Appendix 3

Assessments of the Gulf of Maine haddock[1]

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Summary

The Gulf of Maine haddock population is assessed in three ways. The first considers the haddock in this area to be an isolated stock. The other two incorporate movement into that area, either permanent or temporary, by haddock from Georges Bank. The evidence for such movement from these analyses alone is sufficient to point to scenarios involving limited movement being of similar plausibility to that of an isolated stock. Catch projections under constant fishing mortality are found to be sensitive, in particular, to this possibility of limited movement for the case where the movement is permanent. Assessment results for the most recent recruitment are sensitive to the procedure used to shrink this estimate to the mean.

Introduction

This paper presents results for three approaches to the assessment of the Gulf of Maine (GoM) haddock stock, all of which use SCAA methodology (see, e.g., Butterworth and Rademeyer, 2011). The first approach explores assessment options when the stock is treated as isolated. The second allows for interchanges in the form of permanent migration from (and to) the neighbouring Georges Bank (GB) haddock population. The third approach (known in the IWC Scientific Committee as the "sabbatical model") also allows for interchanges, but these are not of a permanent nature. Some GB haddock may visit the GoM area during a year, and perhaps be caught there; however if not suffering mortality of some form, they return later that same year to the GB area.

The paper first summarises the data used, and then details the methodologies applied for the isolated stock and interchange models, followed by the assumptions made for calculating four-year catch projections. The results of applying these methodologies, together with some sensitivity tests, are then discussed, followed by some concluding remarks.

[1] This paper is a revision of an earlier version presented to the SAW meeting held at the NEFSC, Woods Hole over 2-5 June, 2014. Here Base Case run assumptions have been made to maximise comparability with the preferred ASAP model described in the main text of the report.

Data

The catch and survey based data together with some biological data for the GoM haddock population were kindly provided by Michael Palmer, and are listed in Tables in Annex A.

The second and third assessment approaches, which take interchange (movement) into account, utilise estimates of annual numbers-at-age from the most recent GB haddock assessment for the period from 1977 to 2011 (NEFSC, 2012). These values are listed in Table A8 of Annex A. This Table includes projections to 2017 kindly provided by Liz Brooks; the basis for the computation of these projections is detailed in Table A8's caption.

Methodology

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

Isolated stock

In the interests of maximal comparability with preferred ASAP model of the main text of the report, the following methodological options were chosen/implemented for this Base Case SCAA run (SCAA BC1).

- The stock recruitment curve was assumed to be constant with log-normally distributed residuals. The contribution to the negative log-likelihood from these residuals was calculated assuming a residual CV of 1 (this correspond to a $\sigma_{R,y}$ value of 0.833, which is roughly comparable, though slightly below, the level of variation shown in assessment outputs).
- Selectivities-at-age for the fishery and survey series were estimated separately for each age, though the survey selectivities were set flat above certain ages (see Annex B, section B.4.1, for further details). These decisions were AIC-justified.

Some other choices amongst the standard SCAA options that were made were as follows.

- The multinomial-mimicking "*sqrt(p)*" formulation of the proportions-at-age contribution to the overall negative log-likelihood (Butterworth and Rademeyer, 2012) was used, rather than the "adjusted log-normal", as the former deals more naturally with the relatively large numbers of zeros in the catch-at-age matrices for this stock.
- These proportion-at-age contributions to the negative log likelihood were fully weighted (W_{CAA}=1 – see equation B14), as is broadly comparable to the approach used to set effective sample sizes for the preferred ASAP model. The variance of the associated residuals was estimated assuming age-independence.

The authors' base case choices for implementing the SCAA, differ from those of the preferred ASAP model in one respect.

- The numbers at age vector for the starting year was estimated only to age 3, and thereafter the procedure of equations B9 and B10 of Annex B used (AIC justified).

In addition certain sensitivity runs were pursued:

- An alternative lower value of 0.5 for the recruitment CV for 2013, corresponding to setting $\sigma_{R,y}$ for 2013 to 0.472, was considered to stabilise this estimation to a greater extent. Note that the rightmost term in equation B18 of Annex B includes years to 2010 only, so that changing "weights" in this way on the last year's recruitment does not directly impact the estimate of the geometric mean recruitment R_{gm}.

- The standard deviation of the (transformed) proportion-at-age residuals (σ_{CAA} – see equation B16 of Annex B) for each series was estimated separately for each age rather than for all ages combined.
- The contribution of the proportion-at-age data to the negative log likelihood was down weighted (W_{CAA}=0.5 – see equation B14), to show the effect of possible non-independence of these data.
- The fishing "fleet" was disaggregated into commercial landings, commercial discards, and recreational landings together with recreational discards.

Migration model

There is evidence of interchange between the GoM and GB haddock stocks (e.g. Begg, 1998), but unfortunately the tagging exercises conducted to date have not been designed in a way that allows annual interchange proportions to be estimated reliably. However, since (for example) survey results would have included GB haddock which had moved into the GoM area, it is possible to extend the assessment to take this into account. Normally this would require assessing both stocks simultaneously, but an advantage in this case is that the GB stock is assessed to be so much larger than the GoM stock. This enables the results from the GB stock assessment (NEFSC, 2012) (kindly projected into the future by Liz Brooks, see Table A8 of Annex A) to be used directly, since unlike for the GoM haddock, those GB results would hardly change in such a joint assessment.

In the case of permanent interchange (i.e. migration) between the GoM and GB haddock stocks, equations B1 and B2 of Annex B are replaced by the following equations:

$$N_{y+1,a+1}^{GoM} = \left(N_{y,a}^{GoM} + \mu\rho_y N_{y,a}^{GB} - \lambda N_{y,a}^{GoM}\right)e^{-Z_{y,a}} \qquad \text{for } 1 \le a \le m-2 \qquad (1)$$

$$N_{y+1,m} = \left(N_{y,m-1}^{GoM} + \mu\rho_y N_{y,m-1}^{GB} - \lambda N_{y,m-1}^{GoM}\right)e^{-Z_{y,m-1}} + \left(N_{y,m}^{GoM} + \mu\rho_y N_{y,m}^{GB} - \lambda N_{y,m}^{GoM}\right)e^{-Z_{y,m}} \qquad (2)$$

where

μ is the proportion of the GB haddock (above a critical level) migrating annually and permanently to the Gulf of Maine, with a value estimated when fitting the model,

λ is the proportion of GoM haddock migrating annually and permanently to Georges Bank,

$$\rho_y = \frac{\sum_a N_{y,a}^{GB} - GB_{crit}}{\sum_a N_{y,a}^{GB}} \qquad (3)$$

and

GB_{crit} is the level of 2+ GB haddock numbers below which no GB haddock are assumed to immigrate into the GoM (i.e. the GB stock has to be "large" for any such migration to take place). For all the runs except one sensitivity, $GB_{crit} = 0$. For this sensitivity, $GB_{crit} = 47559$, which is half of the 1977-2013 average of the numbers of 2+ fish, so that movement occurs about 50% of the time over the this period.

The lower bound for age *a* in equation (1) is adjusted to correspond to the lowest age at which interchange takes place. This is taken to be *a*=2 for the Base Case implementation, based on indications to this effect provided in NEFC (1986).

Sabbatical model

Under the sabbatical model for movement, each year a proportion (θ) of the GB haddock "visit" the GoM area each year and mix with the GoM haddock (and hence are assumed to be available for capture in this area, and to be amongst the haddock monitored by the two NEFSC surveys each year). The GoM catches of haddock are taken from GoM and GB haddock in proportion to their relative abundances by age in the GoM area. Hence the fishing mortality F_y applies to both the GoM haddock stock and to the GB haddock "visitors". The total predicted catch C_y^* is computed as:

$$C_y^* = \sum_{a=1}^{m} w_{y,a}^{\mathrm{mid}} N_{y,a}^* S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) \Big/ Z_{y,a} \tag{4}$$

where

$$N_{y,a}^* = \left(N_{y,a}^{GoM} + \theta N_{y,a}^{GB}\right) \tag{5}$$

$$Z_{y,a} = F_y S_{y,a} + M_a \tag{6}$$

and the θ term in equation (5) (where the value of θ is estimated when fitting the model) applies only to ages for which movement is assumed to occur (*a* = 2+ for the Base Case, as for the migration model).

Spawning biomass (equation B5) is computed using the GoM haddock numbers only ($N_{y,a}$), while predicted survey indices (equation B7) and catches-at-age (B17) are computed with the GoM + GB visitors numbers ($N_{y,a}^*$), i.e. equations B7 and B17 are replaced by:

$$N_y^{\mathrm{surv}} = \sum_{a=1}^{m} S_a^{\mathrm{surv}} N_{y,a}^* e^{-Z_{y,a} T^{surv}/12} \tag{7}$$

$$\hat{p}_{y,a}^{surv} = S_a^{\mathrm{surv}} N_{y,a}^* e^{-Z_{y,a} T^{surv}/12} \Big/ \sum_{a'=0}^{m} S_{a'}^{\mathrm{surv}} N_{y,a}^* e^{-Z_{y,a} T^{surv}/12} \tag{8}$$

<u>*Projections*</u>

Four-year projections have been run under constant fishing mortalities of F_{MSY}, where F_{MSY} is taken to be $F_{40\%}$, as estimated in this paper or as estimated for the preferred ASAP model (see Annex B, section B.4.3). For these projections, the following assumptions have been made:

- the weight-at-age and commercial selectivity vectors are taken as the 2009-2013 average, as assumed for the $F_{40\%}$ computations for the preferred ASAP model - see Annex B section B.4.3;
- future recruitments are taken to be constant at their arithmetic mean level over the period chosen for the preferred ASAP model, i.e. 1977 to 2011 (to avoid inclusion of the recruitments for 2012 and 2013 for which the estimates have high variance); and
- in the cases with interchange (permanent migration) between the GoM and GB haddock stocks, the future GB haddock stock and age-structure is projected over the 2012 to 2017 period on the basis detailed in the caption to Table A8 of Annex A.

Results and Discussion

Isolated stock

Comparisons of the results from the preferred ASAP model SCAA Base Case without movement (SCAA-BC1) are provided in Table 1 and Figure 1, and evidence little difference. This SCAA-Base Case exhibits a reasonable fit to the survey indices of abundance and proportion-at-age data for both the fishery and the surveys, and indicates a slightly higher current spawning biomass than the preferred ASAP model does.

Table 1 and Figure 2 show the consequences of reducing the value assumed for the variability ($\sigma_{R,y}$) of the recruitment for the most recent years (2013) to a CV of 0.5 compared to the SCAA-Base Case choice of 1.0. This has a major impact on the estimate of recruitment for the last year, which drops by more than 50%, but the estimate of spawning biomass for 2013 falls only slightly. Formally the choice of 1.0 (corresponding, roughly, to the variability shown by past recruitment) is the most appropriate statistically for the shrinkage to the mean of the estimates that would otherwise result. However this leads to a high variance associated with the 2013 recruitment estimate. A case could be made that a lower choice than 1.0 is appropriate in the interests of providing more robust estimates, but the difficulty is in choosing what value it would be best to set in any such down-weighting parameter. Results are also shown for downweighting the contribution of the proportions-at-age data to the negative log likelihood. This has little impact on estimates, though the confidence intervals shown in Table 1 widen slightly, and those for parameters such as selectivity-at-age somewhat more so.

Allowing for the variance parameter associated with the proportions-at-age residuals (σ_{CAA}) to be estimated separately by age improves the fit to the data, and to an extent which is AIC justified (Table 1 and Figure 3). However, as the impact of allowing for this effect on key results (such as those for spawning biomass) is minimal, this adjustment was not incorporated into the SCAA Base Case to maintain greater comparability with the preferred ASAP model. Similarly, initial attempts to disaggregate the fishing “fleet” into commercial landing, discards and recreational components also led to little difference in such results, and hence was not explored further.

Migration model

Results for the permanent migration model are shown in Table 4 for the best estimate of 0.2% (SCAA BC2) for the annual proportion μ moving from the GB to the GoM area. Results for a range of μ values are shown in Figure 4. These indicate that the estimate of μ = 0.2% is significantly different from zero at the 10% (and 5%) levels, while the diagnostics shown in Figure 5 evidence a satisfactory fit to the data. For μ = 0.2%, the recent spawning biomass estimates are not greatly affected; they do become appreciably larger for higher values of μ, but those results are not compatible with the data. If movement is allowed in the reverse direction as well (i.e. the λ parameter is set to be different from zero), results are hardly affected (see Figure 6), so that λ has been kept at zero for all subsequent results for this model.

Table 4 and Figures 7 to 9 provide results for some sensitivities to SCAA BC2. Changing the age at which fish can move from the GB to the GoM area from 2+ to either 1+ or 3+ impacts results, but only to small extents. The consequences of allowing random annual variation (with a CV = 1.0) about a mean proportional movement of 0.2%, and of precluding movement below an abundance threshold for GB haddock, are also relatively small.

Sabbatical model
Results for the sabbatical model (non-permanent interchange) are given in Table 3 and Figure 10, again indicating reasonable fits to the data. The best estimate of the proportion of GB haddock moving temporarily each year to the GoM area, θ, is 0.75% (SCAA BC3). This is shown to be statistically different from zero at the 10% (and 5%) levels in Figure 11.

Figure 11 also shows spawning biomass trajectories for various values of θ for the component of the haddock in the GoM area belonging to the true GoM stock. Unsurprisingly, this is less for larger values of θ, as those reflect greater proportions of the catch from the GoM area being comprised of GB haddock. In addition, the Figure shows how this proportion has changed over time for the different values of θ. Table 3 and Figure 12 show that changing the age at which fish can move from the GB to the GoM area from 2+ to either 1+ or 3+ has some though not a substantial impact on results.

Overall comparison and Retrospectives
Figure 13 compares the results for the Base Case for no movement model (SCAA BC1) with those for the two models which allow for movement (SCAA-BC2 for permanent and SCAA-BC3 for temporary migration). The first two sets of results are fairly similar, but the sabbatical model (SCAA-BC3) unsurprisingly shows lower spawning biomass and recruitment values as these plots do not include the haddock "visiting" the GoM area from the GB stock, even though those haddock contribute to catches made in the GoM area.

Figure 14 shows retrospective plots for all three models. None reflect serious systematic trends. The estimates of the movement parameters μ and θ are stable and consistently significantly different from zero. Examination of the negative log likelihood contributions in Tables 2 and 3 shows that it is the proportions at age data that provide the key information to allow the values of these parameters to be estimated. These negative log likelihoods also indicate a preference for the migration over the sabbatical model, but not to any substantial extent; indeed from a biological perspective, one might tend to consider the sabbatical model as the more plausible of the two.

Catch projections
Four year catch projections under F_{MSY} are shown in Table 4. For the sabbatical model scenarios, results given reflect the total catch allowed, and this will include a component of GB haddock. The figures in parentheses in Table 4 show the part of this that comes from the "true" GoM haddock stock only. The F_{MSY} values are provided by the $F_{40\%}$ proxy, though this is calculated in two ways: first for the SCAA model estimates (and specific to the model in question with or without movement), and then for the preferred ASAP model (see Annex B, section B.4.3 for details).

These projection results are quite similar for the no movement and sabbatical models, but give values some 20-40% higher for the permanent migration model.

Concluding Remarks

The results above for catch projections (in particular) from these assessment model variants for the GoM haddock stock point to two key factors to which model outputs are particularly sensitive. These are:

1) the extent to which the estimate of recruitment for the most recent year is shrunk to the mean; and

2) how the possibility of exchanges with GB haddock is best to be taken into account; the estimates of annual movement proportions, although small in percentage terms, are statistically significant at the 5% level so that the associated exchange hypotheses are plausible; furthermore in the case of permanent exchange, catch projections under F_{MSY} proxies are increased by amounts in roughly the 20-40% range.

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Table 1: Estimates of abundance and related quantities for the Gulf of Maine haddock for the preferred ASAP model and SCAA runs for isolated stock (with no movement) assessments. Values in parentheses are Hessian based 90% CIs. Biomass units in this and all following tables are mt unless otherwise indicated. The fishing mortality F applies to the commercially fully selected 7+ fish.

	No movement models								
	ASAP	SCAA BC1		CV_{SR}=0.5 in 2013		Age-specific σ_{CAA}		W_{CAA}=0.5	
'-lnL:overall		-1438.7		-1431.8		-1474.5		-692.8	
'-lnL:Index		11.0		14.8		12.5		10.7	
'-lnL:comCAA		-743.9		-743.4		-765.2		-369.1	
'-lnL:indexCAA		-749.8		-748.2		-763.6		-375.3	
'-lnL:catch		0.9		0.8		0.9		0.4	
-lnL:epsμ		0.0		0.0		0.0		0.0	
'-lnL:RecRes		43.1		44.1		41.0		40.5	
B^{sp}_{1977}	9438	7871	(6693; 9049)	7875	(6695; 9055)	7878	(6724; 9032)	8032	(6496; 9568)
B^{sp}_{2013}	4153	5206	(2889; 7522)	3943	(1999; 5887)	4861	(2611; 7111)	5523	(3039; 8008)
$B^{sp}_{2013}/B^{sp}_{1977}$	0.44	0.66	(0.35; 0.97)	0.50	(0.24; 0.76)	0.62	(0.32; 0.92)	0.69	(0.35; 1.02)
$N_{1,1977}$	5997	6441	(5198; 7683)	6428	(5186; 7670)	6821	(5472; 8170)	6359	(4682; 8036)
$N_{1,2011}$	6659	8667	(4771; 12563)	6578	(3422; 9735)	7704	(4135; 11273)	8998	(4637; 13359)
$N_{1,2013}$	16565	15824	(5309; 26339)	6280	(2462; 10098)	14889	(5036; 24742)	14030	(2758; 25302)
$F_{30\%}$		0.74	-	0.73	-	0.69	-	0.74	-
$B_{MSY}(F_{30\%})$		2652	(2299; 3005)	2553	(2211; 2895)	2667	(2324; 3010)	2724	(2262; 3186)
$MSY(F_{30\%})$		908	(828; 988)	873	(797; 948)	910	(826; 994)	932	(839; 1025)
$F_{40\%}$	0.46	0.43	-	0.42	-	0.41	-	0.43	-
$B_{MSY}(F_{40\%})$		3536	(3109; 3964)	3404	(2990; 3817)	3556	(3136; 3977)	3632	(3087; 4177)
$MSY(F_{40\%})$		825	(751; 899)	793	(722; 863)	825	(748; 903)	848	(760; 935)
Spring q	0.25	0.26	(0.22; 0.30)	0.27	(0.23; 0.31)	0.25	(0.22; 0.29)	0.27	(0.22; 0.32)
Fall q	0.92	0.94	(0.71; 1.16)	0.97	(0.74; 1.20)	0.98	(0.76; 1.21)	0.96	(0.65; 1.26)
Spring AddVar		0.10	(0.00*; 0.33)	0.12	(0.00*; 0.37)	0.10	(0.00*; 0.34)	0.10	(0.00*; 0.33)
Fall AddVar		0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)
σ_{Rout}		1.27	(1.21; 1.33)	1.22	(1.17; 1.27)	1.24	(1.18; 1.30)	1.23	(1.16; 1.30)

Table 2: Estimates of abundance and related quantities for the Gulf of Maine haddock for the SCAA migration model (i.e. with movement of 2+ year old haddock for the Base Case BC2). Values in parentheses are Hessian based 90% CIs. The value of μ is the proportion of (here 2+ year old for BC2) GB haddock which permanently migrate to the GoM each year, while λ specifies the proportion of such migration in the reverse direction. The text explains the role of the GBcrit constraint.

	No movement		Migration models												
	SCAA BC1		SCAA BC2		$\lambda=\mu$		1+ moving		3+ moving		GBcrit=50% of 1977-2013 average		Random effects on μ	
'-lnL:overall	-1438.7		-1447.7		-1447.6		-1446.5		-1447.1		-1444.8		-1452.4	
'-lnL:Index	11.0		9.9		9.9		10.2		9.5		10.7		9.7	
'-lnL:comCAA	-743.9		-750.9		-750.9		-750.1		-751.7		-746.0		-757.0	
'-lnL:indexCAA	-749.8		-753.7		-753.8		-753.4		-751.9		-752.6		-756.4	
'-lnL:catch	0.9		0.9		0.9		0.9		0.9		0.9		0.9	
-lnL:epsμ	0.0		0.0		0.0		0.0		0.0		0.0		3.7	
'-lnL:RecRes	43.1		46.1		46.2		45.9		46.1		42.3		46.8	
μ (%)	0		0.20	(0.13; 0.28)	0.20	(0.13; 0.28)	0.18	(0.11; 0.24)	0.22	(0.13; 0.31)	0.28	(0.15; 0.41)	0.20	(0.20; 0.20)
B^{sp}_{1977}	7871	(6693; 9049)	7742	(6570; 8913)	7779	(6602; 8955)	7755	(6584; 8926)	7718	(6549; 8888)	7842	(6663; 9022)	7710	(6541; 8879)
B^{sp}_{2013}	5206	(2889; 7522)	6061	(3690; 8431)	6079	(3703; 8454)	5690	(3428; 7952)	6394	(3873; 8915)	6705	(3819; 9591)	5376	(3050; 7702)
$B^{sp}_{2013}/B^{sp}_{1977}$	0.66	(0.35; 0.97)	0.78	(0.45; 1.11)	0.78	(0.45; 1.11)	0.73	(0.42; 1.05)	0.83	(0.48; 1.18)	0.85	(0.47; 1.24)	0.70	(0.38; 1.02)
$N_{1,1977}$	6441	(5198; 7683)	6259	(5046; 7472)	6309	(5087; 7531)	6274	(5059; 7490)	6286	(5073; 7499)	6406	(5172; 7641)	6206	(5009; 7402)
$N_{1,2011}$	8667	(4771; 12563)	7493	(3983; 11003)	7561	(4019; 11103)	7311	(3857; 10766)	8607	(4875; 12339)	8124	(4176; 12073)	6928	(3388; 10469)
$N_{1,2013}$	15824	(5309; 26339)	15270	(5533; 25007)	15405	(5579; 25231)	14594	(5151; 24037)	16544	(6036; 27052)	16960	(5964; 27956)	13776	(4745; 22807)
$F_{30\%}$	0.74	-	0.62	-	0.62	-	0.63	-	0.61	-	0.63	-	0.64	-
$B_{MSY}(F_{30\%})$	2652	(2299; 3005)	2226	(1841; 2611)	2249	(1864; 2634)	2275	(1898; 2651)	2322	(1936; 2709)	2467	(2072; 2863)	2085	(1741; 2429)
$MSY(F_{30\%})$	908	(828; 988)	755	(676; 835)	763	(683; 843)	773	(694; 851)	788	(711; 864)	837	(753; 921)	708	(623; 793)
$F_{40\%}$	0.43	-	0.37	-	0.37	-	0.38	-	0.37	-	0.38	-	0.38	-
$B_{MSY}(F_{40\%})$	3536	(3109; 3964)	2968	(2509; 3427)	2999	(2540; 3458)	3033	(2584; 3482)	3097	(2640; 3554)	3290	(2819; 3760)	2780	(2359; 3201)
$MSY(F_{40\%})$	825	(751; 899)	684	(612; 756)	691	(619; 764)	700	(629; 771)	713	(644; 783)	758	(681; 836)	642	(564; 720)
Spring q	0.26	(0.22; 0.30)	0.27	(0.23; 0.31)	0.27	(0.23; 0.31)	0.27	(0.23; 0.31)	0.27	(0.23; 0.31)	0.25	(0.21; 0.29)	0.28	(0.24; 0.32)
Fall q	0.94	(0.71; 1.16)	0.92	(0.69; 1.14)	0.91	(0.69; 1.14)	0.93	(0.71; 1.16)	0.91	(0.69; 1.14)	0.85	(0.63; 1.07)	0.98	(0.73; 1.22)
Spring AddVar	0.10	(0.00*; 0.33)	0.08	(0.00*; 0.30)	0.08	(0.00*; 0.30)	0.09	(0.00*; 0.31)	0.08	(0.00*; 0.30)	0.09	(0.00*; 0.31)	0.09	(0.00*; 0.30)
Fall AddVar	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)
σ_{Rout}	1.27	(1.21; 1.33)	1.31	(1.24; 1.39)	1.32	(1.24; 1.39)	1.31	(1.24; 1.38)	1.31	(1.25; 1.38)	1.26	(1.19; 1.32)	1.32	(1.25; 1.40)

Table 3: Estimates of abundance and related quantities for the Gulf of Maine haddock stock for the SCAA sabbatical model. The value of θ is the proportion of GB haddock (aged 2+ for the Base Case BC3) which move temporarily to the GoM area each year; the values shown in the Table do not include those GB fish, and refer to haddock from the GoM stock only). Values in parentheses are Hessian based 90% CIs.

	No movement		Sabbatical models					
	SCAA BC1		SCAA BC3		1+ moving		3+ moving	
'-lnL:overall	-1438.7		-1446.3		-1441.2		-1445.8	
'-lnL:Index	11.0		11.0		10.2		10.0	
'-lnL:comCAA	-743.9		-747.3		-747.6		-749.7	
'-lnL:indexCAA	-749.8		-757.4		-750.1		-753.5	
'-lnL:catch	0.9		0.9		0.9		0.9	
-lnL:epsμ	0.0		0.0		0.0		0.0	
'-lnL:RecRes	43.1		46.4		45.3		46.5	
θ (%)	0		0.75	(0.49; 1.02)	0.53	(0.20; 0.85)	0.64	(0.40; 0.89)
B^{sp}_{1977}	7871	(6693; 9049)	7602	(6419; 8786)	7632	(6453; 8811)	7698	(6514; 8881)
B^{sp}_{2013}	5206	(2889; 7522)	3131	(1580; 4682)	3707	(1671; 5744)	4185	(2427; 5944)
$B^{sp}_{2013}/B^{sp}_{1977}$	0.66	(0.35; 0.97)	0.41	(0.20; 0.63)	0.49	(0.21; 0.76)	0.54	(0.30; 0.79)
$N_{1,1977}$	6441	(5198; 7683)	6255	(5035; 7475)	6304	(5075; 7533)	6284	(5066; 7501)
$N_{1,2011}$	8667	(4771; 12563)	4813	(1933; 7693)	5895	(2177; 9613)	6929	(3792; 10066)
$N_{1,2013}$	15824	(5309; 26339)	12277	(4394; 20160)	12195	(2580; 21810)	14611	(5443; 23777)
$F_{30\%}$	0.74	-	0.69	-	0.71	-	0.69	-
$B_{MSY}(F_{30\%})$	2652	(2299; 3005)	2123	(1761; 2484)	2280	(1861; 2700)	2280	(1926; 2634)
$MSY(F_{30\%})$	908	(828; 988)	725	(640; 810)	780	(675; 885)	777	(697; 856)
$F_{40\%}$	0.43	-	0.41	-	0.41	-	0.41	-
$B_{MSY}(F_{40\%})$	3536	(3109; 3964)	2830	(2390; 3270)	3041	(2524; 3558)	3040	(2614; 3465)
$MSY(F_{40\%})$	825	(751; 899)	658	(580; 736)	708	(612; 804)	706	(633; 778)
Spring q	0.26	(0.22; 0.30)	0.28	(0.24; 0.32)	0.28	(0.24; 0.32)	0.27	(0.23; 0.31)
Fall q	0.94	(0.71; 1.16)	1.01	(0.77; 1.24)	1.02	(0.78; 1.26)	0.98	(0.75; 1.21)
Spring AddVar	0.10	(0.00*; 0.33)	0.09	(0.00*; 0.32)	0.10	(0.00*; 0.33)	0.09	(0.00*; 0.30)
Fall AddVar	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)	0.00	(0.00; 0.00)
σ_{Rout}	1.27	(1.21; 1.33)	1.32	(1.25; 1.39)	1.30	(1.23; 1.38)	1.32	(1.25; 1.39)

Table 4: Catch (mt) projections from 2014 for the three SCAA Base Cases under $F_{40\%}$ as estimated by the SCAA models, and *F*=0.46 (the value of estimated for $F_{40\%}$ for the preferred ASAP model - see Annex B, section B.4.3). The lowest section of the Table shows results for *F*=0.46 from 2015 with 500mt for the 2014 catch for these three Base Cases. For the sabbatical model, the values in parentheses refer to the catch arising from the GoM haddock stock only.

	1	2	3	
	SCAA BC1 "no movement"	SCAA BC2 "migration model"	SCAA BC3 "sabbatical model"	
$F_{40\%}$ (SCAA)	(0.43)	(0.37)	(0.41)	
C_{2014}	1318	1661	1226	(848)
C_{2015}	2018	2503	1918	(1373)
C_{2016}	2414	2909	2326	(1709)
C_{2017}	2793	3294	2711	(2021)
$F_{40\%}$ (ASAP)=0.46 (applied to all three cases)				
C_{2014}	1409	2011	1374	(951)
C_{2015}	2139	2942	2127	(1517)
C_{2016}	2531	3313	2545	(1857)
C_{2017}	2894	3627	2920	(2153)
500mt, $F_{40\%}$ (ASAP)=0.46 (applied to all three cases)				
C_{2014}	500	500	500	(345)
C_{2015}	2341	3315	2264	(1654)
C_{2016}	2702	3604	2661	(1973)
C_{2017}	3030	3842	3013	(2245)

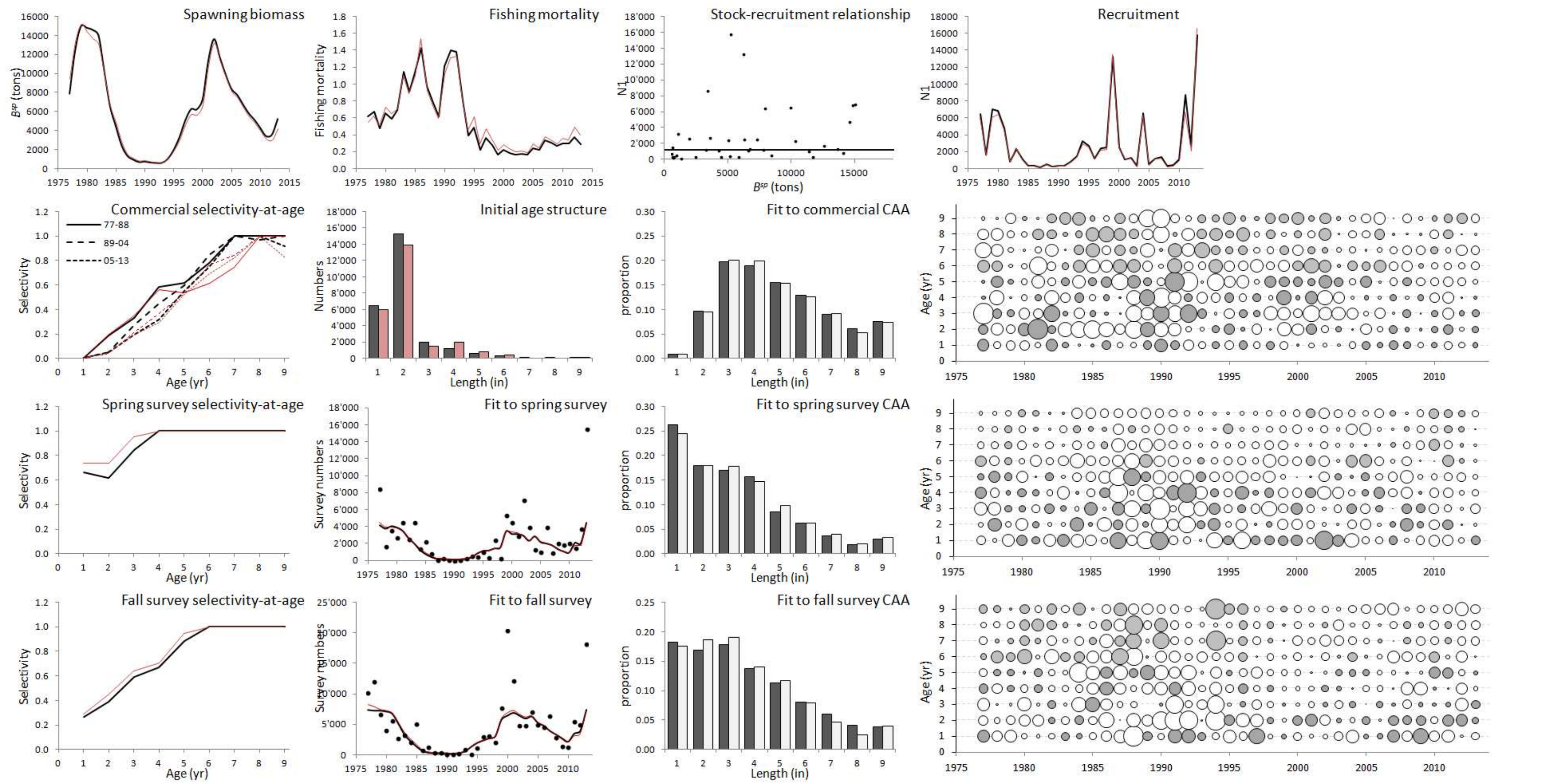

Figure 1: Comparison of the **SCAA-BC1 (isolated stock so no movement)** (in black) results with the **preferred ASAP-model** (in red).The fits to the CAA data are first shown as the averages over all years for each age, and then as bubble plots of standardised residuals. The area of the bubble is proportional to the magnitude of the corresponding residuals. For positive residuals the bubbles are grey, whereas for negative residuals the bubbles are white.

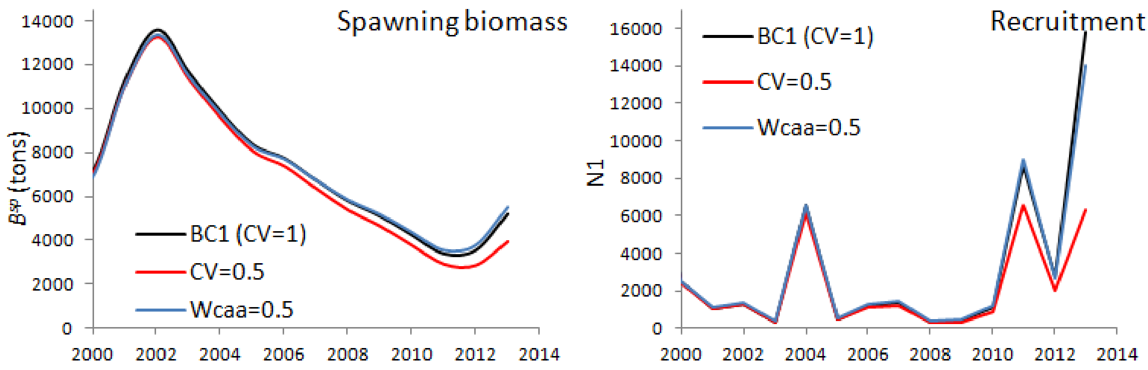

Figure 2: Comparison of spawning biomass and recruitment trajectories for the **SCAA-BC1 (isolated stock so no movement)** with a different stock-recruitment residual CV for 2013 (red lines), and for the proportions-at-age contributions to the negative log likelihood downweighted by a multiplicative factor of 0.5 (blue lines). The SCAA-Base Case assessment uses a CV of 1.0 for recruitment residuals for all years and is shown in black in the plots.

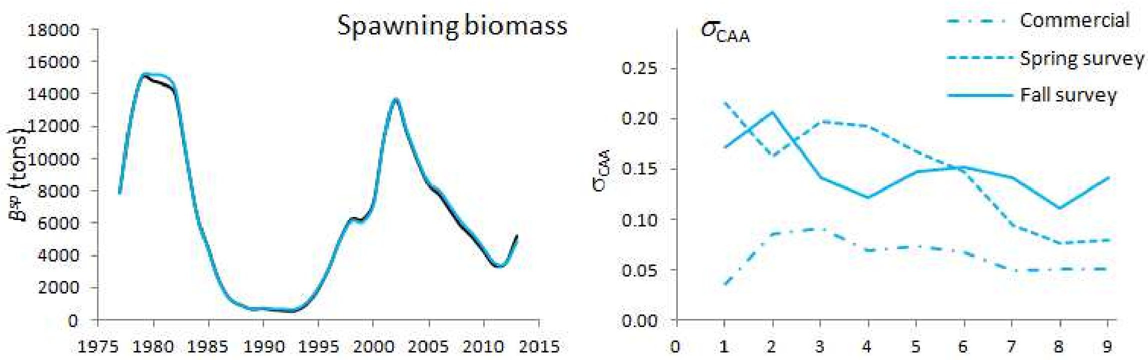

Figure 3: Comparison of spawning biomass trajectories for the **SCAA-Base Case (isolated stock so no movement)** (black line) and the sensitivity using age-specific σ_{CAA} values for the commercial and survey CAA data (blue line). The estimated σ_{CAA} values are also shown.

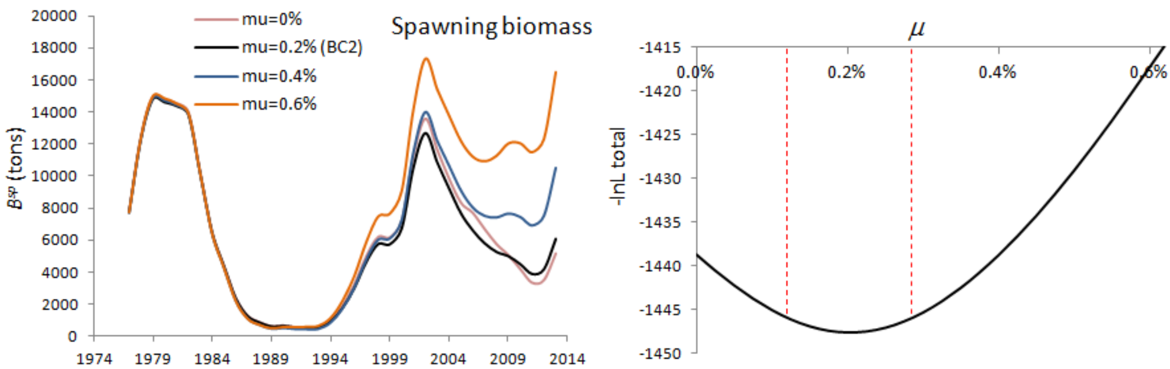

Figure 4: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** with a series of fixed alternative movement proportions. Note that the μ=0% trajectory corresponds to **SCAA-BC1 (with no movement).** The right side plot shows the likelihood profile for the movement proportion μ (the vertical dashed lines correspond to the 90% confidence limits).

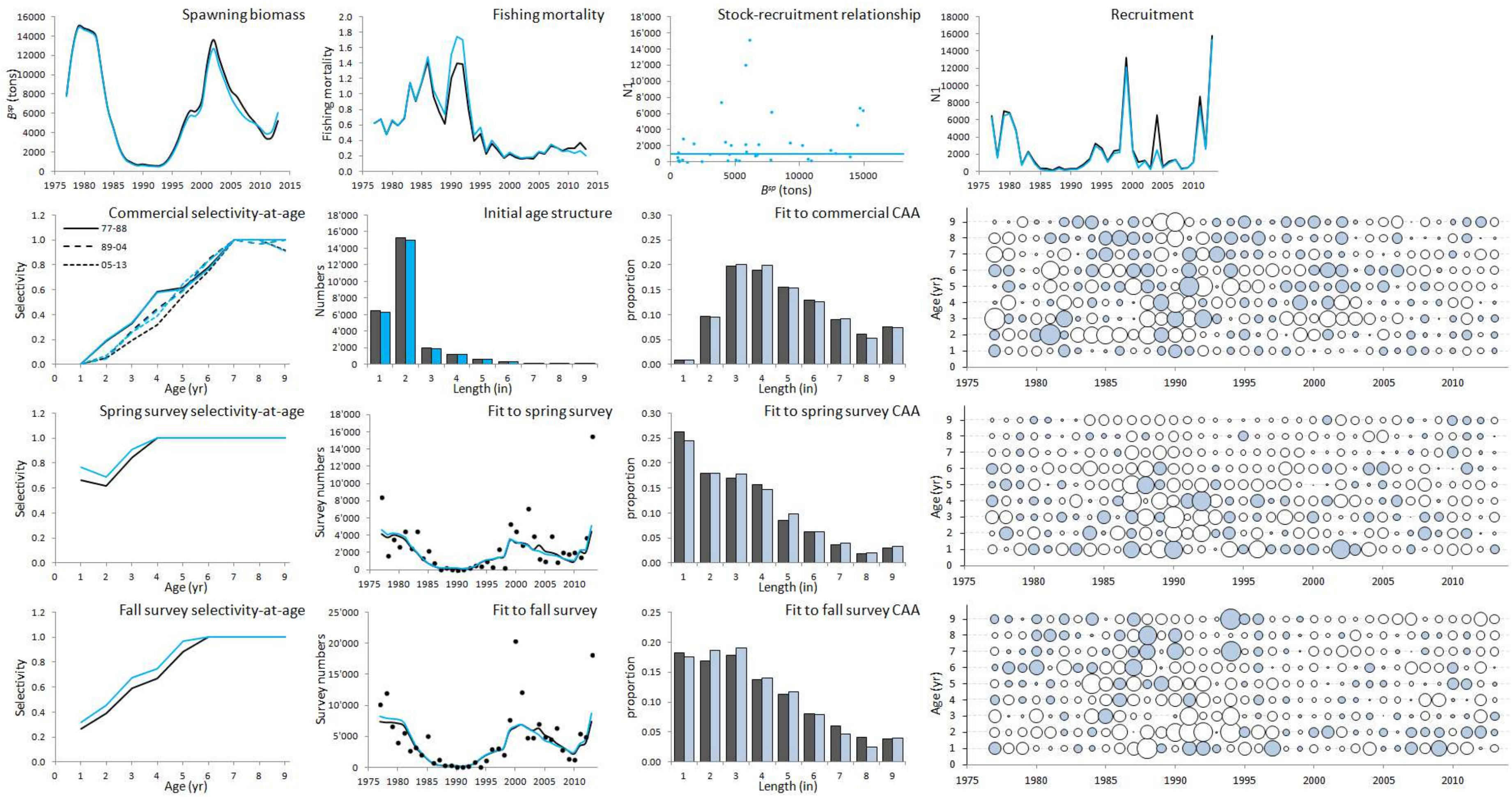

Figure 5: Comparison of the **SCAA-BC1 (isolated stock so no movement)** (in black) and **SCAA-BC2 (with movement)** (in blue) results. The fits to the CAA data are shown for SCAA-BC2 only, first as the averages over all years for each age, and then as bubble plots of standardised residuals. The area of the bubble is proportional to the magnitude of the corresponding residuals. For positive residuals the bubbles are light blue, whereas for negative residuals the bubbles are white.

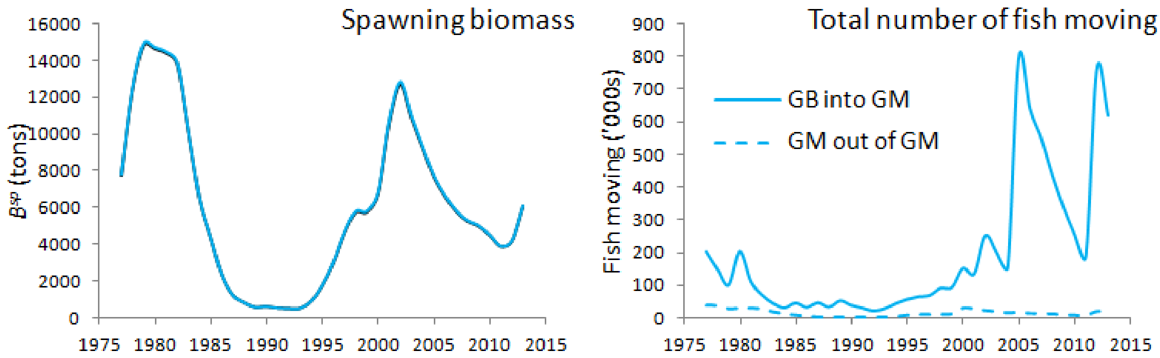

Figure 6: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** (black line) and the sensitivity that also includes Gulf of Maine haddock emigrating out of the Gulf of Maine ($\lambda = \mu$) (blue line, which nearly always covers the black line). The right side-plot shows the total number of fish estimated to move in and out of the Gulf of Maine each year for this sensitivity.

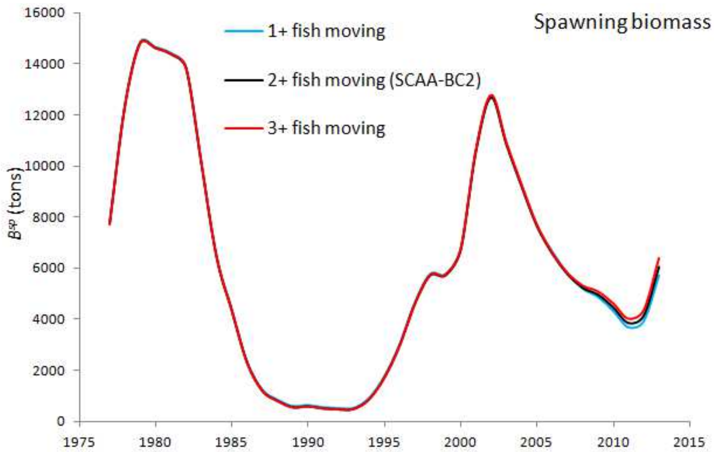

Figure 7: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** with sensitivities to the choice of the age at which fish start to move (note that μ is estimated separately for each of these runs).

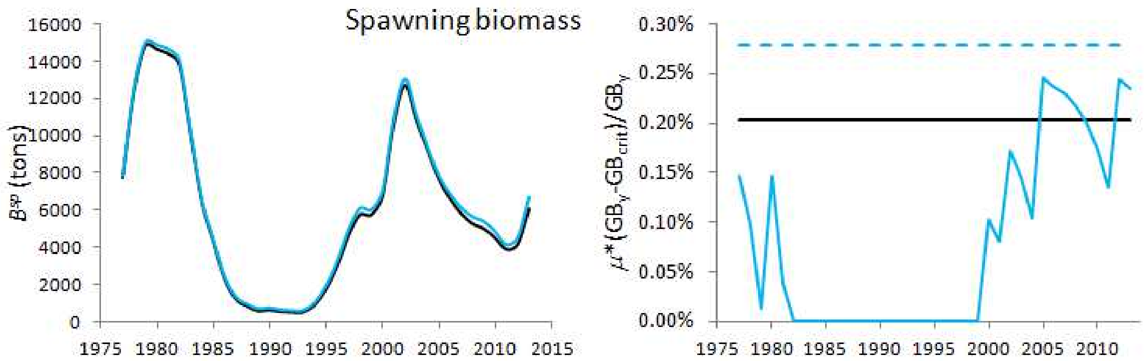

Figure 8: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** (estimated $\mu = 0.20\%$, black line) and the sensitivity in which George's Bank fish move into Gulf of Maine only if the total number of fish of age 2+ is greater than GB_{crit} (see the text for details of how this threshold is defined). The horizontal dashed blue line is the maximum value which the proportion moving can attain in this sensitivity ($\mu = 0.28\%$).

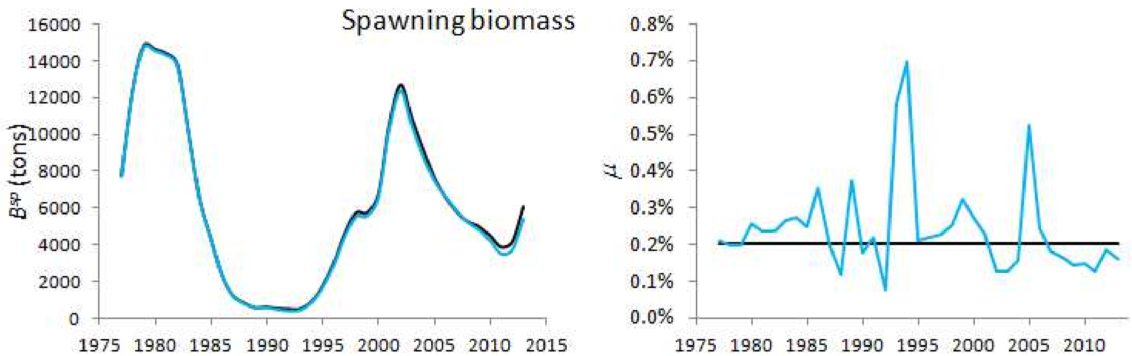

Figure 9: Comparison of spawning biomass trajectories for the **SCAA-BC2 (with movement)** (estimated $\mu = 0.20\%$, black line) and the sensitivity with random effects about μ = 0.20% (fixed) (blue line).The right side plot shows the fixed μ value together with the annual values estimated under the random effects approach.

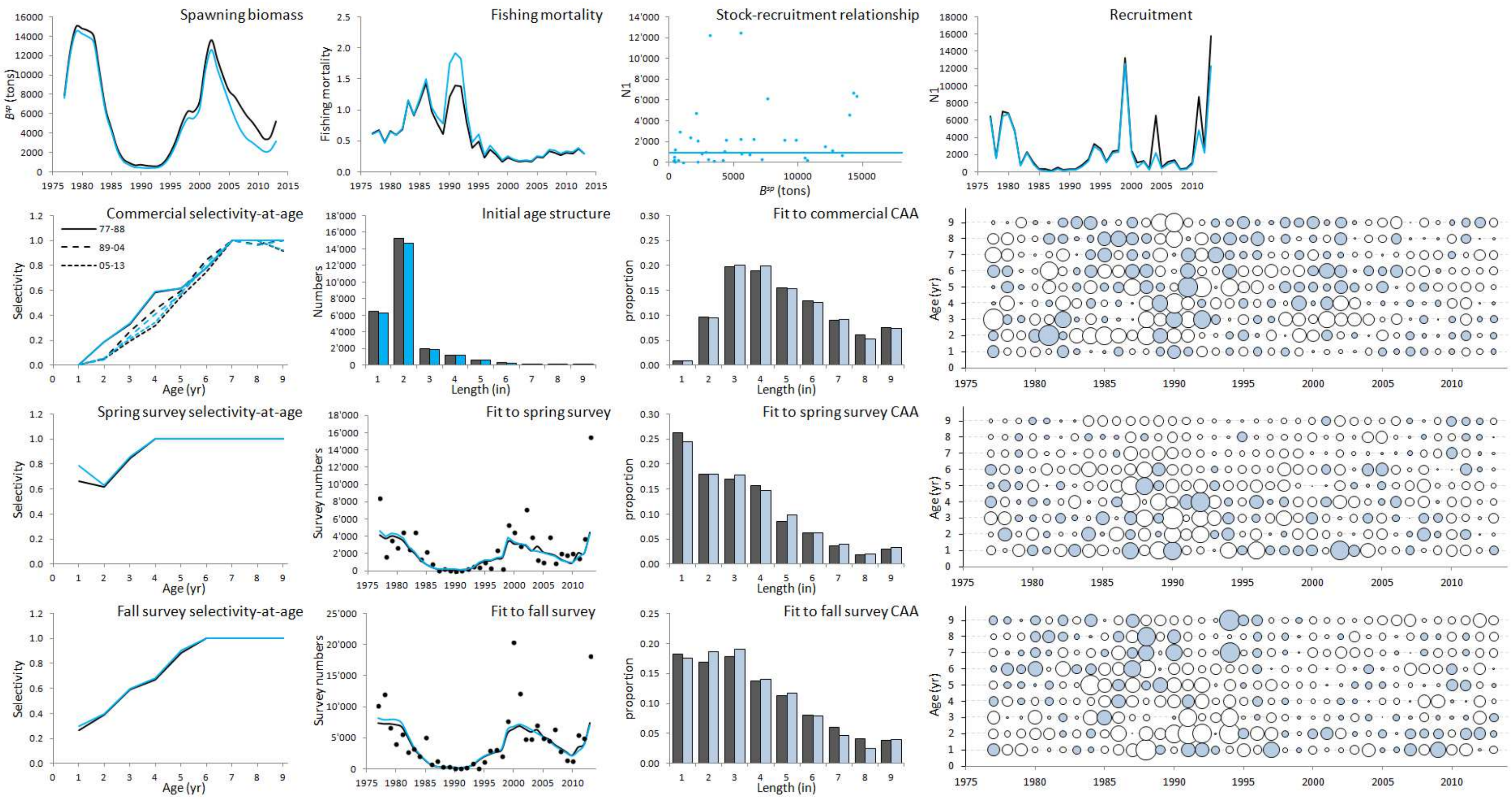

Figure 10: Comparison of the **SCAA-BC1 (isolated stock so no movement)** (in black) and **SCAA-BC3 (sabbatical model)** (in blue) results. The fits to the CAA data are shown for SCAA-BC3 only, first as the averages over all years for each age, and then as bubble plots of standardised residuals. The area of the bubble is proportional to the magnitude of the corresponding residuals. For positive residuals the bubbles are light blue, whereas for negative residuals the bubbles are white.

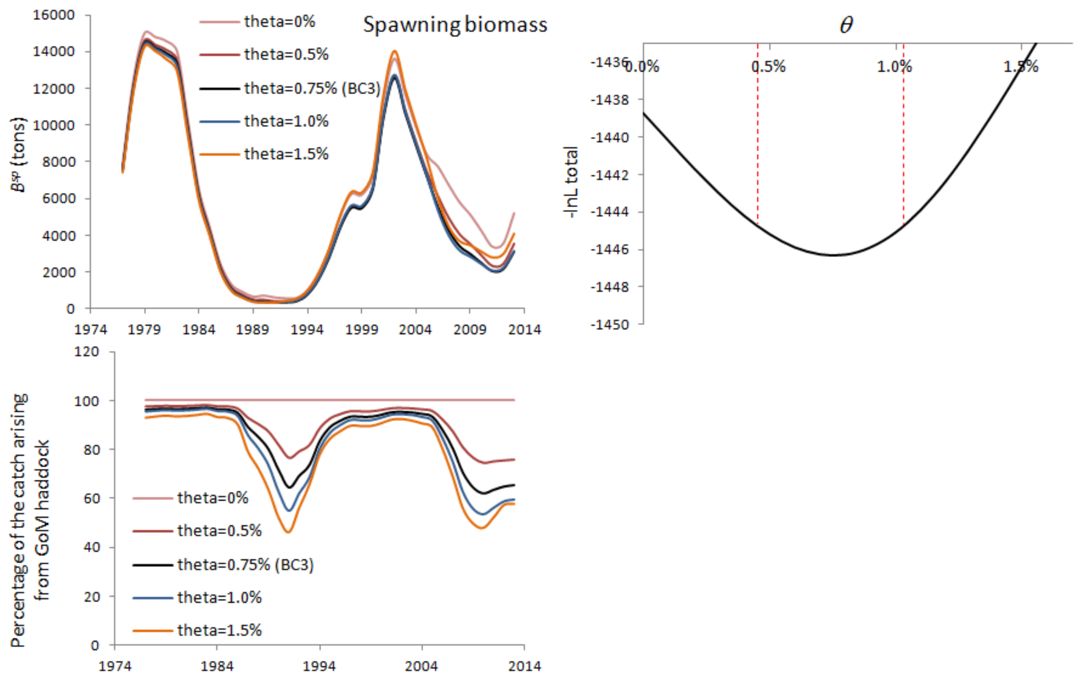

Figure 11: Comparison of spawning biomass trajectories for the **SCAA-BC3 (sabbatical model)** with a series of fixed alternative movement proportions (top left plot). Note that the θ=0% trajectory corresponds to the **SCAA-Base Case with no movement.** The top right side plot shows the likelihood profile for the movement proportion θ (the vertical dashed lines correspond to the 90% confidence limits). The bottom plot shows the percentage of the total haddock catch in the GoM area arising from the "true" GoM haddock stock for a series of θ values.

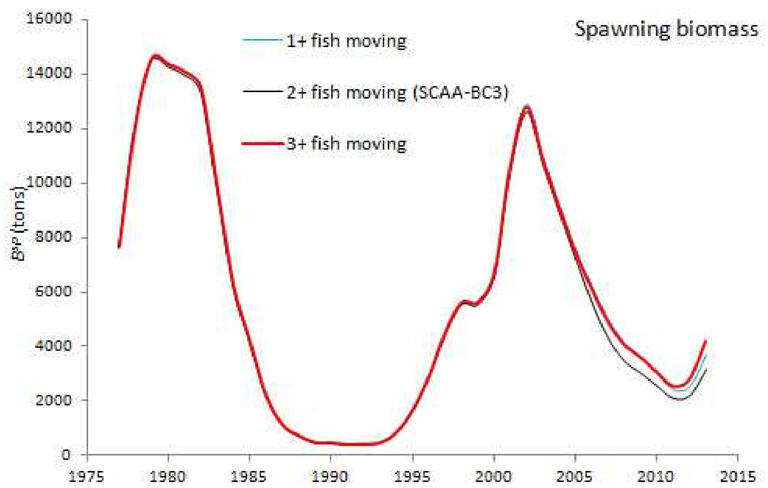

Figure 12: Comparison of spawning biomass trajectories for the **SCAA-BC3 (sabbatical model)** with sensitivities to the choice of the age at which fish start to move (note that θ is estimated separately for each of these runs).

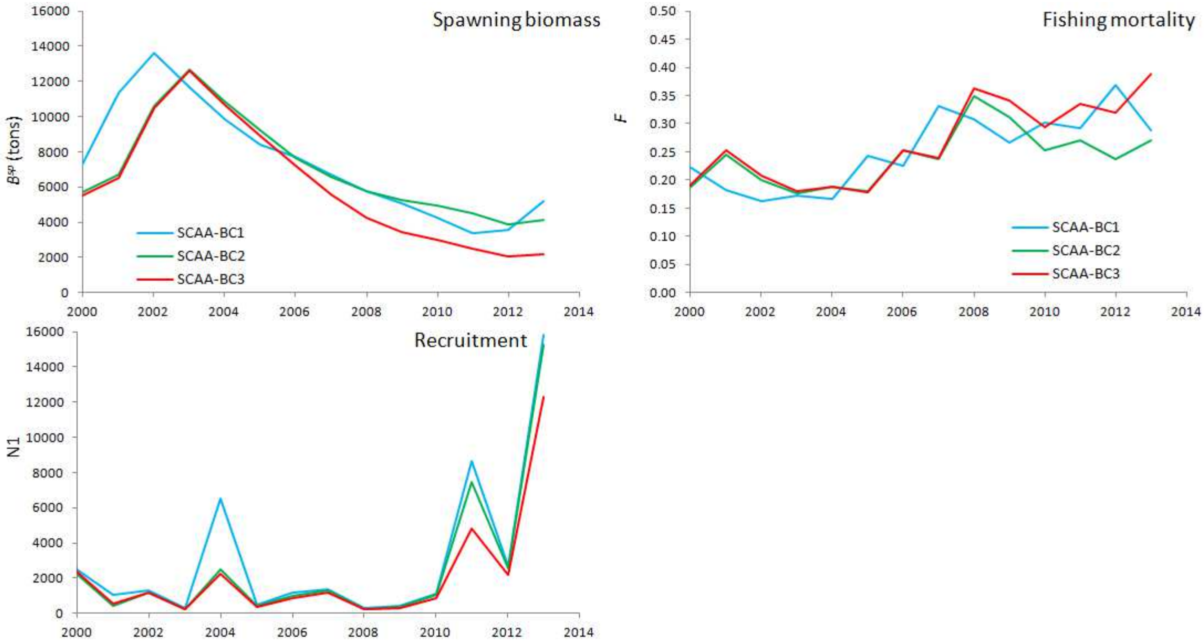

Figure 13: Comparison of spawning biomass, fishing mortality and recruitment trajectories for the **three SCAA Base Cases**. Note that the results shown for SCAA-BC3 (sabbatical model) exclude fish from the GB stock present in the GoM.

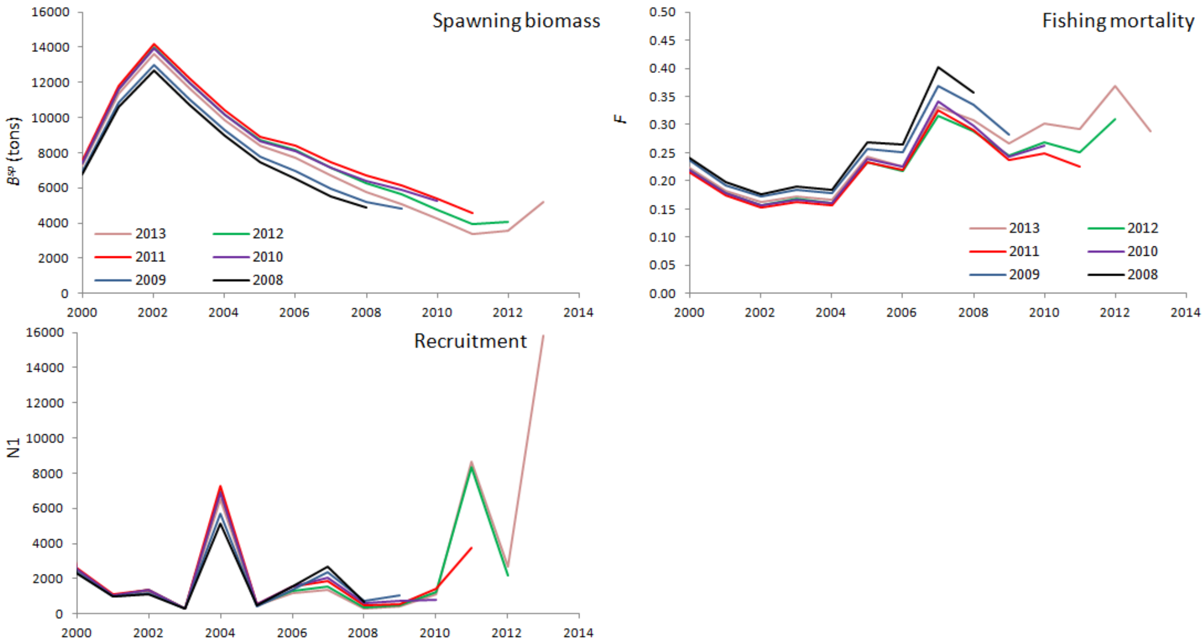

Figure 14a: Retrospective plots for **SCAA-BC1 (no movement).**

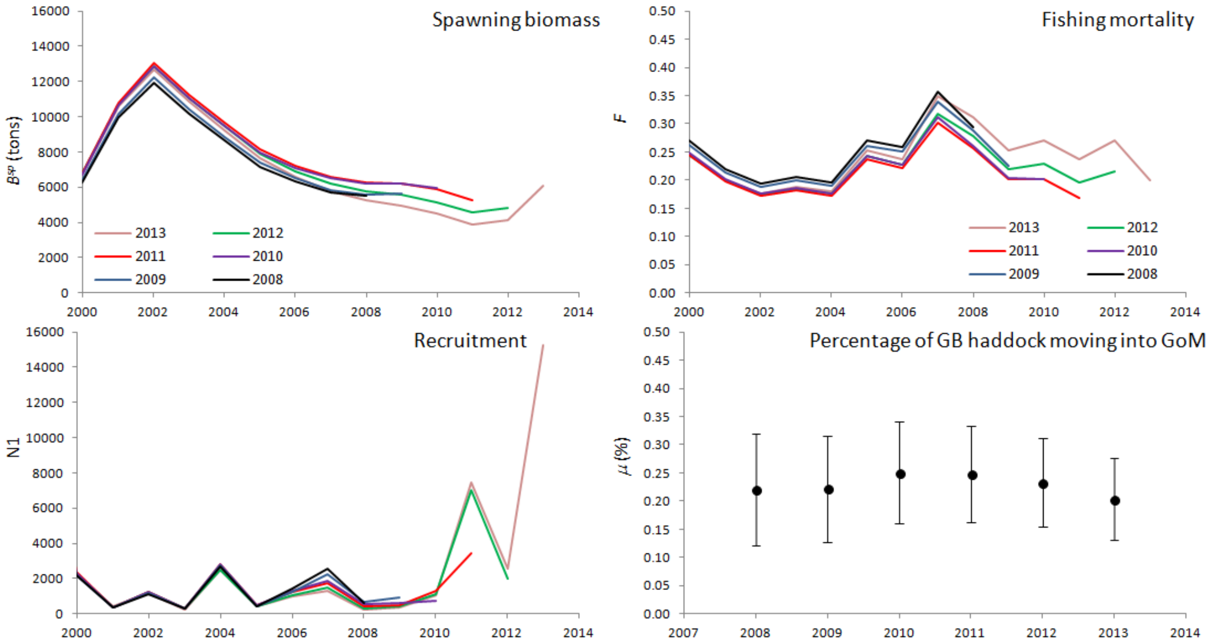

Figure 14b: Retrospective plots for **SCAA-BC2 migration model (permanent movement)**. The error bars for μ show the 90% Hessian-base CIs.

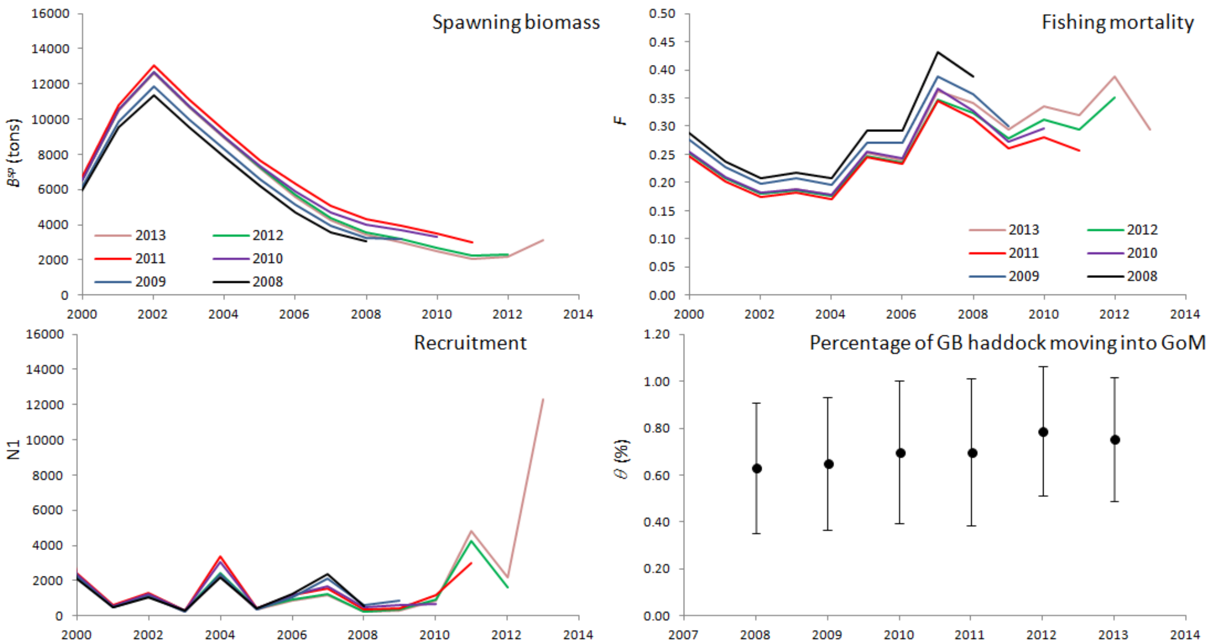

Figure 14c: Retrospective plots for **SCAA-BC3 sabbatical model (temporary movement)**. The error bars for θ show the 90% Hessian-base CIs.

ANNEX A – Data

Table A1: Total catch (metric tons) of haddock from the Gulf of Maine, 1977-2013 (Michael Palmer, pers. commn).

Year	Total catches (mt)	Year	Total catches (mt)	Year	Total catches (mt)
1977	3256.1	1990	472.4	2003	1346.7
1978	5023.5	1991	446.6	2004	1307.9
1979	4387.6	1992	321.4	2005	1576.7
1980	6520.6	1993	206.9	2006	1166.9
1981	6264.5	1994	186.7	2007	1343.2
1982	6941.7	1995	403.7	2008	1161.6
1983	7655.6	1996	341.0	2009	945.6
1984	4101.4	1997	1037.9	2010	958.1
1985	3088.2	1998	988.4	2011	744.2
1986	1922.2	1999	594.1	2012	739.1
1987	909.4	2000	985.5	2013	692.4
1988	438.8	2001	1232.4		
1989	284.6	2002	1251.8		

Table A2: Mean weight-at-age (kg) at the beginning of the year for the Gulf of Maine haddock stock (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	0.043	0.593	0.967	1.822	2.321	2.856	3.539	3.648	4.686
1978	0.083	0.296	0.967	1.400	2.213	2.820	3.948	3.888	6.088
1979	0.143	0.296	0.947	1.492	1.951	2.546	2.937	4.081	4.724
1980	0.169	0.506	0.951	1.463	2.077	2.754	3.095	3.558	4.204
1981	0.185	0.566	1.073	1.520	2.212	2.689	3.502	3.882	3.917
1982	0.151	0.589	0.826	1.800	2.267	2.864	3.322	3.886	4.293
1983	0.105	0.501	0.863	1.311	2.253	2.777	3.237	3.682	4.215
1984	0.123	0.384	0.907	1.471	2.003	2.743	3.413	3.897	4.073
1985	0.139	0.557	0.932	1.513	2.054	2.483	3.370	4.006	4.153
1986	0.174	0.400	1.081	1.247	2.052	2.416	2.850	3.612	4.592
1987	0.146	0.653	0.898	1.547	1.870	2.431	2.857	3.602	5.279
1988	0.142	0.380	0.958	1.607	2.268	2.490	3.178	3.902	5.180
1989	0.126	0.598	0.835	1.398	1.950	2.708	3.025	4.195	4.244
1990	0.135	0.464	1.292	2.375	2.113	2.669	3.275	3.651	4.189
1991	0.146	0.658	1.249	2.025	3.175	2.692	3.192	4.075	3.881
1992	0.165	0.643	1.604	1.926	2.656	3.047	2.480	3.548	3.450
1993	0.149	0.630	1.378	1.898	2.192	2.838	3.226	2.667	3.657
1994	0.148	0.533	1.186	1.866	2.500	2.606	3.315	3.402	3.721
1995	0.162	0.527	0.944	1.678	2.349	3.286	3.395	4.342	5.665
1996	0.076	0.439	0.906	1.436	1.974	2.819	2.953	3.141	3.164
1997	0.147	0.539	1.095	1.329	2.050	2.557	3.065	2.752	3.607
1998	0.124	0.579	1.108	1.800	1.914	2.574	3.170	3.067	2.988
1999	0.077	0.397	1.106	1.523	1.792	2.061	2.543	3.200	3.295
2000	0.137	0.411	0.778	1.402	1.685	1.882	2.143	2.477	3.101
2001	0.122	0.469	0.852	1.190	1.657	1.971	2.120	2.436	2.532
2002	0.086	0.346	0.908	1.252	1.532	1.955	2.385	2.258	2.624
2003	0.147	0.267	0.668	1.076	1.354	1.654	2.112	2.480	2.502
2004	0.107	0.428	0.681	1.109	1.249	1.528	1.761	2.060	2.202
2005	0.133	0.333	0.656	0.940	1.401	1.372	1.663	1.880	2.297
2006	0.121	0.375	0.690	0.722	1.215	1.537	1.461	1.668	2.006
2007	0.122	0.374	0.614	0.938	0.916	1.404	1.632	1.536	1.707
2008	0.096	0.362	0.743	0.954	1.190	1.213	1.565	1.681	1.744
2009	0.136	0.329	0.645	1.016	1.217	1.447	1.382	1.754	1.946
2010	0.150	0.421	0.741	0.928	1.238	1.399	1.674	1.825	2.067
2011	0.177	0.462	0.775	0.959	1.246	1.493	1.671	1.820	2.113
2012	0.125	0.441	0.724	1.041	1.292	1.414	1.670	1.807	1.975
2013	0.138	0.370	0.673	1.048	1.210	1.421	1.532	1.890	2.106

Table A3: Mean weight-at-age (kg) of landings for the Gulf of Maine haddock stock (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	0.113	0.757	1.163	2.008	2.558	3.358	3.709	3.587	4.686
1978	0.113	0.777	1.234	1.684	2.438	3.108	4.642	4.075	6.088
1979	0.337	0.774	1.155	1.805	2.261	2.659	2.775	3.587	4.724
1980	0.468	0.760	1.168	1.852	2.389	3.354	3.602	4.562	4.204
1981	0.560	0.685	1.516	1.978	2.641	3.026	3.657	4.184	3.917
1982	0.376	0.620	0.995	2.137	2.598	3.106	3.646	4.129	4.293
1983	0.181	0.667	1.200	1.727	2.376	2.969	3.373	3.719	4.215
1984	0.313	0.816	1.233	1.803	2.324	3.166	3.923	4.502	4.073
1985	0.315	0.980	1.068	1.859	2.339	2.652	3.588	4.090	4.153
1986	0.503	0.507	1.192	1.456	2.265	2.495	3.062	3.636	4.592
1987	0.350	0.856	1.592	2.008	2.402	2.609	3.272	4.236	5.279
1988	0.331	0.412	1.100	1.623	2.561	2.582	3.871	4.652	5.180
1989	0.251	1.126	1.779	1.824	2.343	2.864	3.543	4.545	4.244
1990	0.296	0.831	1.543	3.331	2.450	3.041	3.745	3.762	4.189
1991	0.347	1.459	1.880	2.657	3.027	2.958	3.350	4.433	3.881
1992	0.448	1.192	1.764	1.973	2.654	3.067	2.079	3.757	3.450
1993	0.364	0.885	1.592	2.041	2.436	3.035	3.393	3.422	3.657
1994	0.362	0.787	1.589	2.186	3.062	2.788	3.620	3.410	3.721
1995	0.275	0.802	1.156	1.774	2.525	3.526	4.133	5.209	5.665
1996	0.337	0.674	1.073	1.803	2.196	3.148	2.473	2.387	3.164
1997	0.354	0.891	1.802	1.662	2.330	2.977	2.985	3.063	3.607
1998	0.250	0.975	1.448	1.827	2.212	2.843	3.376	3.152	2.988
1999	0.266	0.611	1.309	1.608	1.765	1.926	2.281	3.033	3.295
2000	0.260	0.607	1.022	1.535	1.773	2.013	2.390	2.696	3.101
2001	0.242	0.889	1.260	1.490	1.811	2.210	2.243	2.483	2.532
2002	0.121	0.473	1.025	1.340	1.631	2.143	2.598	2.303	2.644
2003	0.318	0.583	0.887	1.230	1.468	1.770	2.134	2.425	2.513
2004	0.185	0.560	0.809	1.373	1.358	1.681	1.820	2.027	2.208
2005	0.286	0.583	0.815	1.139	1.464	1.443	1.684	1.954	2.297
2006	0.238	0.474	0.840	0.745	1.359	1.644	1.507	1.683	2.008
2007	0.243	0.560	0.777	1.121	1.203	1.510	1.625	1.578	1.714
2008	0.156	0.544	0.995	1.207	1.341	1.339	1.700	1.740	1.758
2009	0.304	0.699	0.809	1.135	1.282	1.625	1.563	1.877	1.947
2010	0.350	0.609	0.785	1.129	1.406	1.563	1.731	2.131	2.069
2011	0.341	0.588	1.029	1.191	1.401	1.602	1.801	1.915	2.113
2012	0.246	0.538	0.954	1.106	1.406	1.451	1.742	1.815	1.979
2013	0.283	0.550	0.870	1.267	1.498	1.486	1.658	2.051	2.104

Table A4: Maturity-at-age for Gulf of Maine haddock (Michael Palmer, pers. commn).

Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
0.036	0.284	0.809	0.978	0.998	1.000	1.000	1.000	1.000

Table A5: Total (commercial and recreational landings and discards) catches-at-age for the Gulf of Maine haddock stock (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	39'755	1'762'962	53'167	366'967	184'629	189'299	0	0	2'411
1978	0	374'650	2'291'417	172'388	363'003	208'654	10'580	0	5'290
1979	0	67'315	559'608	1'576'962	183'133	99'093	45'294	10'898	0
1980	0	884'750	104'084	755'832	1'366'770	143'816	95'570	27'794	25'756
1981	2'068	1'604'702	721'620	293'675	342'978	545'064	92'209	117'389	27'084
1982	30'427	620'596	1'519'414	620'677	100'582	300'972	477'524	107'352	75'881
1983	10'807	12'387	836'523	976'308	791'273	148'624	252'954	348'053	115'652
1984	1'202	88'981	49'873	597'996	256'658	364'974	62'198	64'813	147'568
1985	889	30'219	349'627	85'945	356'193	152'044	242'038	47'396	54'557
1986	4'278	10'819	183'531	358'782	81'336	114'028	86'352	102'482	14'690
1987	0	20'569	34'669	106'129	48'809	34'435	56'925	33'835	16'451
1988	305	471	12'442	12'340	54'752	55'564	7'635	15'049	4'149
1989	1'390	23'187	3'477	42'428	19'308	23'964	15'004	764	943
1990	7'007	2'033	143'062	1'686	28'820	17'607	27'466	4'050	0
1991	3'130	7'153	16'338	58'599	28'398	27'861	12'632	5'811	3'140
1992	1'819	13'092	94'371	36'543	19'112	2'246	1'134	0	1'895
1993	3'654	20'094	36'293	22'965	9'918	10'957	4'586	1'713	1'158
1994	6'455	23'681	44'531	13'600	3'419	9'230	5'675	1'711	705
1995	2'722	71'268	90'548	75'684	10'164	6'273	4'656	4'345	3'038
1996	2'789	23'528	129'505	56'458	16'363	4'055	7'112	5'599	1'162
1997	1'673	7'336	166'754	256'770	90'137	18'896	6'878	2'788	2'280
1998	5'833	23'752	25'097	132'738	192'766	52'737	17'433	8'611	7'557
1999	5'325	3'788	39'470	65'848	96'775	69'185	38'452	7'149	5'879
2000	2'355	68'641	66'083	106'777	65'090	128'456	72'058	31'811	25'699
2001	250	29'532	235'124	133'562	96'770	87'348	80'744	40'447	24'091
2002	420	2'372	27'821	275'333	117'143	110'413	32'129	70'430	68'048
2003	112	10'816	6'947	54'106	506'905	90'486	62'967	21'551	70'262
2004	1'834	1'903	14'147	32'957	71'982	512'704	59'670	34'048	51'126
2005	3'102	33'576	6'330	49'301	84'813	138'500	534'892	53'682	71'810
2006	2'461	2'174	123'574	8'459	52'663	71'713	83'463	366'977	61'040
2007	7'838	24'934	17'335	332'664	11'399	54'415	43'212	87'858	371'105
2008	1'779	18'476	55'817	19'091	407'625	5'033	42'176	29'576	225'281
2009	62	3'367	40'230	51'070	15'069	294'907	5'334	31'991	146'769
2010	2'412	6'725	13'762	39'606	52'249	19'113	294'288	3'477	134'175
2011	6'319	19'160	4'549	4'734	50'912	47'368	16'338	181'006	93'273
2012	2'642	110'559	48'841	19'988	12'290	67'218	37'764	13'802	204'436
2013	23'980	36'977	317'467	48'103	18'637	9'159	41'078	27'677	76'878

Table A6: Catch-at-age of haddock in the NEFSC offshore spring research vessel bottom trawl surveys in the Gulf of Maine, 1977-2013 (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+	Cumulative 1-9+	CV
1977	1306.1	4237.2	40.7	1731.1	499.9	700.8	0.0	0.0	0.0	8515.7	(0.31)
1978	107.0	854.5	444.4	37.7	255.0	0.0	0.0	0.0	0.0	1698.5	(0.40)
1979	365.2	121.2	879.4	1587.7	292.3	168.7	114.5	65.3	0.0	3594.3	(0.22)
1980	1319.1	191.3	223.4	684.5	274.2	31.6	0.0	0.0	46.0	2770.0	(0.38)
1981	1396.3	1370.0	688.0	299.7	437.0	208.9	31.7	42.2	50.9	4524.7	(0.25)
1982	0.0	505.5	1168.5	466.4	177.4	86.3	128.5	15.8	15.8	2564.1	(0.31)
1983	1746.6	167.1	1361.8	384.0	608.6	0.0	136.0	67.6	28.1	4499.9	(0.40)
1984	24.3	713.9	68.1	374.5	134.9	0.0	0.0	56.1	0.0	1371.9	(0.41)
1985	16.0	401.1	1349.6	68.3	194.3	103.8	62.4	24.8	0.0	2220.2	(0.38)
1986	63.9	0.0	203.0	453.3	0.0	45.5	91.2	28.7	0.0	885.5	(0.46)
1987	45.0	30.8	38.8	0.0	0.0	0.0	0.0	0.0	0.0	114.6	(0.36)
1988	54.4	0.0	0.0	18.2	149.2	0.0	0.0	13.0	0.0	234.7	(0.52)
1989	0.0	44.6	14.9	0.0	14.9	29.7	0.0	0.0	0.0	104.1	(0.75)
1990	14.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.9	(0.54)
1991	17.8	9.3	9.3	55.9	0.0	0.0	0.0	0.0	0.0	92.2	(0.53)
1992	106.0	0.0	0.0	136.3	0.0	0.0	0.0	0.0	0.0	242.2	(0.59)
1993	326.3	183.4	0.0	0.0	36.2	18.2	0.0	0.0	0.0	564.0	(0.45)
1994	92.2	227.7	145.8	37.2	0.0	0.0	0.0	0.0	0.0	502.9	(0.34)
1995	552.6	300.0	99.1	28.7	0.0	0.0	0.0	28.7	0.0	1009.0	(0.46)
1996	0.0	45.7	183.4	153.4	0.0	0.0	0.0	0.0	0.0	382.5	(0.31)
1997	970.2	262.6	322.1	753.1	87.5	27.9	0.0	0.0	0.0	2423.6	(0.40)
1998	100.6	57.7	0.0	77.4	11.3	0.0	0.0	0.0	0.0	247.0	(0.41)
1999	4663.8	108.8	199.9	36.2	280.9	55.0	0.0	0.0	0.0	5344.7	(0.39)
2000	1293.0	1465.8	1218.3	171.1	155.4	54.4	163.1	0.0	0.0	4521.0	(0.41)
2001	91.4	158.1	1369.4	616.0	218.3	241.1	90.6	53.4	122.5	2960.7	(0.56)
2002	4132.1	257.9	751.4	1772.7	122.7	34.2	27.9	45.5	0.0	7144.4	(0.51)
2003	449.8	260.6	113.6	134.6	2525.9	254.4	151.9	44.6	61.4	3996.9	(0.25)
2004	144.0	0.0	193.1	27.2	119.2	782.2	45.5	0.0	18.2	1329.4	(0.35)
2005	12.9	214.8	0.0	124.0	101.1	274.3	316.4	0.0	36.2	1079.7	(0.39)
2006	224.1	95.7	2068.1	397.9	130.4	24.0	251.9	682.5	72.4	3947.0	(0.45)
2007	194.8	106.2	34.9	303.5	0.0	35.3	36.2	35.3	218.8	965.1	(0.37)
2008	54.4	706.8	508.9	0.0	379.5	0.0	33.4	64.8	368.2	2116.0	(0.49)
2009	40.2	111.5	527.1	274.5	49.8	685.7	0.0	16.9	211.5	1917.3	(0.36)
2010	129.0	15.8	9.9	163.8	161.7	63.3	985.2	0.0	512.8	2041.4	(0.35)
2011	694.6	248.6	12.1	0.0	31.1	218.3	0.0	203.0	136.4	1544.2	(0.34)
2012	666.2	1991.0	241.2	61.4	0.0	203.4	105.6	54.4	406.3	3729.4	(0.41)
2013	11846.9	1011.1	2037.6	168.6	45.3	33.6	145.3	100.2	116.9	15505.4	(0.44)

Table A7: Catch-at-age of haddock in the NEFSC offshore autumn research vessel bottom trawl surveys in the Gulf of Maine, 1977-2013 (Michael Palmer, pers. commn).

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+	Cumulative 1-9+	
1977	3863.8	4289.8	158.9	1309.2	149.9	360.0	0.0	0.0	128.6	10260.4	(0.32)
1978	86.2	1941.1	7098.5	184.7	954.8	1450.9	156.2	0.0	145.2	12017.6	(0.18)
1979	508.5	109.6	1389.5	3425.1	597.4	535.9	153.1	0.0	16.4	6735.6	(0.20)
1980	637.1	365.7	0.0	373.5	1330.3	796.2	226.8	161.1	116.1	4006.9	(0.33)
1981	749.0	588.0	1276.7	421.7	1002.1	1004.6	152.2	386.6	0.0	5581.0	(0.18)
1982	46.3	733.6	1134.3	470.1	61.9	0.0	120.2	120.2	120.2	2806.9	(0.35)
1983	667.8	63.3	845.3	629.9	502.6	222.2	85.5	205.5	0.0	3222.2	(0.28)
1984	263.3	668.2	0.0	365.9	0.0	517.2	0.0	42.7	267.7	2124.9	(0.26)
1985	111.5	495.9	3499.9	21.3	240.6	167.5	487.2	0.0	84.8	5108.6	(0.40)
1986	18.2	0.0	94.7	443.3	127.0	22.7	0.0	74.1	0.0	779.9	(0.41)
1987	0.0	190.5	127.3	118.2	76.2	377.3	222.3	0.0	148.2	1259.9	(0.32)
1988	0.0	0.0	51.9	28.7	114.7	0.0	80.5	143.4	0.0	419.2	(0.65)
1989	74.3	74.3	23.5	14.9	102.5	41.5	23.5	0.0	0.0	354.5	(0.38)
1990	29.7	0.0	70.5	0.0	0.0	0.0	47.1	23.5	0.0	170.8	(0.37)
1991	59.4	0.0	0.0	52.1	0.0	0.0	0.0	0.0	0.0	111.5	(0.60)
1992	181.1	0.0	28.7	0.0	0.0	0.0	0.0	0.0	0.0	209.8	(0.53)
1993	585.0	283.3	37.1	37.1	18.5	0.0	0.0	0.0	0.0	961.0	(0.72)
1994	59.1	0.0	0.0	0.0	0.0	0.0	45.5	0.0	45.5	150.0	(0.42)
1995	117.9	756.6	230.6	45.5	44.7	0.0	0.0	0.0	28.7	1223.9	(0.54)
1996	158.6	244.6	1330.7	774.4	85.0	142.3	88.9	45.5	90.9	2960.9	(0.37)
1997	1663.6	37.7	482.3	724.1	76.9	113.2	0.0	0.0	0.0	3097.8	(0.36)
1998	301.7	521.5	162.7	539.8	379.0	87.9	61.7	30.8	0.0	2085.3	(0.51)
1999	4043.7	744.5	1038.1	316.6	598.6	643.0	212.0	73.8	72.3	7742.6	(0.30)
2000	828.4	14160.3	2112.0	1632.1	531.8	726.5	276.6	92.6	0.0	20360.1	(0.45)
2001	301.1	2876.5	6089.8	899.9	1012.5	376.6	241.5	366.9	64.3	12229.0	(0.25)
2002	150.9	17.2	677.0	3074.0	428.1	180.7	0.0	269.4	95.7	4893.0	(0.35)
2003	0.0	334.7	89.9	630.8	3089.2	439.3	66.6	0.0	209.3	4859.7	(0.20)
2004	435.2	36.2	683.9	313.1	1037.4	4050.5	154.9	195.8	146.5	7053.6	(0.25)
2005	137.1	1995.2	83.9	184.5	375.2	509.4	1431.4	110.7	112.7	4940.2	(0.19)
2006	330.8	104.5	2230.7	33.3	257.3	134.8	363.5	1062.1	91.7	4608.6	(0.26)
2007	1333.5	1061.6	276.6	2665.4	75.9	17.7	204.3	143.0	657.8	6435.8	(0.30)
2008	0.0	505.4	138.7	0.0	1308.7	0.0	201.9	142.7	541.1	2838.4	(0.31)
2009	323.5	115.0	235.2	14.4	50.6	435.4	0.0	64.6	174.6	1413.3	(0.35)
2010	43.1	26.6	62.2	210.5	363.9	139.7	301.1	0.0	151.4	1298.5	(0.47)
2011	1491.4	1045.8	245.9	121.1	1064.0	276.4	169.7	936.0	148.4	5498.7	(0.46)
2012	658.7	4122.1	13.0	0.0	24.7	34.7	34.7	0.0	34.7	4922.6	(0.58)
2013	6333.5	2273.5	8469.4	519.5	325.5	112.6	34.7	0.0	100.5	18169.3	(0.23)

Table A8: Estimated numbers at age for Georges Bank haddock for ages 1-9+ for 1977 to 2011 from NEFSC (2012, Table B17). The projected numbers (in *italics*) for 2012 to 2017 were kindly provided by Liz Brooks, based on the following assumptions (Liz Brooks, pers. commn):

1. the fully selected *F* is 0.15 in 2011 to2016;
2. the recruitment in 2012 does not appear large based on surveys, and hence is possibly similar to recent recruitment (excluding 2010);
3. at fiirst glimpse of 2013 recruitment seems VERY large; here it is arbitrarily assumed to be the same size as 2013 year-class; and
4. recruitment in years 2014-2017 is assumed to be time series median (from Table B17 in GB haddock report: NEFSC, 2012)

Year	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8	Age9+
1977	13'983	86'117	4'726	4'473	2'540	1'132	73	196	558
1978	6'125	11'447	52'655	3'698	3'041	1'610	602	56	270
1979	83'888	5'014	8'680	30'082	2'751	1'975	851	367	176
1980	10'934	68'674	4'081	5'539	18'124	1'775	1'245	412	218
1981	7'364	8'945	28'384	3'027	3'653	9'382	918	529	315
1982	2'581	6'028	5'744	13'325	1'727	2'143	5'355	453	470
1983	3'284	2'112	3'879	3'226	7'533	1'060	1'240	3'370	320
1984	18'080	2'688	1'534	2'438	2'015	4'138	621	846	1'720
1985	2'518	14'801	2'116	986	1'335	1'288	2'044	296	577
1986	16'786	2'061	9'900	1'227	628	670	844	1'190	268
1987	2'614	13'738	1'638	5'549	801	381	391	555	706
1988	19'995	2'140	9'414	1'223	3'066	544	245	239	395
1989	1'364	16'366	1'704	5'517	877	1'656	308	150	230
1990	3'406	1'115	12'081	1'285	3'600	523	927	197	174
1991	2'716	2'732	902	8'362	810	1'939	290	563	213
1992	10'741	2'217	1'799	628	4'719	533	1'123	123	263
1993	15'568	8'718	1'576	1'107	337	2'110	274	538	261
1994	15'420	12'716	6'810	896	601	169	1'063	168	334
1995	12'687	12'601	9'926	4'503	517	364	72	589	156
1996	11'778	10'372	10'232	7'572	3'262	370	271	52	586
1997	23'451	9'637	8'441	7'866	5'372	2'265	244	202	537
1998	14'637	19'187	7'760	6'664	5'768	3'892	1'658	184	382
1999	49'156	11'979	15'501	5'929	4'953	4'032	2'673	1'205	352
2000	11'668	40'242	9'768	11'874	4'366	3'510	2'791	1'843	703
2001	90'866	9'551	32'580	7'433	8'306	3'045	2'398	1'946	1'422
2002	5'551	74'382	7'689	24'515	5'188	5'647	1'903	1'570	2'824
2003	2'870	4'542	60'540	5'983	17'209	3'414	3'629	1'197	2'192
2004	412'375	2'345	3'703	47'812	4'483	11'670	2'251	2'324	1'685
2005	7'985	337'041	1'890	2'922	34'534	3'014	6'917	1'227	1'336
2006	28'833	6'520	275'392	1'510	2'086	20'631	1'769	4'008	1'084
2007	7'123	23'458	5'322	222'615	1'172	1'371	12'024	1'154	2'296
2008	9'365	5'814	19'042	4'148	173'187	801	927	8'192	2'065
2009	4'773	7'660	4'723	15'197	3'122	130'269	552	661	4'480
2010	7'605	3'891	6'152	3'687	11'644	2'298	94'968	376	2'206
2011	374'008	6'195	3'132	4'658	2'672	8'234	1'481	65'649	300
2012	*8'000*	*305'513*	*5'022*	*2'477*	*3'603*	*1'967*	*5'802*	*1'061*	*47'393*
2013	*374'008*	*6'535*	*247'686*	*3'972*	*1'916*	*2'653*	*1'386*	*4'157*	*34'820*
2014	*11'301*	*305'513*	*5'298*	*195'868*	*3'072*	*1'411*	*1'869*	*993*	*28'010*
2015	*11'301*	*9'231*	*247'686*	*4'190*	*151'496*	*2'262*	*994*	*1'339*	*20'842*
2016	*11'301*	*9'231*	*7'484*	*195'868*	*3'240*	*111'547*	*1'594*	*712*	*15'940*
2017	*11'301*	*9'231*	*7'484*	*5'918*	*151'496*	*2'386*	*78'606*	*1'142*	*11'967*

ANNEX B - The Statistical Catch-at-Age Model

The text following sets out the equations and other general specifications of the SCAA 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 then 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).

B.1. Population dynamics

B.1.1 Numbers-at-age

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

$$N_1 = R_{y+1} \quad \text{(B1)}$$

$$N_{y+1,a+1} = N_{y,a}e^{-Z_{y,a}} \qquad \text{for } 1 \le a \le m-2 \quad \text{(B2)}$$

$$N_{y+1,m} = N_{y,m-1}e^{-Z_{y,m-1}} + N_{y,m}e^{-Z_{y,m}} \quad \text{(B3)}$$

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 1-year-old fish) at the start of year *y*,

m is the maximum age considered (taken to be a plus-group, and set here to be 9).

$Z_{y,a} = F_y S_{y,a} + M_a$ 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 1-year old) at the start of year *y* is taken as an average recruitment, allowing for annual fluctuation about the deterministic relationship.

$$R_y = R_{gm}e^{\varsigma_y} \quad \text{(B4)}$$

R_{gm} is the geometric mean (median under a log-normality assumption) recruitment over the period considered (see equation B18 below),

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

The spawning biomass at the start of year *y*, is computed as:

$$B_y^{\rm sp} = \sum_{a=1}^{m} f_a w_{y,a}^{\rm strt} N_{y,a} e^{-Z_{y,a}/4} \tag{B5}$$

because spawning for the haddock stock under consideration is taken to occur three months after the start of the year and some mortality has therefore occurred,

where

$w_{y,a}^{\rm strt}$ is the mass of fish of age *a* during spawning (Table A2), and

f_a is the proportion of fish of age *a* that are mature (Table A4).

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

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

$$C_y = \sum_{a=1}^{m} w_{y,a}^{\rm mid} C_{y,a} = \sum_{a=1}^{m} w_{y,a}^{\rm mid} N_{y,a} \ S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B6}$$

where

$w_{y,a}^{\rm mid}$ denotes the mass of fish of age *a* landed in year *y* (Table A3),

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

The model estimate of survey index is computed as:

$$N_y^{\rm surv} = \sum_{a=1}^{m} S_a^{\rm surv} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \tag{B7}$$

where

S_a^{surv} is the survey selectivity for age *a*, which is taken to be year-independent, and

T^{surv} is the month in which the survey is taking place (T^{surv}=4 for spring surveys and T^{surv}=10 for fall surveys)

B.1.4. Initial conditions

For the first year (y_0) considered in the model, the numbers-at-age are estimated directly for ages 1 to a^{est}, with a parameter ϕ mimicking recent average fishing mortality for ages above a^{est}, i.e.

$$N_{y_0,a} = N_{{\rm start},a} \qquad \text{for } 1 \le a \le a^{est} \tag{B8}$$

and

$$N_{{\rm start},a} = N_{{\rm start},a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } a^{est} < a \le m-1 \tag{B9}$$

$$N_{{\rm start},m} = N_{{\rm start},m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \Big/ (1 - e^{-M_m} (1 - \phi S_m)) \tag{B10}$$

B.2. The (penalised) likelihood function

The model can be fit to (a subset of) survey abundance indices, and commercial and survey 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 (- $\ell\mathrm{n}L$) are as follows.

B2.1. Survey abundance data

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

$$I_y^{surv} = \hat{I}_y^{surv} \exp\left(\varepsilon_y^{surv}\right) \quad \text{or} \quad \varepsilon_y^{surv} = \ell\mathrm{n}\left(I_y^{surv}\right) - \ell\mathrm{n}\left(\hat{I}_y^{surv}\right) \tag{B11}$$

where

I_y^{surv} is the survey biomass index for survey *surv* in year *y*,

$\hat{I}_y^{surv} = \hat{q}^{surv}\widehat{N}_y^{surv}$ is the corresponding model estimate, where

$\hat{q}^{surv}$ is the constant of proportionality (catchability) for the survey series *surv*, and

ε_y^{surv} from $N\left(0, \left(\sigma_y^{surv}\right)^2\right)$.

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

$$-\ell\mathrm{n}\, L^{\mathrm{survey}} = \sum_{surv}\sum_{y}\left\{\ell\mathrm{n}\left(\sqrt{\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2}\right) + \left(\varepsilon_y^{surv}\right)^2 / \left[2\left(\left(\sigma_y^{surv}\right)^2 + \left(\sigma_{Add}^{surv}\right)^2\right)\right]\right\} \tag{B12}$$

where

σ_y^{surv} is the standard deviation of the residuals for the logarithm of index *i* in year *y* (which is input), and

σ_{Add}^{surv} is the square root of the additional variance for survey biomass series *surv*, which is estimated in the model fitting procedure, with an upper bound of 0.5.

The catchability coefficient q^{surv} for survey biomass index *surv* is estimated by its maximum likelihood value:

$$\ell n\, \hat{q}^{surv} = 1/n_{surv} \sum_{y}\left(\ln I_y^{surv} - \ln \widehat{N}_y^{surv}\right) \tag{B13}$$

B.2.3. Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function is given by:

$$-\ell\mathrm{n}\, L^{\mathrm{CAA}} = W_{CAA}\sum_{y}\sum_{a}\left[\ell n\left(\sigma_a^{com}\right) + \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / 2\left(\sigma_a^{\mathrm{com}}\right)^2\right] \tag{B14}$$

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*, where

$$\hat{C}_{y,a} = N_{y,a} \; S_{y,a} F_y \left(1 - e^{-Z_{y,a}}\right) / Z_{y,a} \tag{B15}$$

W_{CAA} is a relative weighting accorded to these data in the negative log-likelihood, which is set equal to 1 for the Base Case runs in these analyses,

and

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

$$\hat{\sigma}_{CAA}^{com} = \sqrt{\sum_y \left(\sqrt{p_{y,a}} - \sqrt{\hat{p}_{y,a}}\right)^2 / \sum_y 1} \tag{B16}$$

This formulation mimics a multinomial form for the error distribution by forcing a near-equivalent variance-mean relationship for the error distributions.

Commercial catches-at-age are incorporated in the likelihood function using equation (B14), for which the summation over age *a* is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group), taken here as 1 and 9 respectively.

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 (equation (B14)) where:

$p_{y,a}^{surv} = C_{y,a}^{surv} / \sum_{a'} C_{y,a'}^{surv}$ is the observed proportion of fish of age *a* in year *y* for survey *surv*,

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

$$\hat{p}_{y,a}^{surv} = S_a^{\text{surv}} N_{y,a} e^{-Z_{y,a} T^{surv}/12} \Big/ \sum_{a'=0}^{m} S_{a'}^{\text{surv}} N_{y,a'} e^{-Z_{y,a'} T^{surv}/12} \tag{B17}$$

As for the commercial data, the minus and plus groups for both surveys are taken here as 1 and 9 respectively.

B.2.5. Stock-recruitment function residuals

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

$$-\ell nL^{\text{pen}} = W_{SRpen} \left[\sum_{y=1977}^{2013} \left[\varepsilon_y^2 / 2\sigma_{\text{R,y}}^2\right] + 10000 \left(\sum_{y=1977}^{2010} \varepsilon_y \right)^2 \right] \tag{B18}$$

where

ε_y from $N\left(0, (\sigma_{R,y})^2\right)$,

$\sigma_{R,y} = \sqrt{\ln\left(CV_y^2 + 1\right)}$ is the standard deviation of the log-residuals, which is input. For the SCAA-Base assessment, $CV_y = 1$ for all years.

$W_{SRpen} = 1$.

Note that the purpose of the second term on the right hand side of equation B.18 is to ensure that R_{gm} corresponds to the geometric mean (likely to closely approximate the median) of the pre-2011 recruitments.

B.2.5. Catches

$$-\ell nL^{\text{Catch}} = \sum_u \sum_y \left[\frac{\ell n C_y - \ell n \hat{C}_y}{2\sigma^2_{\text{C,y}}} \right] \qquad \text{(B19)}$$

where

C_y is the observed catch in year *y*,

$\hat{C}_y$ is the predicted catch in year *y*, and

$\sigma_{\text{C,y}}$ is the input CV in year *y*. It is taken to be 0.15 over 1977-1981, 0.1 over 1982-1988 and 0.05 thereafter, as for the preferred ASAP model..

B.3. Estimation of precision

Where quoted, CV's or 90% probability interval estimates are based on the Hessian.

B.4. Model parameters

B.4.1. Fishing selectivity-at-age:

The commercial and survey fishing selectivities are estimated separately for each age. For the NEFSC offshore surveys, the fishing selectivities are assumed to be flat from age 4 and 6 onwards for the spring and fall surveys respectively.

The commercial selectivity is taken to differ over three blocks, as for the preferred ASAP model: 1977-1988, 1989-2004 and 2005-2013. These selectivities are set to 1 for age 7, and may not increase for greater ages.

B.4.2. Natural mortality

This was set to 0.2, independent of year and age.

B.4.3. Biological reference points

In the computation of the biological reference points, the weight-at-age, maturity-at-age and commercial selectivity vectors are taken as the average over the 2009-2013 period.