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Initial Applications of Statistical Catch-at-Age Assessment Methodology to the Greenland Halibut Resource

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Summary

Statistical Catch-at-Age (SCAA) assessment methodology is applied to the Greenland halibut resource, with full algebraic specifications of the approach provided in an Appendix. Results are reported for a baseline run and eight sensitivities. These are all duplicated given that the estimates of historical biomass are very sensitive to whether or not the commercial catch-at-age data for the first two years are included in fitting the assessment model. In most cases current biomasses are estimated to be above B_{MSY} and increasing, with MSY estimates typically close to 25000t.

Introduction

This document provides baseline Statistical-Catch-at-Age (SCAA) assessments of the Greenland halibut resource based on data provided following NAFO WebEx meetings to discuss appropriate choices. A number of sensitivity results are also reported, related to different choices for biological parameter inputs and fitting to different combinations of survey series.

Data and Methodology

The catch and survey based data (including catch-at-age information) and some biological data are listed in Tables in Appendix A. Table 1 lists the different combinations of survey series considered for the various assessments.

The details of the SCAA assessment methodology are provided in Appendix B.

Results

Historical biomass estimates were found to be very sensitive to which commercial catch-at-age (CAA) data were included in the assessment model fit, so that two baseline assessments were specified for which the historical levels of biomass differed substantially:

a) Baseline StartA:14+ for the plus group, M=0.2, h=0.9,W_{CAA}=0.1 for both survey and commercial CAA. Survey series, see Table 1.
b) Baseline StartB: As baseline StartA but omitting 1975 and 1976 commercial CAA from the fit.

Results are given in Table 2 and Figures 1 and 2.

All sensitivities are carried out for both StartA and StartB baseline specifications:

c) 10+ instead of 14+ for the plus group: Tables 3a and 3b, Figures 3a and 3b
d) M=0.12 instead of 0.2: Tables 3a and 3b, Figures 3a and 3b
e) 10+ for the plus group and M=0.12 instead of 0.2: Tables 3a and 3b, Figures 3a and 3b
f) O1, O2 and O3: different survey series used, see Table 1: Tables 3a and 3b, Figures 4a and 4b and Figures 5-7
g) h=0.5 instead of h=0.9: Tables 3a and 3b, Figures 8a and 8b
h) M increase: M is 0.2 for ages 0 to 10 then increase linearly to 0.5 at age 14+ Tables 3a and 3b, Figures 8a and 8b

Table 4 gives MSY-related estimates for the various assessments, together with Hessian-based 95% CIs. F_{MSY} is in terms of the apical F – the fishing mortality on the age class with a maximum selectivity of 1. The computation of F_{MSY} requires the iterative solution of a non-linear equation; hence no Hessian-based CI is available, and other MSY-related values are conditional on the MLE of F_{MSY}.

Discussion

Some notable features of the results are as follows.

- Unsurprisingly, given the wide differences in historical estimates of abundances for the StartA and StartB assessments, CI estimates for biomasses early in the period of the assessment are much higher than for more recent years
- Estimates of current biomasses are generally somewhat above B_{MSY}, but drop below this for lower steepness values and the O1 and O2 choices of abundance indices.
- There is a lack of fit of the two baseline runs to the EU 3M 0-700m catch-at-age data: there is a clear pattern in the residuals and the models predict too many 8 year olds on average.
- There are no other obvious indications of lack of fit for the baseline runs (we have yet to fully check all the sensitivities).
- Recent spawning and exploitable biomasses are increasing except for the sensitivity with a 10+ plus group and M=0.12 (both StartA and StartB baselines) and for the sensitivity with the O2 choices of abundance indices.
- MSY estimates are typically close to 25000 tons, unless steepness h is set lower than 0.9. However note that the model fit for this lower value of his notably worse in terms of the (penalised) log likelihood (see Tables 3a and 3b).

Table 1: Survey data series used in the various sensitivity runs, showing the period covered by each survey.

Survey	Baseline	O1	O2	O3
Can. Fall 2J3K	1996-2015	1996-2015	1996-2015	1996-2015
Can. Spring 3LNO	1996-2014	1996-2014	1996-2014	1996-2014
EU 3M 0-700m	1995-2003	1995-2015	1995-2015	1995-2003
EU 3M 0-1400m	2004-2015			2004-2015
EU 3m 700-1400m		2004-2015	2004-2015	
EU 3L		2006-2015		
EU 3NO		1997-2015	1997-2015	1997-2015
Can. Fall 3LNO		1996-2015	1996-2015	1996-2015

Table 2: Results of SCAA baseline runs StartA and StartB; values shown in **bold** are fixed on input. Hessian-based CVs are shown in parentheses.

	StartA		StartB	
-lnL:Overall	-104.50		-104.42	
	-lnL:Index	-lnL:CAA	-lnL: index	-lnL: CAA
Can. Fall 2J3K	-7.56	-3.96	-7.73	-3.88
EU 3M 0-700m	-5.09	0.97	-5.11	0.95
EU 3M 0-1400m	-0.25	-4.21	-0.11	-4.20
EU 3m 700-1400m	-	-	-	-
Can. Spring 3LNO	14.62	-1.10	14.66	-1.11
EU 3L	-	-	-	-
EU 3NO	-	-	-	-
Can. Fall 3LNO	-	-	-	-
Commercial		-9.15		-8.91
-lnL:RecRes	-33.10		-33.19	
-lnL:CatchPen	-55.69		-55.80	
h	**0.90**		**0.90**	
M	**0.20**		**0.20**	
ϑ	0.09	(2.93)	0.46	(0.63)
K^{sp}	597	(0.09)	625	(0.14)
$B^{sp}{}_{1975}$	362	(1.49)	46	(2.06)
$B^{sp}{}_{2015}$	131	(0.41)	138	(0.43)
$B^{sp}{}_{2015}/K^{sp}$	0.22	(0.35)	0.22	(0.34)
$B^{sp}{}_{2015}/B^{sp}{}_{1975}$	0.36	(1.52)	3.01	(2.23)
$B^{5\text{-}9}{}_{1975}$	196	(0.60)	167	(0.36)
$B^{5\text{-}9}{}_{2015}$	127	(0.19)	132	(0.21)
$B^{5\text{-}9}{}_{2015}/B^{5\text{-}9}{}_{1975}$	0.65	(0.63)	0.79	(0.47)
	σ index	σ CAA	σ index	σ CAA
Can. Fall 2J3K	0.16	0.15	0.16	0.15
EU 3M 0-700m	0.15	0.23	0.15	0.22
EU 3M 0-1400m	0.24	0.11	0.24	0.11
EU 3m 700-1400m	-	-	-	-
Can. Spring 3LNO	0.55	0.19	0.55	0.19
EU 3L	-	-	-	-
EU 3NO	-	-	-	-
Can. Fall 3LNO	-	-	-	-
Commercial		0.15		0.14

Table 3a: Results of various SCAA variants based on baseline run StartA. Hessian-based CVs are shown in parentheses.

	StartA		10+ plus group		M=0.12		10+ plus group, M=0.12		O1*		O2		O3		h=0.5		M increase (linear from 0.2 age 10 to 0.5 age 14+)	
-lnL:Overall	-104.50		-106.22		-104.32		-107.75		-75.43		-71.08		-92.04		-101.86		-104.72	
	-lnL:Index	-lnL:CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA
Can. Fall 2J3K	-7.56	-3.96	-7.31	-3.66	-7.80	-3.72	-7.83	-4.05	-6.13	-4.53	-6.16	-4.45	-7.42	-4.08	-7.19	-3.33	-7.74	-3.67
EU 3M 0-700m	-5.09	0.97	-5.21	1.13	-5.18	1.05	-6.00	0.63	13.19	-0.04	12.65	-0.18	-5.20	0.55	-2.04	-0.52	-4.72	0.76
EU 3M 0-1400m	-0.25	-4.21	-0.16	-4.22	-0.28	-4.39	-1.24	-3.90	-	-	-	-	-0.43	-4.26	0.27	-4.26	-0.07	-4.06
EU 3m 700-1400m	-	-	-	-	-	-	-	-	1.77	-5.45	2.25	-5.03	-	-	-	-	-	-
Can. Spring 3LNO	14.62	-1.10	14.32	-1.23	14.80	-1.06	13.29	-0.86	14.03	-1.68	13.74	-1.74	14.14	-1.36	14.11	-1.06	14.45	-1.19
EU 3L	-	-	-	-	-	-	-	-	-4.16	-0.71	-	-	-	-	-	-	-	-
EU 3NO	-	-	-	-	-	-	-	-	8.66	1.39	9.00	1.15	6.88	1.91	-	-	-	-
Can. Fall 3LNO	-	-	-	-	-	-	-	-	3.81	-1.34	3.26	-1.18	3.54	-0.93	-	-	-	-
Commercial		-9.15		-10.79		-9.10		-9.61		-8.40		-8.05		-8.67		-8.66		-9.08
-lnL:RecRes	-33.10		-33.17		-33.06		-32.62		-31.18		-31.45		-31.65		-32.80		-33.51	
-lnL:CatchPen	-55.69		-55.93		-55.57		-55.57		-54.67		-54.86		-55.07		-56.38		-55.89	
h	**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**	
M	**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**	
ϑ	0.09	(2.93)	0.06	(28.18)	0.01	(43.29)	0.00	(1000.00)	0.00	-	0.00	(53.91)	0.09	(3.12)	0.19	(0.76)	0.07	(3.94)
K^{sp}	597	(0.09)	544	(0.08)	1210	(0.10)	881	(0.10)	531	-	520	(0.07)	585	(0.08)	2171	(0.46)	366	(0.07)
B^{sp}_{1975}	362	(1.49)	444	(1.67)	1312	(1.50)	1479	(0.61)	919	-	826	(1.38)	386	(1.41)	252	(0.46)	232	(1.35)
B^{sp}_{2015}	131	(0.41)	107	(0.36)	278	(0.41)	109	(0.44)	70	-	59	(0.45)	131	(0.34)	310	(0.28)	109	(0.30)
B^{sp}_{2015}/K^{sp}	0.22	(0.35)	0.20	(0.33)	0.23	(0.35)	0.12	(0.40)	0.13	-	0.11	(0.45)	0.22	(0.29)	0.14	(0.61)	0.30	(0.25)
$B^{sp}_{2015}/B^{sp}_{1975}$	0.36	(1.52)	0.24	(1.68)	0.21	(1.36)	0.07	(0.76)	0.08	-	0.07	(1.31)	0.34	(1.42)	1.23	(0.43)	0.47	(1.37)
$B^{5\text{-}9}_{1975}$	196	(0.60)	174	(0.83)	226	(0.76)	277	(0.61)	350	-	320	(0.71)	203	(0.58)	187	(0.22)	209	(0.55)
$B^{5\text{-}9}_{2015}$	127	(0.19)	109	(0.17)	121	(0.18)	82	(0.15)	98	-	88	(0.16)	118	(0.16)	181	(0.24)	136	(0.17)
$B^{5\text{-}9}_{2015}/B^{5\text{-}9}_{1975}$	0.65	(0.63)	0.63	(0.85)	0.53	(0.74)	0.29	(0.64)	0.28	-	0.27	(0.68)	0.58	(0.61)	0.97	(0.32)	0.65	(0.58)
	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA
Can. Fall 2J3K	0.16	0.15	0.16	0.16	0.16	0.16	0.16	0.15	0.18	0.15	0.17	0.15	0.16	0.15	0.17	0.16	0.16	0.16
EU 3M 0-700m	0.15	0.23	0.15	0.23	0.15	0.23	0.15	0.21	0.45	0.20	0.44	0.20	0.15	0.21	0.19	0.18	0.15	0.22
EU 3M 0-1400m	0.24	0.11	0.24	0.12	0.24	0.11	0.22	0.12	-	-	-	-	0.23	0.11	0.25	0.11	0.24	0.12
EU 3m 700-1400m	-	-	-	-	-	-	-	-	0.28	0.10	0.29	0.10			-	-	-	-
Can. Spring 3LNO	0.55	0.19	0.54	0.19	0.55	0.19	0.51	0.20	0.53	0.18	0.52	0.18	0.53	0.19	0.53	0.19	0.54	0.19
EU 3L	-	-	-	-	-	-	-	-	0.16	0.17	-	-	-	-	-	-	-	-
EU 3NO	-	-	-	-	-	-	-	-	0.38	0.20	0.39	0.20	0.35	0.21	-	-	-	-
Can. Fall 3LNO	-	-	-	-	-	-	-	-	0.30	0.18	0.29	0.18	0.29	0.18	-	-	-	-
Commercial		0.15		0.14		0.15		0.15		0.15		0.15		0.15		0.15		0.15

* Not converged

Table 3b: Results of various SCAA variants based on baseline run StartB. Hessian-based CVs are shown in parentheses.

	StartB		10+ plus group		*M*=0.12		10+ plus group, *M*=0.12		O1*		O2*		O3		*h*=0.5		*M* increase (linear from 0.2 age 10 to 0.5 age 14+)	
-lnL:Overall	-104.42		-106.17		-103.94		-107.89		-75.09		-70.71		-91.85		-101.94		-104.59	
	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA	-lnL: index	-lnL: CAA
Can. Fall 2J3K	-7.73	-3.88	-7.53	-3.51	-7.75	-3.71	-7.96	-4.14	-6.06	-4.53	-6.02	-4.27	-7.47	-4.05	-7.24	-3.32	-7.86	-3.59
EU 3M 0-700m	-5.11	0.95	-5.36	1.15	-5.24	1.07	-6.03	0.51	13.10	-0.06	10.74	-0.99	-5.24	0.55	-2.00	-0.59	-4.82	0.78
EU 3M 0-1400m	-0.11	-4.20	0.02	-4.27	-0.20	-4.36	-1.43	-3.75					-0.40	-4.23	0.30	-4.25	-0.03	-4.05
EU 3m 700-1400m	-	-							1.77	-5.39	3.06	-4.58	-	-				
Can. Spring 3LNO	14.66	-1.11	14.34	-1.25	14.79	-1.08	13.06	-0.80	13.99	-1.70	13.24	-2.06	14.15	-1.37	14.13	-1.10	14.49	-1.19
EU 3L	-	-	-	-	-	-	-	-	-4.10	-0.73	-	-	-	-	-	-	-	-
EU 3NO	-	-	-	-	-	-	-	-	8.69	1.37	10.13	0.78	6.86	1.94	-	-	-	-
Can. Fall 3LNO	-	-	-	-	-	-	-	-	3.76	-1.33	1.62	-1.11	3.58	-0.92	-	-	-	-
Commercial		-8.91		-10.42		-8.77		-9.18		-8.03		-5.83		-8.44		-8.72		-8.86
-lnL:RecRes	-33.19		-33.31		-33.10		-32.63		-31.19		-30.78		-31.69		-32.80		-33.51	
-lnL:CatchPen	-55.80		-56.05		-55.59		-55.54		-54.65		-54.63		-55.13		-56.34		-55.95	
h	**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**		**0.90**	
M	**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**		**0.20**	
ϑ	0.46	(0.63)	0.53	(0.90)	0.25	(1.76)	0.00	(1000.00)	0.16	-	0.02	-	0.37	(1.05)	0.28	(0.53)	0.46	(0.73)
K^{sp}	625	(0.14)	561	(0.12)	1225	(0.11)	860	(0.11)	530	-	486	-	594	(0.10)	2413	(0.57)	373	(0.09)
$B^{sp}{}_{1975}$	46	(2.06)	53	(2.87)	447	(2.32)	2068	(0.68)	455	-	1227	-	91	(2.41)	190	(0.53)	33	(2.10)
$B^{sp}{}_{2015}$	138	(0.43)	108	(0.37)	263	(0.41)	116	(0.47)	66	-	32	-	130	(0.35)	297	(0.28)	112	(0.31)
$B^{sp}{}_{2015}/K^{sp}$	0.22	(0.34)	0.19	(0.32)	0.21	(0.35)	0.13	(0.44)	0.13	-	0.07	-	0.22	(0.30)	0.12	(0.73)	0.30	(0.25)
$B^{sp}{}_{2015}/B^{sp}{}_{1975}$	3.01	(2.23)	2.02	(2.97)	0.59	(2.26)	0.06	(0.71)	0.15	-	0.03	-	1.43	(2.47)	1.56	(0.47)	3.33	(2.18)
$B^{5\text{-}9}{}_{1975}$	167	(0.36)	153	(0.40)	192	(0.66)	388	(0.68)	326	-	505	-	187	(0.46)	206	(0.22)	179	(0.37)
$B^{5\text{-}9}{}_{2015}$	132	(0.21)	110	(0.18)	120	(0.18)	82	(0.16)	96	-	68	-	119	(0.17)	176	(0.24)	138	(0.18)
$B^{5\text{-}9}{}_{2015}/B^{5\text{-}9}{}_{1975}$	0.79	(0.47)	0.72	(0.47)	0.62	(0.67)	0.21	(0.69)	0.29	-	0.14	#DIV/0!	0.64	(0.52)	0.85	(0.32)	0.77	(0.45)
	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA	σ index	σ CAA
Can. Fall 2J3K	0.16	0.15	0.16	0.16	0.16	0.16	0.16	0.15	0.18	0.15	0.18	0.15	0.16	0.15	0.17	0.16	0.16	0.16
EU 3M 0-700m	0.15	0.22	0.15	0.23	0.15	0.23	0.15	0.21	0.45	0.20	0.40	0.19	0.15	0.21	0.19	0.18	0.15	0.22
EU 3M 0-1400m	0.24	0.11	0.24	0.12	0.24	0.11	0.21	0.13	-	-	-	-	0.23	0.11	0.25	0.11	0.24	0.12
EU 3m 700-1400m	-	-	-	-	-	-	-	-	0.28	0.10	0.31	0.11			-	-	-	-
Can. Spring 3LNO	0.55	0.19	0.54	0.19	0.55	0.19	0.50	0.20	0.53	0.18	0.50	0.18	0.53	0.19	0.53	0.19	0.54	0.19
EU 3L	-	-	-	-	-	-	-	-	0.16	0.17	-	-	-	-	-	-	-	-
EU 3NO	-	-	-	-	-	-	-	-	0.38	0.20	0.41	0.20	0.35	0.21	-	-	-	-
Can. Fall 3LNO	-	-	-	-	-	-	-	-	0.29	0.18	0.26	0.18	0.29	0.18	-	-	-	-
Commercial		0.14		0.14		0.15		0.14		0.15		0.16		0.15		0.15		0.14

* Not converged

Table 4: MSY and related quantities for the various SCAA variants based on baseline run StartA (top two rows) and baseline run StartB (bottom two rows).

	StartA	10+ plus group	M=0.12	10+ plus group, M=0.12	O1*	O2	O3	h=0.5	M increase (linear from 0.2 age 10 to 0.5 age 14+)
MSY	26.58 (0.08)	25.47 (0.08)	25.51 (0.08)	22.05 (0.09)	24.46 -	24.41 (0.07)	26.10 (0.07)	43.56 (0.46)	28.23 (0.06)
F_{MSY}	0.60	0.58	0.58	0.60	0.56	0.52	0.62	0.21	0.58
B^{sp}_{MSY}	90.16 (0.25)	88.63 (0.23)	194.57 (0.24)	149.57 (0.18)	80.82 -	79.75 (0.39)	88.17 (0.22)	695.25 (0.51)	54.65 (0.26)
B^{sp}_{MSY}/K^{sp}	0.15 (0.23)	0.16 (0.21)	0.16 (0.24)	0.17 (0.14)	0.15 -	0.15 (0.38)	0.15 (0.21)	0.32 (0.20)	0.15 (0.25)
$B^{sp}_{2015}/B^{sp}_{MSY}$	1.45 (0.43)	1.21 (0.39)	1.43 (0.47)	0.73 (0.37)	0.87 -	0.74 (0.35)	1.48 (0.35)	0.45 (0.67)	1.99 (0.37)
B^{5-9}_{MSY}	110.89 (0.11)	103.39 (0.10)	98.70 (0.12)	84.13 (0.10)	104.70 -	105.59 (0.12)	109.10 (0.10)	377.99 (0.49)	117.15 (0.11)
$B^{5-9}_{2015}/B^{5-9}_{MSY}$	1.14 (0.18)	1.06 (0.17)	1.22 (0.19)	0.97 (0.13)	0.93 -	0.83 (0.15)	1.08 (0.16)	0.48 (0.61)	1.16 (0.18)
	StartB	10+ plus group	M=0.12	10+ plus group, M=0.12	O1*	O2*	O3	h=0.5	M increase (linear from 0.2 age 10 to 0.5 age 14+)
MSY	27.78 (0.12)	26.53 (0.12)	25.86 (0.09)	21.27 (0.10)	24.48 -	24.70 -	26.48 (0.09)	48.49 (0.57)	28.75 (0.08)
F_{MSY}	0.60	0.56	0.58	0.62	0.55	0.39	0.62	0.21	0.58
B^{sp}_{MSY}	94.46 (0.26)	92.55 (0.24)	196.93 (0.25)	143.97 (0.19)	80.70 -	79.13 -	89.44 (0.23)	772.64 (0.61)	55.71 (0.26)
B^{sp}_{MSY}/K^{sp}	0.15 (0.24)	0.16 (0.23)	0.16 (0.24)	0.17 (0.15)	0.15 -	0.16 -	0.15 (0.21)	0.32 (0.19)	0.15 (0.25)
$B^{sp}_{2015}/B^{sp}_{MSY}$	1.46 (0.43)	1.17 (0.39)	1.33 (0.46)	0.80 (0.38)	0.82 -	0.40 -	1.46 (0.35)	0.38 (0.78)	2.00 (0.37)
B^{5-9}_{MSY}	115.79 (0.14)	107.47 (0.12)	100.11 (0.12)	81.55 (0.10)	105.02 -	106.40 -	110.77 (0.11)	420.65 (0.60)	119.30 (0.12)
$B^{5-9}_{2015}/B^{5-9}_{MSY}$	1.14 (0.18)	1.03 (0.17)	1.20 (0.19)	1.01 (0.13)	0.91 -	0.64 -	1.07 (0.16)	0.42 (0.72)	1.16 (0.18)

* Not converged

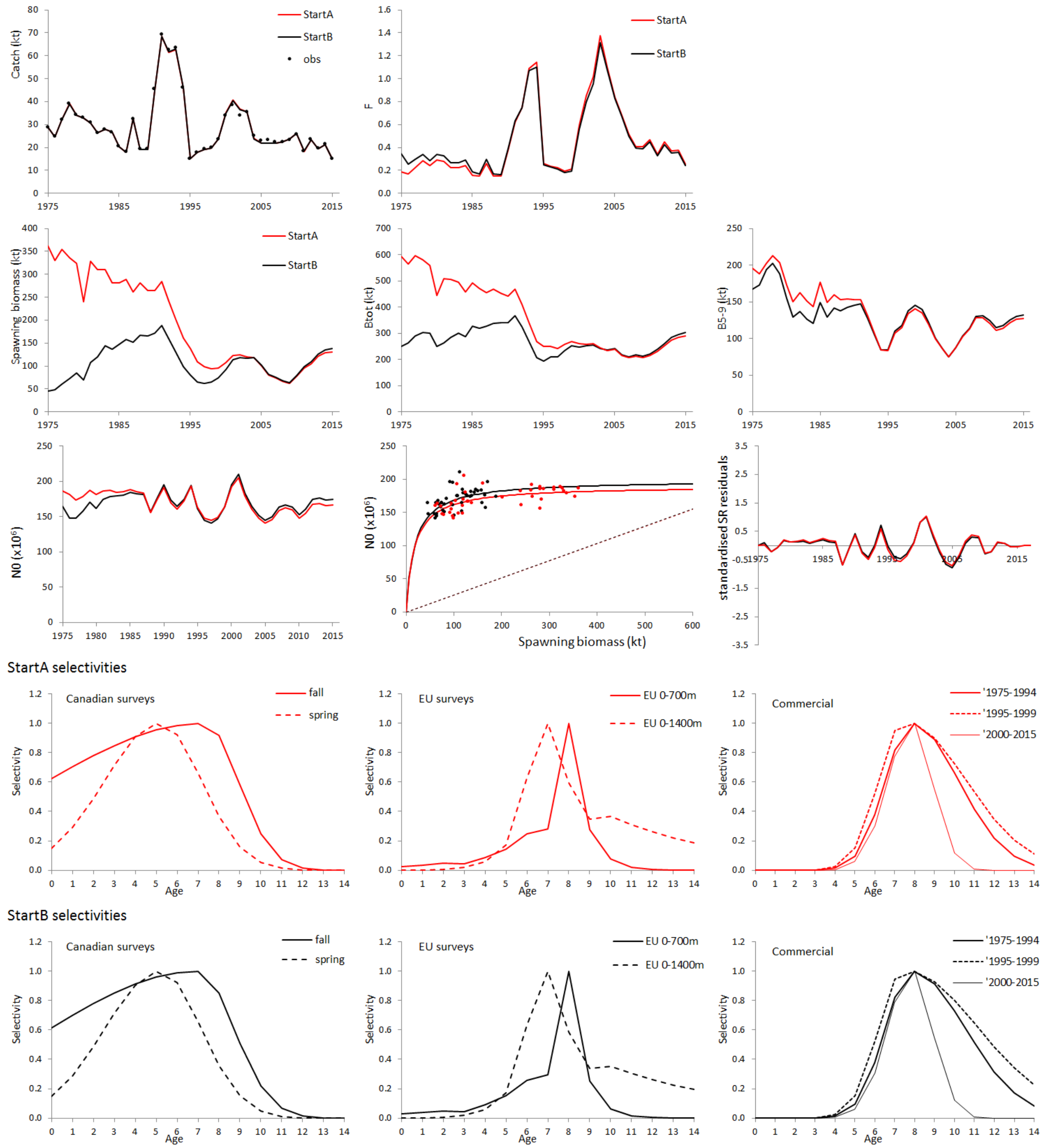

Fig. 1. Results for SCAA baseline variants StartA and StartB.

Fig. 2. Fits to the survey data for SCAA baseline variants StartA and StartB.

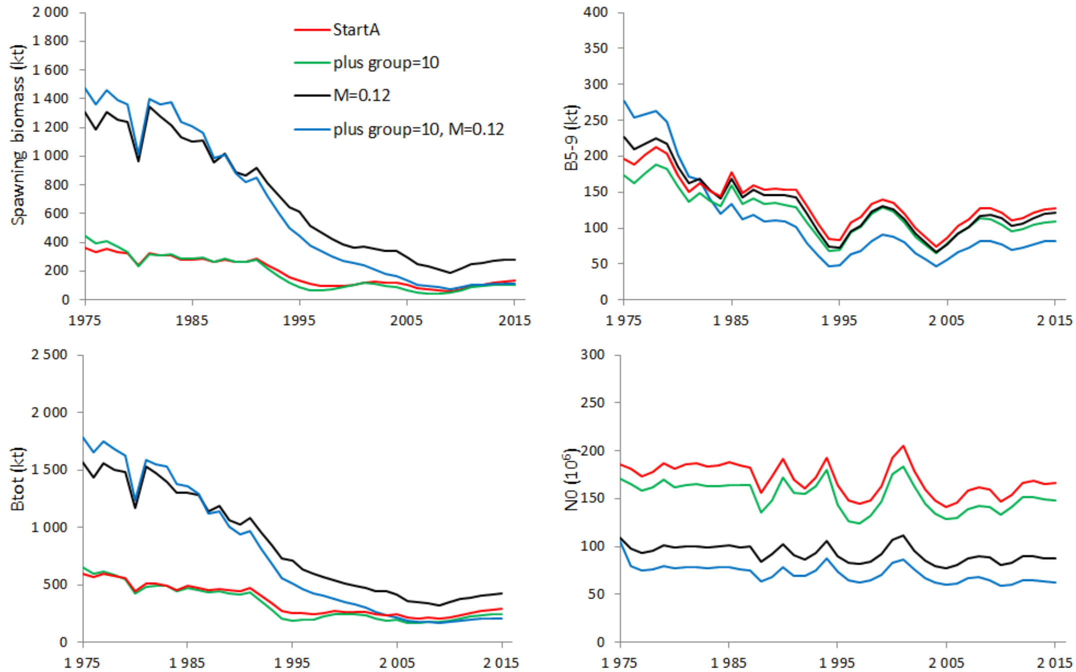

Fig. 3a. Biomass (spawning, 5-9 and total) and recruitment trajectories for baseline run StartA and the three variants: 10 instead of 14 plus-group, M=0.12 instead of M=0.2 and a combination of the two: M=0.12 and 10+.

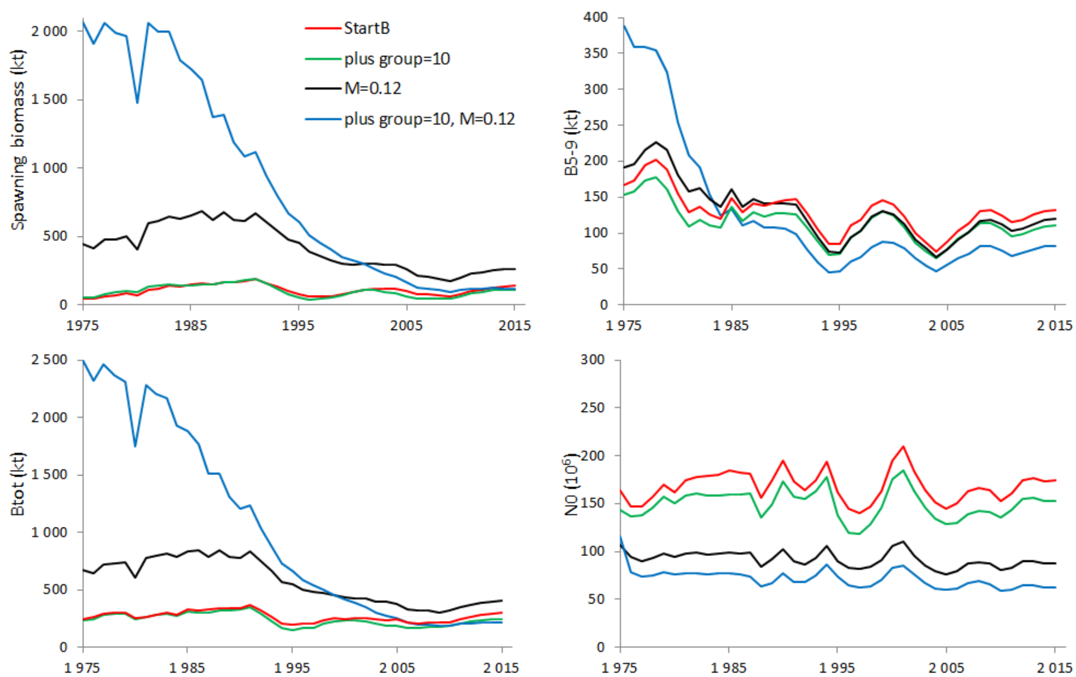

Fig. 3b. Biomass (spawning, 5-9 and total) and recruitment trajectories for baseline run StartB and the three variants: 10 instead of 14 plus-group, M=0.12 instead of M=0.2 and a combination of the two: M=0.12 and 10+.

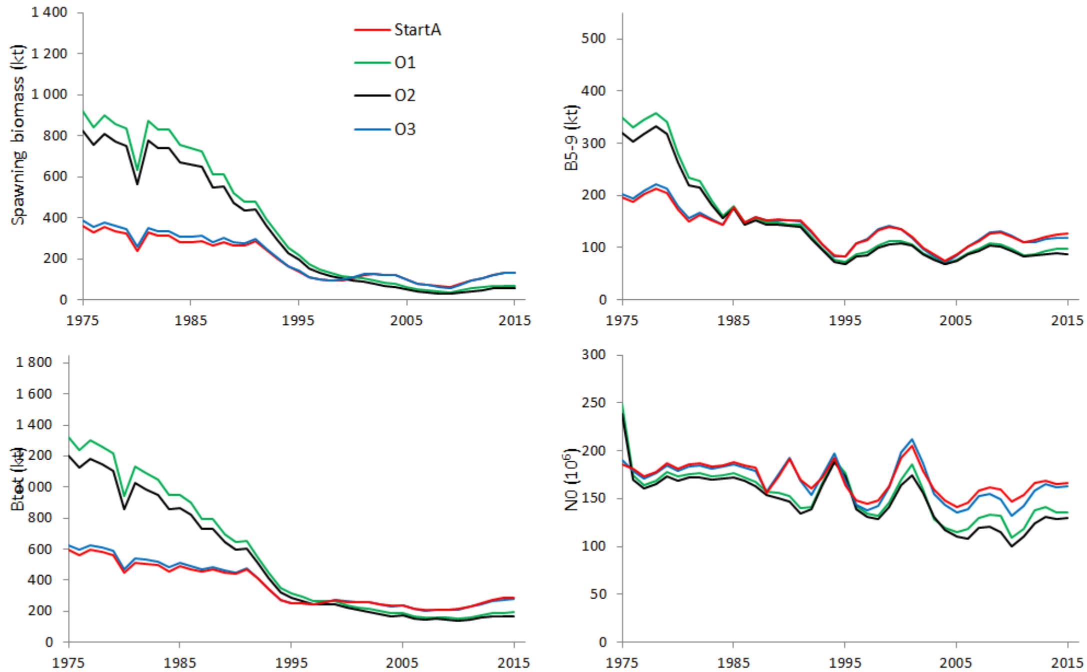

Fig. 4a. Biomass (spawning, 5-9 and total) and recruitment trajectories for baseline run StartA and the three variants based on different survey series.

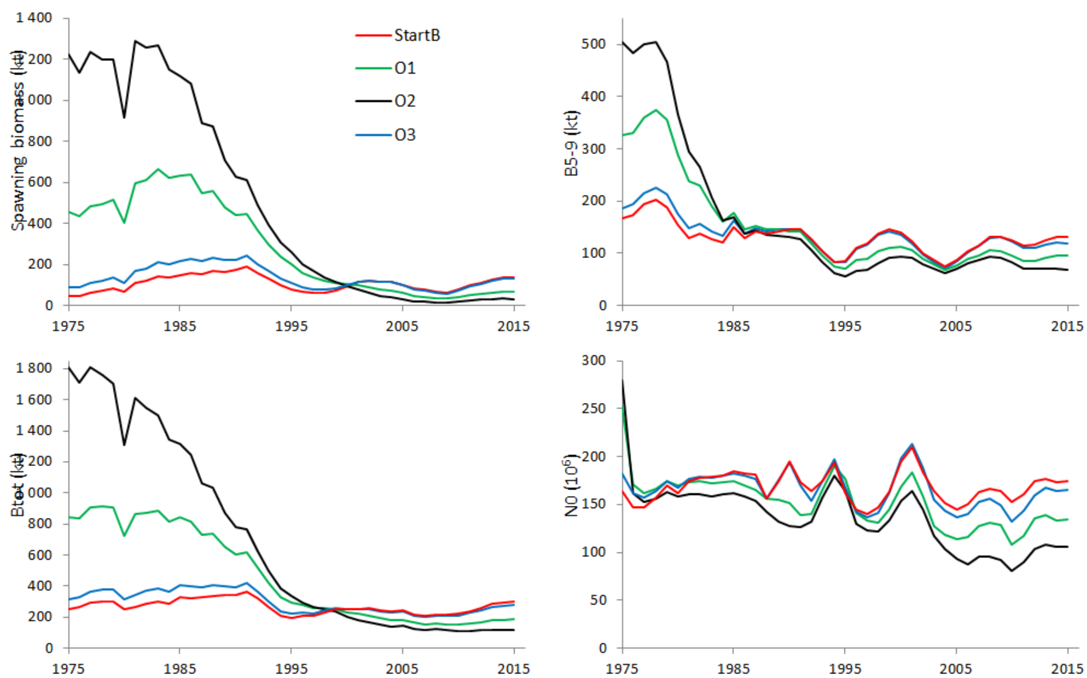

Fig. 4b. Biomass (spawning, 5-9 and total) and recruitment trajectories for baseline run StartB and the three variants based on different survey series.

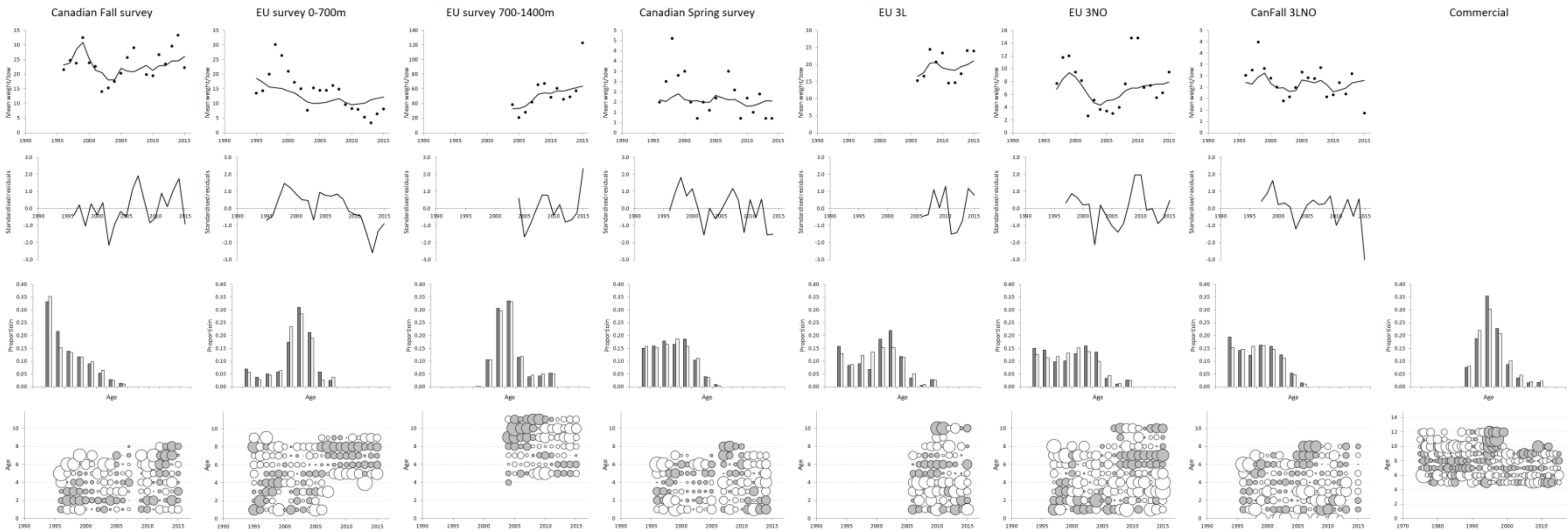

Fig. 5. Fits to the survey biomass indices and catch-at-age data for variant O1 based on StartA baseline run.

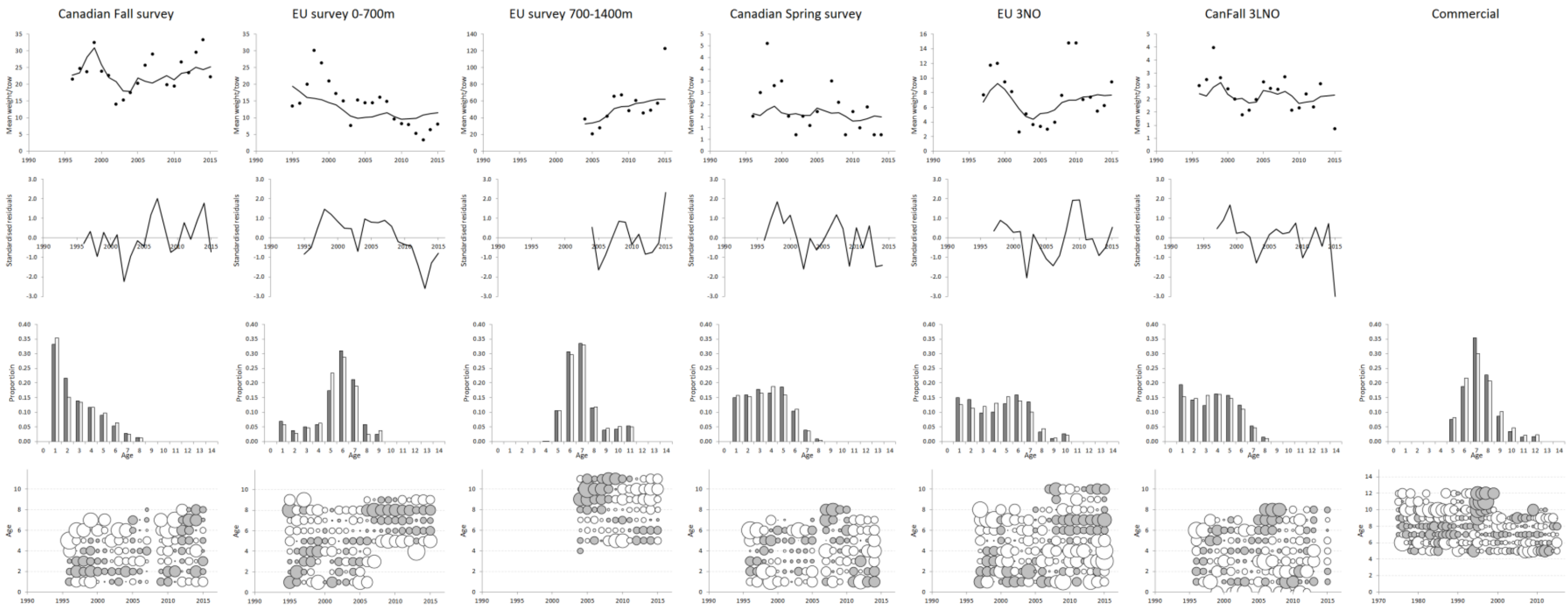

Fig.6. Fits to the survey biomass indices and catch-at-age data for variant O2 based on StartA baseline run.

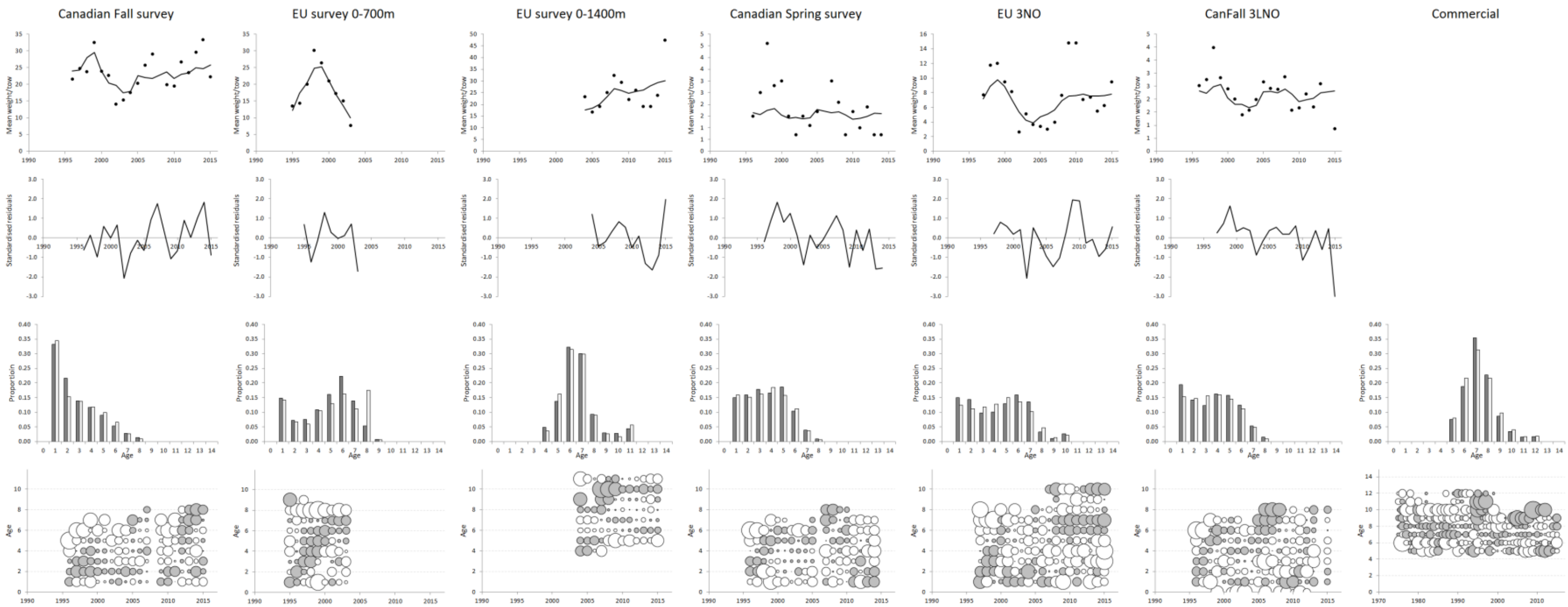

Fig.7. Fits to the survey biomass indices and catch-at-age data for variant O3 based on StartA baseline run.

Fig. 8a. Biomass (spawning, 5-9 and total) and recruitment trajectories for baseline run StartA and two variants.

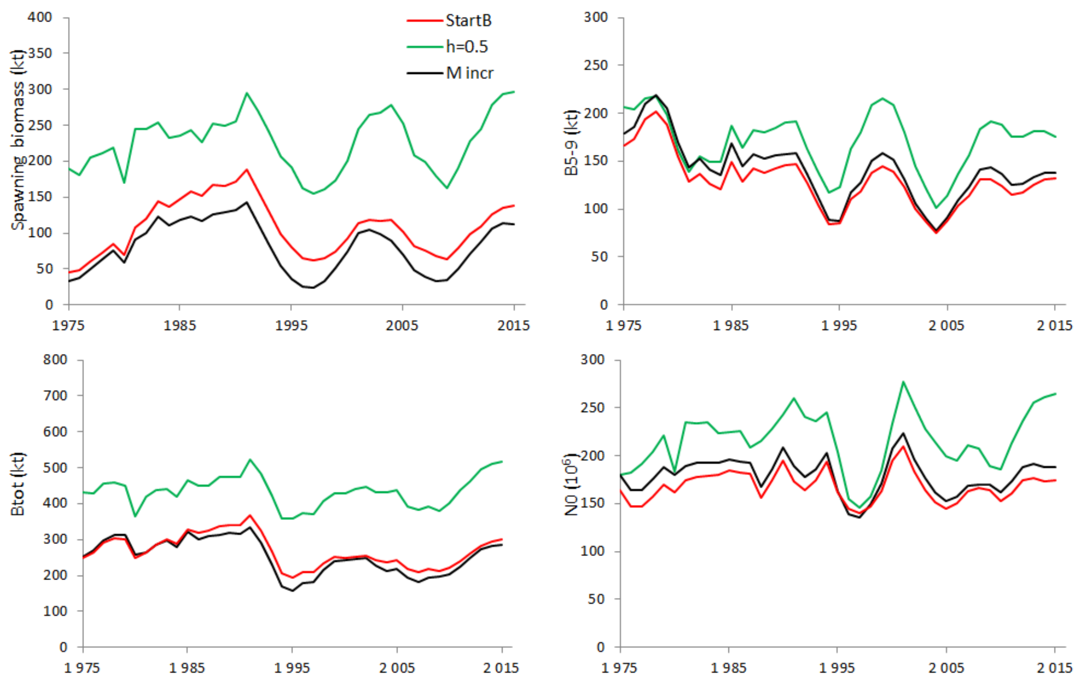

Fig. 8b. Biomass (spawning, 5-9 and total) and recruitment trajectories for baseline run StartB and two variants.

APPENDIX A – Data

Table A1: Landings (tons) for Greenland Halibut in Sub-area 2 and Div. 3KLMNO.

Year	Landings (t)	Year	Landings (t)
1975	28817	1996	17715
1976	24608	1997	19201
1977	32047	1998	19863
1978	39069	1999	23488
1979	34102	2000	33850
1980	32867	2001	38425
1981	30756	2002	33975
1982	26277	2003	35432
1983	27863	2004	25126
1984	26711	2005	22866
1985	20347	2006	23075
1986	17981	2007	22229
1987	32447	2008	22191
1988	19219	2009	23281
1989	19229	2010	25681
1990	45416	2011	18290
1991	69197	2012	23385
1992	62372	2013	19659
1993	63545	2014	21353
1994	46040	2015	15080
1995	15087		

Table A2. Catch at age matrix (000s) for Greenland Halibut in Sub-Area 2 and Divisions 3KLMNO.

Year	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	127	481	1966	4850	5894	5370	1263	401	93	35	15	17
2014	0	0	119	263	1106	3818	5784	7441	1314	302	85	34	11	15
2015	0	0	59	89	429	1237	4037	5546	1571	223	58	22	9	19

Table A3. Catch weights-at-age (kg) matrix for Greenland Halibut in Sub-Area 2 and Divisions 3KLMNO.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
1975	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	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	0.000	0.000	0.125	0.215	0.314	0.541	0.870	1.270	1.755	2.250	2.818	3.610	4.489	5.840
2012	0.000	0.000	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	0.000	0.000	0.140	0.270	0.420	0.630	0.870	1.230	1.820	2.470	3.310	3.850	4.440	5.790
2014	0.000	0.000	0.150	0.240	0.400	0.613	0.890	1.280	1.900	2.550	3.360	3.930	4.600	5.530
2015	0.000	0.000	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 A4: Proportion mature-at-age for Greenland Halibut in Sub-Area 2 and Divisions 3KLMNO.

1	2	3	4	5	6	7	8	9	10	11	12	13	14+
0	0	0	0	0	0	0	0	0	1	1	1	1	1

Table A5: Survey catch-at-age data (numbers) and biomass indices (mean weight (kg) per tow) for Greenland Halibut in Sub-Area 2 and Divisions 3KLMNO.

Canadian Fall 3J3K

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
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	21.60
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	24.80
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	23.80
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	32.50
2000	3.08	38.60	22.09	16.48	13.29	13.90	7.27	2.17	0.50	0.06	0.03	0.02	0.00	0.00	0.01	23.90
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	22.70
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	14.10
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	15.30
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	17.50
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	20.30
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	25.70
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	29.10
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	19.90
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	19.50
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	26.70
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	23.50
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	29.60
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	33.30
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	22.30

Canadian Spring 3LNO

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
1996	0.00	1.62	4.24	4.60	2.18	0.83	0.28	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50
1997	0.00	1.16	3.92	5.16	3.23	1.46	0.51	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	2.50
1998	0.00	0.23	0.84	3.89	6.22	4.96	1.24	0.33	0.07	0.01	0.00	0.00	0.00	0.00	0.00	4.60
1999	0.00	0.29	0.55	1.15	1.98	3.39	1.09	0.24	0.05	0.01	0.00	0.00	0.00	0.00	0.00	2.80
2000	0.02	0.79	1.07	1.07	1.51	1.95	2.04	0.56	0.03	0.01	0.00	0.00	0.00	0.00	0.00	3.00
2001	0.00	0.57	0.71	0.74	0.68	0.80	0.72	0.28	0.02	0.00	0.00	0.00	0.00	0.00	0.00	1.50
2002	0.00	0.64	0.57	0.60	0.58	0.61	0.21	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.70
2003	0.00	0.93	2.14	1.66	1.57	1.06	0.21	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1.50
2004	0.00	0.66	0.57	1.18	1.18	1.16	0.26	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	1.10
2005	0.00	0.35	0.31	1.09	0.95	1.37	0.82	0.21	0.03	0.00	0.00	0.00	0.00	0.00	0.00	1.70
2007	0.00	1.60	0.52	0.80	0.40	1.41	1.49	1.12	0.18	0.02	0.00	0.00	0.00	0.00	0.00	3.00
2008	0.00	0.44	0.77	0.96	0.71	1.25	0.75	0.64	0.28	0.02	0.01	0.00	0.00	0.00	0.00	2.10
2009	0.00	0.27	0.22	0.19	0.39	0.45	0.26	0.13	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.70
2010	0.00	0.77	0.66	0.52	0.40	0.84	1.08	0.35	0.14	0.02	0.01	0.00	0.00	0.00	0.00	1.70
2011	0.00	1.96	1.40	0.92	0.65	0.62	0.29	0.16	0.10	0.01	0.00	0.00	0.00	0.00	0.00	1.00
2012	0.02	0.32	0.80	2.48	1.40	1.16	0.50	0.18	0.06	0.02	0.00	0.00	0.00	0.00	0.00	1.90
2013	0.00	1.28	0.68	0.05	0.38	0.61	0.23	0.11	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.70
2014	0.00	1.62	1.19	0.32	0.20	0.24	0.24	0.14	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.70

Canadian Fall 3LNO

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
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	0.00	0.00	2.52
1997	0.24	1.22	3.33	4.46	3.63	1.88	0.48	0.11	0.04	0.00	0.00	0.00	0.00	0.00	0.00	2.76
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	0.00	0.00	3.98
1999	0.22	0.04	0.62	0.73	1.04	1.97	1.67	0.39	0.04	0.01	0.01	0.00	0.00	0.00	0.00	2.82
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	0.00	0.00	2.39
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	0.00	0.00	2.01
2002	0.13	1.28	0.90	1.04	1.01	0.91	0.39	0.17	0.04	0.01	0.00	0.00	0.00	0.00	0.00	1.40
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	0.00	0.00	1.59
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	0.00	0.00	1.99
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	0.00	0.00	2.67
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	0.00	0.00	2.42
2007	0.10	0.83	0.47	0.27	0.81	0.61	1.24	0.75	0.21	0.02	0.01	0.00	0.00	0.00	0.00	2.38
2008	0.26	0.95	0.28	0.82	1.13	0.90	1.00	0.76	0.44	0.04	0.00	0.00	0.00	0.00	0.00	2.87
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	0.00	0.00	1.58
2010	0.44	1.95	0.62	0.86	0.68	0.68	0.67	0.31	0.11	0.02	0.01	0.00	0.00	0.00	0.00	1.66
2011	0.33	1.30	4.13	1.20	2.02	0.93	0.67	0.32	0.06	0.02	0.01	0.00	0.00	0.00	0.00	2.21
2012	0.33	0.62	0.20	0.45	1.19	0.93	0.70	0.27	0.08	0.01	0.00	0.00	0.00	0.00	0.00	1.71
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	0.00	0.00	2.59
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	0.00	0.00	0.87

Table A5: continued

EU 3M 0-700m

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
1995	0.00	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	13.52
1996	0.00	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	14.42
1997	0.00	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	20.01
1998	0.00	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	30.13
1999	0.00	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	26.37
2000	0.00	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	21.08
2001	0.00	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	17.25
2002	0.00	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	15.05
2003	0.00	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	7.73
2004	0.00	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	15.28
2005	0.00	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	14.55
2006	0.00	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	14.56
2007	0.00	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	16.22
2008	0.00	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	14.91
2009	0.00	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	0.02	9.67
2010	0.00	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	8.28
2011	0.00	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	8.05
2012	0.00	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	5.34
2013	0.00	0.01	0.00	0.01	0.14	0.80	2.16	0.89	0.20	0.05	0.06	0.02	0.01	0.01	0.01	3.48
2014	0.00	0.03	0.00	0.00	0.12	1.35	2.88	1.95	0.35	0.08	0.08	0.03	0.01	0.02	0.01	6.43
2015	0.00	0.05	0.02	0.00	0.06	0.89	4.28	2.60	0.61	0.15	0.14	0.06	0.02	0.00	0.00	8.18

EU 3M 0-1400m

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
2004	0.00	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	23.33
2005	0.00	0.36	0.53	2.09	1.73	5.28	6.79	3.42	0.99	0.26	0.41	0.23	0.13	0.06	0.05	16.71
2006	0.00	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	19.17
2007	0.00	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	25.10
2008	0.00	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	32.35
2009	0.00	0.05	0.01	0.03	0.08	1.13	6.80	11.43	3.55	0.93	1.03	0.36	0.28	0.25	0.24	29.44
2010	0.00	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	22.13
2011	0.00	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	26.15
2012	0.00	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	19.20
2013	0.00	0.01	0.00	0.01	0.32	2.11	7.03	4.53	1.64	0.53	0.84	0.34	0.29	0.13	0.22	19.11
2014	0.00	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	23.92
2015	0.00	0.03	0.01	0.01	0.12	2.54	14.85	14.04	4.62	1.67	1.41	0.78	0.29	0.17	0.41	47.52

EU 3M 700-1400m

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
2004	0.00	0.02	0.00	0.06	0.73	5.99	12.36	9.57	3.15	1.59	0.84	0.61	0.36	0.40	0.49	38.72
2005	0.00	0.00	0.00	0.02	0.26	2.22	5.26	4.37	1.70	0.55	0.96	0.57	0.35	0.18	0.16	20.85
2006	0.00	0.00	0.00	0.04	0.40	5.61	10.65	7.29	2.56	0.79	0.71	0.63	0.32	0.11	0.14	28.00
2007	0.00	0.03	0.00	0.05	0.20	4.60	12.39	13.93	5.51	1.51	1.31	0.72	0.40	0.17	0.21	42.10
2008	0.00	0.00	0.00	0.00	0.12	3.05	15.33	24.73	7.09	2.67	2.02	1.05	0.62	0.33	0.64	65.72
2009	0.00	0.00	0.00	0.02	0.05	1.83	12.90	25.56	8.64	2.33	2.48	0.88	0.69	0.64	0.67	67.28
2010	0.00	0.00	0.00	0.02	0.05	1.83	12.90	25.56	8.64	2.33	2.48	0.88	0.69	0.64	0.67	48.64
2011	0.00	0.00	0.00	0.03	0.11	3.33	12.66	18.09	6.15	2.85	3.34	1.29	0.75	0.63	0.53	60.79
2012	0.00	0.00	0.00	0.02	0.27	5.09	12.49	11.23	4.76	1.93	1.96	1.27	0.52	0.27	0.74	45.73
2013	0.00	0.00	0.00	0.02	0.67	4.62	16.38	11.47	4.40	1.44	2.34	0.95	0.81	0.35	0.63	49.00
2014	0.00	0.00	0.00	0.01	0.25	5.51	17.91	16.30	4.06	1.15	1.70	0.91	0.41	0.53	0.60	57.41
2015	0.00	0.00	0.00	0.02	0.24	5.69	35.08	35.94	12.28	4.57	3.86	2.17	0.83	0.50	1.19	122.81

Table A5: continued

EU 3L

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
2006	0.00	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	15.32
2007	0.00	5.56	1.33	2.16	0.82	9.22	8.58	4.16	0.63	0.18	0.15	0.06	0.01	0.01	0.03	16.64
2008	0.00	3.44	0.62	5.73	1.64	6.61	11.00	7.85	1.54	0.43	0.32	0.17	0.04	0.05	0.16	24.40
2009	0.00	7.11	1.48	1.16	2.50	7.54	8.20	5.77	1.63	0.37	0.40	0.09	0.07	0.03	0.11	20.75
2010	0.00	1.29	3.50	2.12	3.32	7.39	8.14	4.54	1.67	0.84	0.53	0.16	0.18	0.17	0.20	23.41
2011	0.00	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	14.61
2012	0.00	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	0.06	14.67
2013	0.00	13.05	1.72	1.11	4.00	6.19	6.92	3.30	0.66	0.37	0.31	0.13	0.13	0.09	0.14	17.31
2014	0.00	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	24.09
2015	0.00	1.51	4.71	2.58	2.62	2.99	8.86	3.89	2.62	0.62	0.81	0.25	0.27	0.12	0.23	23.90

EU 3NO

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14+	Mean weight/tow
1997	0.00	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	7.73
1998	0.00	1.71	5.24	9.09	8.47	5.06	2.77	1.10	0.66	0.21	0.08	0.03	0.03	0.02	0.03	11.73
1999	0.15	4.38	4.81	7.21	9.31	6.29	2.92	0.78	0.49	0.23	0.09	0.03	0.05	0.03	0.05	12.00
2000	0.00	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	9.48
2001	0.00	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	8.17
2002	0.00	2.91	0.64	1.02	0.70	1.14	0.92	0.44	0.23	0.02	0.01	0.02	0.02	0.01	0.02	2.64
2003	0.00	3.56	2.40	1.69	1.91	1.58	0.90	0.78	0.26	0.06	0.04	0.01	0.07	0.01	0.02	5.10
2004	0.00	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	3.68
2005	0.00	1.07	0.97	1.81	1.04	1.32	1.44	0.68	0.19	0.08	0.06	0.03	0.03	0.02	0.02	3.39
2006	0.00	2.31	1.12	0.41	1.55	1.38	0.82	0.52	0.23	0.05	0.03	0.02	0.02	0.01	0.01	3.03
2007	0.00	1.81	0.65	0.51	0.32	1.48	1.40	1.02	0.29	0.10	0.09	0.03	0.03	0.00	0.02	3.98
2008	0.00	0.62	0.99	0.90	0.69	0.94	2.70	2.50	0.74	0.40	0.15	0.10	0.03	0.02	0.04	7.66
2009	0.00	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	14.78
2010	0.00	0.37	2.21	0.94	0.73	3.42	5.58	5.16	1.24	0.39	0.26	0.24	0.04	0.02	0.05	14.80
2011	0.00	2.20	1.30	0.48	0.62	0.95	2.01	2.12	0.43	0.23	0.24	0.05	0.06	0.02	0.10	7.09
2012	0.00	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	7.37
2013	0.00	0.27	0.45	0.23	0.81	1.18	1.48	1.22	0.33	0.21	0.24	0.13	0.09	0.03	0.09	5.46
2014	0.00	0.51	1.28	0.26	0.15	0.54	1.65	1.75	0.45	0.21	0.23	0.18	0.11	0.05	0.10	6.24
2015	0.00	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	9.49

Appendix B

Algebraic details of the Statistical Catch-at-Age Model

The text following sets out the equations and other general specifications of the Statistical Catch-at-Age (SCAA) assessment model applied to Greenland halibut, followed by details of the contributions to the (penalised) log-likelihood function from the different sources of data available and assumptions concerning the stock-recruitment relationship. Quasi-Newton minimization is applied to minimize the total negative log-likelihood function to estimate parameter values (the package AD Model Builder™, Otter Research, Ltd is used for this purpose).

Where options are provided under a particular section, the section concludes with a statement in **bold** as to which option was selected for the baseline run selected.

B.1. Population dynamics

B.1.1 Numbers-at-age

The resource dynamics are modelled by the following set of population dynamics equations:

$$N_{y+1,0} = R_{y+1} \qquad \text{(B.1)}$$

$$N_{y+1,a+1} = N_{y,a}e^{-Z_{y,a}} \quad \text{for } 0 \le a \le m-2 \qquad \text{(B.2)}$$

$$N_{y+1,m} = N_{y,m-1}e^{-Z_{y,m-1}} + N_{y,m}e^{-Z_{y,m}} \qquad \text{(B.3)}$$

where

$N_{y,a}$ is the number of fish of age *a* at the start of year *y*,

R_y is the recruitment (number of 0-year-old fish) at the start of year *y*,

m is the maximum age considered (taken to be a plus-group).

$Z_{y,a} = F_y S_{y,a} + M_a$ is the total mortality in year *y* on fish of age *a*, where

M_a denotes the natural mortality rate for fish of age *a*,

F_y is the fishing mortality of a fully selected age class in year *y*, and

$S_{y,a}$ is the commercial selectivity at age *a* for year *y*.

B.1.2. Recruitment

The number of recruits (i.e. new 0-year olds) at the start of year *y* is assumed to be related to the spawning stock size (i.e. the biomass of mature fish) by Beverton-Holt stock-recruitment relationship, allowing for annual fluctuation about the deterministic relationship.

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{\left(\varphi_y - (\sigma_R)^2/2\right)} \qquad \text{(B.4)}$$

where

α and β are spawning biomass-recruitment relationship parameters,

φ_y reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation σ_R (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process.

B_y^{sp} is the spawning biomass at the start of year *y*, computed as:

$$B_y^{sp} = \sum_{a=1}^{m} f_a\, w_{y,a}^{strt} N_{y,a} \qquad \text{(B.5)}$$

where

$w_{y,a}^{strt}$ is the mass of fish of age *a* during spawning, and

f_a is the proportion of fish of age *a* that are mature.

In order to work with estimable parameters that are more biologically meaningful, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation (virgin) equilibrium spawning biomass B_0 and the steepness, *h*, of the stock-recruitment relationship, which is the proportion of the virgin recruitment R_0 that is realised at a spawning biomass level of 20% of the virgin spawning biomass:

$$\alpha = \frac{4hR_0}{5h-1} \quad \text{(B.6)}$$

and

$$\beta = \frac{B_0(1-h)}{5h-1} \quad \text{(B.7)}$$

where

$$R_0 = B_0 \Big/ \left[\sum_{a=1}^{m-1} f_a w_{y_0,a}^{strt} exp\left(-\sum_{a'=0}^{a-1} M_{a'}\right) + f_m w_{y_0,m}^{strt} \frac{exp\left(-\sum_{a'=0}^{m-1} M_{a'}\right)}{1-exp(-M_m)} \right] \quad \text{(B.8)}$$

For baseline run, *h* is fixed to 0.9 and σ_R=0.2.

B.1.3. Total catch and catches-at-age

The total catch by mass in year *y* is given by:

$$C_y = \sum_{a=0}^{m} w_{y,a}^{mid} C_{y,a} = \sum_{a=0}^{m} w_{y,a}^{mid} N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \quad \text{(B.9)}$$

where

$w_{y,a}^{mid}$ denotes the mass of fish of age *a* landed in year *y*,

$C_{y,a}$ is the catch-at-age, i.e. the number of fish of age *a*, caught in year *y*.

B.1.4. Initial conditions

As the first year for which data are available for the Greenland halibut stock considered clearly does not correspond to the first year of (appreciable) exploitation, one cannot necessarily make the conventional assumption in the application of SCAA's that this initial year reflects a population (and its age-structure) at pre-exploitation equilibrium. For the first year (y_0) considered in the model therefore, the starting numbers-at-age are estimated directly for ages 0 to a_m, and an average fishing mortality is applied for ages a_m +1 to *m*:

$$N_{y_0,a} = \begin{cases} \text{estimated} & \text{for } 0 \le a \le a_m \\ N_{y_0,a-1} e^{-M_{a-1}} \left(1 - \vartheta S_{y_0,a-1}\right) & \text{for } a_m < a < m \\ N_{y_0,m-1} e^{-M_{m-1}} \left(1 - \vartheta S_{y_0,m-1}\right) / \left(1 - e^{-M_m}\left(1 - \vartheta S_{y_0,m}\right)\right) & \text{for } a = m \end{cases} \quad \text{(B.10)}$$

where ϑ characterises the average fishing proportion over the years immediately preceding y_0.

For baseline run, ϑ is estimated directly in the model fitting procedure and $a_m = 5$.

B.2. The (penalised) likelihood function

The model can be fit to (a subset of) survey biomass indices, and commercial and survey catch-at-age and catch-at-age data to estimate model parameters (which may include residuals about the stock-recruitment function, facilitated through the incorporation of a penalty function described below). Contributions by each of these to the negative of the (penalised) log-likelihood ($-\ell nL$) are as follows.

B.2.1. Survey biomass data

The likelihood is calculated assuming that a survey biomass index is lognormally distributed about its expected value:

$$I_y^i = \hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i = ln\left(I_y^i\right) - ln\left(\hat{I}_y^i\right) \quad \text{(B.11)}$$

where

I_y^i is the survey index for survey *i* in year *y*,
$\hat{I}_y^i = \hat{q}^i \hat{B}_y^i$ is the corresponding model estimate, where
$\hat{q}^i$ is the constant of proportionality (catchability) for the survey biomass series *i*, and
ε_y^i from $N\left(0, \left(\sigma_y^i\right)^2\right)$.

The model estimate of survey biomass index is computed as:

$$B_y^i = \sum_{a=0}^{m} w_{y,a}^i S_a^i N_{y,a} e^{-Z_{y,a} T^i/12} \tag{B.12}$$

where
S_a^i is the survey selectivity for age *a*, which is taken to be year-independent.
T^i is the month in which the survey is taking place (see Table B1), and
$w_{y,a}^i$ denotes the mass of fish of age *a* from survey *i* in year *y*.

The contribution of the survey biomass data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-lnL^{\text{survey}} = \sum_i \sum_y \left\{ ln\left(\sqrt{\left(\sigma_y^i\right)^2 + \left(\sigma_{Add}^i\right)^2}\right) + \frac{\left(\varepsilon_y^i\right)^2}{2\left(\left(\sigma_y^i\right)^2 + \left(\sigma_{Add}^i\right)^2\right)} \right\} \tag{B.13}$$

where
σ_y^i is the standard deviation of the residuals for the logarithm of index *i* in year *y*, and
σ_{Add}^i is the square root of the additional variance for survey biomass series *i*, which is estimated in the model fitting procedure, with an upper bound of 0.5.

In this case, however, external estimates of σ_y^i (from survey sampling variance) are not available. So homoscedasticity of residuals is assumed, so that estimation of additional variance falls away and $\sigma_y^i = \sigma^i$ is estimated in the fitting procedure by its maximum likelihood value (with a minimum estimate of 0.15 imposed to prevent overweighting through overfitting):

$$\sigma^i = \sqrt{\frac{1}{n^i} \sum_y \left(lnI_y^i - ln\left(q^i B_y^i\right)\right)^2} \tag{B.14}$$

The constant of proportionality q^i for survey biomass index *i* is estimated by its maximum likelihood value:

$$lnq^i = \frac{1}{n^i} \sum_y \left(lnI_y^i - lnB_y^i\right) \tag{B.15}$$

B.2.3. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of an "adjusted" lognormal error distribution is given by:

$$-lnL^{CAA} = w^{CAA} \sum_y \sum_a \left[ln\left(\frac{\sigma_a^{com}}{\sqrt{p_{y,a}}}\right) + p_{y,a}\left(lnp_{y,a} - ln\hat{p}_{y,a}\right)^2 / 2(\sigma_a^{com})^2 \right] \tag{B.16}$$

where
$p_{y,a} = C_{y,a} / \sum_{a'} C_{y,a'}$ is the observed proportion of fish caught in year *y* that are of age *a*,
$\hat{p}_{y,a} = \hat{C}_{y,a} / \sum_{a'} \hat{C}_{y,a'}$ is the model-predicted proportion of fish caught in year *y* that are of age *a*,
with

$$\hat{C}_{y,a} = N_{y,a} S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B.17}$$

and
σ_a^{com} is the standard deviation associated with the catch-at-age data, which is estimated in the fitting procedure by:

$$\hat{\sigma}_a^{com} = \sqrt{\sum_y p_{y,a}\left(lnp_{y,a} - ln\hat{p}_{y,a}\right)^2 / \sum_y 1} \tag{B.18}$$

The w^{CAA} weighting factor in equation B.16 may be set to a value less than 1 to downweight the contribution of the catch-at-lage data (which tend to be positively correlated between adjacent age groups) to the overall negative log-likelihood compared to that of the survey biomass data.

Commercial catches-at-age are incorporated in the likelihood function using equation (B.16), for which the summation over age a is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group).

For the baseline run, $\boldsymbol{w^{CAA} = 0.1}$.

B.2.4. Survey catches-at-age

The survey catches-at-age are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age, assuming an "adjusted" lognormal error distribution (equation (B.16)) where:

$p^i_{y,a} = C^i_{y,a} / \sum_{a'} C^i_{y,a'}$ is the observed proportion of fish of age a in year y for survey i,

$\hat{p}^i_{y,a}$ is the expected proportion of fish of age a in year y in the survey i, given by:

$$\hat{p}^i_{y,a} = S^i_a N_{y,a} e^{-Z_{y,a} T^i/12} / \sum_{a'} S^i_{a'} N_{y,a'} e^{-Z_{y,a'} T^i/12} \quad \text{(B.19)}$$

B.2.5. Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be lognormally distributed. Thus, the contribution of the recruitment residuals to the negative of the (now penalised) log-likelihood function is given by:

$$-lnL^{pen} = \sum_{y=y_1}^{y_2} \left(\varphi_y^2 / 2\sigma_R^2\right) \quad \text{(B.20)}$$

where

φ_y from $N(0, \sigma_R^2)$,

σ_R is the standard deviation of the log-residuals, which is input.

B.2.7. Catches

$$-lnL^{Catch} = \sum_y \frac{lnC_y - ln\hat{C}_y}{2\sigma_C^2} \quad \text{(B.21)}$$

where

C_y is the observed catch in year y,

$\hat{C}_y$ is the predicted catch in year y (equation B.9), and

$\sigma_C = 0.1$ is the input CV input.

B.3. Estimation of precision

Where quoted, CV's or 95% probability interval estimates are based on the Hessian.

B.4. Model parameters

B.4.1. Fishing selectivity-at-age:

For the surveys, the fishing selectivities are either estimated separately for ages a_1 to age a_2 or are modelled by a double normal shape:

$$S_a = \begin{cases} exp\left(-\frac{(a-a_{max})^2}{2\sigma_{left}^2}\right) & \text{for } a \le a_{max} \\ exp\left(-\frac{(a-a_{max})^2}{2\sigma_{right}^2}\right) & \text{for } a > a_{max} \end{cases} \quad \text{(B.22)}$$

where σ_{left}, σ_{right} and a_{max} are estimable parameters.

B.4.2. Other parameters

b: Model parameters

Stock-recruit standard dev.			
σ_R	0.2		
Model plus group			
m	14		
CAA minus and plus groups	a_{minus}	a_{plus}	T^i
Can. Fall 2J3K	1	8	9
Can. Spring 3LNO	1	8	3
EU 3M 0-700m	1	9	6
EU 3M 0-1400m	4	11	6
EU 3m 700-1400m	4	11	6
EU 3L	1	10	6
EU 3NO	1	10	6
Can. Fall 3LNO	0	8	9
Commercial	5	12	
Natural mortality:			
M	0.2, age-independent		
Proportion mature-at-age:			
f_a	input, see Table A4		
Weight-at-age:			
$w_{y,a}^{strt}$	input, see Table A3		
$w_{y,a}^{mid}$	input, see Table A3		
$w_{y,a}^{i}$	input, see Table A3		