NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE AUTHOR(S)

Northwest Atlantic Fisheries Organization

Serial No. N6659 **NAFO SCR Doc. 17-010**

<u>SCIENTIFIC COUNCIL MEETING – JUNE 2017</u>

A Simple SAM-style State-Space Stock Assessment Model for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO

Paul M. Regular[1], Noel G. Cadigan[2], M. Joanne Morgan[1], Brian P. Healey[1]

[1]Fisheries and Oceans Canada, P.O.Box 5667, St. John's, NL, A1C 5X1, Canada
[2]Center for Fisheries Ecosystem Research, Marine Institute of Memorial University of Newfoundland, P.O.Box 4920, St. John's, NL A1c 5R3, Canada

04 June, 2017

Various model formulations of a state-space stock assessment model were explored. The different formulations included examination of using different survey data series, a range of natural mortalities and variations in error on landings and process error. A series of quasi-spatial formulations were also explored. Most formulations showed similar results with a peak in recruitment in the mid 1990s, two main peaks in fishing mortality (late 1980s through early 1990s and in the early 2000s), and biomass generally lower in recent years than the peak of the late 1980s. The whole stock model, M1, was not overly sensitive to the various survey data series options. Trends were largely the same but the magnitude of recruitment, abundance and biomass increased, and average F decreased with increasing values of M. Estimates appear not to be sensitive to the assumed level of error in the landings and were fairly stable across a range of manually supplied levels of process error. There were no prominent retrospective patterns across the main model.

Introduction

We present results from 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. Likewise, observations from trawl survey data and catch statistics are used to estimate parameters of the population dynamics model. A key distinction from other assessment models, however, is that a state-space model attempts to differentiate variation stemming from natural processes (process error; e.g. natural mortality, immigration, emigration) from variation stemming from survey and fishery observations (observation error; e.g. sampling error). This model also attempts to account for correlation in fishing mortality rates across ages and years such that fish of similar ages from similar time periods are assumed to have experienced comparable fishing mortality rates. Finally, recruitment was simply assumed to be random as initial study indicated there was little evidence of a stock-recruitment relationship.

Two formulations of the SAM-style model were developed and tested: 1) a standard whole-stock model (denoted M1), and 2) an experimental quasi-spatial variant (S1). The latter was motivated by apparent conflicts in the survey data. Specifically, trends in stock size in the Flemish Cap (FC) area seem different from those observed in the NL shelf (NS) region. This suggests that there may be important spatial differences that are not incorporated into M1, potentially decreasing its reliability as an assessment of the stock as a whole. The lack of reliability may depend on changes in the relative magnitude of the NS and FC stock components (or, indeed, if there are other spatial differences not accounted for here). The new quasi-spatial model formulation attempts to address this issue in a simple way. While this model still treats the stock as a whole in terms of modelling recruitment and mortality rates, it allows a variable time and age-specific proportion of the stock to move from one region to another.

Though conceptually simple, state-space models have been notoriously difficult to fit due to the numerical challenge of splitting process and observation error. However, recent advances in estimation tools such as Template Model Builder (Kristensen et al. 2016) have facilitated the fitting of state-space models that require few user supplied parameters. As such, parameter estimates from such models are largely data driven if the model is correctly specified.

Methods

Catch and survey data used are listed in Appendix A and the details of the SAM-style formulation are described in Appendix B. Different combinations of survey inputs used are listed in Table 1 and the tests run using different data and parameter inputs are listed in Table 2. In this report, we highlight sensitivity tests to different data inputs, alternate plus group (A = 10 or 14), the assumed level of natural mortality (M = 0.12, 0.20 or 0.30), the assumed level of variation between reported landings and their model predicted values (σ_C = 0.1, 0.20 or 0.30), and varying degrees of process error variance (σ_δ = 0.0001, 0.001, 0.01, 0.05, 0.10, 0.15 and 0.20).

Results and Discussion

- In general, both the M1 and S1 models show similar trends in recruitment, total abundance and F across a range of data and parameter inputs (Figure 1). For instance, all show a peak in recruitment in the mid 1990s and two main peaks in fishing mortality (late 1980s early 1990s and in the early 2000s). Most formulations indicate that current biomass is lower than the peak of the late 1980s.
- The whole stock model, M1, was not overly sensitive to the various survey data series options (confidence intervals of recruitment, abundance, biomass and average F estimates overlap; Figure 2). The base option stands out the most, with slightly shallower peaks in recruitment and abundance, perhaps because it used less survey data. All are comparable, but M1_O3 was considered the base case.
- Trends were largely the same but the magnitude of recruitment, abundance and biomass increased, and average F decreased with increasing values of M (Figure 3). Estimates appear not to be sensitive to the assumed level of error in the landings (σ_C; Figure 3).

- Model fits were fairly stable across a range of manually supplied levels of σ_δ (Figure 4). Setting σ_δ very close to zero effectively turns off process error; negative log likelihood values indicated that this resulted in a poorer fit (Table 3). Negative log likelihood was lowest when σ_δ was equal to 0.15, which is the value estimated by model M1_O3 (Table 3, 6).
- While there were small systematic retrospective patterns, particularly with biomass estimates, the estimates largely remained within the confidence limits of the model (retros from M1_O3 shown in Figure 5). The pattern in the biomass estimates may be related to the apparent increase in the plus group biomass and associated decrease in selectivity of the plus group in recent years (Figure 13). These trends require further investigation.
- Estimates of survey CV's were fairly consistent, with the exception of CV estimates from the 3M survey for age groups 1-3 (Figure 6). There are poor residual patterns from the fit to age groups 1-3 from the 3M survey (Figures 8, 9).
- Survey catchability was generally dome shaped, peaking between ages 5-7, with the exception of the CAN_FALL_2J3K survey which shows a linear decrease in catchability (Figure 10).
- The M1 model provided a good fit to the catch data (landings and proportions at age; Figures 11, 12).
- The S1 model was built to try and resolve some apparent conflicts in the data. While it does provide a better fit (Table 3, Figure 8), there are some unresolved discrepancies in the fit of this model when supplied different data options (Figure 16). This model formulation requires further testing.

Conclusion

In summary, both models presented appear to perform well and both provide similar estimates. Sensitivity test indicate that the models are generally robust to changes in assumed parameter values. Residual patterns indicate that there are some issues with the whole-stock model (M1), particularly with its fit to the 3M survey. This is not surprising since analyses of the raw data indicate that there have been shifts in the distribution of this species. Whole-stock models are not designed to account for such shifts and, as such, the quasi-spatial model (S1) was built to try and account for changes in the distribution. The S1 formulation, however, is experimental and requires further testing. The retrospective analysis of M1 indicates that this model could provide reliable advice from one year to the next. Simulation testing of this model will allow further demonstration of the reliability of estimated values.

Table 1 - Research vessel survey time series options.

	base	O1	O2	O3	O4
CAN_FALL_2J3K	1996-2015	1996-2015	1996-2015	1996-2015	1996-2015
CAN_SPRN_3LNO	1996-2014	1996-2014	1996-2014	1996-2014	1996-2014
CAN_FALL_3LNO		1996-2015	1996-2015	1996-2015	1996-2015
EU_SUMR_3L		2006-2015			2006-2015
EU_SPRN_3NO		1997-2015	1997-2015	1997-2015	1997-2015
EU_SUMR_3M_lt700	1995-2003	1995-2015	1995-2015	1995-2003	1995-2003
EU_SUMR_3M_lt1400	2004-2015			2004-2015	2004-2015
EU_SUMR_3M_gt700		2004-2015	2004-2015		

Table 2 - Parametrization and inputs used in main model runs.

Name	Model	Data	y	A	M	σ_C
M1_base	M1	base	1995	10	0.12	0.1
M1_O1	M1	O1	1995	10	0.12	0.1
M1_O2	M1	O2	1995	10	0.12	0.1
M1_O3	M1	O3	1995	10	0.12	0.1
M1_O3_A14	M1	O3	1995	10	0.12	0.1
M1_O3_nm_0.20	M1	O3	1995	10	0.20	0.1
M1_O3_nm_0.30	M1	O3	1995	10	0.30	0.1
M1_O3_pe_0.0001	M1	O3	1995	10	0.12	0.1
M1_O3_pe_0.001	M1	O3	1995	10	0.12	0.1
M1_O3_pe_0.01	M1	O3	1995	10	0.12	0.1
M1_O3_pe_0.05	M1	O3	1995	10	0.12	0.1
M1_O3_pe_0.10	M1	O3	1995	10	0.12	0.1
M1_O3_pe_0.15	M1	O3	1995	10	0.12	0.1
M1_O3_pe_0.20	M1	O3	1995	10	0.12	0.1
M1_O3_sigmaC_0.20	M1	O3	1995	10	0.12	0.2
M1_O3_sigmaC_0.30	M1	O3	1995	10	0.12	0.3
M1_O4	M1	O4	1995	10	0.12	0.1
S1_base	S1	base	1995	10	0.12	0.1
S1_O1	S1	O1	1995	10	0.12	0.1
S1_O2	S1	O2	1995	10	0.12	0.1
S1_O4	S1	O4	1995	10	0.12	0.1

Table 3 - Likelihood table for M1 and S1 models using different data and parameter inputs. Comparable models (i.e. those that use the same data) are separated by dashes.

	nll	k	AIC	maxgrad	comp
M1_base	780	58	1676	0.00051	1
S1_base	729	61	1580	0.00069	1
	-	-	-	-	-
M1_O1	1412	88	2999	0.00064	2
S1_O1	1283	91	2747	0.0013	2
	-	-	-	-	-
M1_O2	1346	78	2848	0.00074	3
S1_O2	1190	81	2541	0.00072	3
	-	-	-	-	-
M1_O4	1200	88	2575	0.00088	4
S1_O4	1133	91	2449	0.00074	4
	-	-	-	-	-
M1_O3	1134	78	2425	0.00049	5
M1_O3_nm_0.20	1136	78	2428	0.00069	5
M1_O3_nm_0.30	1139	78	2433	0.0019	5
M1_O3_sigmaC_0.20	1118	78	2391	0.00046	5
M1_O3_sigmaC_0.30	1111	78	2378	0.00034	5

M1_O3_pe_0.0001	1156	77	2466	0.00065	5
M1_O3_pe_0.001	1156	77	2466	0.00053	5
M1_O3_pe_0.01	1156	77	2466	0.00029	5
M1_O3_pe_0.05	1149	77	2451	0.00045	5
M1_O3_pe_0.10	1138	77	2430	0.00082	5
M1_O3_pe_0.15	1134	77	2423	0.00029	5
M1_O3_pe_0.20	1139	77	2432	0.00058	5

Table 4 - Estimates of survey error for M1 models using different survey data options.

	M1_base	M1_O1	M1_O2	M1_O3	M1_O4
$\sigma_{CAN\_FALL\_2J3K:1-3}$	0.31	0.24	0.24	0.25	0.26
$\sigma_{CAN\_FALL\_2J3K:4-7}$	0.30	0.34	0.32	0.30	0.32
$\sigma_{CAN\_FALL\_2J3K:8-10}$	0.44	0.52	0.52	0.44	0.46
$\sigma_{CAN\_SPRN\_3LNO:1-3}$	0.70	0.64	0.65	0.64	0.63
$\sigma_{CAN\_SPRN\_3LNO:4-7}$	0.63	0.55	0.55	0.55	0.55
$\sigma_{CAN\_SPRN\_3LNO:8-10}$	0.71	0.68	0.68	0.65	0.65
$\sigma_{EU\_SUMR\_3M:1-3}$	1.54			1.51	1.51
$\sigma_{EU\_SUMR\_3M:4-7}$	0.49			0.46	0.45
$\sigma_{EU\_SUMR\_3M:8-10}$	0.39			0.40	0.40
$\sigma_{CAN\_FALL\_3LNO:1-3}$		0.66	0.67	0.67	0.66
$\sigma_{CAN\_FALL\_3LNO:4-7}$		0.41	0.39	0.39	0.41
$\sigma_{CAN\_FALL\_3LNO:8-10}$		0.70	0.67	0.65	0.67
$\sigma_{EU\_SPRN\_3NO:1-3}$		0.86	0.86	0.85	0.86
$\sigma_{EU\_SPRN\_3NO:4-7}$		0.59	0.60	0.60	0.59
$\sigma_{EU\_SPRN\_3NO:8-10}$		0.38	0.40	0.42	0.40
$\sigma_{EU\_SUMR\_3L:1-3}$		0.66			0.65
$\sigma_{EU\_SUMR\_3L:4-7}$		0.32			0.32
$\sigma_{EU\_SUMR\_3L:8-10}$		0.35			0.36
$\sigma_{EU\_SUMR\_3M\_gt700:1-3}$		0.87	0.85		
$\sigma_{EU\_SUMR\_3M\_gt700:4-7}$		0.58	0.60		
$\sigma_{EU\_SUMR\_3M\_gt700:8-10}$		0.29	0.30		
$\sigma_{EU\_SUMR\_3M\_lt700:1-3}$		2.45	2.44		
$\sigma_{EU\_SUMR\_3M\_lt700:4-7}$		0.84	0.84		
$\sigma_{EU\_SUMR\_3M\_lt700:8-10}$		0.87	0.86		

Table 5 - Estimates of survey error for S1 models using different survey data options.

	S1_base	S1_O1	S1_O2	S1_O4
$\sigma_{CAN\_FALL\_2J3K:1-3}$	0.31	0.31	0.32	0.30
$\sigma_{CAN\_FALL\_2J3K:4-7}$	0.22	0.25	0.27	0.25
$\sigma_{CAN\_FALL\_2J3K:8-10}$	0.33	0.42	0.44	0.39
$\sigma_{CAN\_SPRN\_3LNO:1-3}$	0.69	0.66	0.65	0.65
$\sigma_{CAN\_SPRN\_3LNO:4-7}$	0.56	0.55	0.56	0.54
$\sigma_{CAN\_SPRN\_3LNO:8-10}$	0.58	0.56	0.53	0.55
$\sigma_{EU\_SUMR\_3M:1-3}$	1.51			0.45
$\sigma_{EU\_SUMR\_3M:4-7}$	0.46			0.22
$\sigma_{EU\_SUMR\_3M:8-10}$	0.33			0.34
$\sigma_{CAN\_FALL\_3LNO:1-3}$		0.69	0.68	0.68
$\sigma_{CAN\_FALL\_3LNO:4-7}$		0.39	0.41	0.39
$\sigma_{CAN\_FALL\_3LNO:8-10}$		0.59	0.56	0.58
$\sigma_{EU\_SPRN\_3NO:1-3}$		0.87	0.83	0.85
$\sigma_{EU\_SPRN\_3NO:4-7}$		0.59	0.58	0.60
$\sigma_{EU\_SPRN\_3NO:8-10}$		0.41	0.43	0.42
$\sigma_{EU\_SUMR\_3L:1-3}$		0.66		0.66
$\sigma_{EU\_SUMR\_3L:4-7}$		0.33		0.33
$\sigma_{EU\_SUMR\_3L:8-10}$		0.34		0.33
$\sigma_{EU\_SUMR\_3M\_gt700:1-3}$		1.31	0.74	
$\sigma_{EU\_SUMR\_3M\_gt700:4-7}$		0.69	0.57	
$\sigma_{EU\_SUMR\_3M\_gt700:8-10}$		0.31	0.35	
$\sigma_{EU\_SUMR\_3M\_lt700:1-3}$		0.68	0.59	
$\sigma_{EU\_SUMR\_3M\_lt700:4-7}$		0.28	0.22	
$\sigma_{EU\_SUMR\_3M\_lt700:8-10}$		0.53	0.42	

Table 6 - Parameter estimates for M1 models using different survey data options.

	M1_base	M1_O1	M1_O2	M1_O3	M1_O4
σ_{δ}	0.09	0.14	0.14	0.15	0.15
σ_F	0.19	0.17	0.17	0.18	0.18
σ_{main}	0.57	0.60	0.63	0.56	0.54
σ_R	0.27	0.36	0.36	0.35	0.35
σ_X	0.22	0.24	0.23	0.23	0.23
$\varphi_{F,a}$	0.48	0.48	0.48	0.49	0.49
$\varphi_{F,y}$	0.97	0.97	0.97	0.97	0.97

Table 7 - Parameter estimates for S1 models using different survey data options.

	S1_base	S1_O1	S1_O2	S1_O4
σ_δ	0.00	0.06	0.07	0.07
σ_D	0.18	0.20	0.21	0.20
σ_F	0.14	0.14	0.14	0.14
σ_{main}	0.51	0.53	0.52	0.48
σ_R	0.24	0.36	0.39	0.36
σ_X	0.24	0.25	0.23	0.24
$\varphi_{D,a}$	0.94	0.90	0.90	0.90
$\varphi_{D,y}$	0.91	0.99	0.99	0.99
$\varphi_{F,a}$	0.45	0.46	0.45	0.46
$\varphi_{F,y}$	0.96	0.96	0.96	0.95

Table 8 - Parameter estimates for M1 and S1 models using different fixed values of natural mortality.

	M1_O3	M1_O3_nm_0.20	M1_O3_nm_0.30	M1_O3_sigmaC_0.20	M1_O3_sigmaC_0.30
σ_δ	0.15	0.15	0.16	0.11	0.10
σ_F	0.18	0.18	0.18	0.18	0.19
σ_{main}	0.56	0.56	0.56	0.56	0.56
σ_R	0.35	0.35	0.36	0.35	0.34
σ_X	0.23	0.22	0.22	0.20	0.18
$\varphi_{F,a}$	0.49	0.50	0.51	0.52	0.56
$\varphi_{F,y}$	0.97	0.97	0.97	0.97	0.97

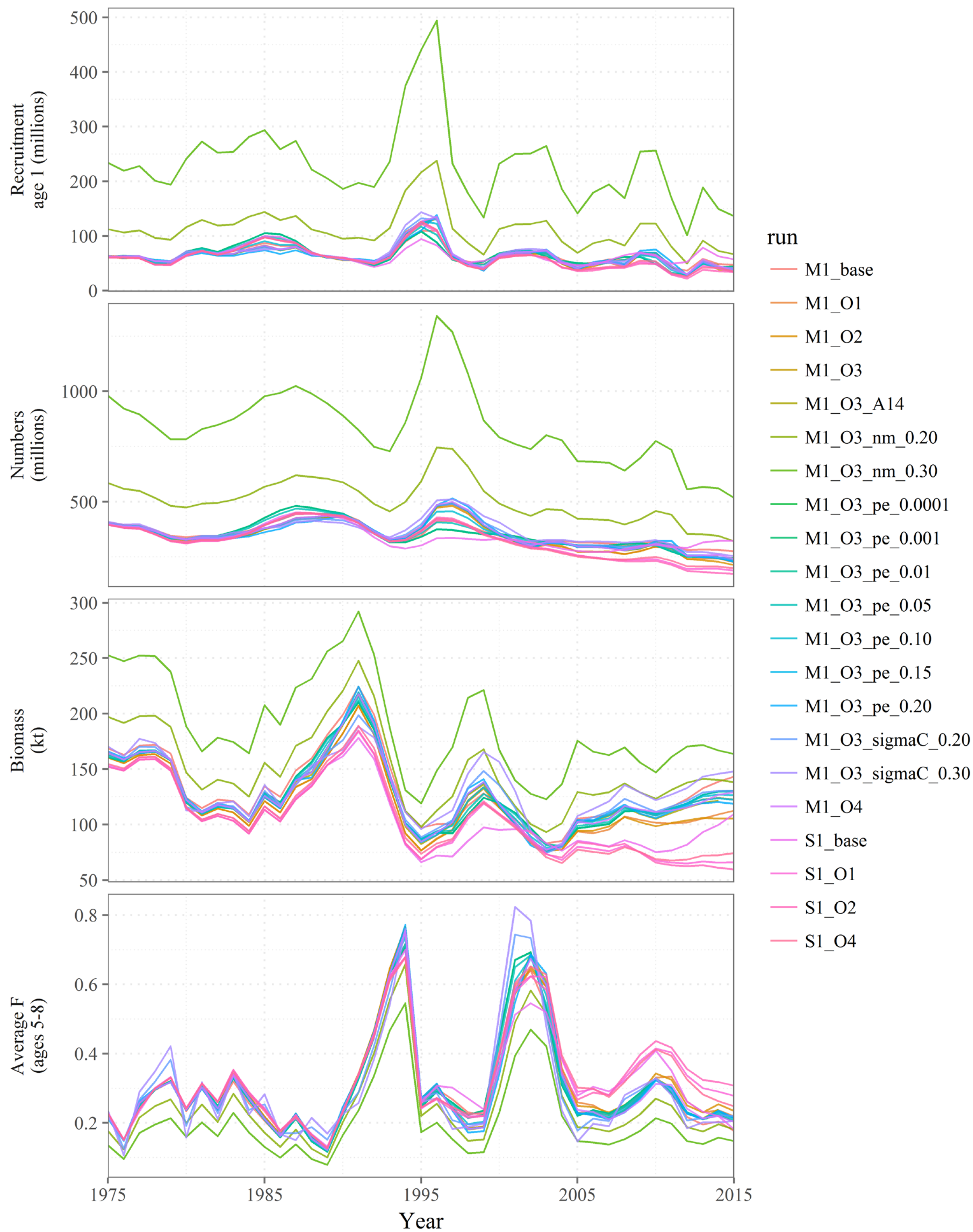

Fig. 1. Estimates of recruitment, numbers, total biomass, and average F from main model tests.

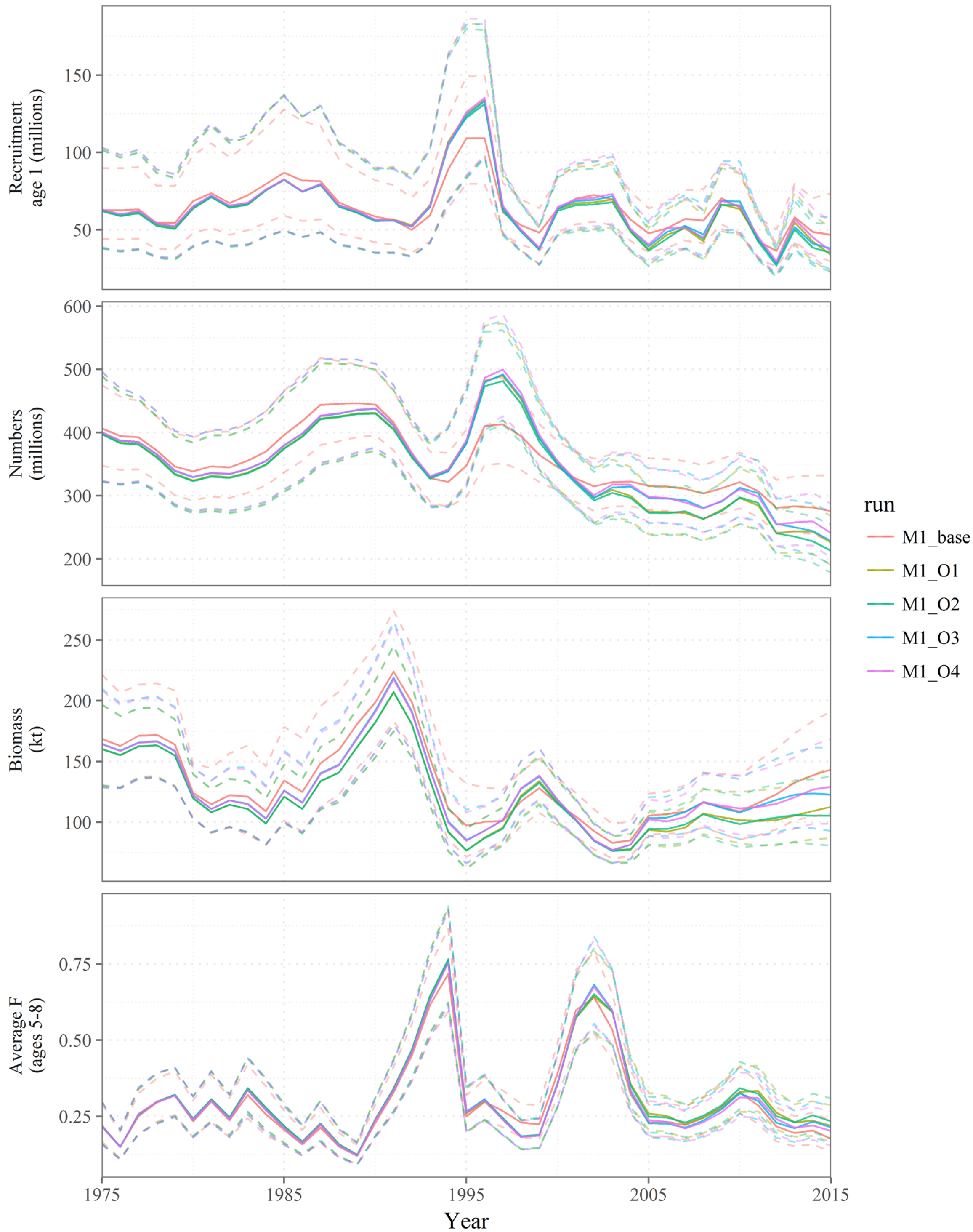

Fig. 2. Estimates of recruitment, numbers, total biomass, and average F, with 95% confidence intervals (dashed lines), from M1 model using different data options.

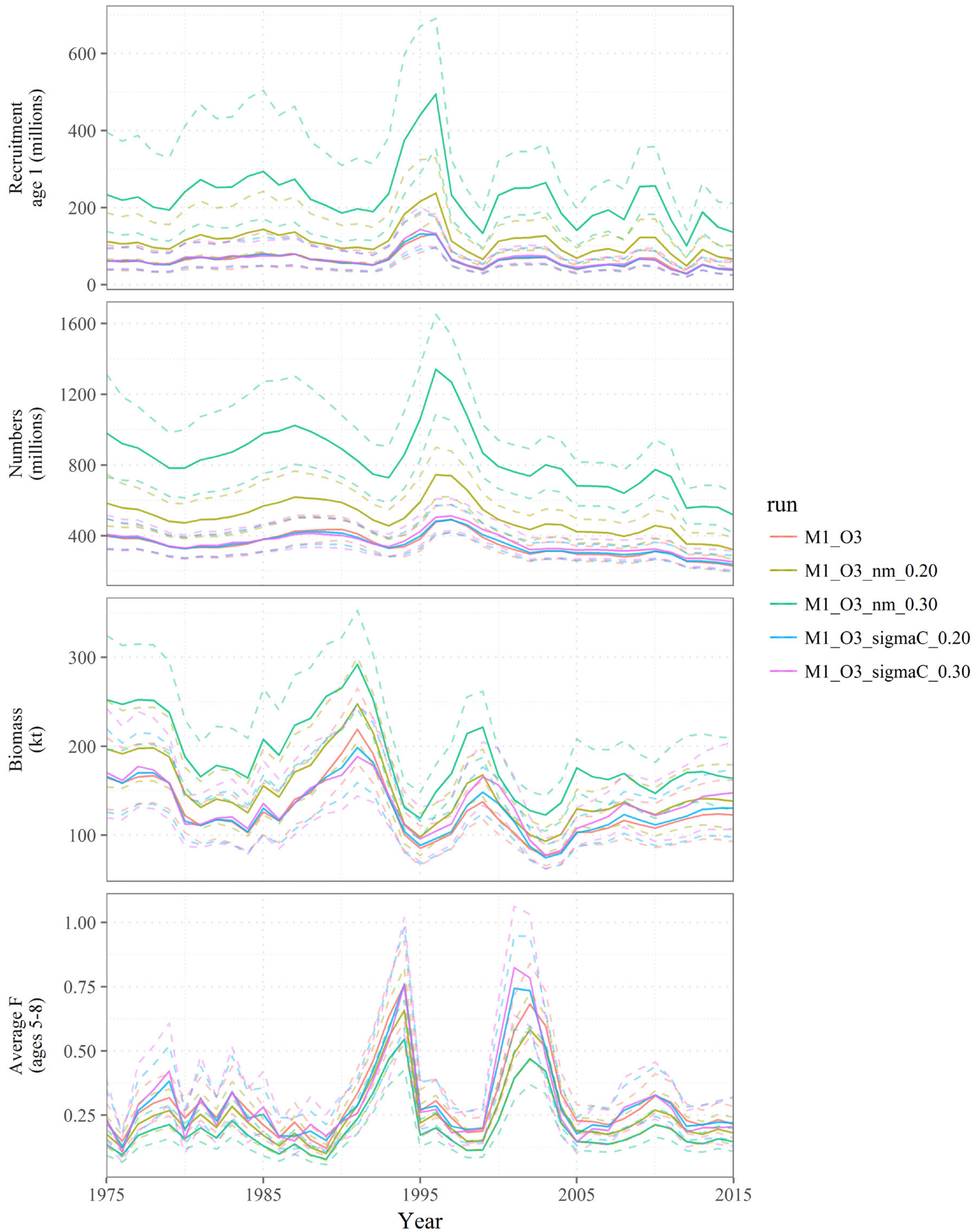

Fig.3. Estimates of recruitment, numbers, total biomass, and average F, with 95% confidence intervals (dashed lines), from M1_O3 model using different M ('nm') and σ_C ('sigmaC') inputs.

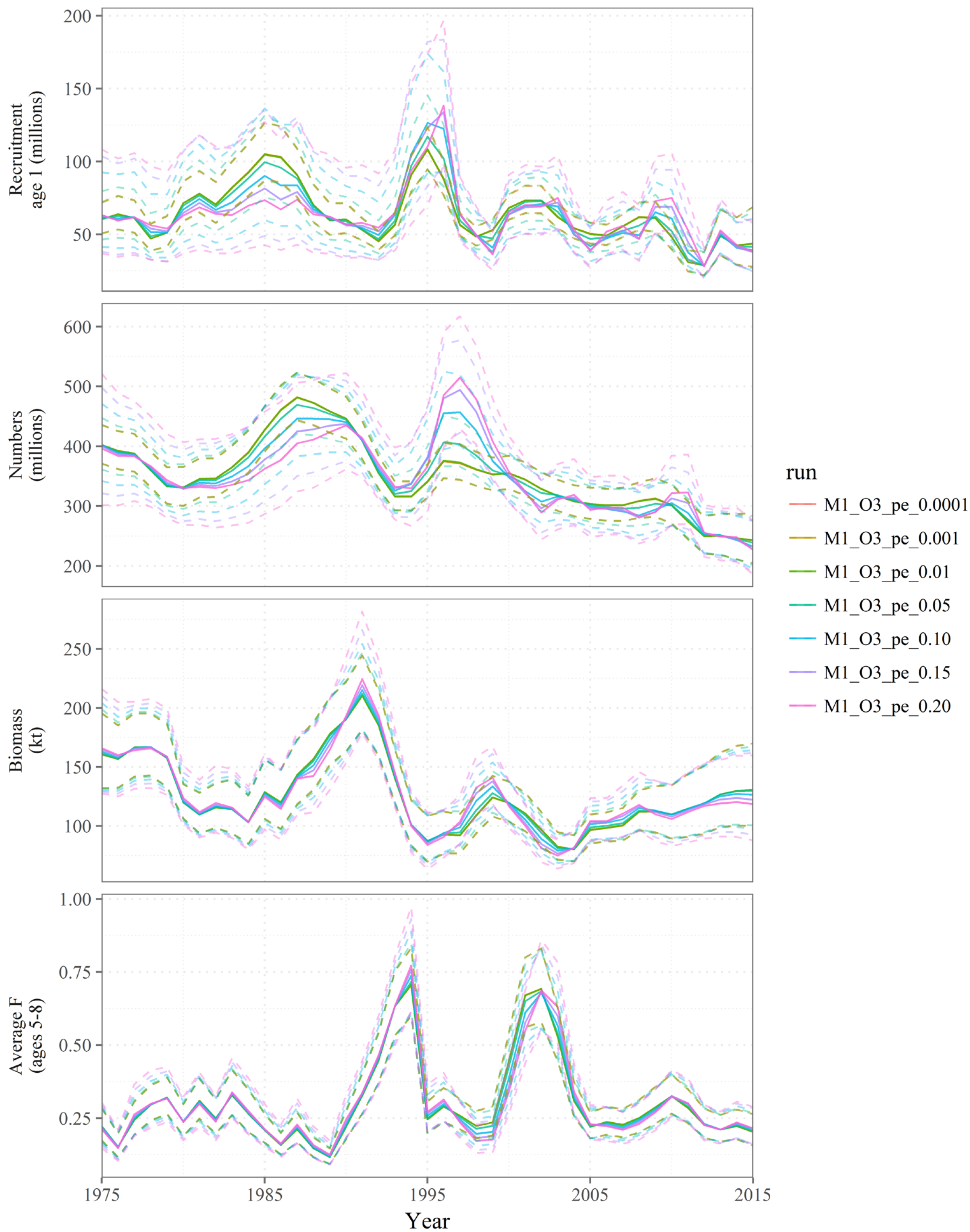

Fig. 4. Estimates of recruitment, numbers, total biomass, and average F, with 95% confidence intervals (dashed lines), from M1_O3 model fixing the process error (σ_δ, 'pe') at a range of levels.

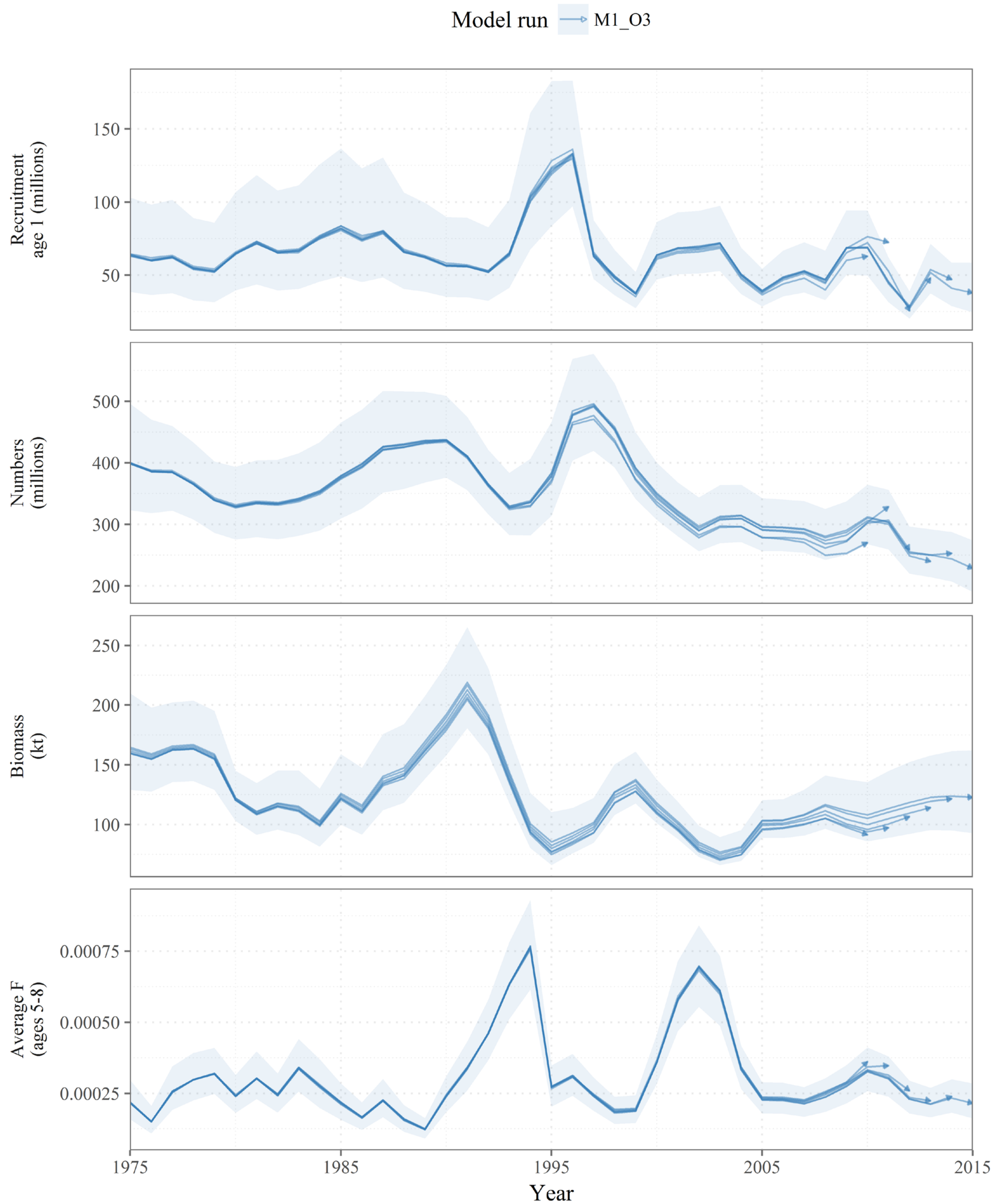

Fig. 5. Retrospective patterns in estimates of recruitment, numbers, total biomass, and average F, with 95% confidence intervals (shaded area), from model M1_O3.

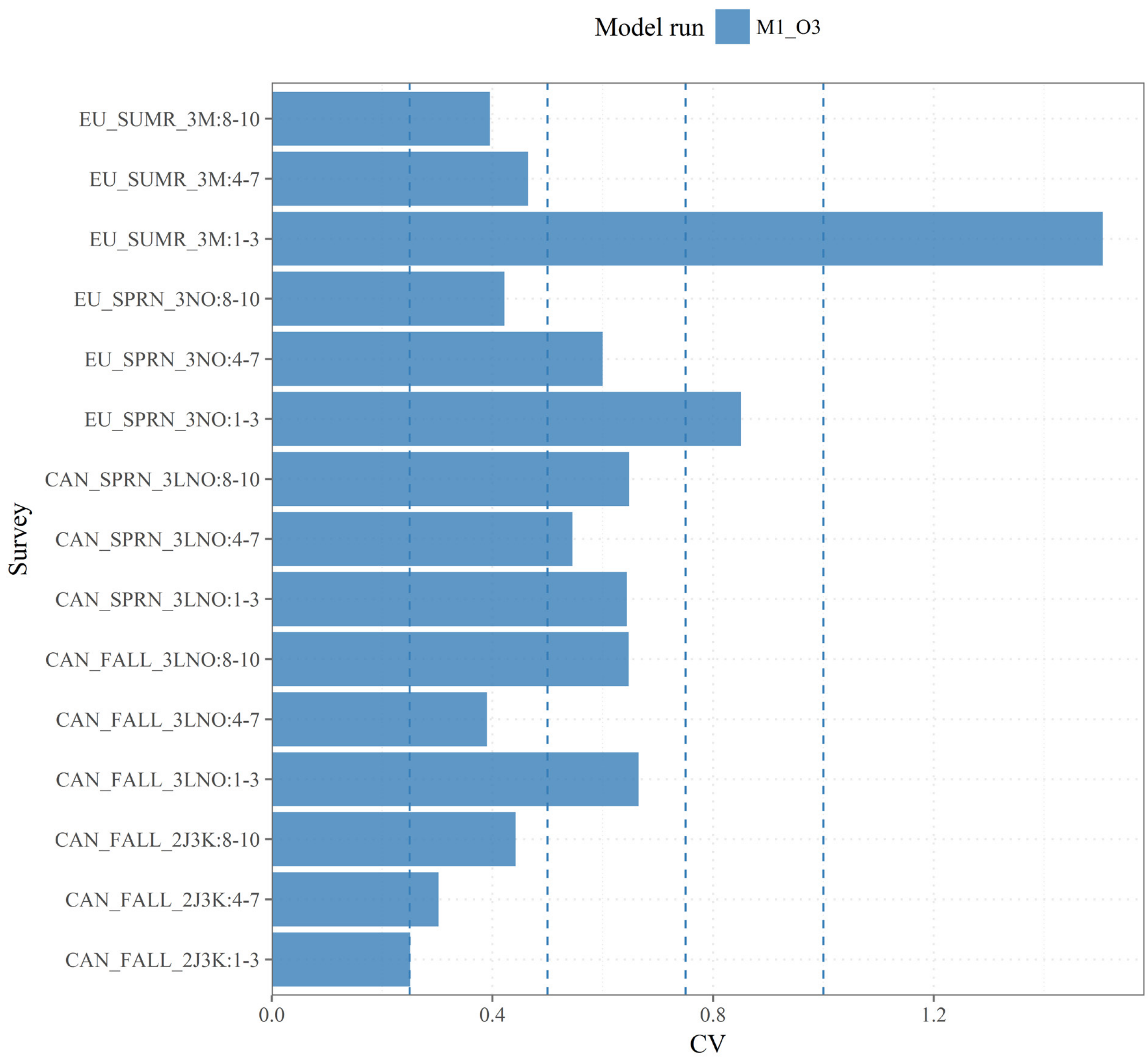

Fig. 6. Estimates of survey CV from model M1_O3. Age ranges follow the survey name.

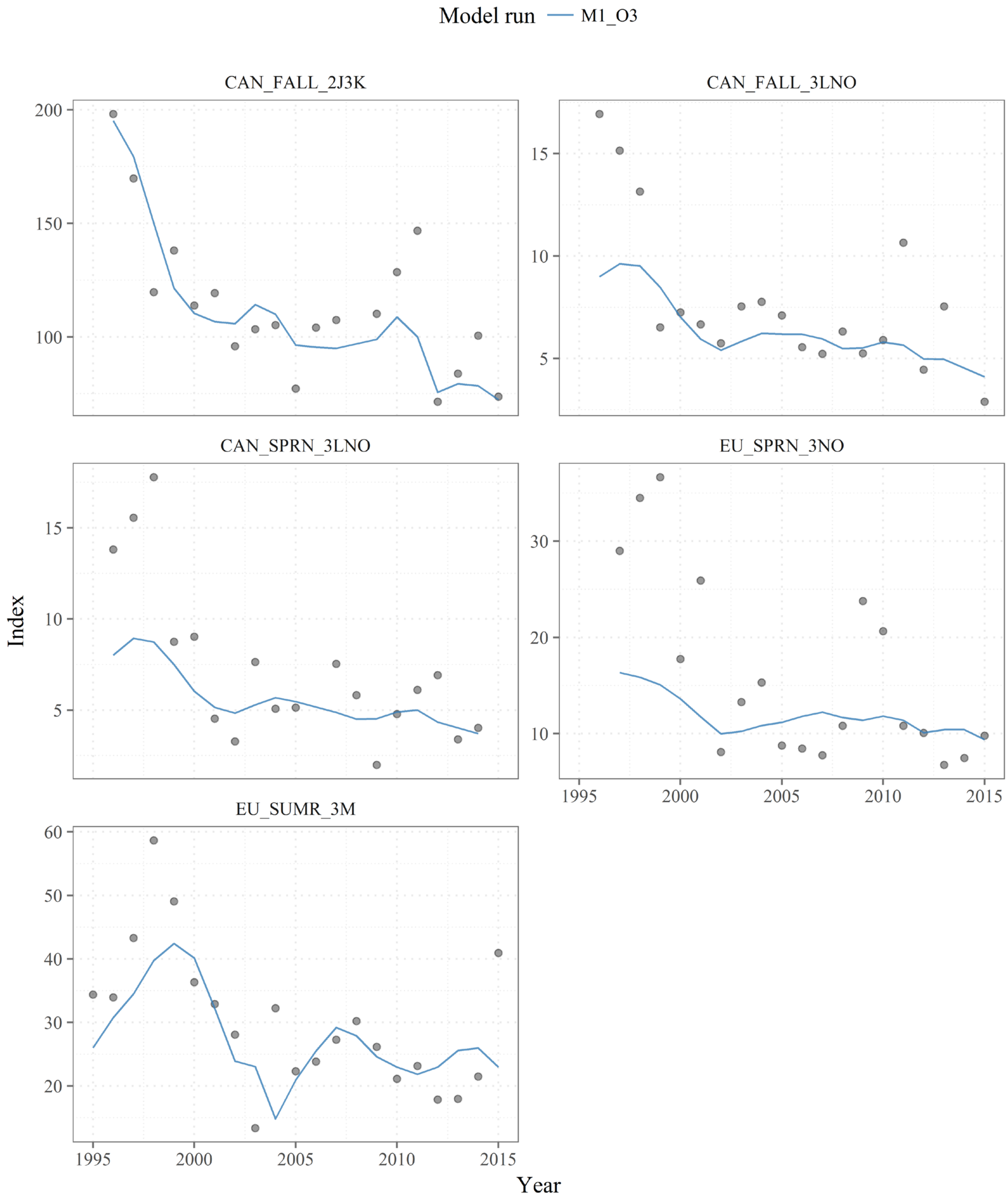

Fig. 7. Age aggregated observed and predicted survey indices from model M1_O3.

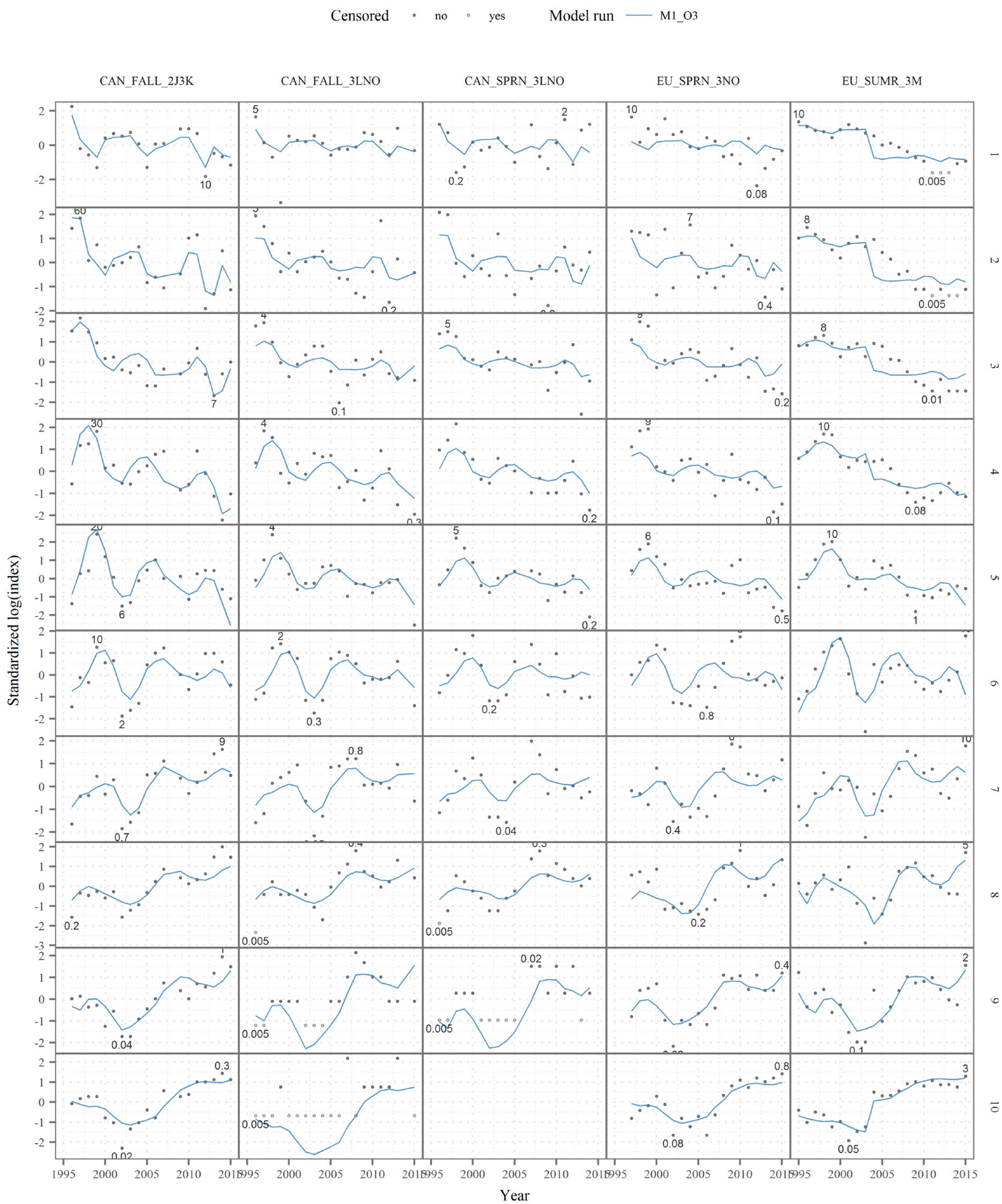

Fig. 8. Observed and predicted survey indices at age for model M_O3. Log(index) standardized by survey and age. Min and max index values are indicated.

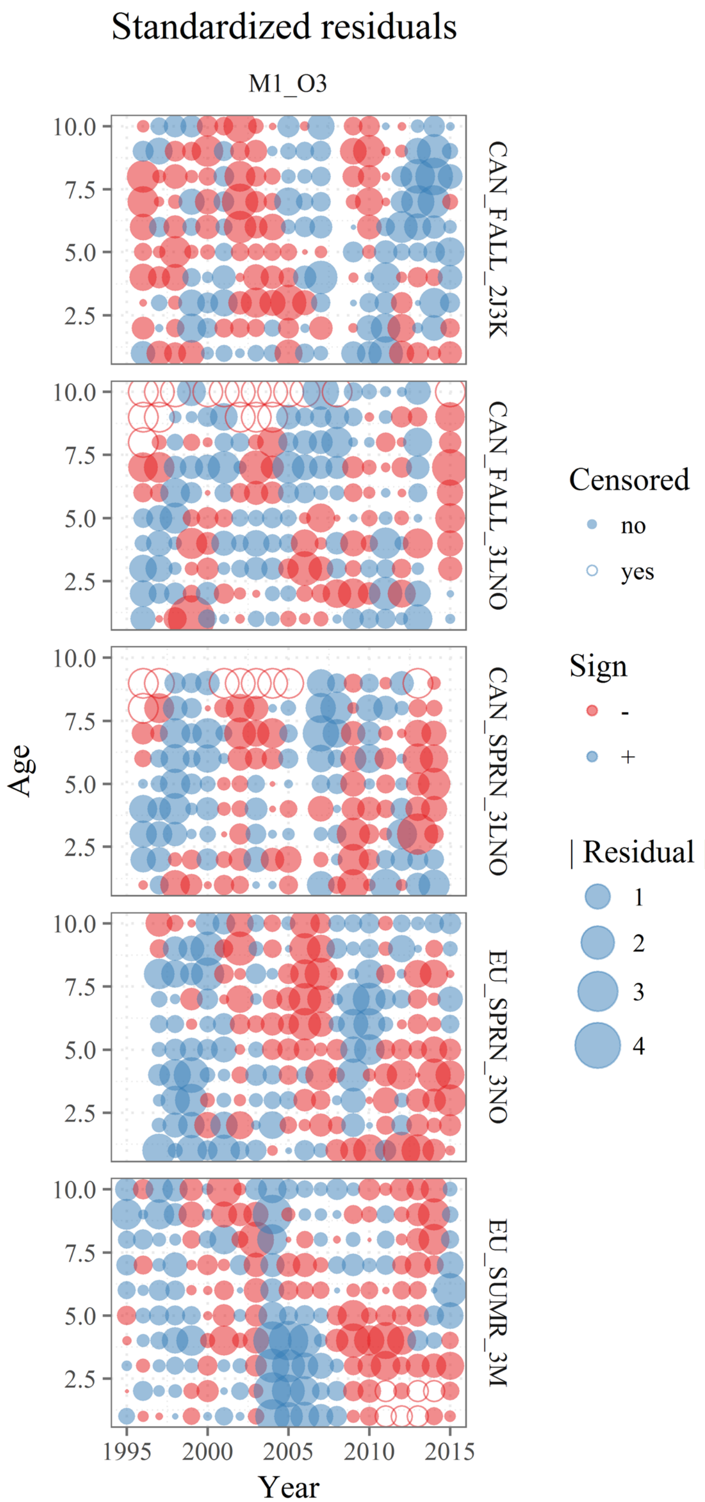

Fig. 9. Matrix plot of index at age residuals by survey for model M1_O3.

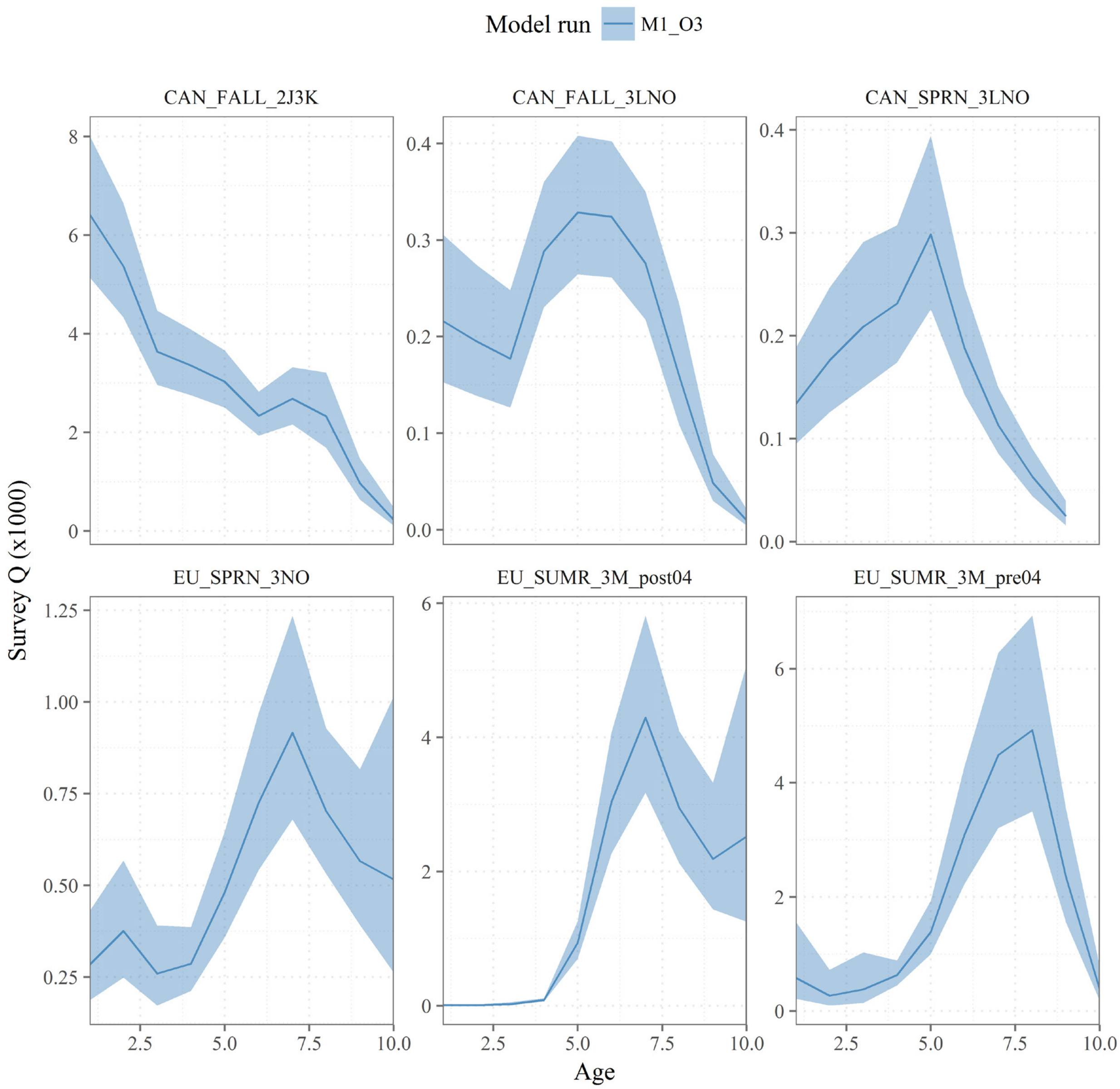

Fig. 10. Age patterns in survey catchability parameters, with 95% confidence intervals, from model M1_O3

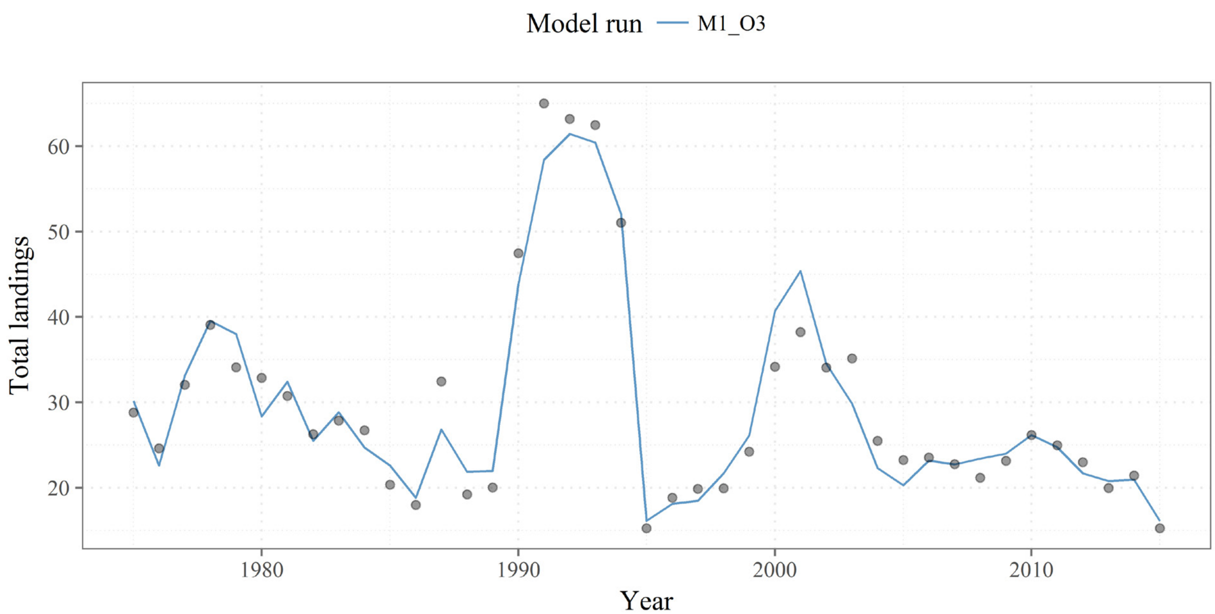

Fig. 11. Model fits (lines) to total landings (dots) from model M1_O3

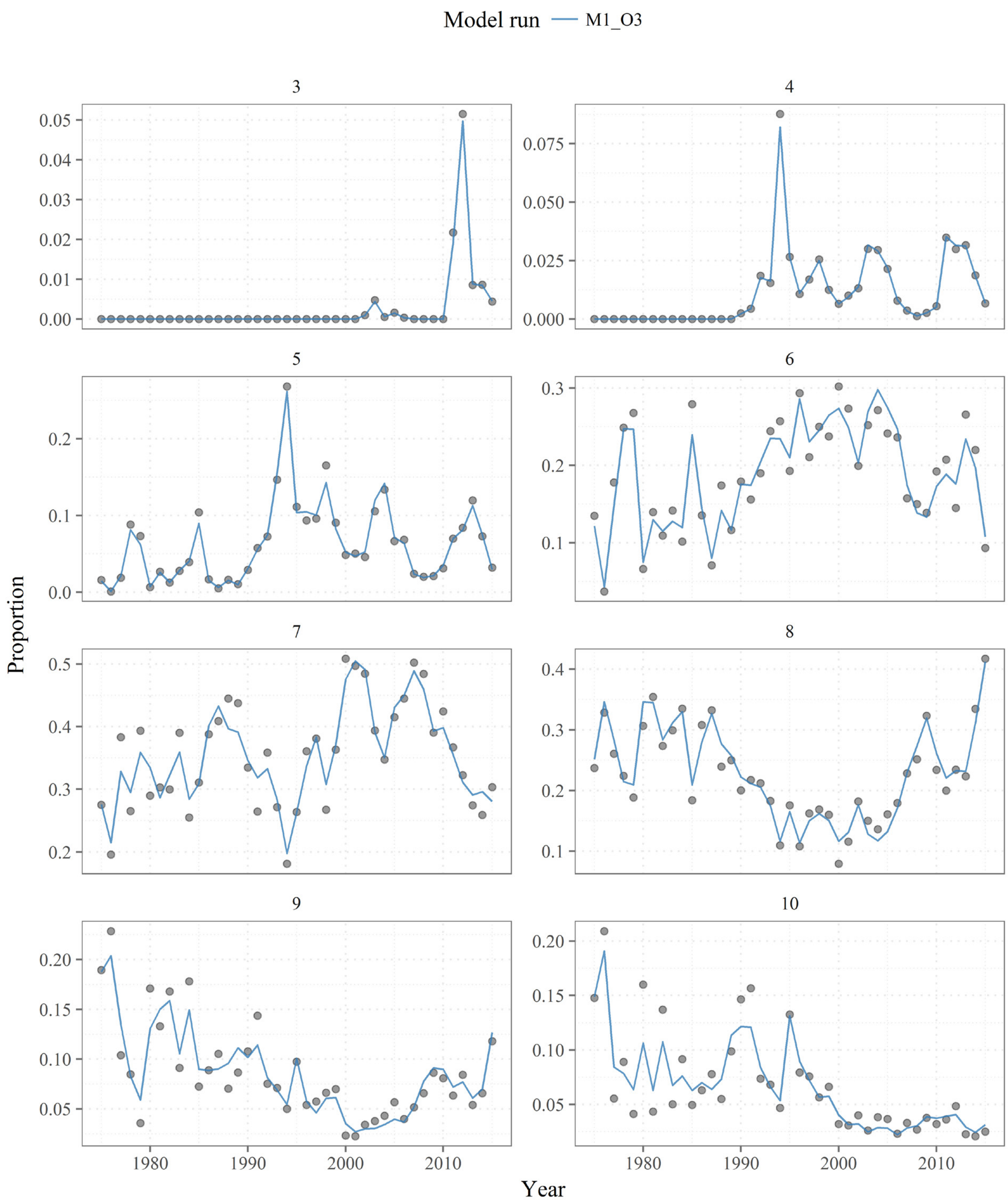

Fig. 12. Fits to catch proportions at age from model M1_O3

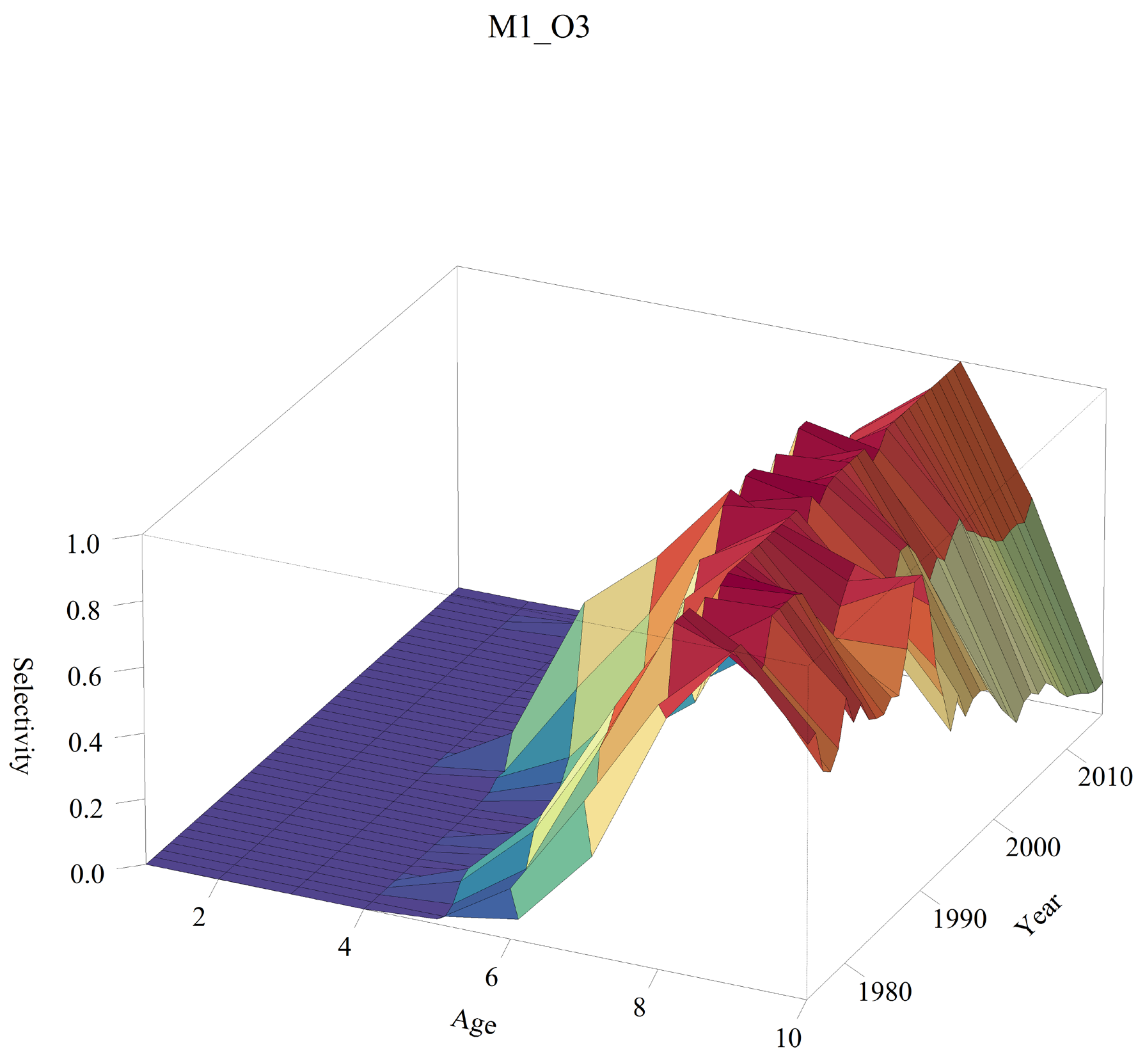

Fig. 13. Age pattern in selectivity from model M1_O3.

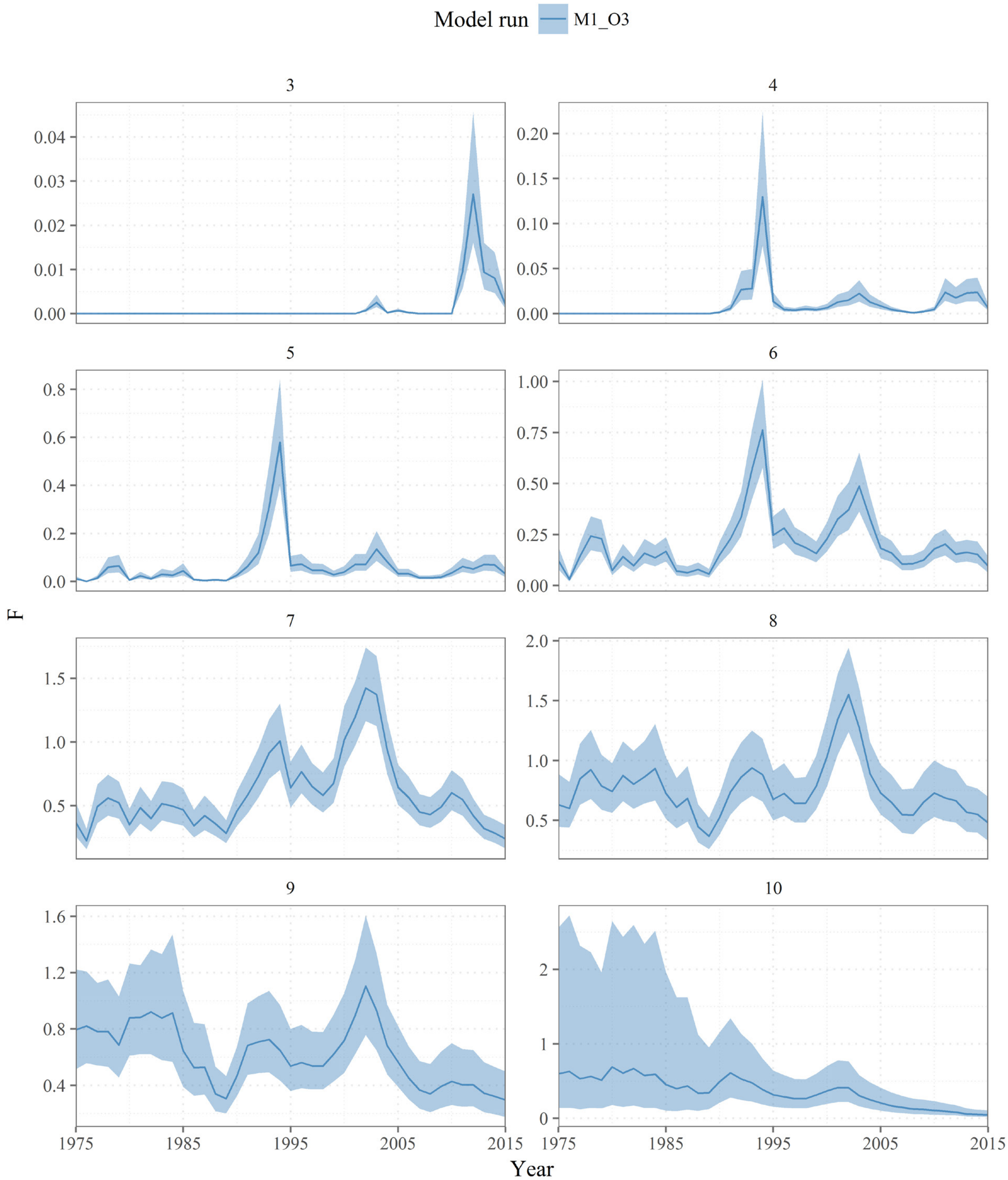

Fig. 14. Fishing mortality, with 95% confidence intervals (shaded area), at age from model M1_O3.

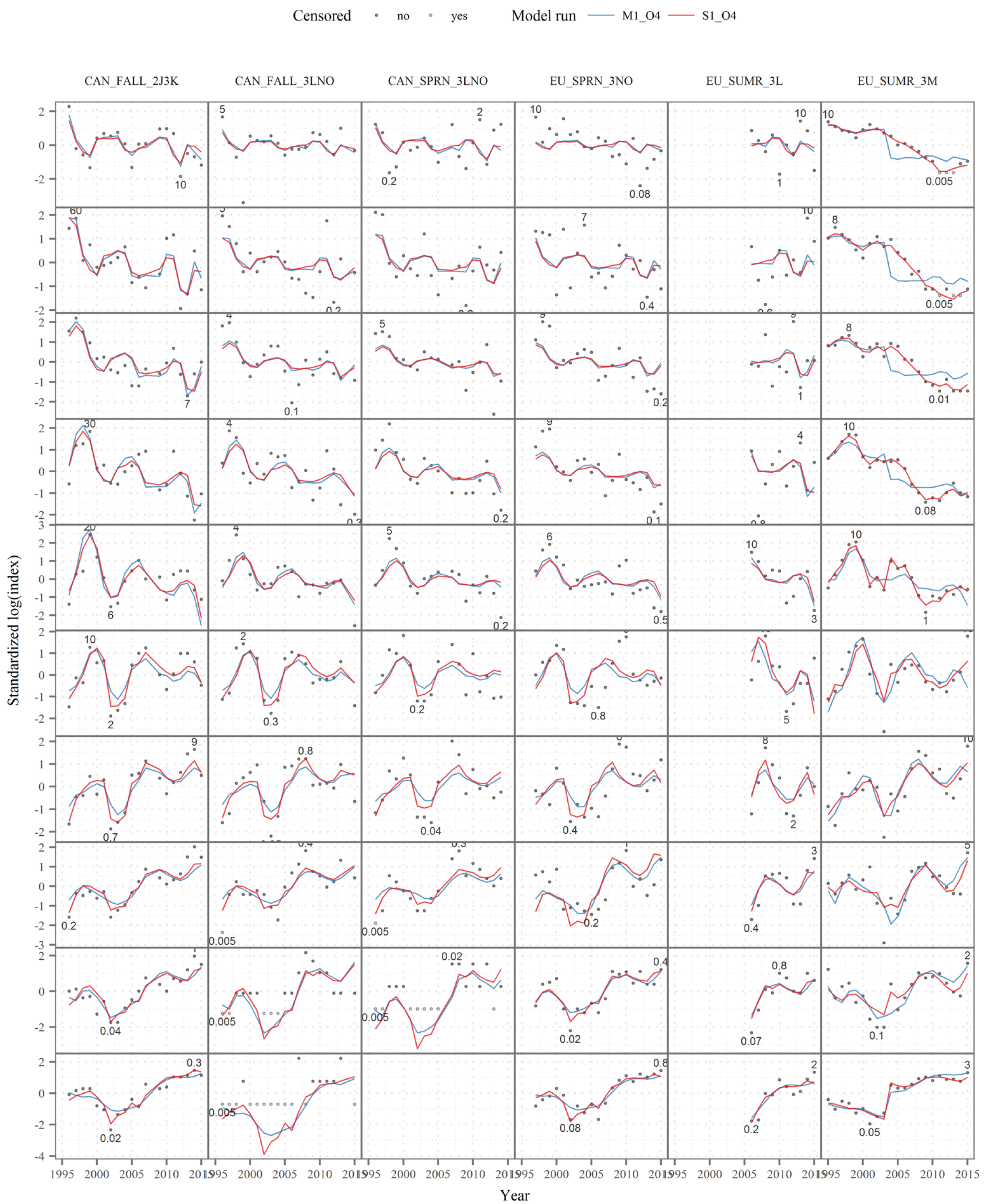

Fig. 15. Observed and predicted survey indices at age for models M1_O4 and S1_O4. Log(index) standardized by survey and age. Min and max index values are indicated.

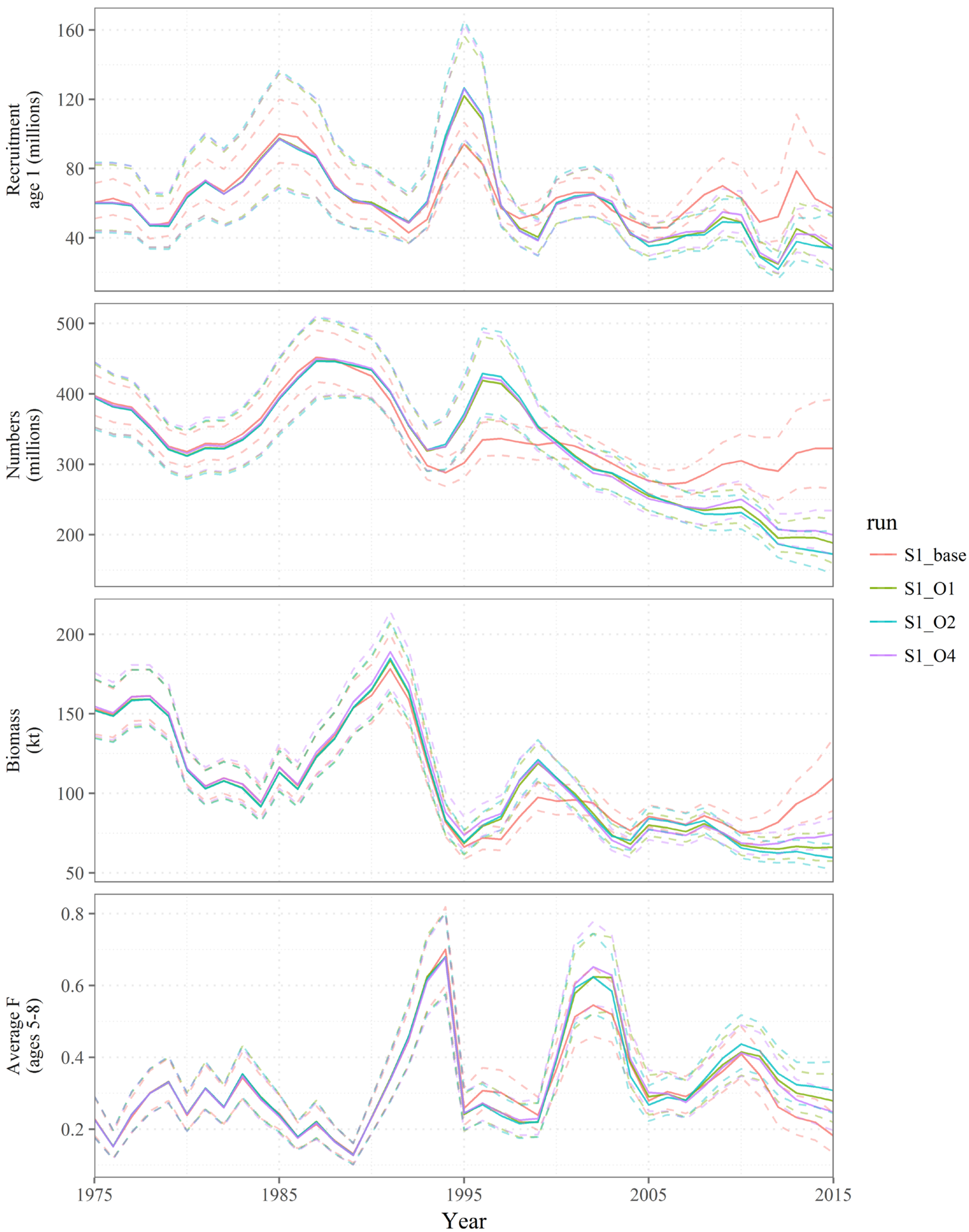

Fig. 16. Estimates of recruitment, numbers, total biomass, and average F, with 95% confidence intervals (dashed lines), from S1 models using different survey data options.

Appendix A: Data

Table 9 - 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
2008	21.180
2009	23.156
2010	26.174
2011	24.960
2012	22.980
2013	19.980
2014	21.430
2015	15.270

Table 10 - Catch at age estimates for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1975	0	0	0	0	334	2819	5750	4956	3961	1688	702	135	279	288
1976	0	0	0	0	17	610	3231	5413	3769	2205	829	260	101	53
1977	0	0	0	0	534	5012	10798	7346	2933	1013	220	130	116	84
1978	0	0	0	0	2982	8415	8970	7576	2865	1438	723	367	222	258
1979	0	0	0	0	2386	8727	12824	6136	1169	481	287	149	143	284
1980	0	0	0	0	209	2086	9150	9679	5398	3828	1013	128	53	27
1981	0	0	0	0	863	4517	9806	11451	4307	890	256	142	43	69
1982	0	0	0	0	269	2299	6319	5763	3542	1684	596	256	163	191
1983	0	0	0	0	701	3557	9800	7514	2295	692	209	76	106	175
1984	0	0	0	0	902	2324	5844	7682	4087	1259	407	143	106	183
1985	0	0	0	0	1983	5309	5913	3500	1380	512	159	99	87	86
1986	0	0	0	0	280	2240	6411	5091	1469	471	244	140	70	117
1987	0	0	0	0	137	1902	11004	8935	2835	853	384	281	225	349
1988	0	0	0	0	296	3186	8136	4380	1288	465	201	105	107	129
1989	0	0	0	0	181	1988	7480	4273	1482	767	438	267	145	71
1990	0	0	0	95	1102	6758	12632	7557	4072	2692	1204	885	434	318
1991	0	0	0	220	2862	7756	13152	10796	7145	3721	1865	1216	558	422
1992	0	0	0	1064	4180	10922	20639	12205	4332	1762	1012	738	395	335
1993	0	0	0	1010	9570	15928	17716	11918	4642	1836	1055	964	401	182
1994	0	0	0	5395	16500	15815	11142	6739	3081	1103	811	422	320	215
1995	0	0	0	323	1352	2342	3201	2130	1183	540	345	273	251	201
1996	0	0	0	190	1659	5197	6387	1914	956	504	436	233	143	89
1997	0	0	0	335	1903	4169	7544	3215	1139	606	420	246	137	89
1998	0	0	0	552	3575	5407	5787	3653	1435	541	377	161	92	51
1999	0	0	0	297	2149	5625	8611	3793	1659	623	343	306	145	151
2000	0	0	0	271	2029	12583	21175	3299	973	528	368	203	129	104
2001	0	0	0	448	2239	12163	22122	5154	1010	495	439	203	156	75
2002	0	0	37	479	1662	7239	17581	6607	1244	659	360	224	126	81
2003	0	0	203	1279	4491	10723	16764	6385	1614	516	290	144	76	85
2004	0	0	17	897	4062	8236	10542	4126	1307	529	289	184	87	75
2005	0	0	40	534	1652	5999	10313	3996	1410	444	244	114	64	46
2006	0	0	10	216	1869	6450	12144	4902	1089	372	136	47	32	40
2007	0	0	0	88	570	3732	11912	5414	1230	472	163	80	41	29
2008	0	0	0	29	448	3312	10697	5558	1453	393	115	46	26	15
2009	0	0	0	61	476	3121	8801	7276	1949	508	206	67	31	34
2010	0	0	0	146	825	5077	11202	6171	2134	520	214	64	22	21
2011	0	0	430	690	1385	4101	7257	3953	1255	455	155	66	21	18
2012	0	0	1216	706	1982	3422	7618	5529	1992	657	287	134	36	29
2013	0	0	125	460	1744	3873	3997	3255	787	240	49	16	8	17
2014	0	0	119	259	1007	3041	3583	4626	910	199	49	18	7	15
2015	0	0	59	89	429	1237	4037	5546	1571	223	58	22	9	19

Table 11 - Catch weight-at-age estimates for Greenland Halibut in NAFO Subarea 2 and Divisions 3KLMNO.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1975	0	0	0.126	0.244	0.609	0.760	0.955	1.190	1.580	2.210	2.700	3.370	3.880	5.764
1976	0	0	0.126	0.244	0.609	0.760	0.955	1.190	1.580	2.210	2.700	3.370	3.880	5.144
1977	0	0	0.126	0.244	0.609	0.760	0.955	1.190	1.580	2.210	2.700	3.370	3.880	5.992
1978	0	0	0.126	0.244	0.609	0.760	0.955	1.190	1.580	2.210	2.700	3.370	3.880	5.894
1979	0	0	0.126	0.244	0.609	0.760	0.955	1.190	1.580	2.210	2.700	3.370	3.880	6.077
1980	0	0	0.126	0.244	0.514	0.659	0.869	1.050	1.150	1.260	1.570	2.710	3.120	5.053
1981	0	0	0.126	0.244	0.392	0.598	0.789	0.985	1.240	1.700	2.460	3.510	4.790	7.426
1982	0	0	0.126	0.244	0.525	0.684	0.891	1.130	1.400	1.790	2.380	3.470	4.510	7.359
1983	0	0	0.126	0.244	0.412	0.629	0.861	1.180	1.650	2.230	3.010	3.960	5.060	7.061
1984	0	0	0.126	0.244	0.377	0.583	0.826	1.100	1.460	1.940	2.630	3.490	4.490	7.016
1985	0	0	0.126	0.244	0.568	0.749	0.941	1.240	1.690	2.240	2.950	3.710	4.850	7.010
1986	0	0	0.126	0.244	0.350	0.584	0.811	1.100	1.580	2.120	2.890	3.890	4.950	7.345
1987	0	0	0.126	0.244	0.364	0.589	0.836	1.160	1.590	2.130	2.820	3.600	4.630	6.454
1988	0	0	0.126	0.244	0.363	0.569	0.805	1.163	1.661	2.216	3.007	3.925	5.091	7.164
1989	0	0	0.126	0.244	0.400	0.561	0.767	1.082	1.657	2.237	2.997	3.862	4.919	6.370
1990	0	0	0.090	0.181	0.338	0.546	0.766	1.119	1.608	2.173	2.854	3.731	4.691	6.391
1991	0	0	0.126	0.244	0.383	0.592	0.831	1.228	1.811	2.461	3.309	4.142	5.333	7.081
1992	0	0	0.175	0.289	0.430	0.577	0.793	1.234	1.816	2.462	3.122	3.972	5.099	6.648
1993	0	0	0.134	0.232	0.368	0.547	0.809	1.207	1.728	2.309	2.999	3.965	4.816	6.489
1994	0	0	0.080	0.196	0.330	0.514	0.788	1.179	1.701	2.268	2.990	3.766	4.882	6.348
1995	0	0	0.080	0.288	0.363	0.531	0.808	1.202	1.759	2.446	3.122	3.813	4.893	6.790
1996	0	0	0.161	0.242	0.360	0.541	0.832	1.272	1.801	2.478	3.148	3.856	4.953	6.312
1997	0	0	0.120	0.206	0.336	0.489	0.771	1.159	1.727	2.355	3.053	3.953	5.108	6.317
1998	0	0	0.119	0.228	0.373	0.543	0.810	1.203	1.754	2.351	3.095	4.010	5.132	6.124
1999	0	0	0.176	0.253	0.358	0.533	0.825	1.253	1.675	2.287	2.888	3.509	4.456	5.789
2000	0	0	0.000	0.254	0.346	0.524	0.787	1.192	1.774	2.279	2.895	3.645	4.486	5.531
2001	0	0	0.000	0.249	0.376	0.570	0.830	1.168	1.794	2.367	2.950	3.715	4.585	5.458
2002	0	0	0.217	0.251	0.369	0.557	0.841	1.193	1.760	2.277	2.896	3.579	4.407	5.477
2003	0	0	0.188	0.247	0.389	0.564	0.822	1.199	1.651	2.166	2.700	3.404	4.377	5.409
2004	0	0	0.180	0.249	0.376	0.535	0.808	1.196	1.629	2.146	2.732	3.538	4.381	5.698
2005	0	0	0.252	0.301	0.396	0.564	0.849	1.247	1.691	2.177	2.705	3.464	4.264	5.224
2006	0	0	0.129	0.267	0.405	0.605	0.815	1.092	1.495	1.874	2.396	3.139	3.747	4.701
2007	0	0	0.000	0.276	0.389	0.581	0.833	1.137	1.500	1.948	2.607	3.057	3.869	4.954
2008	0	0	0.000	0.278	0.404	0.617	0.891	1.195	1.605	2.038	2.804	3.247	4.232	4.721
2009	0	0	0.000	0.279	0.390	0.599	0.862	1.158	1.611	2.099	2.549	3.118	3.432	4.431
2010	0	0	0.000	0.250	0.350	0.570	0.840	1.210	1.650	2.100	2.610	3.310	4.180	5.220
2011	0	0	0.130	0.210	0.310	0.530	0.850	1.250	1.750	2.230	2.780	3.560	4.410	5.840
2012	0	0	0.170	0.240	0.300	0.570	0.890	1.280	1.750	2.290	2.810	3.620	4.400	5.730
2013	0	0	0.140	0.270	0.420	0.630	0.870	1.250	1.830	2.470	3.260	3.840	4.360	5.790
2014	0	0	0.150	0.240	0.400	0.620	0.890	1.310	1.920	2.530	3.320	3.890	4.550	5.540
2015	0	0	0.160	0.240	0.410	0.630	0.890	1.220	1.760	2.490	3.270	3.810	4.360	5.390

Table 12 - Index at age estimates from the research vessel surveys

CAN_FALL_2J3K

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1996	4.92	98.68	47.82	32.01	9.54	6.28	2.47	0.84	0.19	0.18	0.04	0.02	0.01	0.02	0.01
1997	2.18	28.05	58.62	43.61	21.13	10.37	5.01	2.00	0.64	0.20	0.06	0.03	0.02	0.01	0.00
1998	1.52	23.35	25.07	31.19	21.87	10.86	4.45	2.07	0.57	0.13	0.06	0.03	0.02	0.01	0.00
1999	6.46	15.99	34.42	24.07	28.28	20.04	10.53	3.81	0.70	0.14	0.07	0.02	0.01	0.03	0.00
2000	3.09	38.57	21.94	16.43	13.20	13.76	7.21	2.16	0.50	0.06	0.03	0.02	0.00	0.00	0.01
2001	8.49	43.90	22.72	17.00	14.07	9.77	7.59	3.40	0.69	0.11	0.02	0.01	0.00	0.01	0.00
2002	8.30	40.67	24.08	12.50	9.68	6.03	1.97	0.72	0.19	0.04	0.01	0.00	0.00	0.00	0.00
2003	9.94	45.70	26.67	11.69	9.49	6.39	2.27	0.89	0.27	0.04	0.02	0.01	0.01	0.00	0.00
2004	4.15	32.49	32.93	13.89	12.31	9.21	2.68	1.20	0.36	0.08	0.03	0.01	0.00	0.01	0.00
2005	5.07	16.06	16.15	8.56	13.84	10.98	6.85	3.96	0.66	0.12	0.03	0.03	0.01	0.01	0.01
2006	3.75	32.34	17.98	8.50	17.60	13.03	9.11	4.18	1.15	0.18	0.03	0.02	0.01	0.00	0.00
2007	2.21	32.61	14.51	12.81	18.77	9.57	10.35	6.17	2.14	0.34	0.08	0.04	0.02	0.01	0.01
2009	5.49	50.62	19.15	11.40	8.42	9.89	5.40	3.59	1.39	0.25	0.08	0.02	0.01	0.01	0.01
2010	19.54	50.94	39.25	14.81	9.45	6.74	3.77	2.20	1.02	0.18	0.07	0.04	0.02	0.01	0.01
2011	4.81	44.14	42.06	20.97	18.79	10.32	5.50	3.15	1.26	0.33	0.13	0.06	0.02	0.00	0.01
2012	5.16	12.28	9.61	11.27	11.86	10.96	9.03	4.31	1.69	0.29	0.11	0.05	0.02	0.01	0.02
2013	0.10	24.32	12.92	6.74	7.40	10.91	9.09	7.76	3.96	0.50	0.15	0.04	0.02	0.02	0.01
2014	3.10	22.08	30.41	11.39	4.54	7.96	7.38	8.92	6.62	0.97	0.20	0.04	0.02	0.01	0.04
2015	0.50	17.17	13.98	15.14	7.77	6.82	4.18	3.91	3.92	0.65	0.14	0.06	0.01	0.01	0.02

CAN_FALL_3LNO

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1996	0.25	5.27	4.92	3.84	1.41	1.00	0.40	0.08	0.00	0.00	0.00	0.00	0.00	0	0
1997	0.24	1.22	3.33	4.46	3.63	1.88	0.47	0.11	0.04	0.00	0.00	0.00	0.00	0	0
1998	0.06	0.53	1.76	1.86	2.99	4.10	1.50	0.32	0.08	0.01	0.00	0.00	0.00	0	0
1999	0.22	0.04	0.62	0.73	1.04	1.97	1.67	0.39	0.04	0.01	0.00	0.00	0.00	0	0
2000	0.12	1.76	1.24	0.39	0.78	1.21	1.35	0.47	0.04	0.01	0.00	0.00	0.00	0	0
2001	0.49	1.40	0.62	0.68	1.39	0.75	1.15	0.61	0.05	0.01	0.00	0.00	0.00	0	0
2002	0.13	1.28	0.90	1.04	1.01	0.91	0.39	0.17	0.04	0.00	0.00	0.00	0.00	0	0
2003	0.17	1.79	1.07	1.55	1.87	0.91	0.28	0.05	0.02	0.00	0.00	0.00	0.00	0	0
2004	0.06	1.18	1.32	1.56	1.69	1.51	0.39	0.10	0.01	0.00	0.00	0.00	0.00	0	0
2005	0.08	0.60	0.89	0.50	1.76	1.58	1.14	0.56	0.06	0.01	0.00	0.00	0.00	0	0
2006	0.16	0.85	0.49	0.12	0.68	1.33	1.35	0.59	0.13	0.01	0.00	0.00	0.00	0	0
2007	0.09	0.83	0.47	0.27	0.81	0.61	1.24	0.75	0.21	0.02	0.01	0.00	0.00	0	0
2008	0.25	0.95	0.28	0.82	1.13	0.90	1.00	0.76	0.44	0.04	0.00	0.00	0.00	0	0
2009	0.23	2.15	0.24	0.42	0.47	0.88	0.61	0.30	0.14	0.03	0.01	0.00	0.00	0	0
2010	0.44	1.95	0.62	0.86	0.67	0.68	0.67	0.31	0.11	0.02	0.01	0.00	0.00	0	0
2011	0.33	1.30	4.13	1.20	2.02	0.93	0.67	0.32	0.06	0.02	0.00	0.00	0.00	0	0
2012	0.33	0.62	0.20	0.45	1.18	0.93	0.70	0.27	0.08	0.01	0.00	0.00	0.00	0	0
2013	0.08	2.77	1.00	0.37	0.41	1.02	1.06	0.62	0.26	0.01	0.01	0.01	0.01	0	0
2015	0.05	0.78	0.60	0.33	0.31	0.25	0.34	0.17	0.10	0.01	0.00	0.00	0.00	0	0

CAN_SPRN_3LNO

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1996	0.00	1.62	4.24	4.60	2.18	0.83	0.28	0.06	0.00	0.00	0.00	0	0	0	0
1997	0.00	1.16	3.92	5.16	3.23	1.46	0.51	0.10	0.01	0.00	0.00	0	0	0	0
1998	0.00	0.23	0.84	3.89	6.21	4.96	1.24	0.33	0.07	0.01	0.00	0	0	0	0
1999	0.00	0.29	0.55	1.15	1.98	3.39	1.09	0.24	0.05	0.01	0.00	0	0	0	0
2000	0.02	0.79	1.07	1.07	1.51	1.95	2.04	0.56	0.03	0.01	0.00	0	0	0	0
2001	0.00	0.57	0.71	0.74	0.68	0.80	0.72	0.28	0.02	0.00	0.00	0	0	0	0
2002	0.00	0.64	0.57	0.60	0.58	0.61	0.21	0.05	0.01	0.00	0.00	0	0	0	0
2003	0.00	0.93	2.14	1.66	1.57	1.06	0.21	0.05	0.01	0.00	0.00	0	0	0	0
2004	0.00	0.66	0.57	1.18	1.18	1.16	0.26	0.04	0.02	0.00	0.00	0	0	0	0
2005	0.00	0.35	0.31	1.09	0.95	1.37	0.82	0.21	0.03	0.00	0.00	0	0	0	0
2007	0.00	1.60	0.52	0.80	0.40	1.41	1.49	1.12	0.18	0.02	0.00	0	0	0	0
2008	0.00	0.44	0.77	0.96	0.71	1.25	0.75	0.64	0.28	0.02	0.01	0	0	0	0
2009	0.00	0.27	0.22	0.19	0.39	0.45	0.26	0.13	0.07	0.01	0.00	0	0	0	0
2010	0.00	0.77	0.66	0.52	0.40	0.84	1.08	0.35	0.14	0.02	0.01	0	0	0	0
2011	0.00	1.96	1.40	0.92	0.65	0.62	0.29	0.16	0.10	0.01	0.00	0	0	0	0
2012	0.02	0.32	0.80	2.48	1.40	1.16	0.50	0.18	0.06	0.02	0.00	0	0	0	0
2013	0.00	1.28	0.68	0.05	0.38	0.61	0.23	0.11	0.04	0.00	0.00	0	0	0	0
2014	0.00	1.62	1.19	0.32	0.20	0.24	0.24	0.14	0.06	0.01	0.00	0	0	0	0

EU_SPRN_3NO

	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1997	9.92	5.52	3.49	3.81	2.24	1.97	1.22	0.60	0.07	0.05	0.05	0.02	0.01	0.03
1998	1.71	5.24	9.08	8.47	5.06	2.77	1.10	0.66	0.21	0.08	0.03	0.03	0.02	0.03
1999	4.38	4.80	7.21	9.31	6.29	2.92	0.77	0.49	0.23	0.09	0.03	0.05	0.03	0.05
2000	2.92	0.49	0.80	1.39	3.84	4.42	2.56	0.71	0.28	0.08	0.06	0.04	0.05	0.12
2001	8.87	5.90	1.18	1.07	2.84	3.96	1.56	0.22	0.06	0.05	0.04	0.05	0.05	0.06
2002	2.91	0.64	1.02	0.69	1.14	0.92	0.44	0.23	0.02	0.01	0.02	0.02	0.01	0.02
2003	3.56	2.40	1.68	1.91	1.58	0.90	0.78	0.26	0.06	0.04	0.01	0.07	0.01	0.02
2004	1.22	6.96	2.09	2.06	1.24	0.85	0.51	0.21	0.05	0.03	0.01	0.03	0.02	0.02
2005	1.07	0.97	1.81	1.04	1.32	1.44	0.68	0.19	0.08	0.06	0.02	0.03	0.02	0.02
2006	2.31	1.12	0.41	1.55	1.38	0.81	0.52	0.22	0.05	0.03	0.02	0.02	0.00	0.01
2007	1.81	0.64	0.51	0.32	1.48	1.40	1.02	0.29	0.10	0.09	0.03	0.03	0.00	0.02
2008	0.62	0.99	0.90	0.69	0.93	2.70	2.50	0.74	0.40	0.15	0.10	0.03	0.02	0.04
2009	0.70	3.22	2.21	2.61	2.73	4.94	5.67	0.85	0.35	0.19	0.14	0.03	0.02	0.12
2010	0.37	2.21	0.94	0.73	3.42	5.58	5.16	1.23	0.39	0.26	0.24	0.04	0.02	0.05
2011	2.20	1.30	0.48	0.62	0.95	2.01	2.12	0.43	0.22	0.24	0.05	0.06	0.02	0.10
2012	0.08	1.80	1.34	0.44	1.09	1.71	2.00	0.54	0.40	0.34	0.11	0.05	0.06	0.12
2013	0.27	0.45	0.23	0.81	1.17	1.48	1.22	0.33	0.21	0.24	0.13	0.09	0.03	0.09
2014	0.51	1.28	0.26	0.14	0.54	1.65	1.74	0.45	0.21	0.23	0.18	0.11	0.05	0.10
2015	0.93	0.62	0.20	0.21	0.47	1.81	3.38	0.94	0.44	0.35	0.19	0.10	0.03	0.12

EU_SUMR_3L

	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
2006	8.58	3.95	2.30	3.36	11.41	7.15	2.36	0.41	0.07	0.13	0.06	0.01	0.03	0.02
2007	5.56	1.33	2.16	0.82	9.22	8.58	4.16	0.63	0.18	0.15	0.05	0.01	0.01	0.03
2008	3.44	0.61	5.73	1.64	6.61	11.00	7.85	1.54	0.43	0.32	0.16	0.04	0.05	0.16
2009	7.11	1.48	1.16	2.50	7.54	8.20	5.77	1.62	0.37	0.40	0.09	0.06	0.03	0.11
2010	1.28	3.50	2.12	3.32	7.39	8.14	4.53	1.67	0.84	0.53	0.16	0.18	0.17	0.20
2011	4.60	1.57	1.80	1.57	3.54	5.26	2.37	1.46	0.69	0.32	0.33	0.13	0.06	0.11
2012	3.18	2.58	8.65	2.41	4.13	5.66	2.27	0.66	0.40	0.33	0.18	0.10	0.03	0.05
2013	13.05	1.72	1.11	4.00	6.19	6.92	3.30	0.66	0.37	0.30	0.13	0.13	0.09	0.14
2014	8.49	9.98	2.56	1.43	7.33	6.92	5.47	1.83	0.84	0.45	0.33	0.22	0.08	0.20
2015	1.51	4.71	2.58	2.62	2.99	8.86	3.88	2.62	0.62	0.81	0.25	0.27	0.12	0.23

EU_SUMR_3M

	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1995	12.41	2.54	2.23	1.91	2.66	5.10	3.77	2.12	1.31	0.26	0.07	0.02	0.00	0.01
1996	5.84	7.97	2.41	3.04	4.20	5.82	2.49	1.62	0.42	0.09	0.03	0.04	0.00	0.01
1997	3.33	3.78	6.00	6.50	7.11	8.46	4.99	2.15	0.66	0.22	0.03	0.02	0.02	0.02
1998	2.74	2.13	7.68	11.00	12.33	11.30	7.84	2.62	0.75	0.20	0.03	0.01	0.02	0.00
1999	1.06	0.70	3.01	10.47	13.41	12.58	5.55	1.82	0.35	0.10	0.01	0.00	0.00	0.01
2000	3.75	0.29	0.60	2.16	7.09	14.10	5.40	2.32	0.45	0.11	0.05	0.00	0.00	0.00
2001	8.03	1.43	1.81	0.99	2.79	7.79	6.63	3.21	0.18	0.04	0.01	0.00	0.00	0.00
2002	4.08	2.94	2.79	1.67	3.79	5.59	5.73	1.28	0.13	0.06	0.02	0.01	0.00	0.00
2003	2.20	1.00	0.61	1.51	2.48	2.94	1.93	0.47	0.13	0.10	0.02	0.00	0.00	0.00
2004	1.40	2.19	2.92	1.54	6.80	9.16	4.95	1.46	0.73	0.37	0.26	0.16	0.15	0.17
2005	0.36	0.53	2.09	1.73	5.28	6.79	3.42	0.98	0.26	0.41	0.23	0.13	0.06	0.05
2006	0.45	0.26	0.44	0.91	5.85	8.56	4.68	1.39	0.42	0.36	0.30	0.15	0.05	0.04
2007	0.25	0.05	0.39	0.29	3.84	9.09	8.57	2.88	0.72	0.59	0.30	0.17	0.07	0.07
2008	0.13	0.07	0.10	0.16	2.03	9.00	12.53	3.18	1.14	0.87	0.44	0.25	0.13	0.22
2009	0.05	0.01	0.03	0.08	1.13	6.80	11.43	3.54	0.93	1.03	0.36	0.28	0.25	0.24
2010	0.03	0.01	0.02	0.11	2.00	6.01	7.83	2.50	0.98	0.83	0.31	0.17	0.12	0.19
2011	0.00	0.00	0.01	0.09	1.85	6.70	8.49	2.57	1.11	1.22	0.46	0.26	0.22	0.19
2012	0.00	0.01	0.04	0.16	2.42	5.78	5.00	1.92	0.75	0.74	0.48	0.19	0.10	0.27
2013	0.00	0.00	0.01	0.32	2.11	7.03	4.52	1.64	0.53	0.84	0.34	0.29	0.13	0.22
2014	0.02	0.00	0.01	0.16	2.78	8.04	6.87	1.62	0.45	0.64	0.33	0.15	0.19	0.22
2015	0.03	0.01	0.01	0.12	2.54	14.85	14.04	4.61	1.67	1.41	0.78	0.29	0.17	0.41

EU_SUMR_3M_gt700

	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
2004	0.02	0	0.06	0.73	5.99	12.36	9.57	3.15	1.58	0.84	0.61	0.36	0.40	0.49
2005	0.00	0	0.02	0.26	2.22	5.26	4.37	1.70	0.54	0.96	0.57	0.35	0.18	0.15
2006	0.00	0	0.04	0.40	5.61	10.65	7.29	2.56	0.79	0.71	0.63	0.32	0.11	0.14
2007	0.03	0	0.05	0.20	4.60	12.39	13.93	5.50	1.51	1.31	0.72	0.40	0.17	0.21
2008	0.00	0	0.00	0.12	3.05	15.33	24.73	7.09	2.67	2.02	1.05	0.62	0.33	0.64
2009	0.00	0	0.02	0.05	1.83	12.90	25.56	8.64	2.33	2.48	0.88	0.69	0.64	0.67
2010	0.00	0	0.02	0.05	1.83	12.90	25.56	8.64	2.33	2.48	0.88	0.69	0.64	0.67
2011	0.00	0	0.03	0.11	3.33	12.66	18.09	6.15	2.85	3.34	1.29	0.75	0.63	0.53
2012	0.00	0	0.02	0.27	5.09	12.49	11.23	4.76	1.93	1.96	1.27	0.52	0.27	0.74
2013	0.00	0	0.02	0.67	4.62	16.38	11.47	4.40	1.44	2.34	0.95	0.81	0.35	0.63
2014	0.00	0	0.01	0.25	5.51	17.91	16.30	4.06	1.15	1.70	0.91	0.41	0.53	0.60
2015	0.00	0	0.02	0.24	5.69	35.08	35.94	12.28	4.57	3.86	2.17	0.83	0.50	1.19

EU_SUMR_3M_lt700

	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1995	12.41	2.54	2.23	1.91	2.66	5.10	3.77	2.12	1.31	0.26	0.07	0.02	0.00	0.01
1996	5.84	7.97	2.41	3.04	4.20	5.82	2.49	1.62	0.42	0.09	0.03	0.04	0.00	0.01
1997	3.33	3.78	6.00	6.50	7.11	8.46	4.99	2.15	0.66	0.22	0.03	0.02	0.02	0.02
1998	2.74	2.13	7.68	11.00	12.33	11.30	7.84	2.62	0.75	0.20	0.03	0.01	0.02	0.00
1999	1.06	0.70	3.01	10.47	13.41	12.58	5.55	1.82	0.35	0.10	0.01	0.00	0.00	0.01
2000	3.75	0.29	0.60	2.16	7.09	14.10	5.40	2.32	0.45	0.11	0.05	0.00	0.00	0.00
2001	8.03	1.43	1.81	0.99	2.79	7.79	6.63	3.21	0.18	0.04	0.01	0.00	0.00	0.00
2002	4.08	2.94	2.79	1.67	3.79	5.59	5.73	1.28	0.13	0.06	0.02	0.01	0.00	0.00
2003	2.20	1.00	0.61	1.51	2.48	2.94	1.93	0.47	0.13	0.10	0.02	0.00	0.00	0.00
2004	2.19	3.29	4.37	1.97	6.96	7.80	2.54	0.64	0.29	0.13	0.08	0.05	0.01	0.00
2005	0.54	0.81	3.18	2.50	6.89	7.59	2.92	0.61	0.11	0.12	0.06	0.02	0.00	0.00
2006	0.68	0.39	0.65	1.18	5.97	7.46	3.31	0.77	0.22	0.18	0.13	0.06	0.01	0.00
2007	0.37	0.08	0.57	0.34	3.44	7.37	5.76	1.51	0.31	0.21	0.08	0.05	0.01	0.00
2008	0.20	0.10	0.15	0.19	1.50	5.70	6.16	1.13	0.35	0.26	0.12	0.05	0.02	0.01
2009	0.08	0.01	0.04	0.10	0.75	3.61	4.05	0.89	0.19	0.27	0.08	0.06	0.04	0.01
2010	0.05	0.01	0.04	0.06	1.11	3.07	2.94	0.89	0.32	0.17	0.06	0.03	0.01	0.00
2011	0.00	0.00	0.00	0.08	1.08	3.58	3.46	0.68	0.21	0.11	0.02	0.01	0.01	0.01
2012	0.00	0.01	0.05	0.11	1.02	2.27	1.75	0.44	0.14	0.10	0.07	0.02	0.01	0.02
2013	0.01	0.00	0.00	0.14	0.80	2.16	0.89	0.20	0.05	0.05	0.01	0.01	0.01	0.01
2014	0.02	0.00	0.00	0.12	1.35	2.88	1.95	0.35	0.08	0.08	0.03	0.01	0.01	0.01
2015	0.05	0.02	0.00	0.06	0.89	4.28	2.60	0.61	0.15	0.14	0.06	0.01	0.00	0.00

Appendix B: Model description

M1: Stochastic Cohort model with plus group

Process equations

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 with noise models via observation equations. Here we use a stochastic cohort model with a plus group to model the unobserved states:

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

The ages are 1-10+ and years are 1975-2015. $Z_{a,y} = F_{a,y} + M_{a,y}$, where $M_{a,y} = 0.12$ is the base case assumption. The recruitments, $N_{1,1}, \ldots N_{1,Y}$, are treated as uncorrelated lognormal random variables,

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

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

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

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 in process errors were therefore fixed to be near zero, similar to standard SAM, to minimize potential confounding with recruitment.

Catches are modelled using the Baranov catch equation,

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

The process error model is different than Cadigan (2015), where process errors were included in M and affected both the population model and catch equation. Fishing moralities are modelled as a stochastic process similar to the δ process errors, with

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

However, there are no commercial catches at ages 1 and 2 so we fixed F's at zero for these ages. Turbot are rarely reported as catch at age 3 and catches at age 4 tend to be much lower than older ages. Hence, we fixed $\varphi_{F,a}$ 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.

Observation equations

The observation models are similar to the traditional approaches used for NW 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

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

The $-t_{s,y}Z_{a,y}$ term projects beginning-of-year log-abundance to the time of each survey. We use this model for all survey ages and years, including the plus group age for plus group survey indices. The $q_{s,a}$'s are catchability parameters. Survey variances were split out and self-weighted by age groups 1-3, 4-7, and 8-10+. Weighting by survey and age group minimized some large residual patterns observed at younger ages in earlier versions of this model. Similar to Cadigan (2015), we assume indices with a zero value are because of low stock abundance in the survey area and not because the fish were missed by mistake. We assume that these zero's represent stock densities that are below a detection limit which we set at 0.005 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.

We do not freely estimate the $\sigma^2_{s,G(a)}$ error variances, because sometimes 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 $\sigma^2_{s,G(a)}$ to vary only when the data really warrant it. We achieve this goal using random effects. We model

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

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

Total catch and age compositions were treated separately. Total catch was modelled as lognormal, $\log(C_{obs,y}) = \log(C_y) + \varepsilon_{C,y}$, where $\varepsilon_{C,y} \overset{iid}{\sim} N(0, \sigma^2_C)$ [$\sigma^2_C = 0.1$ is the base case assumption], and age compositions were modelled 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 $P_{a,y} = C_{a,y}/C_y$. 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 observed catch at age data,

$$P_{a,y} = \frac{C_{obs,a,y}}{\sum_{a=1}^{A} C_{obs,y,a}}, \;\; a = 1, \ldots, A,$$

and then calculating conditional probabilities

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

the continuation-ratio logit is obtained by

$$X_a = \log\left(\frac{\pi_a}{1-\pi_a}\right), \ \ a = 1, \ldots, A-1.$$

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.

S1: A Quasi-Spatial Model

The proposed base case model (M1) does not fit 3M surveys very well, particularly the long time-series ≤ 700m index. The trends in Greenland halibut stock size in the Flemish Cap (FC) area seem different than for the NL shelf (NS) region, as indicated by the different trends in the 3M ≤ 700m survey compared to surveys in NAFO Divisions 3KLMNO. This suggests that there may be important spatial differences that are not incorporated into M1, potentially decreasing its reliability as an assessment of the stock as a whole. The new model formulation (referred to as S1) attempts to address this issue in a simple way.

The model still treats the stock as a whole in terms of modelling recruitment and mortality rates. In the new formulation the stock is considered to simply have an age-specific spatial distribution for the FC and NS areas that changes smoothly over years. Effectively, this means that an adjustment to catchability parameters is applied separately to the FC and NS areas. Survey indices are related to the total abundance in their respective FC or NS areas. The abundance in the NS area is a fraction d of the total abundance, and d is age (a) and year (y) specific; that is,

$$N_{NS,a,y} = d_{a,y} N_{a,y}$$

and

$$N_{FC,a,y} = (1 - d_{a,y}) N_{a,y}$$

Note that $N_{NS,a,y} + N_{FC,a,y} = N_{a,y}$. The 3M surveys are modelled using the observation equation

$$\log(I_{s\in FC,a,y}) = \log(q_{s,a}) + \log(N_{FC,a,y}) - t_{s,y} + \varepsilon_{s,a,y}$$

and the surveys in NAFO divisions 2J3KLNO are models using

$$\log(I_{s\in NS,a,y}) = \log(q_{s,a}) + \log(N_{NS,a,y}) - t_{s,y} + \varepsilon_{s,a,y}$$

We assume that the $d_{a,y}$'s vary smoothly with age and years which we approximate using a lag 1 autoregressive process in both age and year for the logit of $d_{a,y}$. If $U(x) = \log(x/(1-x))$ denotes the logit function, then

$$Cov\{U(d_{a,y}), U(d_{a-j,y-k})\} = \frac{\sigma_d^2 \varphi_{d,a}^j \varphi_{d,y}^k (\sigma_d^2 \varphi_{d,a}^j \varphi_{d,y}^k)}{(1-\varphi_{d,a}^2)(1-\varphi_{d,y}^2)}, \quad Corr\{U(d_{a,y}), U(d_{a-j,y-k})\} = \varphi_{d,a}^j \varphi_{d,y}^k$$

This is similar to the approach used to account for spatial changes in the over-wintering distribution of Northern cod described in Cadigan (2015).

It is important to note that in this approach the stock dynamics are not modelled separately for the FC and NS areas. In particular, region-specific cohort dynamics are not accounted for. Cohort dynamics are only modelled for the stock as a whole. Fish movements and area-specific variations in stock productivity (i.e recruitment and mortality rates) are accounted for, in composite, by the $d_{a,y}$ effects.

Appendix C: Session info

This report was generated using Rmarkdown.

```
## R version 3.3.2 (2016-10-31)
## Platform: x86_64-w64-mingw32/x64 (64-bit)
## Running under: Windows 7 x64 (build 7601) Service Pack 1
##
## locale:
## [1] LC_COLLATE=English_United States.1252
## [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
##
## attached base packages:
## [1] grid      stats     graphics  grDevices utils     datasets  methods
## [8] base
##
## other attached packages:
##  [1] data.table_1.10.4    RColorBrewer_1.1-2   fields_8.15
##  [4] maps_3.1.1           spam_1.4-0           corrplot_0.77
##  [7] gridExtra_2.2.1      ggthemes_3.4.0       ggplot2_2.2.1
## [10] TMB_1.7.10           RevoUtilsMath_10.0.0
##
## loaded via a namespace (and not attached):
##  [1] Rcpp_0.12.10     knitr_1.15.20    magrittr_1.5     munsell_0.4.3
##  [5] colorspace_1.3-2 lattice_0.20-35  highr_0.6        stringr_1.2.0
##  [9] plyr_1.8.4       tools_3.3.2      gtable_0.2.0     htmltools_0.3.6
## [13] assertthat_0.2.0 yaml_2.1.14      lazyeval_0.2.0   rprojroot_1.2
## [17] digest_0.6.12    tibble_1.3.0     bookdown_0.3.19  Matrix_1.2-10
## [21] reshape2_1.4.2   codetools_0.2-15 evaluate_0.10    rmarkdown_1.5
## [25] labeling_0.3     stringi_1.1.5    RevoUtils_10.0.2 scales_0.4.1
## [29] backports_1.0.5
```

References

Cadigan, Noel G. 2015. "A State-Space Stock Assessment Model for Northern Cod, Including Under-Reported Catches and Variable Natural Mortality Rates." *Canadian Journal of Fisheries and Aquatic Sciences* 73 (2). NRC Research Press: 296–308.

Kristensen, Kasper, Anders Nielsen, Casper W Berg, Hans Skaug, and Bradley M Bell. 2016. "TMB: Automatic Differentiation and Laplace Approximation." *Journal of Statistical Software* 70 (1): 1–21.

Nielsen, Anders, and Casper W Berg. 2014. "Estimation of Time-Varying Selectivity in Stock Assessments Using State-Space Models." *Fisheries Research* 158. Elsevier: 96–101.