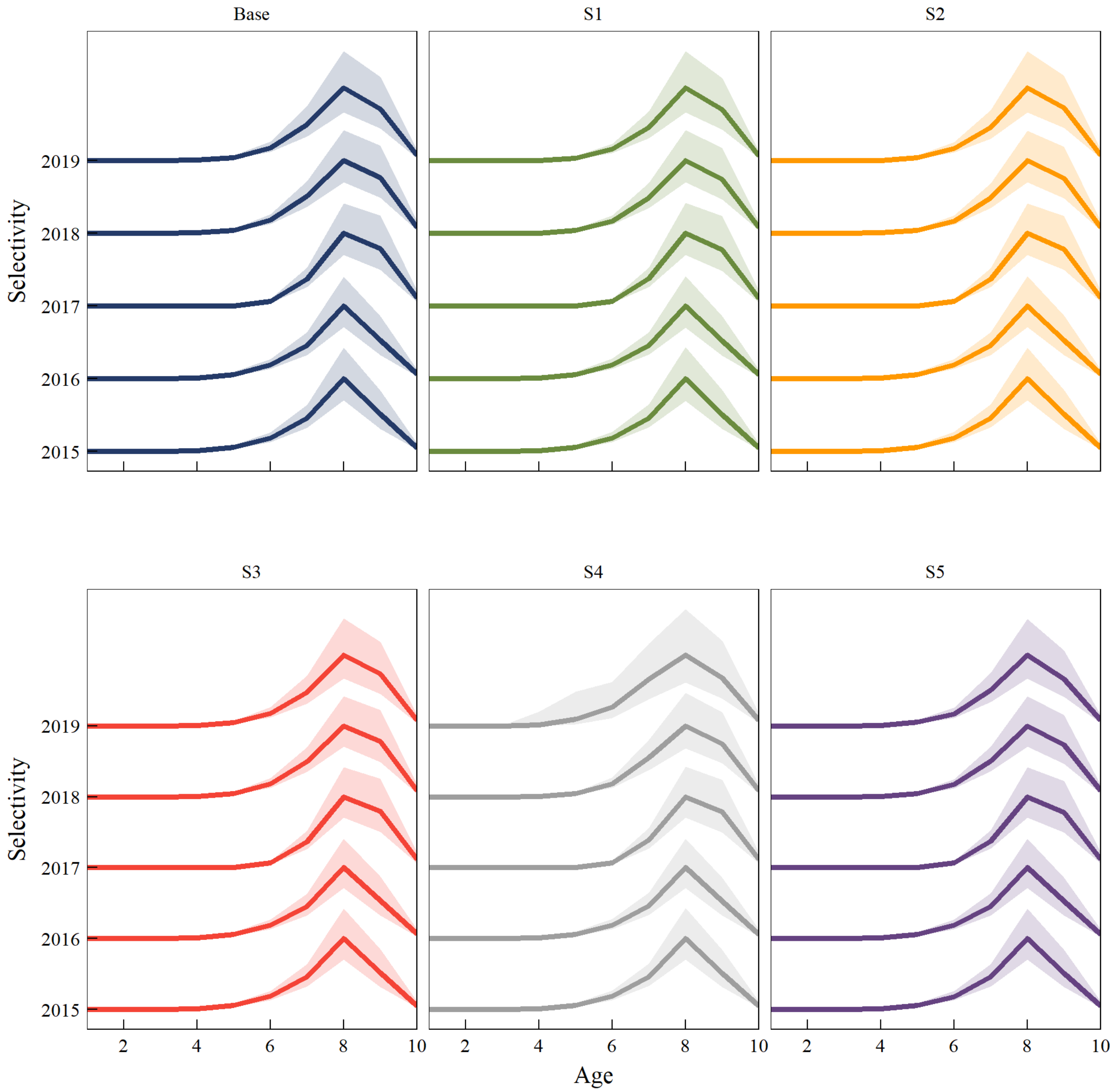


Figure 3. Selectivity curves from the most recent five years.

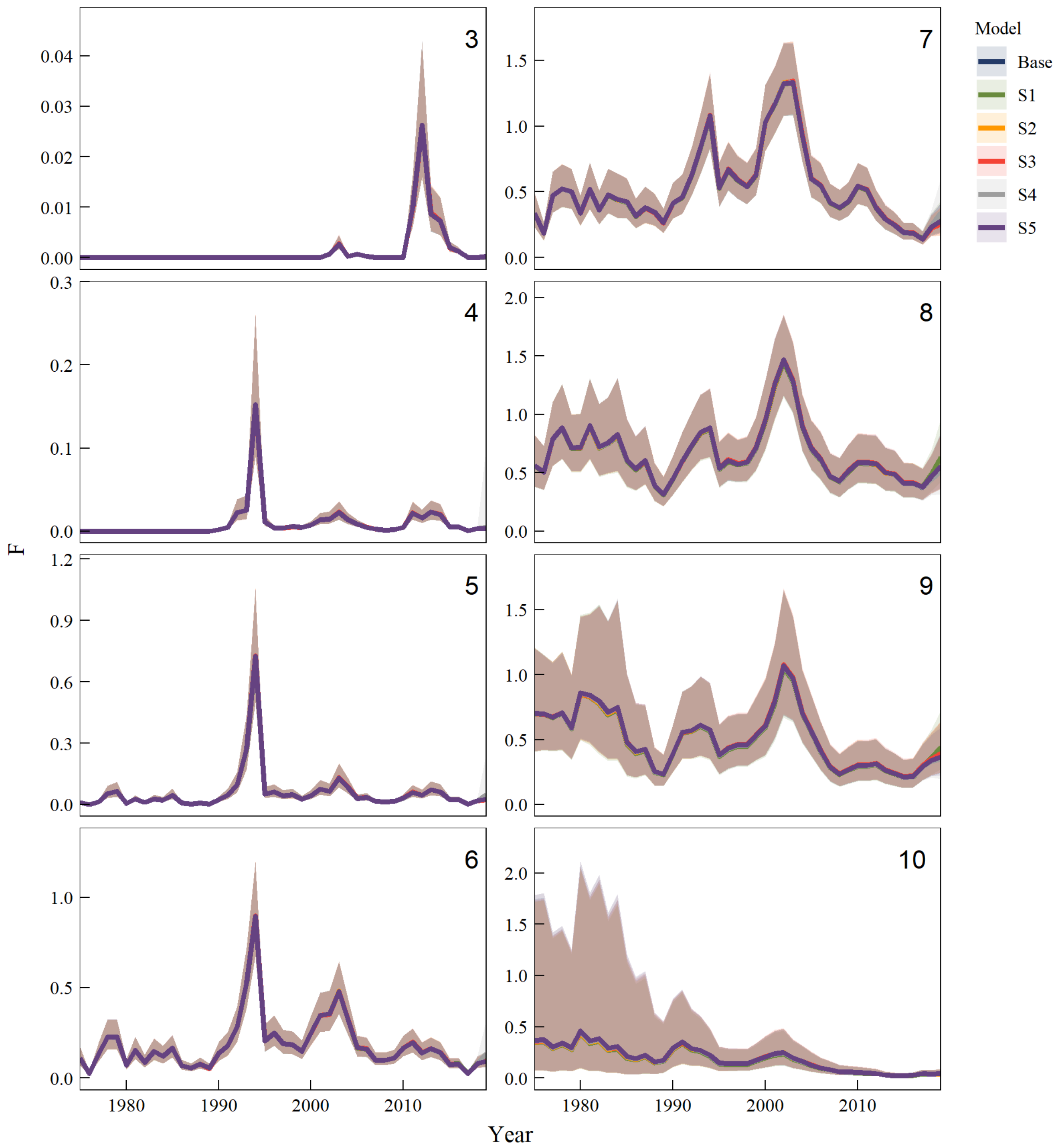


Figure 4. Fishing mortality at age.

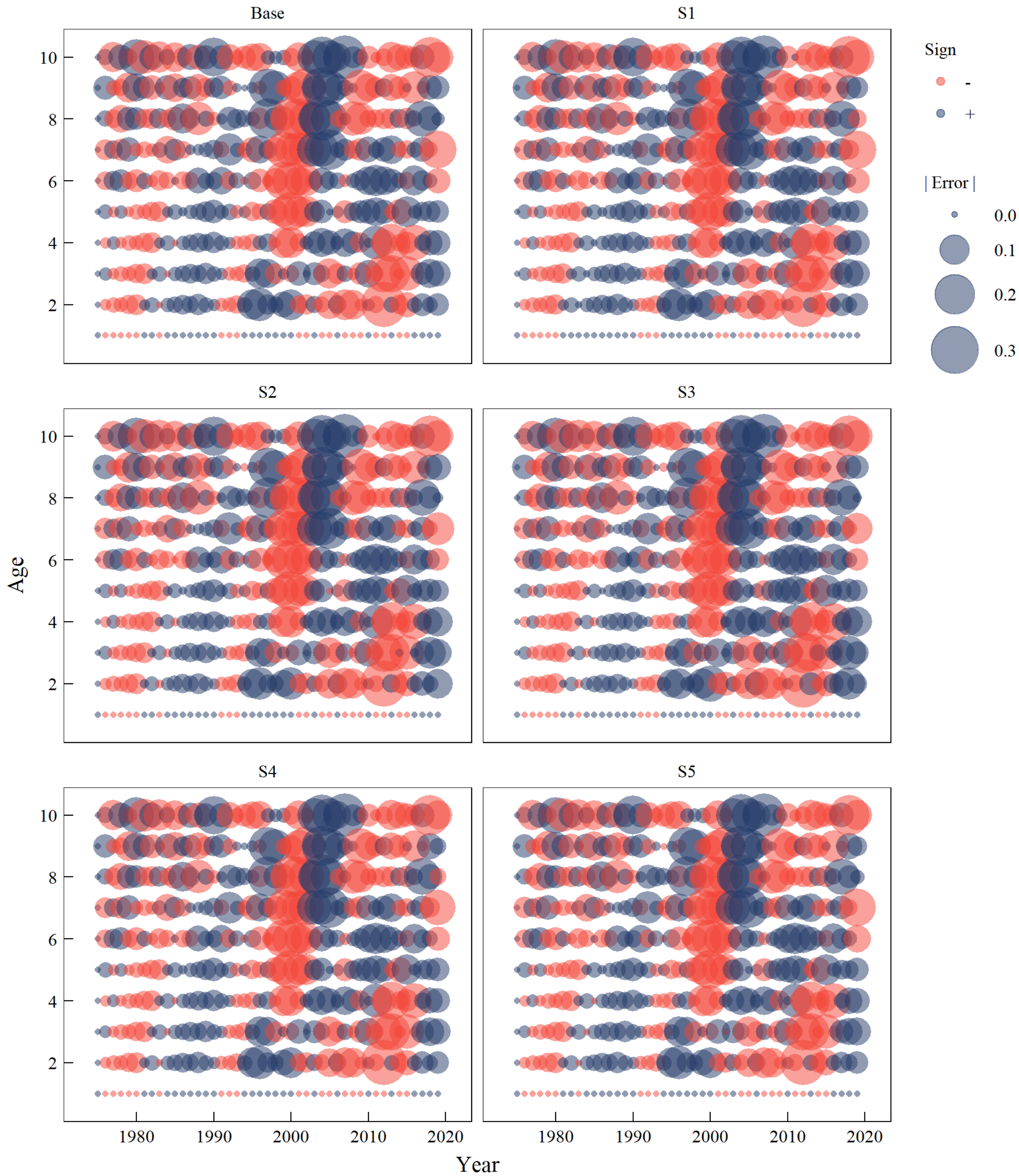


Figure 5. Matrix plot of predicted process errors.

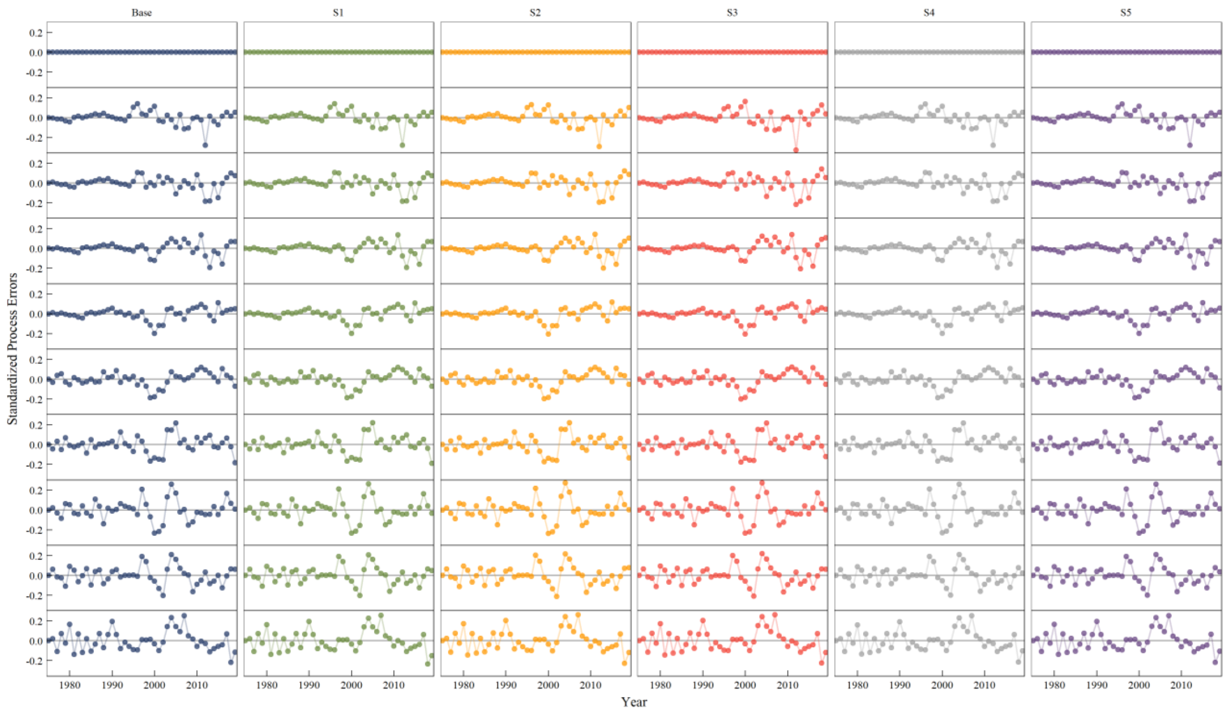


Figure 6. Predicted process error at age.

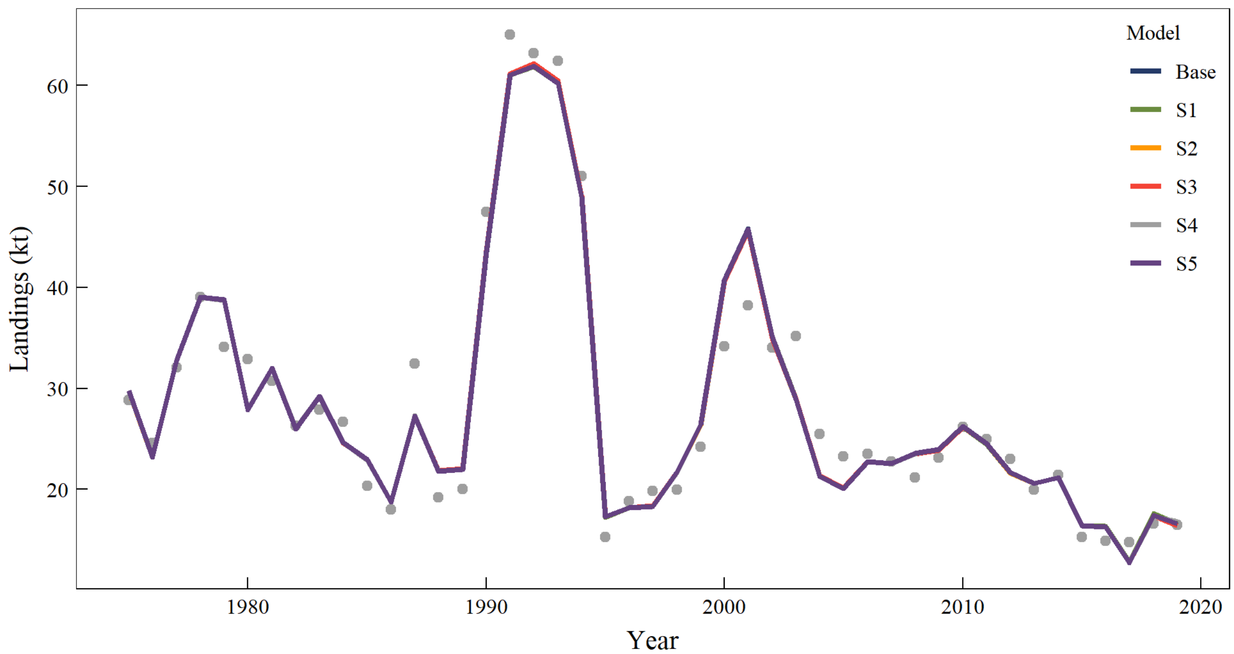


Figure 7. Observed and predicted landings (kt).

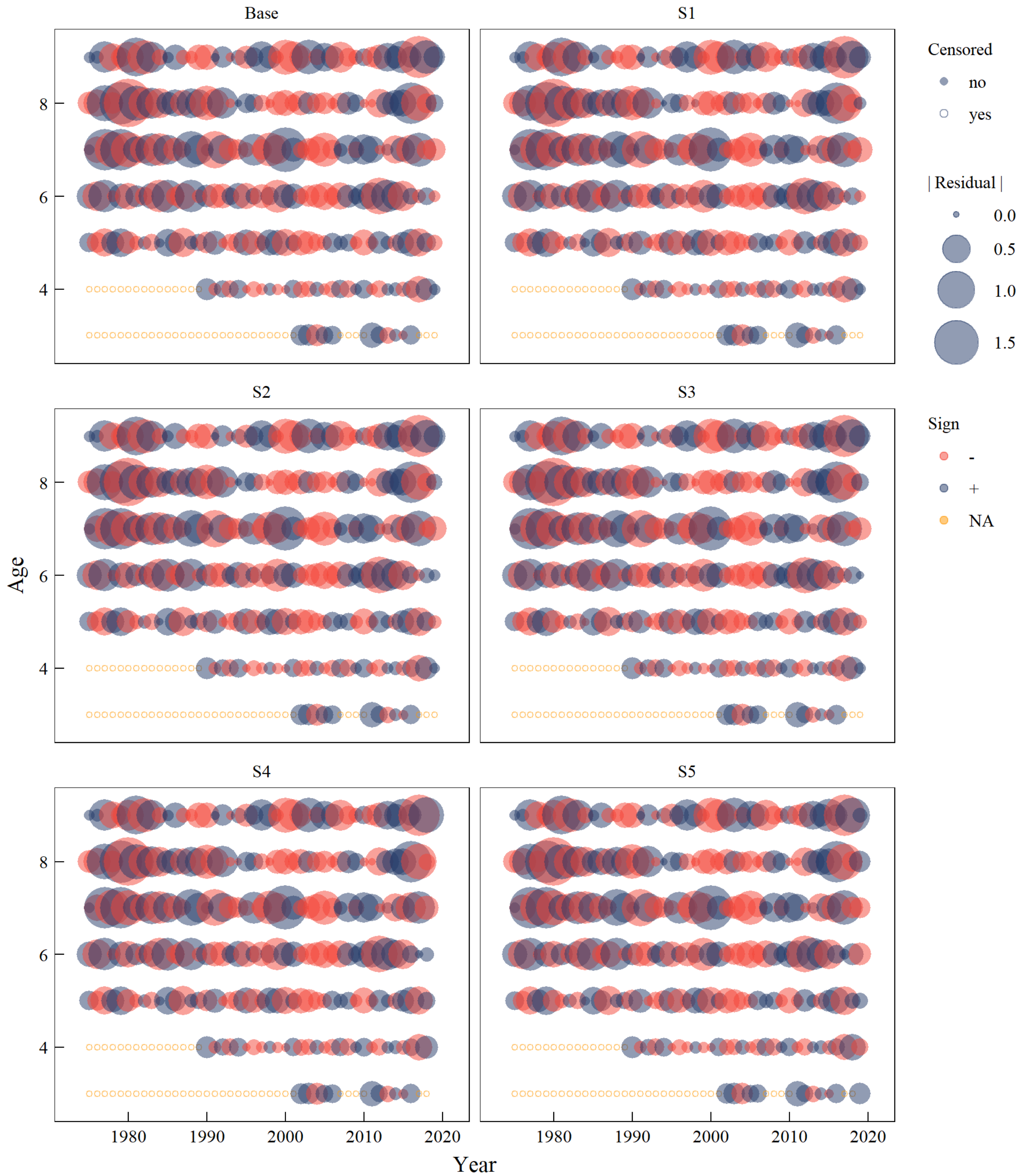


Figure 8. Matrix plot of standardized residuals for catch at age continuation ratio logits (observed minus predicted).

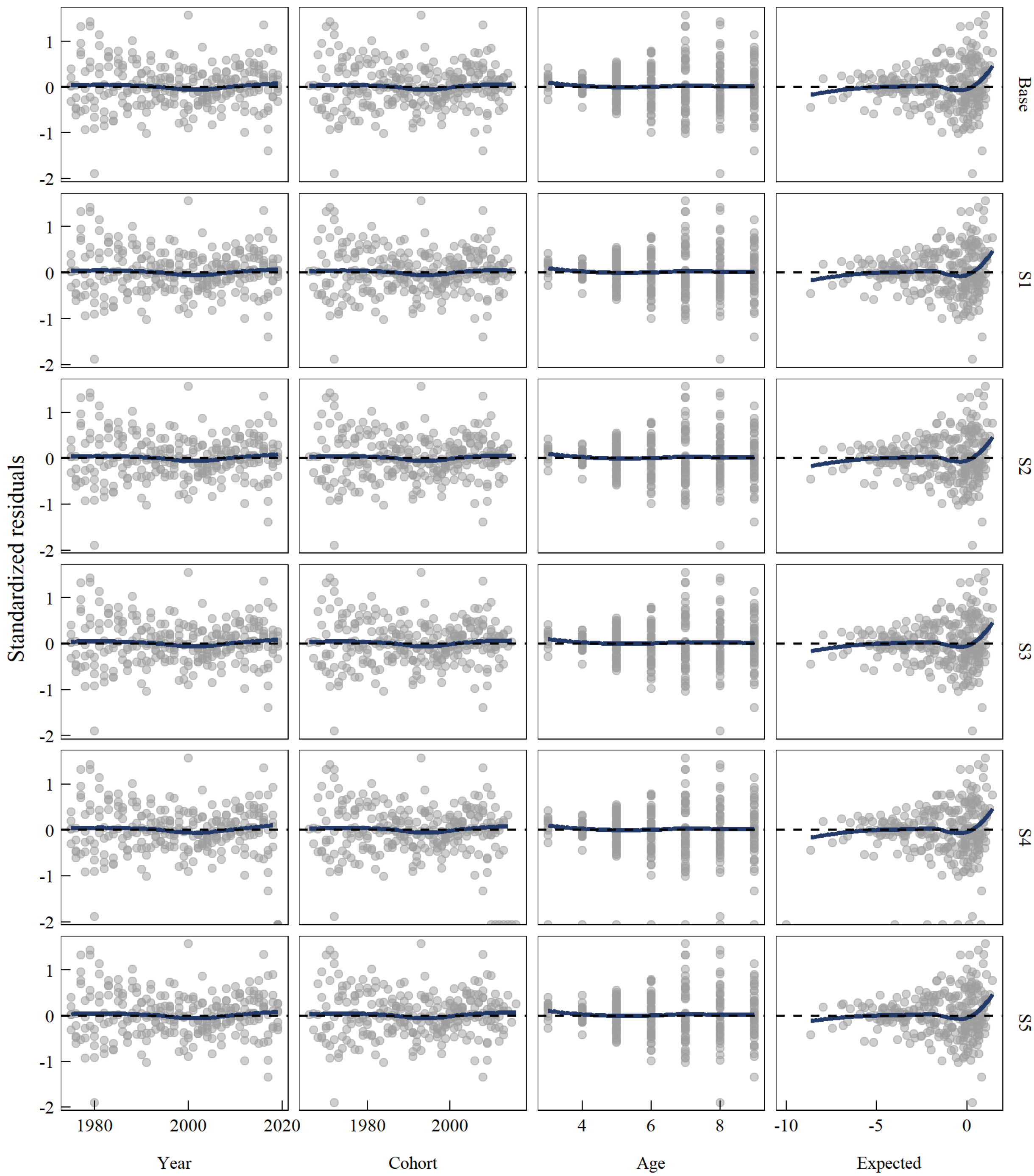


Figure 9. Standardized residuals for catch at age continuation ratio logits versus year, cohort, age, and predicted value.

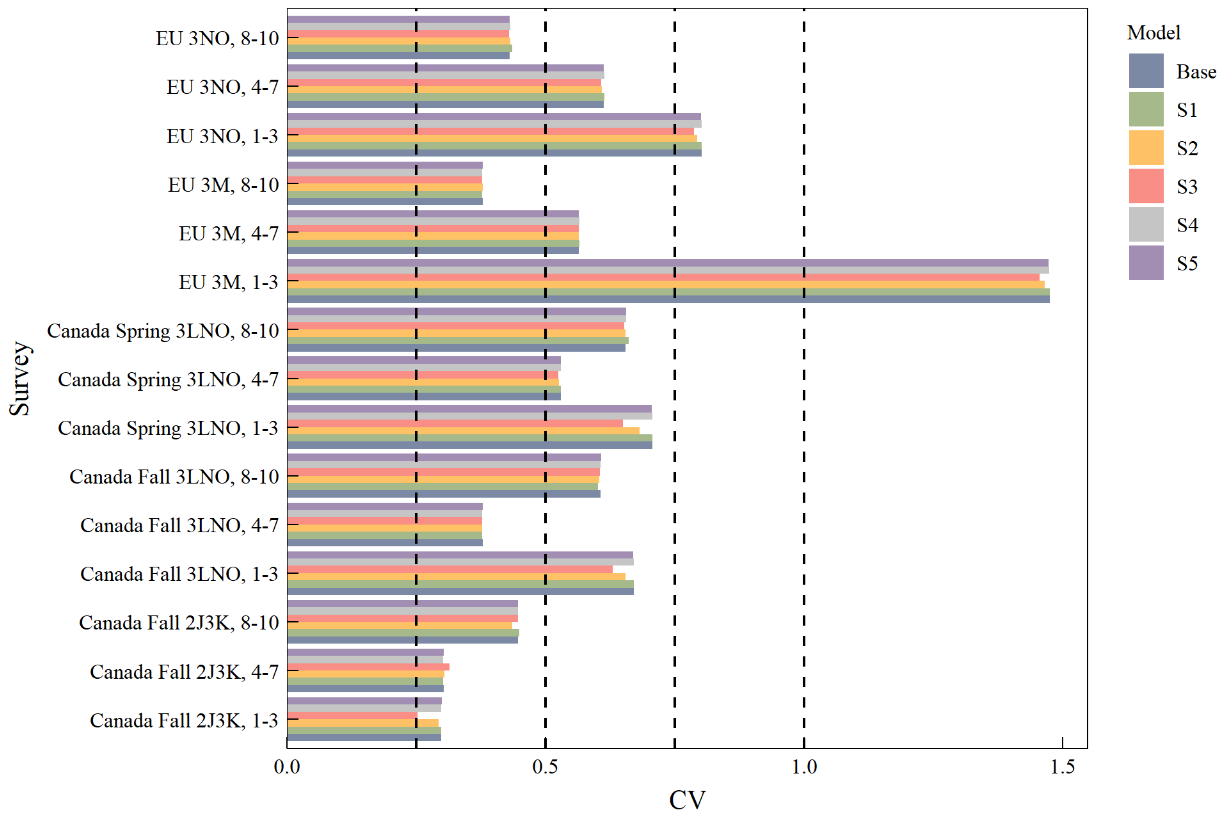


Figure 10. Estimates of survey CV. Age ranges follow the survey name.

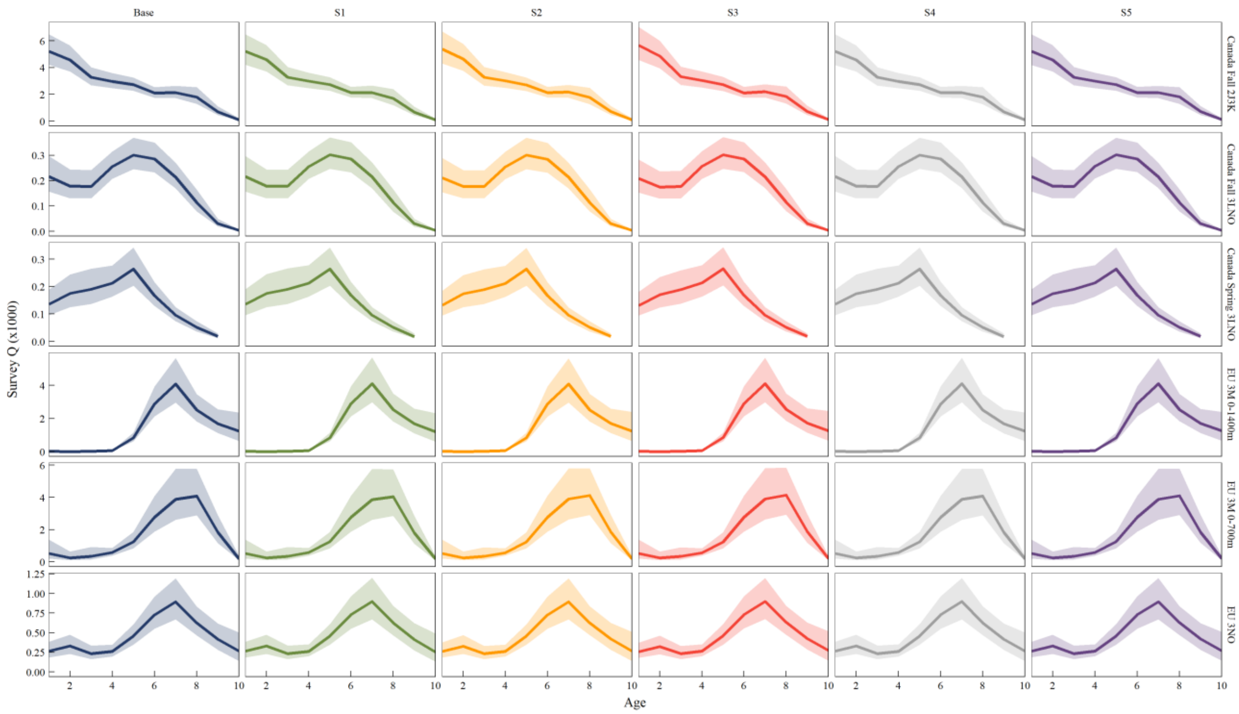


Figure 11. Age patterns in survey catchability parameters, with 95% confidence intervals.

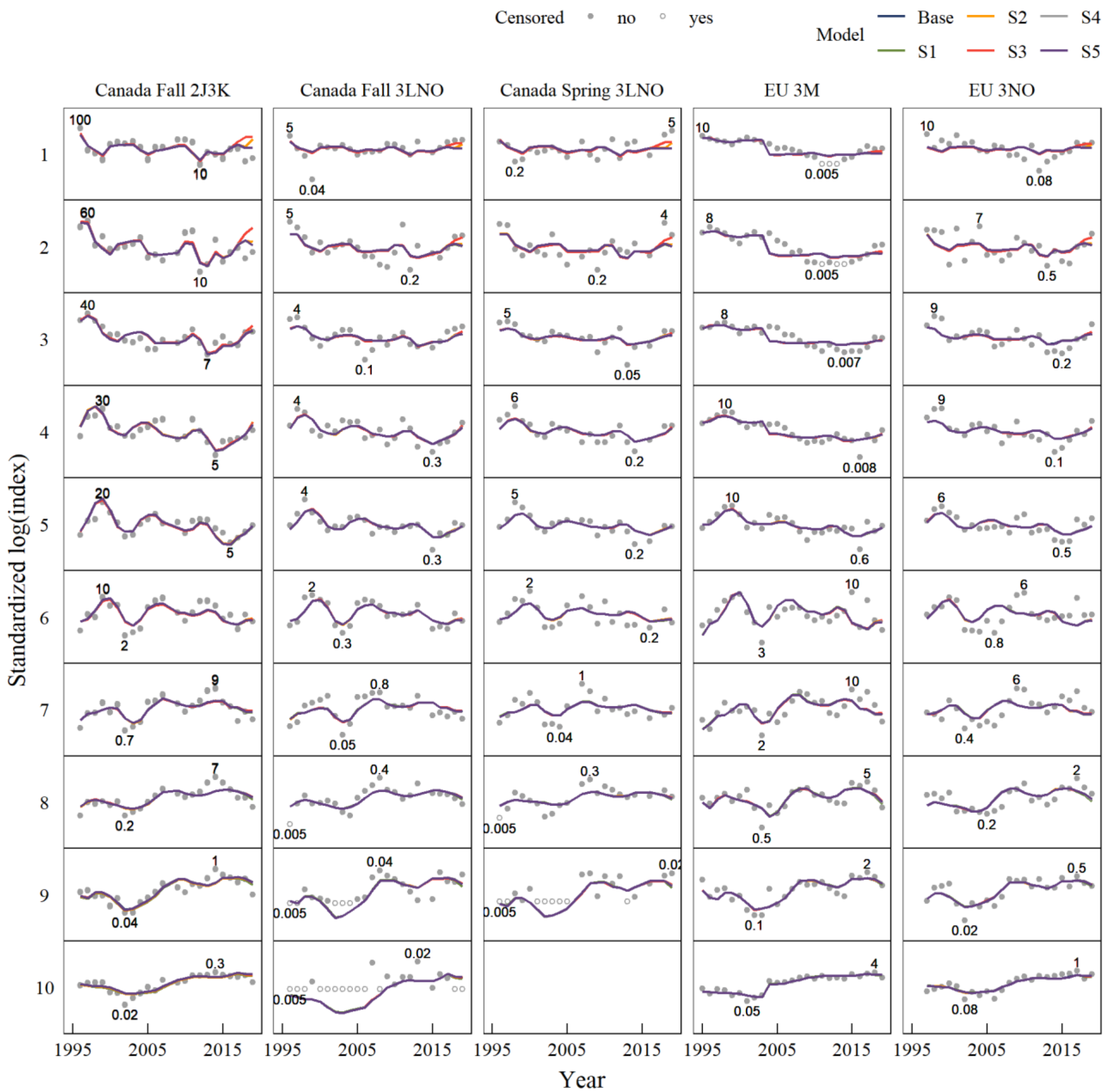


Figure 12. Observed and predicted survey indices at age. Log(index) standardized by survey and age. Min and max observed index values are indicated.

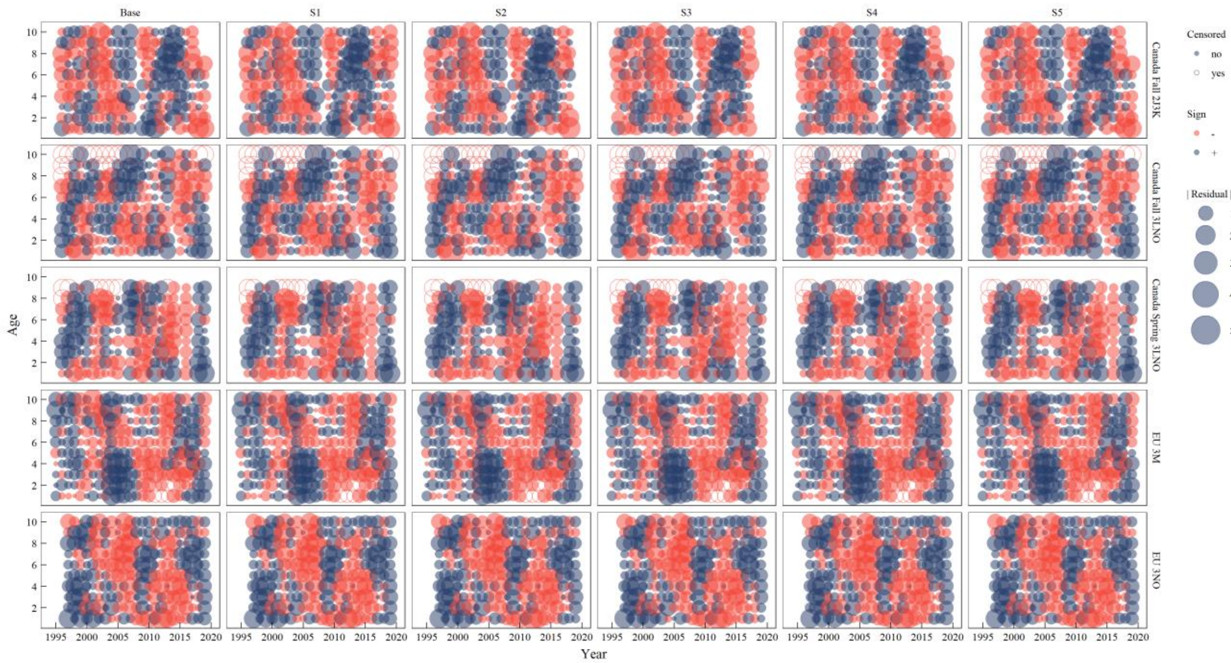


Figure 13. Matrix plot of standardized residuals for index at age by survey.

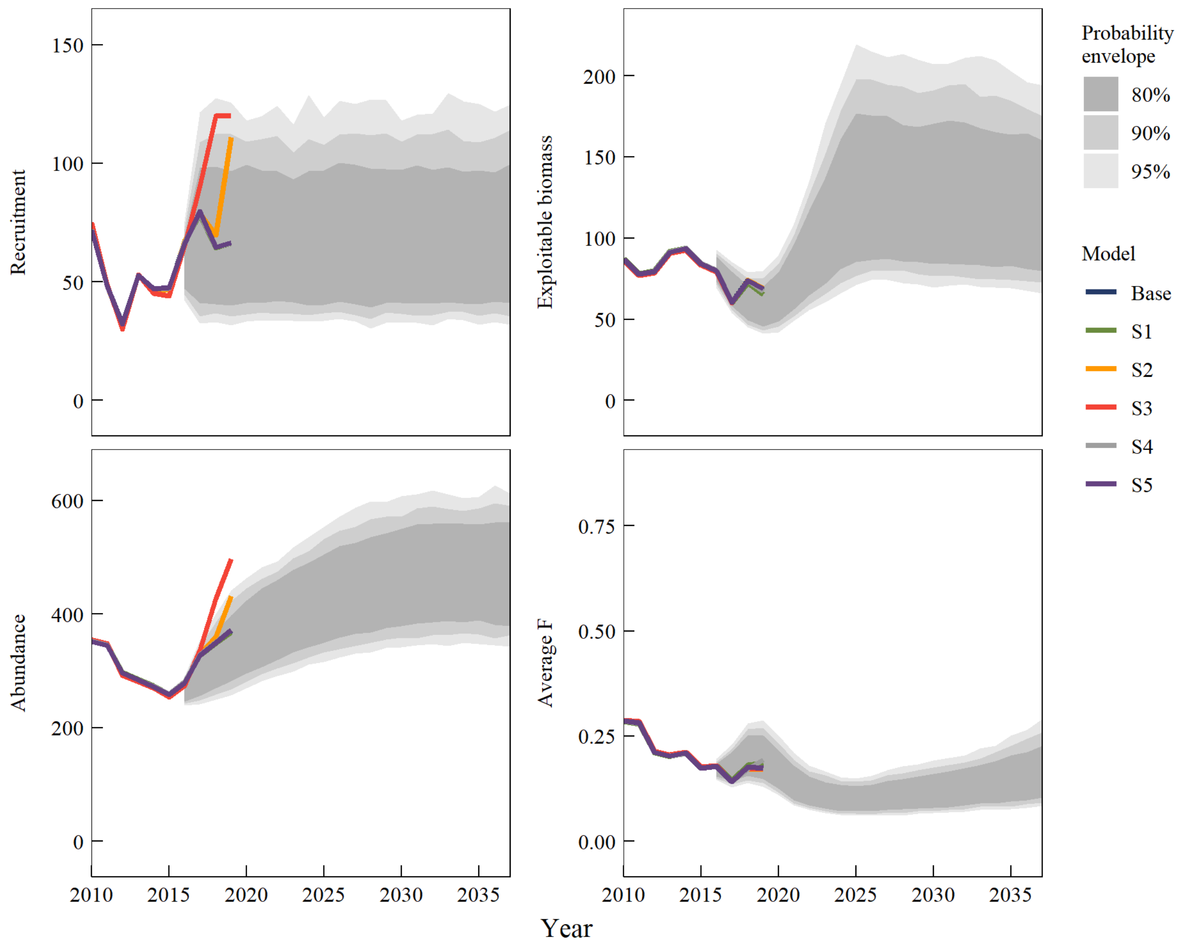


Figure 14. Current SSM estimates of recruitment (age 1), total abundance (ages 1-10+), exploitable biomass (ages 5-9), and average F (ages 5-9) compared to projections produced using revised MSE simulations from 2017 (see Varkey et al., **2020** for details). Grey shaded areas represent 80%, 90% and 95% probability envelopes from the base case SSM simulation.

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 5.

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 1975-2019. $Z_{a,y} = F_{a,y} + M_{a,y}$, 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

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

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

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

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

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

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),

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

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,

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

and then calculating conditional probabilities

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

the continuation-ratio logit is obtained by

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

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 5. 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 6. Landings (kt) of Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO.

Year	Landings
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
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

Year	Landings
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

Table 7. 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	2819	5750	4956	3961	3092
1976	0	0	0	0	17	610	3231	5413	3769	3448
1977	0	0	0	0	534	5012	10798	7346	2933	1563
1978	0	0	0	0	2982	8415	8970	7576	2865	3008
1979	0	0	0	0	2386	8727	12824	6136	1169	1344
1980	0	0	0	0	209	2086	9150	9679	5398	5049
1981	0	0	0	0	863	4517	9806	11451	4307	1400
1982	0	0	0	0	269	2299	6319	5763	3542	2890
1983	0	0	0	0	701	3557	9800	7514	2295	1258
1984	0	0	0	0	902	2324	5844	7682	4087	2098
1985	0	0	0	0	1983	5309	5913	3500	1380	943
1986	0	0	0	0	280	2240	6411	5091	1469	1042
1987	0	0	0	0	137	1902	11004	8935	2835	2092
1988	0	0	0	0	296	3186	8136	4380	1288	1007
1989	0	0	0	0	181	1988	7480	4273	1482	1688
1990	0	0	0	95	1102	6758	12632	7557	4072	5533
1991	0	0	0	220	2862	7756	13152	10796	7145	7782
1992	0	0	0	1064	4180	10922	20639	12205	4332	4242
1993	0	0	0	1010	9570	15928	17716	11918	4642	4438
1994	0	0	0	5395	16500	15815	11142	6739	3081	2871
1995	0	0	0	323	1352	2342	3201	2130	1183	1610
1996	0	0	0	190	1659	5197	6387	1914	956	1405
1997	0	0	0	335	1903	4169	7544	3215	1139	1498
1998	0	0	0	552	3575	5407	5787	3653	1435	1222
1999	0	0	0	297	2149	5625	8611	3793	1659	1568
2000	0	0	0	271	2029	12583	21175	3299	973	1332
2001	0	0	0	448	2239	12163	22122	5154	1010	1368
2002	0	0	37	479	1662	7239	17581	6607	1244	1450
2003	0	0	203	1279	4491	10723	16764	6385	1614	1111
2004	0	0	17	897	4062	8236	10542	4126	1307	1164
2005	0	0	40	534	1652	5999	10313	3996	1410	912
2006	0	0	10	216	1869	6450	12144	4902	1089	627
2007	0	0	0	88	570	3732	11912	5414	1230	785
2008	0	0	0	29	448	3312	10697	5558	1453	595

Year	1	2	3	4	5	6	7	8	9	10+
2009	0	0	0	61	476	3121	8801	7276	1949	846
2010	0	0	0	146	825	5077	11202	6171	2134	841
2011	0	0	430	690	1385	4101	7257	3953	1255	715
2012	0	0	1216	706	1982	3422	7618	5529	1992	1143
2013	0	0	125	460	1744	3873	3997	3255	787	330
2014	0	0	119	259	1007	3041	3583	4626	910	288
2015	0	0	59	89	429	1237	4037	5546	1571	331
2016	0	0	39	116	445	1294	2457	6072	1399	445
2017	0	0	0	2	38	442	2688	4623	2922	1671
2018	0	0	0	117	516	1582	2671	4587	2923	830
2019[a]	0	0	0	221	752	2038	3168	4288	2605	947
2019[b]	0	0	16	162	981	1836	3364	4510	2334	1021

[a]Catch at age constructed using age-length key burrowed from 2018
[b]Alternative catch at age constructed using age-length key averaged across 2015-2018

Table 8. 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[a]	0.00	0.00	0.19	0.28	0.41	0.60	0.85	1.19	1.73	2.65
2019[b]	0.00	0.00	0.16	0.28	0.42	0.61	0.86	1.24	1.81	2.73

[a]Catch weights at age constructed using age-length key burrowed from 2018
[b]Alternative catch weights at age constructed using age-length key averaged across 2015-2018

Table 9. Stratified estimates of mean number per tow at age from Canadian and EU research vessel surveys.

Year	1	2	3	4	5	6	7	8	9	10+
Canada Fall 2J3K										
1996	98.68	47.82	32.01	9.54	6.28	2.47	0.84	0.19	0.18	0.10
1997	28.05	58.62	43.61	21.13	10.37	5.01	2.00	0.64	0.20	0.12
1998	23.35	25.07	31.19	21.87	10.86	4.45	2.07	0.56	0.13	0.12
1999	15.99	34.42	24.07	28.28	20.04	10.53	3.81	0.70	0.14	0.13
2000	38.60	22.09	16.48	13.29	13.89	7.27	2.17	0.50	0.06	0.05
2001	43.90	22.72	17.00	14.07	9.76	7.59	3.40	0.69	0.11	0.05
2002	40.67	24.08	12.50	9.68	6.03	1.97	0.72	0.19	0.04	0.02
2003	45.70	26.67	11.69	9.49	6.39	2.27	0.89	0.27	0.04	0.03
2004	32.49	32.93	13.89	12.31	9.21	2.68	1.20	0.36	0.08	0.05
2005	16.06	16.15	8.56	13.84	10.98	6.85	3.96	0.66	0.12	0.08
2006	32.34	17.98	8.50	17.60	13.03	9.11	4.18	1.15	0.18	0.06
2007	32.61	14.51	12.81	18.77	9.57	10.35	6.17	2.14	0.34	0.15
2009	50.62	19.15	11.40	8.42	9.89	5.39	3.59	1.39	0.25	0.13
2010	50.94	39.25	14.81	9.45	6.74	3.77	2.20	1.02	0.18	0.14
2011	44.14	42.06	20.97	18.79	10.32	5.50	3.15	1.26	0.33	0.22
2012	12.28	9.61	11.27	11.86	10.96	9.03	4.30	1.69	0.29	0.22
2013	24.57	12.71	6.85	7.47	10.78	9.07	7.84	3.90	0.51	0.24
2014	22.08	30.41	11.39	4.54	7.96	7.38	8.92	6.62	0.97	0.30
2015	17.17	13.98	15.14	7.77	6.82	4.18	3.91	3.92	0.65	0.24
2016	29.65	19.47	10.81	8.15	4.83	4.89	3.01	2.09	0.51	0.21
2017	30.57	22.79	10.20	8.77	5.72	2.64	1.26	0.96	0.37	0.20
2018	14.19	15.65	18.46	9.05	7.04	4.96	2.20	1.00	0.48	0.23
2019	16.52	19.53	19.17	12.12	8.82	3.65	1.38	0.41	0.15	0.13
Canada Fall 3LNO										
1996	5.27	4.92	3.84	1.41	1.00	0.40	0.08	0.00	0.00	0.00
1997	1.22	3.33	4.46	3.63	1.88	0.47	0.11	0.04	0.00	0.00
1998	0.53	1.76	1.86	2.99	4.10	1.50	0.32	0.08	0.01	0.00
1999	0.04	0.62	0.73	1.04	1.97	1.67	0.39	0.04	0.01	0.01
2000	1.76	1.24	0.39	0.78	1.21	1.35	0.47	0.04	0.01	0.00
2001	1.40	0.62	0.68	1.39	0.75	1.15	0.61	0.05	0.01	0.00
2002	1.28	0.90	1.04	1.01	0.91	0.39	0.17	0.04	0.00	0.00
2003	1.79	1.07	1.55	1.87	0.91	0.28	0.05	0.02	0.00	0.00
2004	1.18	1.32	1.56	1.69	1.51	0.39	0.10	0.01	0.00	0.00

Year	1	2	3	4	5	6	7	8	9	10+
2005	0.60	0.89	0.50	1.76	1.58	1.14	0.56	0.06	0.01	0.00
2006	0.85	0.49	0.12	0.68	1.33	1.35	0.59	0.13	0.01	0.00
2007	0.83	0.47	0.27	0.81	0.61	1.24	0.75	0.21	0.02	0.02
2008	0.95	0.28	0.82	1.13	0.90	1.00	0.76	0.44	0.04	0.00
2009	2.15	0.24	0.42	0.47	0.88	0.61	0.30	0.14	0.03	0.01
2010	1.95	0.62	0.86	0.67	0.68	0.67	0.31	0.11	0.02	0.01
2011	1.30	4.13	1.20	2.02	0.93	0.67	0.32	0.06	0.02	0.01
2012	0.62	0.20	0.45	1.18	0.93	0.70	0.27	0.08	0.01	0.01
2013	2.77	1.00	0.37	0.41	1.02	1.06	0.62	0.26	0.01	0.02
2015	0.78	0.60	0.33	0.31	0.25	0.34	0.17	0.10	0.01	0.01
2016	1.30	0.44	0.56	0.50	0.63	0.38	0.21	0.09	0.03	0.01
2017	2.60	0.86	1.32	0.55	0.57	0.34	0.16	0.09	0.02	0.01
2018	3.13	1.81	1.64	0.94	1.14	0.71	0.22	0.06	0.02	0.00
2019	3.22	1.96	2.00	1.64	0.99	0.49	0.14	0.03	0.03	0.00
Canada Spring 3LNO										
1996	1.62	4.25	4.60	2.19	0.83	0.28	0.06	0.00	0.00	
1997	1.16	3.92	5.16	3.23	1.46	0.51	0.10	0.01	0.00	
1998	0.23	0.84	3.89	6.21	4.96	1.24	0.33	0.07	0.01	
1999	0.29	0.55	1.15	1.99	3.39	1.09	0.24	0.05	0.01	
2000	0.79	1.07	1.07	1.51	1.95	2.04	0.56	0.03	0.01	
2001	0.56	0.71	0.74	0.68	0.80	0.72	0.28	0.02	0.00	
2002	0.64	0.57	0.60	0.58	0.61	0.21	0.05	0.01	0.00	
2003	0.93	2.14	1.67	1.57	1.06	0.21	0.05	0.01	0.00	
2004	0.66	0.57	1.18	1.18	1.16	0.26	0.04	0.02	0.00	
2005	0.35	0.31	1.09	0.95	1.37	0.82	0.21	0.02	0.00	
2007	1.60	0.52	0.80	0.40	1.40	1.49	1.12	0.18	0.02	
2008	0.44	0.77	0.96	0.71	1.25	0.75	0.64	0.28	0.02	
2009	0.27	0.22	0.19	0.39	0.45	0.26	0.13	0.07	0.01	
2010	0.77	0.66	0.52	0.40	0.84	1.08	0.35	0.14	0.02	
2011	1.96	1.40	0.92	0.64	0.62	0.29	0.16	0.10	0.01	
2012	0.32	0.80	2.48	1.40	1.16	0.50	0.18	0.06	0.02	
2013	1.28	0.68	0.05	0.38	0.61	0.23	0.11	0.04	0.00	
2014	1.62	1.19	0.32	0.20	0.24	0.24	0.14	0.06	0.01	
2016	0.42	0.56	0.37	0.46	0.30	0.20	0.08	0.05	0.01	
2018	3.06	4.46	1.84	1.34	0.90	0.64	0.10	0.09	0.02	
2019	4.52	2.10	1.79	1.41	0.89	0.28	0.18	0.05	0.02	

Year	1	2	3	4	5	6	7	8	9	10+
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
2004	2.19	3.29	4.37	1.97	6.96	7.80	2.54	0.64	0.29	0.28
2005	0.54	0.81	3.18	2.50	6.89	7.59	2.92	0.61	0.11	0.21
2006	0.68	0.39	0.65	1.18	5.97	7.46	3.31	0.77	0.22	0.37
2007	0.37	0.08	0.57	0.34	3.44	7.37	5.76	1.51	0.31	0.35
2008	0.20	0.10	0.15	0.19	1.50	5.70	6.16	1.13	0.35	0.48
2009	0.08	0.01	0.04	0.10	0.75	3.61	4.05	0.89	0.19	0.46
2010	0.05	0.01	0.04	0.06	1.11	3.07	2.94	0.89	0.32	0.27
2011	0.00	0.00	0.00	0.08	1.08	3.58	3.46	0.68	0.20	0.15
2012	0.00	0.01	0.05	0.11	1.02	2.27	1.75	0.44	0.14	0.23
2013	0.01	0.00	0.00	0.14	0.80	2.16	0.89	0.20	0.05	0.10
2014	0.02	0.00	0.00	0.12	1.35	2.88	1.95	0.35	0.08	0.15
2015	0.05	0.02	0.00	0.06	0.89	4.28	2.60	0.61	0.15	0.22
2016	0.26	0.02	0.01	0.00	0.33	2.27	2.81	0.91	0.27	0.30
2017	1.15	0.05	0.03	0.10	1.33	3.82	3.57	0.91	0.28	0.32
2018	0.46	0.27	0.32	0.10	1.41	3.36	2.10	0.62	0.19	0.27
2019	0.57	0.36	0.28	0.47	2.06	2.92	1.79	0.51	0.25	0.20
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

Year	1	2	3	4	5	6	7	8	9	10+
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
EU 3M 700-1400m										
2004	0.02	0.00	0.06	0.73	5.99	12.36	9.57	3.15	1.58	2.69
2005	0.00	0.00	0.02	0.26	2.22	5.26	4.37	1.70	0.54	2.20
2006	0.00	0.00	0.04	0.40	5.61	10.65	7.29	2.56	0.79	1.91
2007	0.03	0.00	0.05	0.20	4.60	12.39	13.93	5.50	1.51	2.81
2008	0.00	0.00	0.00	0.12	3.05	15.33	24.73	7.09	2.67	4.66
2009	0.00	0.00	0.02	0.05	1.83	12.90	25.56	8.64	2.33	5.35
2010	0.00	0.00	0.02	0.05	1.83	12.90	25.56	8.64	2.33	5.35
2011	0.00	0.00	0.03	0.11	3.33	12.66	18.09	6.15	2.85	6.54
2012	0.00	0.00	0.02	0.27	5.09	12.49	11.23	4.75	1.92	4.76
2013	0.00	0.00	0.02	0.67	4.62	16.38	11.47	4.40	1.44	5.07
2014	0.00	0.00	0.01	0.25	5.51	17.91	16.30	4.06	1.15	4.16
2015	0.00	0.00	0.02	0.24	5.69	35.08	35.94	12.28	4.57	8.54
2016	0.00	0.02	0.00	0.01	1.07	9.85	21.55	9.73	3.76	5.84
2017	0.00	0.00	0.02	0.68	9.69	26.20	30.15	12.30	5.62	9.33
2018	0.00	0.03	0.01	0.16	3.51	11.01	16.87	7.82	4.24	12.00
2019	0.00	0.00	0.03	0.89	4.96	7.29	6.58	2.85	2.14	5.23
EU-Spain 3NO										
1997	9.92	5.52	3.49	3.81	2.24	1.97	1.22	0.60	0.07	0.15
1998	1.71	5.24	9.08	8.47	5.06	2.77	1.10	0.66	0.21	0.20
1999	4.38	4.80	7.21	9.31	6.29	2.92	0.77	0.49	0.23	0.24
2000	2.92	0.49	0.80	1.39	3.84	4.42	2.56	0.71	0.28	0.34
2001	8.87	5.90	1.18	1.07	2.84	3.96	1.56	0.22	0.06	0.25
2002	2.91	0.64	1.02	0.69	1.14	0.92	0.44	0.23	0.02	0.08
2003	3.56	2.40	1.68	1.91	1.58	0.90	0.78	0.26	0.06	0.15
2004	1.22	6.96	2.09	2.06	1.24	0.85	0.51	0.21	0.05	0.11
2005	1.07	0.97	1.81	1.04	1.32	1.44	0.68	0.19	0.08	0.16
2006	2.31	1.12	0.41	1.55	1.38	0.81	0.52	0.22	0.05	0.08
2007	1.81	0.64	0.51	0.32	1.48	1.40	1.02	0.29	0.10	0.17

Year	1	2	3	4	5	6	7	8	9	10+
2008	0.62	0.99	0.90	0.69	0.93	2.70	2.50	0.74	0.40	0.35
2009	0.70	3.22	2.21	2.61	2.73	4.94	5.67	0.85	0.35	0.50
2010	0.37	2.21	0.94	0.73	3.42	5.58	5.16	1.23	0.39	0.62
2011	2.20	1.30	0.48	0.62	0.95	2.01	2.12	0.43	0.22	0.47
2012	0.08	1.80	1.34	0.44	1.09	1.71	2.00	0.54	0.40	0.67
2013	0.27	0.45	0.23	0.81	1.17	1.48	1.22	0.33	0.21	0.58
2014	0.51	1.28	0.26	0.14	0.54	1.65	1.74	0.45	0.21	0.67
2015	0.93	0.62	0.20	0.21	0.47	1.81	3.38	0.94	0.44	0.78
2016	1.08	0.54	0.34	0.45	0.51	1.86	2.55	0.90	0.22	0.81
2017	3.37	1.66	0.88	1.10	2.38	4.38	4.62	1.68	0.51	1.04
2018	2.35	2.00	0.97	0.80	1.64	1.88	1.61	0.94	0.29	0.50
2019	3.34	4.20	4.10	2.77	2.62	1.98	1.25	0.64	0.24	0.79

Appendix C. Retrospective results

The following tables and figures are from model fits to data that have been retrospectively truncated one year at a time. Note that terminal years are used as the labels and that results from 2017 are reproduced here when the terminal year is 2016 because the inputs and model structure are the same.

Tables

Table 10. Key parameter estimates from each retrospective peel of data. See Table 5 for parameter descriptions.

Parameter	2012	2013	2014	2015	2016	2017	2018	2019
$\sigma_{\text{Canada Fall 2J3K},1-3}$	0.25	0.23	0.24	0.25	0.25	0.24	0.27	0.30
$\sigma_{\text{Canada Fall 2J3K},4-7}$	0.30	0.30	0.30	0.31	0.30	0.31	0.30	0.30
$\sigma_{\text{Canada Fall 2J3K},8-10}$	0.33	0.37	0.44	0.44	0.44	0.44	0.45	0.45
$\sigma_{\text{Canada Fall 3LNO},1-3}$	0.67	0.68	0.68	0.67	0.66	0.66	0.67	0.67
$\sigma_{\text{Canada Fall 3LNO},4-7}$	0.35	0.36	0.36	0.39	0.39	0.39	0.39	0.38
$\sigma_{\text{Canada Fall 3LNO},8-10}$	0.55	0.57	0.57	0.62	0.60	0.59	0.60	0.61
$\sigma_{\text{Canada Spring 3LNO},1-3}$	0.53	0.63	0.63	0.64	0.64	0.64	0.69	0.71
$\sigma_{\text{Canada Spring 3LNO},4-7}$	0.50	0.52	0.54	0.54	0.54	0.55	0.54	0.53
$\sigma_{\text{Canada Spring 3LNO},8-10}$	0.69	0.71	0.69	0.70	0.68	0.68	0.67	0.65
$\sigma_{\text{EU 3NO},1-3}$	0.81	0.84	0.84	0.85	0.83	0.82	0.81	0.80
$\sigma_{\text{EU 3NO},4-7}$	0.60	0.59	0.59	0.60	0.60	0.63	0.62	0.61
$\sigma_{\text{EU 3NO},8-10}$	0.48	0.47	0.46	0.44	0.44	0.45	0.44	0.43
$\sigma_{\text{EU 3M},1-3}$	1.42	1.50	1.55	1.54	1.51	1.51	1.50	1.48
$\sigma_{\text{EU 3M},4-7}$	0.46	0.45	0.45	0.46	0.57	0.59	0.57	0.56
$\sigma_{\text{EU 3M},8-10}$	0.37	0.38	0.41	0.40	0.39	0.39	0.38	0.38
σ_{main}	0.53	0.55	0.56	0.57	0.56	0.57	0.57	0.57
σ_{Δ}	0.38	0.38	0.38	0.38	0.37	0.38	0.37	0.37
σ_X	0.19	0.18	0.18	0.18	0.17	0.18	0.20	0.19
σ_r	0.36	0.34	0.33	0.34	0.34	0.33	0.32	0.32
r	11.11	11.09	11.09	11.07	11.06	11.07	11.08	11.10
σ_F	0.19	0.20	0.21	0.21	0.21	0.22	0.21	0.21
σ_δ	0.17	0.16	0.16	0.15	0.15	0.14	0.14	0.15
$\varphi_{F,y}$	0.97	0.97	0.97	0.97	0.98	0.97	0.98	0.98
$\varphi_{F,a}$	0.52	0.52	0.53	0.53	0.53	0.50	0.49	0.50

Table 11. Estimates of recruitment (age 1; millions) from each retrospective peel of data.

Year	2012	2013	2014	2015	2016	2017	2018	2019
1975	65.34	64.73	64.72	63.77	63.57	62.88	63.39	64.27
1976	60.40	60.20	60.42	59.37	59.24	59.84	60.63	61.33
1977	61.17	61.05	61.30	60.32	60.16	60.23	60.92	61.71
1978	55.65	55.70	55.99	54.36	54.32	54.31	55.13	56.07
1979	52.78	53.11	53.45	52.04	51.87	52.23	53.21	53.90
1980	66.25	65.96	66.29	65.87	65.84	66.09	66.39	67.17
1981	71.79	70.88	70.82	70.58	70.37	69.75	70.04	70.88
1982	66.19	65.60	65.66	65.03	64.88	64.84	65.14	65.92
1983	68.33	67.87	68.10	68.10	67.98	68.90	68.98	69.50
1984	73.66	72.64	72.47	72.71	72.36	72.84	73.13	73.59
1985	78.63	77.22	76.90	77.59	77.22	78.47	78.72	79.02
1986	72.78	71.85	71.63	72.42	71.93	73.83	74.29	74.28
1987	82.99	81.38	81.09	81.91	81.68	81.65	81.28	81.80
1988	71.04	70.13	69.95	69.88	69.55	70.08	70.28	70.69
1989	68.77	68.10	68.11	67.72	67.44	67.38	67.37	67.97
1990	62.66	62.34	62.41	62.00	61.58	62.18	62.60	62.95
1991	62.19	61.97	62.21	61.53	61.54	61.45	61.35	62.02
1992	57.21	57.38	57.70	56.41	55.97	56.25	56.67	57.11
1993	70.89	71.15	71.32	70.78	70.21	70.69	70.70	71.10
1994	113.61	110.91	110.02	112.21	111.26	111.85	110.25	110.14
1995	137.47	129.80	128.69	132.93	131.63	132.41	132.26	132.81
1996	150.42	146.06	144.79	145.54	144.07	144.14	142.35	141.88
1997	71.92	69.02	69.90	70.35	70.16	70.82	73.30	74.66
1998	52.68	53.49	53.95	54.16	53.77	54.89	56.41	56.56
1999	40.36	40.25	40.90	41.23	40.80	42.10	43.86	44.04
2000	70.39	69.29	69.74	69.76	69.40	70.07	71.84	72.68
2001	74.95	74.33	74.75	74.97	74.31	75.00	76.99	77.85
2002	76.10	74.49	75.07	75.51	74.78	75.71	77.63	78.39
2003	79.52	78.32	78.58	78.53	77.98	78.25	79.75	80.53
2004	55.55	55.17	55.58	55.32	55.04	55.33	56.77	57.37
2005	42.36	41.98	42.79	43.10	43.00	43.84	46.01	46.74
2006	53.03	53.08	53.69	53.47	53.43	53.75	55.00	55.47
2007	58.69	57.87	58.41	57.86	57.87	58.25	58.60	58.49
2008	49.58	51.15	51.26	51.32	51.27	52.25	53.17	52.58
2009	72.42	75.60	75.49	75.37	74.74	75.57	75.04	73.96

Year	2012	2013	2014	2015	2016	2017	2018	2019
2010	79.68	76.67	76.33	75.41	74.51	74.47	73.13	72.23
2011	58.53	51.56	50.50	49.38	49.21	49.02	48.66	48.48
2012	27.93	29.73	31.37	30.74	30.42	31.17	32.19	32.38
2013		52.63	58.80	56.80	52.63	53.36	53.47	52.77
2014			50.79	44.79	44.09	45.30	47.07	47.20
2015				41.33	41.70	42.75	46.06	47.34
2016					57.41	58.51	64.11	67.01
2017						69.80	70.34	78.26
2018							55.46	64.49
2019								66.23

Table 12. Estimates of exploitable biomass (ages 5-9; Kt) from each retrospective peel of data.

Year	2012	2013	2014	2015	2016	2017	2018	2019
1975	91.59	91.76	91.92	91.91	92.06	91.34	91.33	91.67
1976	92.77	93.06	93.35	93.52	93.85	93.23	93.48	93.94
1977	109.14	109.54	109.91	110.34	110.65	110.80	111.17	111.48
1978	116.92	117.23	117.45	117.89	118.08	118.53	119.24	119.50
1979	114.89	115.08	115.39	115.32	115.70	115.15	115.70	116.45
1980	93.46	93.68	93.91	93.73	93.98	93.74	94.72	95.49
1981	81.47	81.75	82.15	82.00	82.49	81.89	82.61	83.55
1982	79.08	79.54	80.03	79.94	80.43	80.20	81.35	82.33
1983	73.64	74.25	74.89	74.86	75.49	75.07	75.98	77.04
1984	65.80	66.52	67.22	67.42	68.03	67.90	68.85	69.82
1985	88.74	89.44	90.25	90.54	91.33	90.45	91.21	92.49
1986	77.01	77.65	78.35	78.58	79.27	78.40	78.87	80.02
1987	92.40	93.07	93.80	94.04	94.86	93.92	94.33	95.66
1988	95.94	96.56	97.22	97.89	98.70	98.05	98.20	99.29
1989	109.44	109.80	110.17	110.75	111.42	110.99	110.96	111.93
1990	120.98	121.13	121.15	121.56	122.16	122.09	122.30	123.23
1991	136.90	136.87	136.70	136.95	137.81	137.46	137.68	138.82
1992	128.99	128.86	128.59	128.63	129.61	128.84	128.64	129.82
1993	104.02	103.95	103.57	103.67	104.50	103.76	103.58	104.53
1994	70.00	70.02	69.66	70.03	70.62	70.24	70.02	70.60
1995	42.24	42.35	42.16	42.82	43.24	43.16	42.79	43.08
1996	45.80	46.11	46.23	47.03	47.24	47.26	46.66	46.81
1997	55.19	55.35	55.50	55.56	55.72	55.27	54.70	55.08
1998	84.60	84.78	85.16	84.06	84.22	83.15	82.32	83.11
1999	100.95	101.28	101.86	101.53	101.78	100.92	100.00	100.52
2000	102.64	103.14	103.70	104.38	104.83	104.53	103.55	103.73
2001	89.76	90.05	90.37	91.02	91.71	91.83	91.07	91.00
2002	61.29	62.01	62.59	63.52	63.83	64.59	63.90	63.51
2003	53.76	54.42	54.98	55.68	56.12	56.40	55.69	55.51
2004	56.30	56.82	57.20	57.23	57.47	57.36	56.77	56.85
2005	76.16	76.34	76.81	75.91	76.64	75.98	75.13	75.59
2006	92.78	92.73	93.36	92.25	93.26	92.37	91.20	91.83
2007	100.65	100.71	101.69	100.55	102.09	100.39	98.94	100.02
2008	103.66	104.89	107.16	106.35	108.35	105.94	104.14	105.42
2009	90.47	92.04	94.26	94.57	96.37	94.70	93.13	93.88

Year	2012	2013	2014	2015	2016	2017	2018	2019
2010	84.58	85.79	87.50	87.82	89.52	87.79	86.33	87.16
2011	77.09	77.57	78.31	78.41	79.98	78.62	77.33	77.96
2012	78.96	80.31	80.55	80.27	82.22	80.69	79.21	79.81
2013		93.14	93.86	93.01	95.10	93.39	91.22	91.65
2014			98.84	97.23	97.82	95.86	93.31	93.79
2015				89.13	87.77	86.23	83.99	84.54
2016					80.99	81.69	79.90	80.08
2017						60.39	61.12	60.70
2018							76.81	74.09
2019								67.85

Table 13. Estimates of average F (ages 5-9; Kt) from each retrospective peel of data.

Year	2012	2013	2014	2015	2016	2017	2018	2019
1975	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
1976	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
1977	0.27	0.27	0.27	0.27	0.27	0.26	0.26	0.26
1978	0.30	0.30	0.30	0.30	0.29	0.29	0.29	0.29
1979	0.32	0.32	0.32	0.32	0.32	0.32	0.31	0.31
1980	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
1981	0.38	0.38	0.38	0.38	0.38	0.37	0.37	0.36
1982	0.26	0.26	0.25	0.25	0.25	0.26	0.25	0.25
1983	0.35	0.34	0.34	0.34	0.33	0.33	0.33	0.32
1984	0.29	0.29	0.28	0.28	0.28	0.28	0.27	0.27
1985	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.21
1986	0.17	0.17	0.16	0.16	0.16	0.17	0.17	0.16
1987	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.20
1988	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15
1989	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
1990	0.23	0.23	0.23	0.23	0.23	0.22	0.22	0.22
1991	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
1992	0.40	0.40	0.41	0.40	0.40	0.40	0.40	0.40
1993	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.57
1994	0.86	0.86	0.86	0.85	0.85	0.84	0.85	0.84
1995	0.23	0.22	0.22	0.22	0.22	0.22	0.23	0.22
1996	0.28	0.28	0.28	0.27	0.27	0.27	0.27	0.27
1997	0.22	0.22	0.22	0.22	0.22	0.23	0.23	0.23
1998	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.19
1999	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.18
2000	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38
2001	0.58	0.58	0.58	0.58	0.58	0.58	0.59	0.58
2002	0.67	0.66	0.65	0.65	0.64	0.64	0.65	0.65
2003	0.63	0.63	0.63	0.61	0.61	0.60	0.61	0.61
2004	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
2005	0.22	0.22	0.22	0.22	0.22	0.22	0.23	0.22
2006	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
2007	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
2008	0.21	0.21	0.20	0.20	0.20	0.20	0.21	0.21
2009	0.24	0.24	0.23	0.23	0.22	0.23	0.23	0.23

Year	2012	2013	2014	2015	2016	2017	2018	2019
2010	0.29	0.29	0.29	0.29	0.28	0.28	0.29	0.29
2011	0.29	0.28	0.28	0.28	0.27	0.28	0.28	0.28
2012	0.23	0.21	0.21	0.21	0.20	0.21	0.21	0.21
2013		0.21	0.20	0.20	0.19	0.20	0.20	0.20
2014			0.20	0.20	0.20	0.21	0.21	0.21
2015				0.17	0.17	0.17	0.17	0.17
2016					0.17	0.18	0.18	0.18
2017						0.14	0.14	0.14
2018							0.16	0.17
2019								0.18

Figures

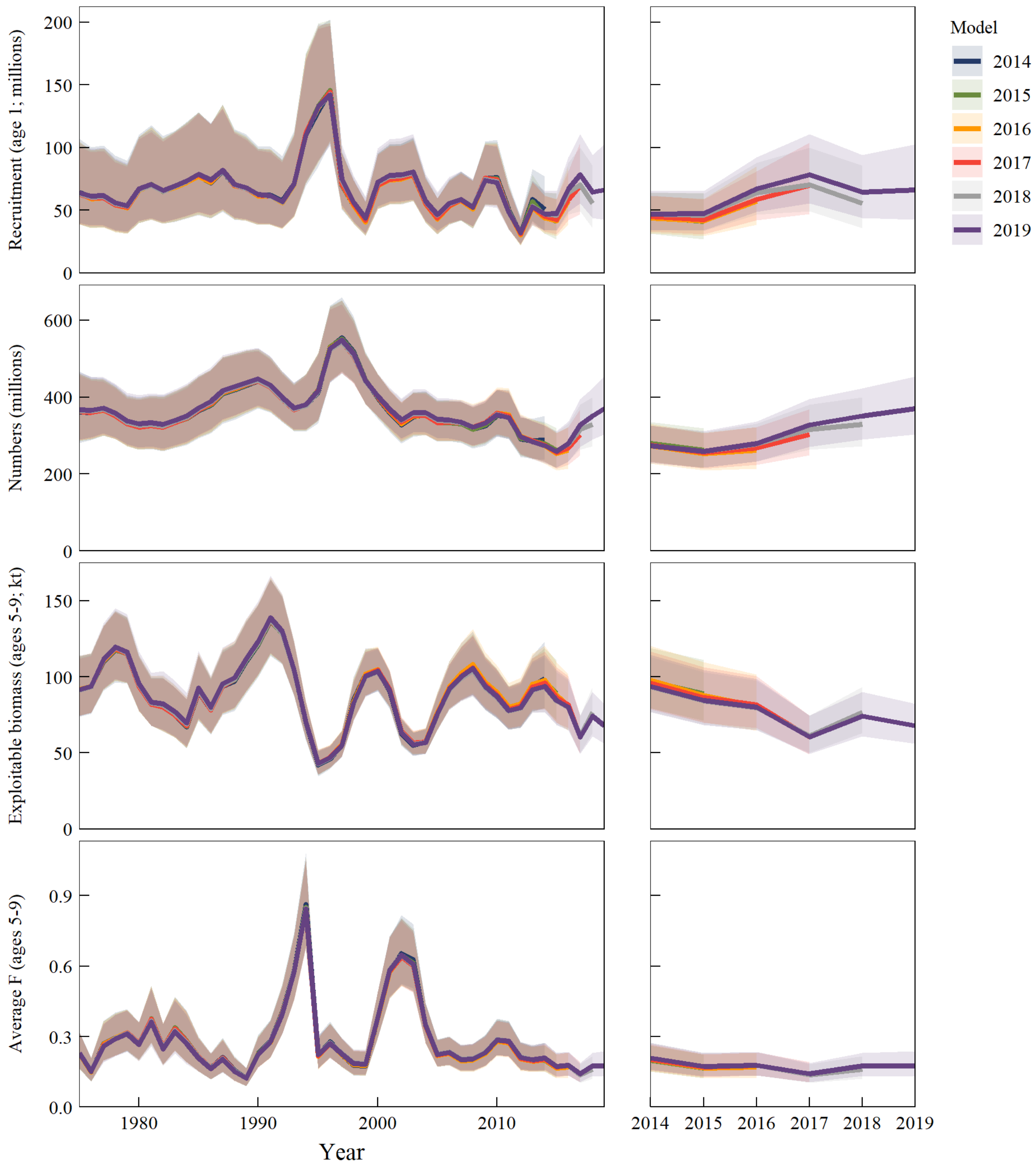
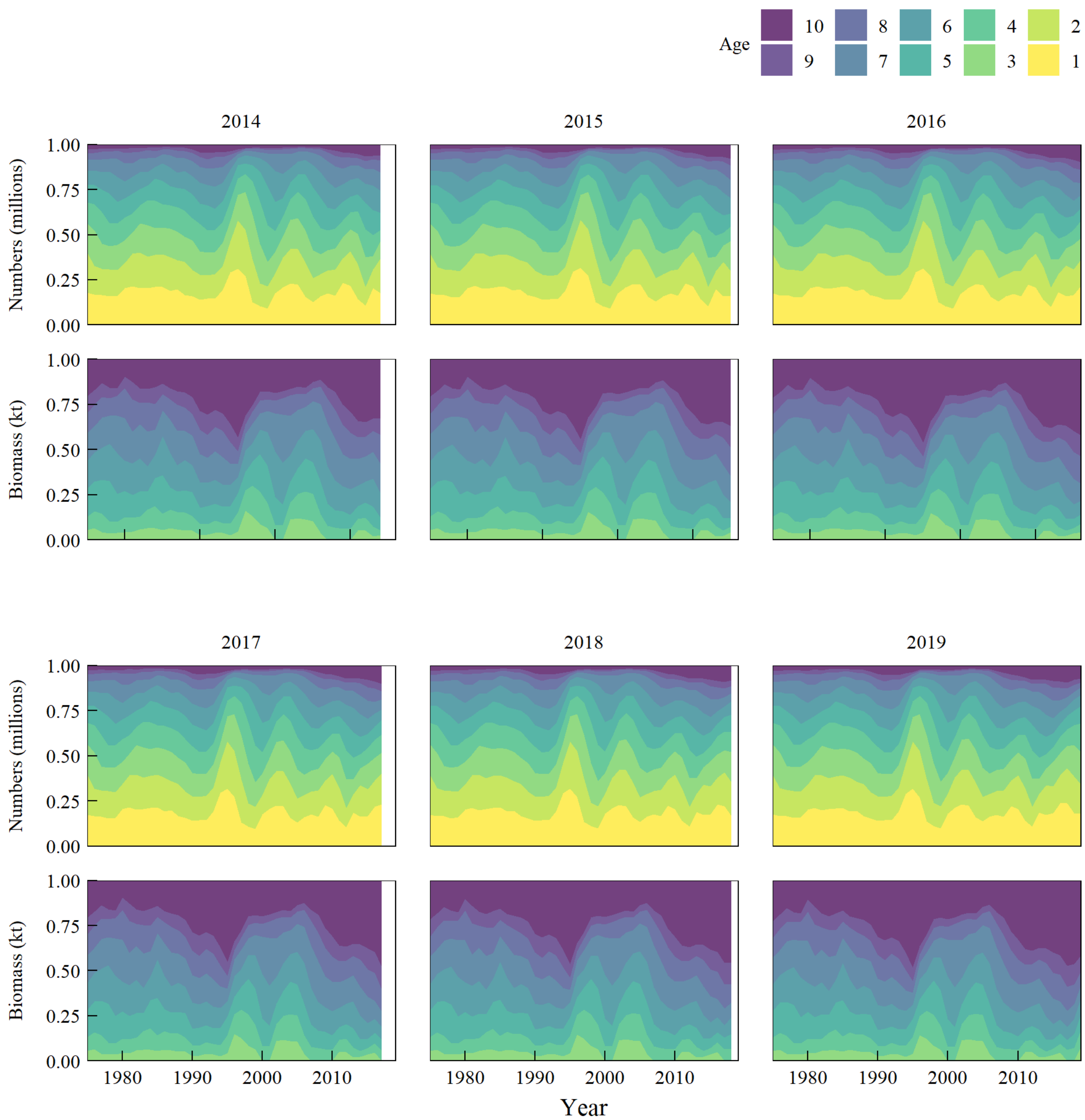


Figure 15. Estimates of recruitment (age 1), numbers, exploitable biomass (ages 5-9), and average F (ages 5-9), with 95% confidence intervals, for the whole time-series (left) and from the last 5 years (right).


Age
10
9
8
7
6
5
4
3
2
1
2014
2015
2016
2017
2018
2019
Numbers (millions)
Biomass (kt)
0.00
0.25
0.50
0.75
1.00
1980
1990
2000
2010
Year

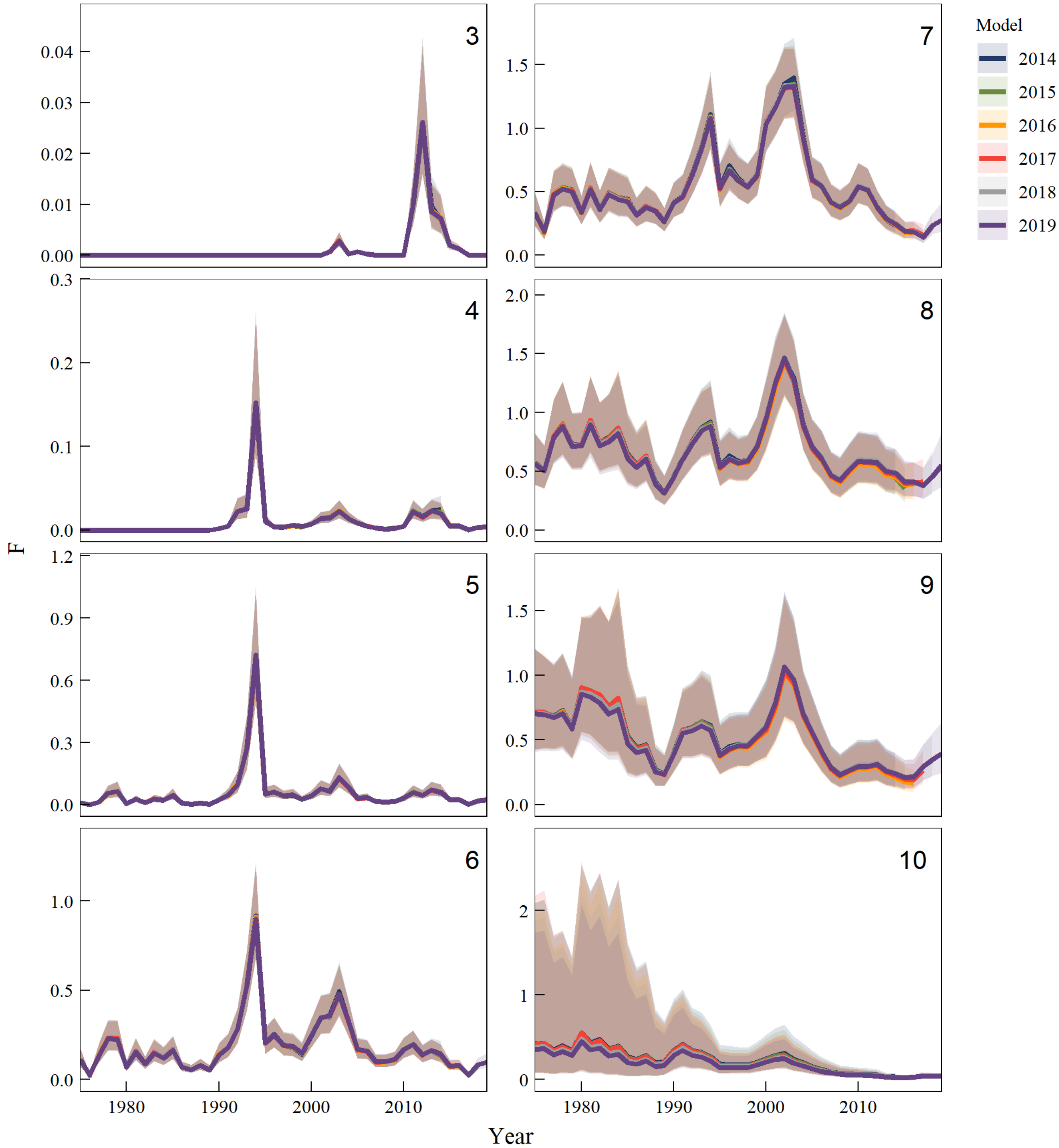


Figure 16. Fishing mortality at age.

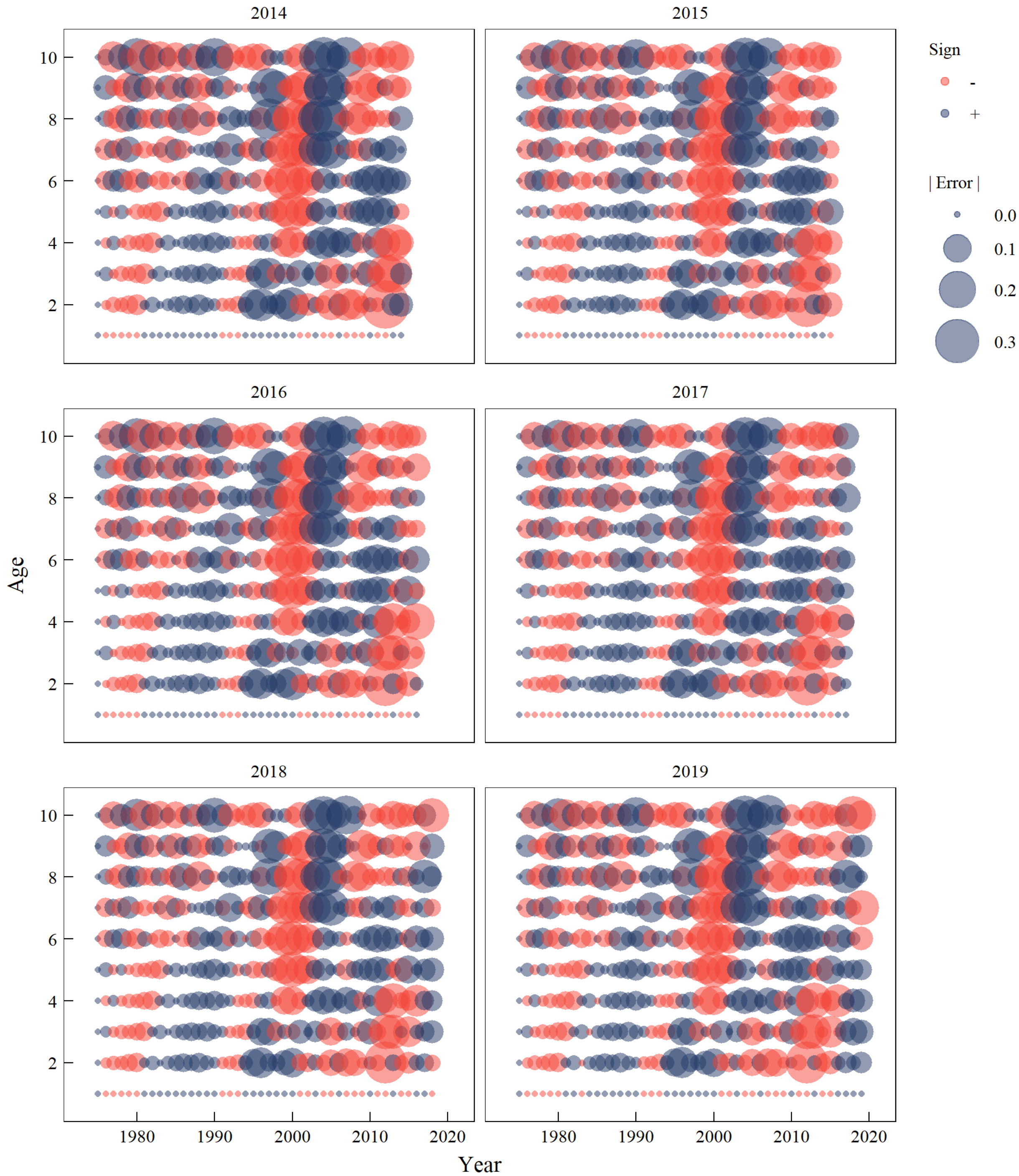


Figure 17. Matrix plot of predicted process errors.

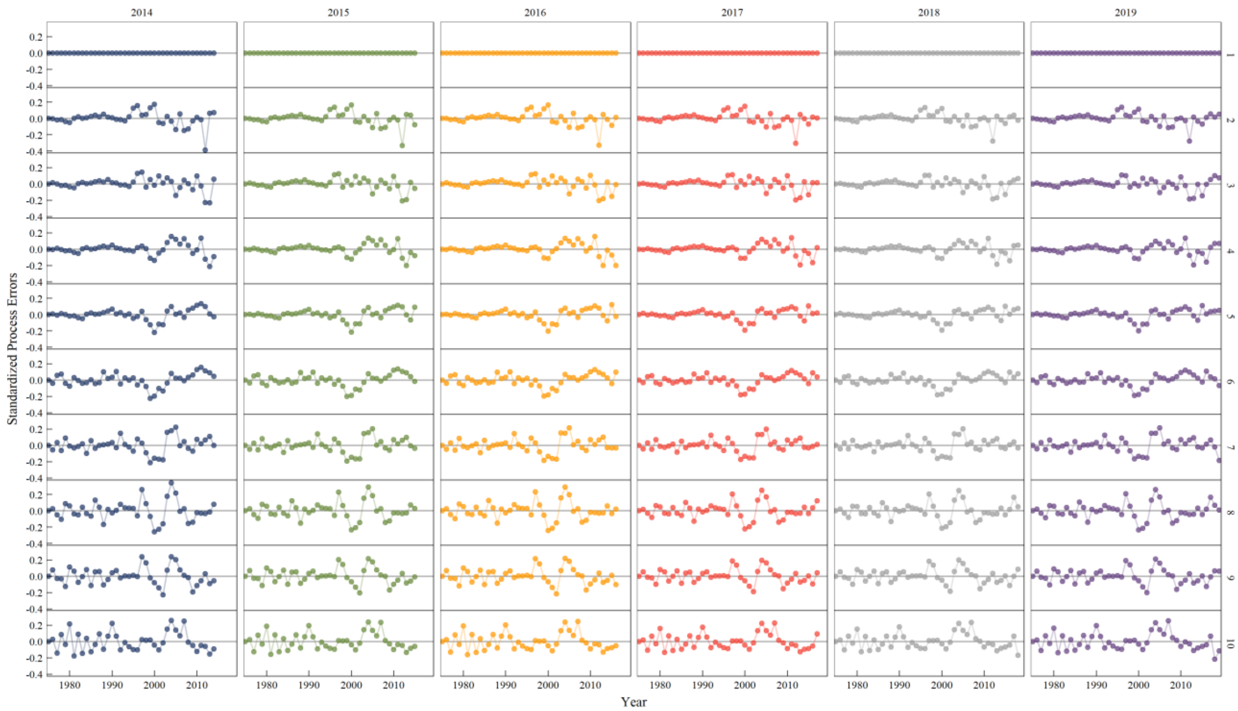


Figure 18. Predicted process error at age.

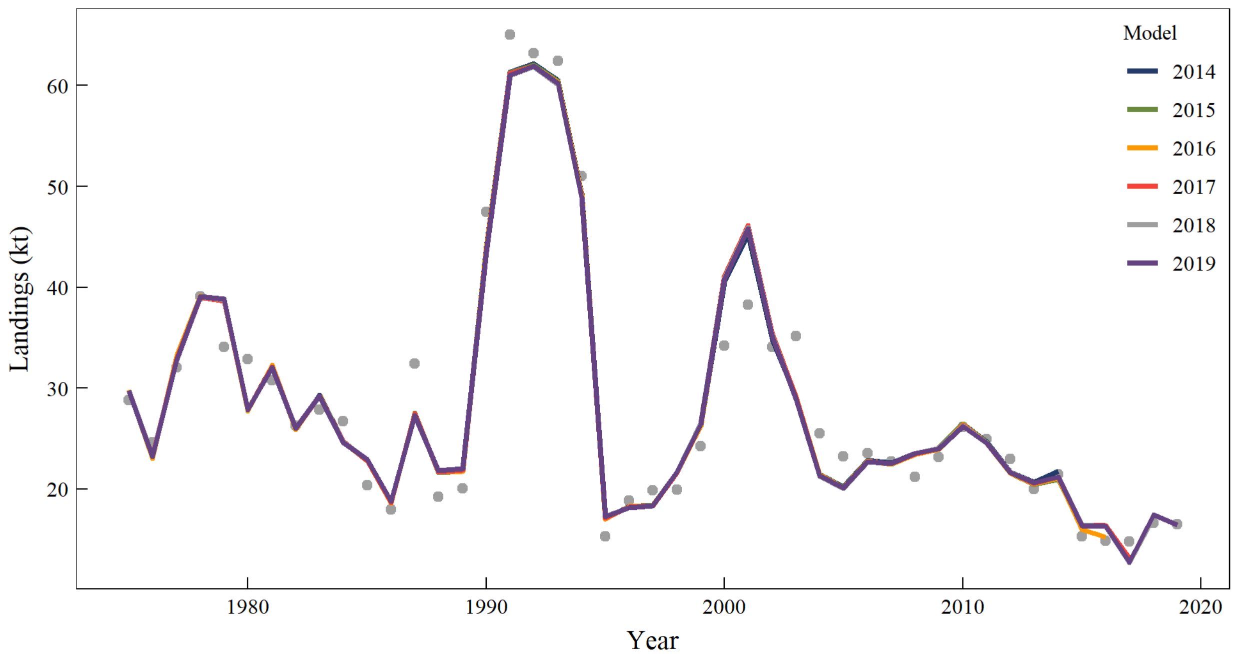


Figure 19. Observed and predicted landings (kt).

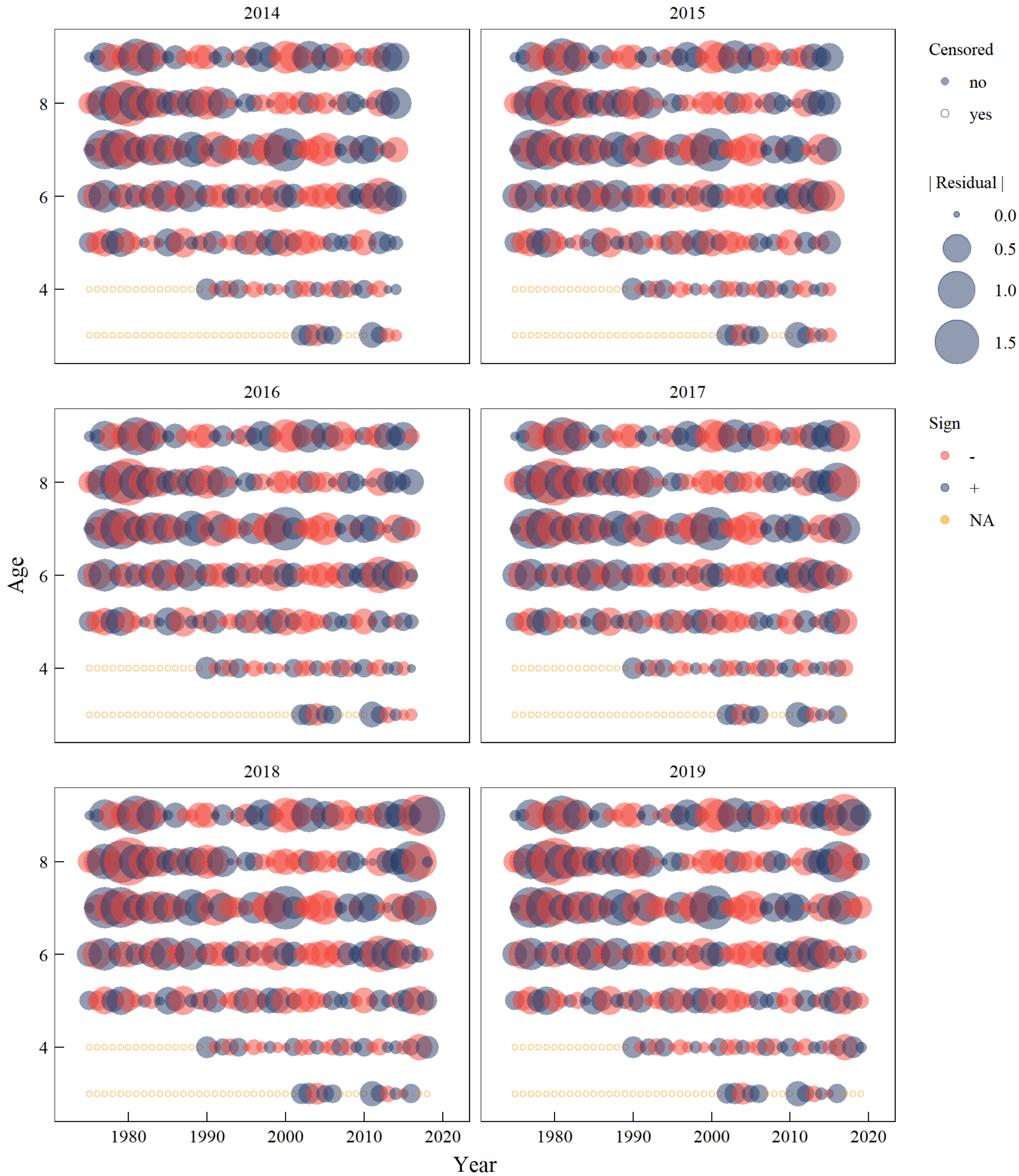


Figure 20. Matrix plot of standardized residuals for catch at age continuation ratio logits (observed minus predicted).

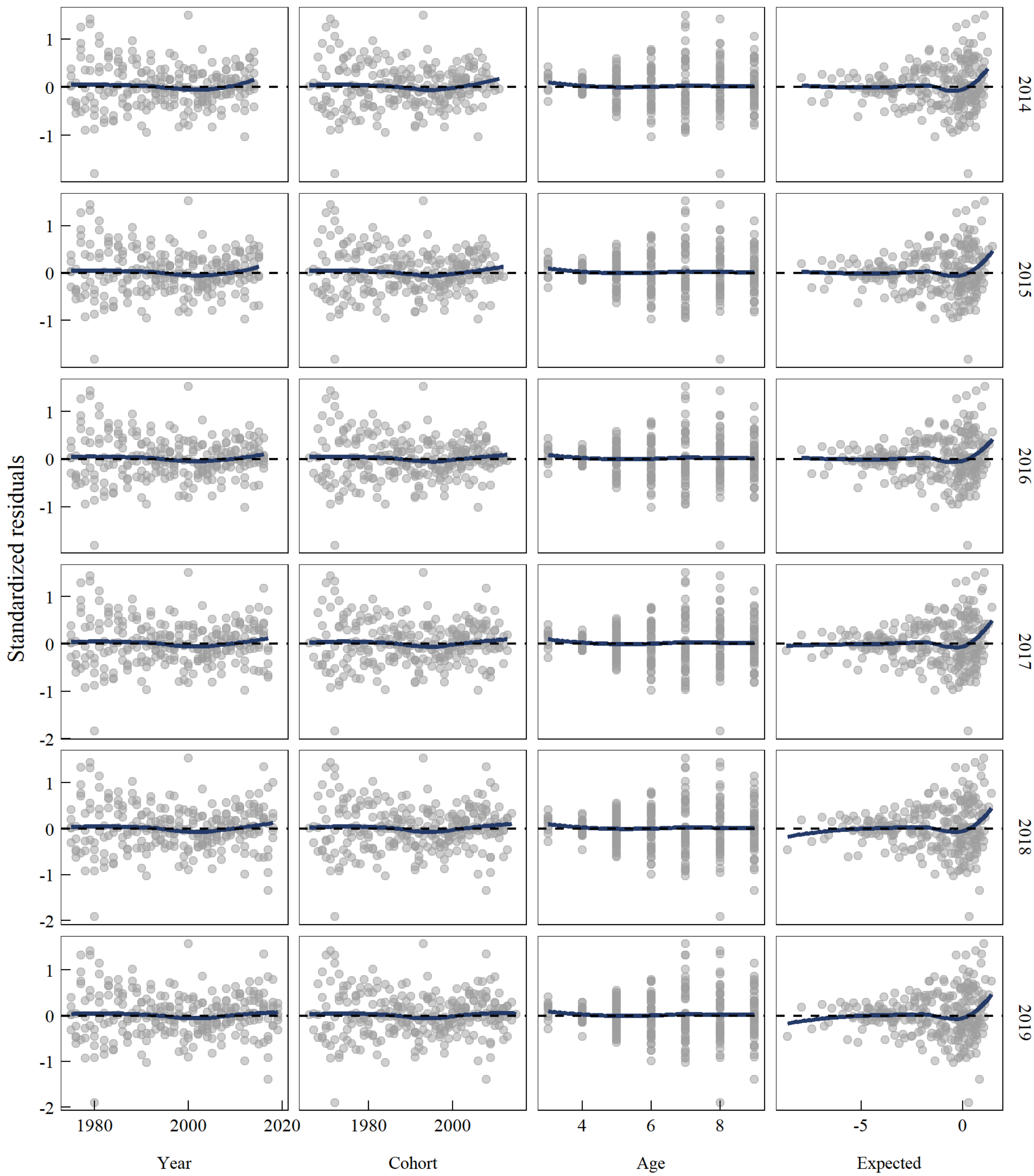


Figure 21. Standardized residuals for catch at age continuation ratio logits versus year, cohort, age, and predicted value.

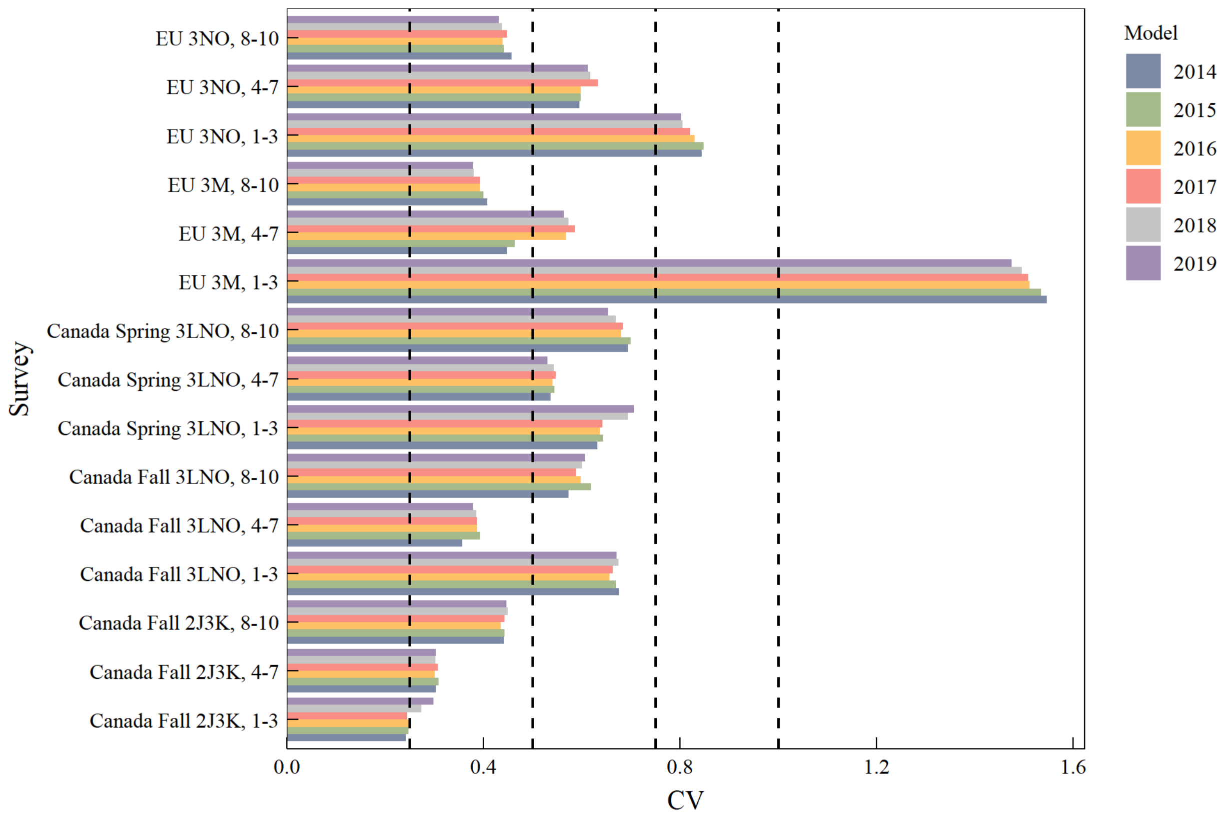


Figure 22. Estimates of survey CV. Age ranges follow the survey name.

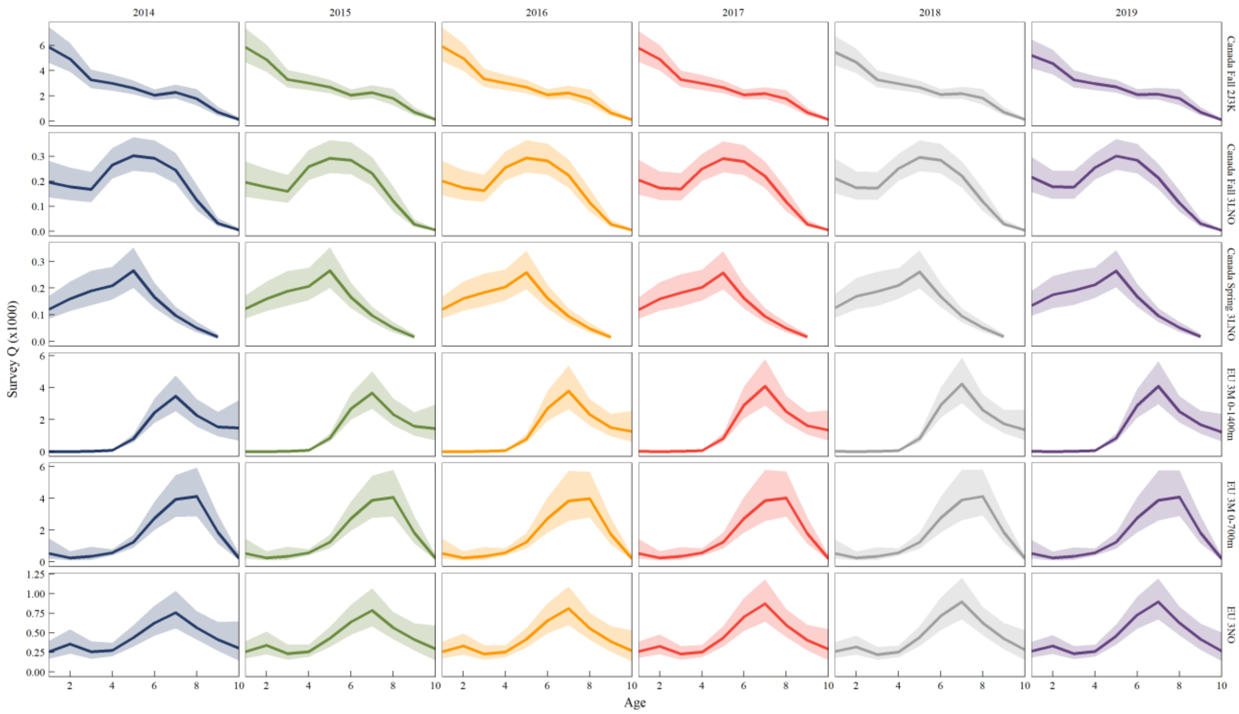


Figure 23. Age patterns in survey catchability parameters, with 95% confidence intervals.

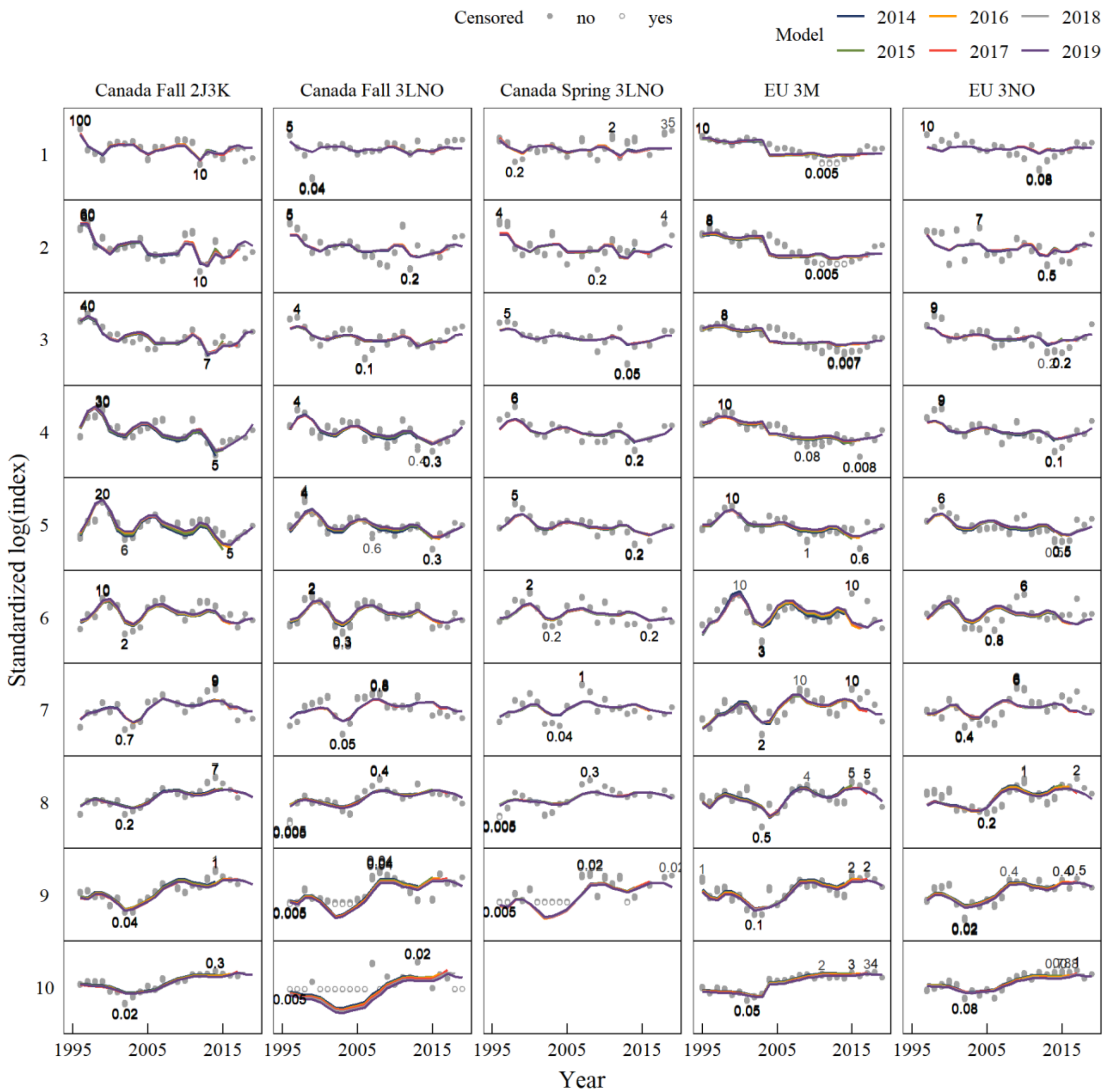


Figure 24. Observed and predicted survey indices at age. Log(index) standardized by survey and age. Min and max observed index values are indicated.

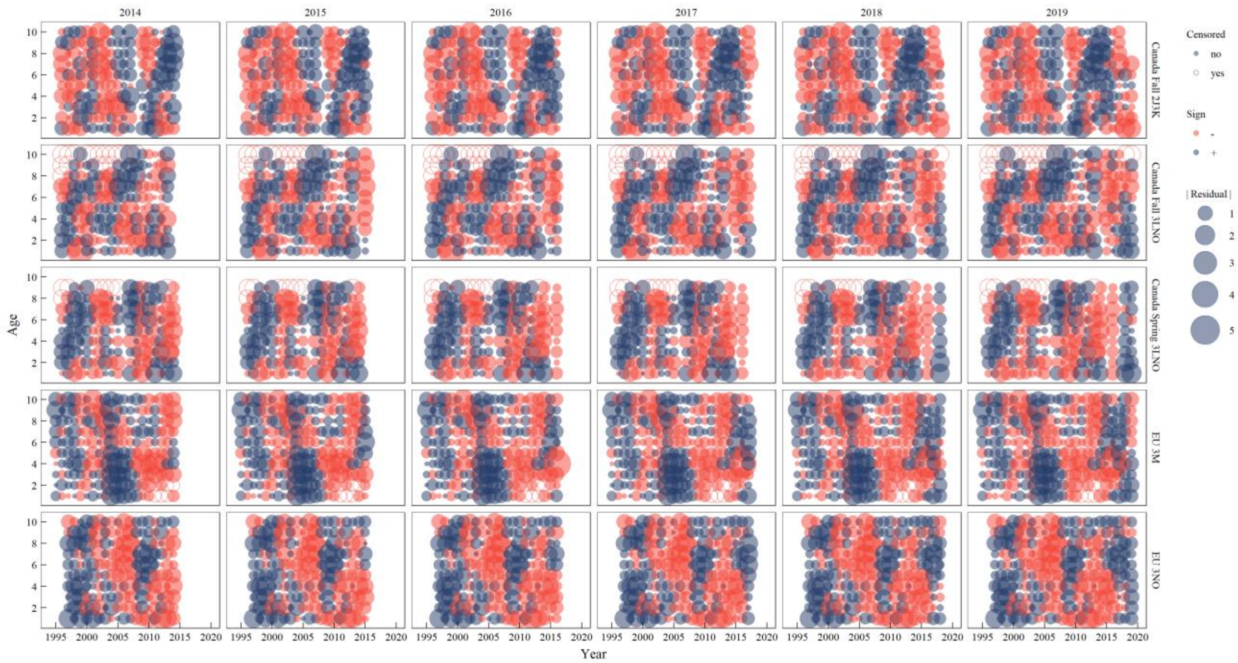


Figure 25. Matrix plot of standardized residuals for index at age by survey.

Appendix D. Session info

```
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#> Running under: Windows 10 x64 (build 16299)
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#> [2] LC_CTYPE=English_United States.1252
#> [3] LC_MONETARY=English_United States.1252
#> [4] LC_NUMERIC=C
#> [5] LC_TIME=English_United States.1252
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#> attached base packages:
#> [1] stats     graphics  grDevices utils     datasets  methods   bas
e
#>
#> other attached packages:
#>  [1] readxl_1.3.1         here_0.1             ghalAssess_0.0.1
#>  [4] RcppEigen_0.3.3.7.0  TMB_1.7.16           tibble_3.0.1
#>  [7] tidyr_1.1.0          dplyr_0.8.5          flextable_0.5.10.001
#> [10] ggpubr_0.3.0         ggplot2_3.3.0        NAFOdown_0.0.1
#>
#> loaded via a namespace (and not attached):
#>  [1] Rcpp_1.0.4.6      lattice_0.20-41   assertthat_0.2.1  rprojroo
t_1.3-2
#>  [5] digest_0.6.25     R6_2.4.1          cellranger_1.1.0  backport
s_1.1.7
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3.0
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