SBW2015P1B1

A Management Strategy Evaluation

for Campbell Island Rise

southern blue whiting

ISL Client Report
for
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Executive summary

A management strategy evaluation (MSE) was performed for the Campbell Island Rise southern blue whiting stock (SBW6I) to determine an appropriate limit reference point, target biomass range, and harvest control rule (HCR). The proposed management strategies were designed to be consistent with New Zealand's Harvest Strategy Standard (MFish, 2008), and the Marine Stewardship Council's certification requirements (MSC, 2014).

As part of the MSE the most recent assessment for SBW6I was revised. The revised assessment estimated natural mortality (M) and used a new prior on the mature-biomass acoustic q (borrowing the prior for Bounty Platform that incorporated the recent large increase in target strength uncertainty). Estimation of virgin biomass (B_0) and M was confounded and it was necessary to use a strongly informed prior on M to stabilize the assessment estimates. This prior very likely introduced a negative bias for M and B_0 and hence gave a conservative (rather than risk-neutral) assessment. Stock status in the 2013 calendar year was estimated at 68–126% B_0 (with 95% probability).

The revised stock assessment results were used to ground-truth the operating model used in the MSE. In particular, the joint posterior of stock-recruitment steepness (h) and M was used to capture the uncertainty in the productivity of the stock. Bayesian estimation was used to estimate reference points for the operating model and performance indicators for the numerous HCRs that were trialed.

The limit reference point (LRP) was defined to be the maximum of 20% B_0 and 50% B_{MSY}. The estimates of deterministic B_{MSY}, for Beverton-Holt and Ricker stock-recruit relationships over a range of h and M values, were all less than 40% B_0 and hence the LRP was estimated at 20% B_0 with total certainty. A target biomass range of 30–60% B_0 was selected to trial HCRs. The objective was to find HCRs that maintained spawning stock biomass above the lower bound of the target biomass range "most of the time" (at least 70%) and rarely allowed it to go below the LRP (no more than 5% of the time).

One of the major requirements of the Industry is that SBW6I TACCs are relatively stable from year to year. To accommodate this requirement, four HCRs were developed which differed only in the level of constraint that they imposed on year-to-year changes in TACC. All of the HCRs were built on the same relationship between estimated stock status and next year's exploitation rate. This relationship has a maximum exploitation rate of 20% when stock status is estimated at 60% B_0 or higher with the exploitation rate monotonically decreasing to zero at 10% B_0. The "provisional" TACC from a stock assessment is the exploitation rate multiplied by the estimated vulnerable biomass. The final TACC is equal to the provisional TACC if it is inside the constraints defined by the HCR, otherwise it is set equal to one of the constraints (i.e., the maximum or the minimum TACC allowed in that year).

With the relationship between stock status and exploitation rate that the four HCRs share, the highest long-term yield is achieved when no constraints are placed on annual changes in

TACC. However, without any constraints, the annual variation in TACCs would be far too high to be practical for the Industry (e.g., fishing capacity might have to very high one year and then substantially reduced the next). The four HCRs presented here have contrasting outcomes in terms of the likely variability of TACCs and the possible increases in TACC over the next few years. There is a trade-off between variability and yield; the lower the variability, the lower the average yield; the higher the variability the higher the average yield.

All four of the HCRs have acceptable risk profiles and will very likely meet MSC requirements and MPI's harvest strategy standard. All of the rules, over the long term, will lead to substantial changes in TACC as SSB fluctuates due to natural changes in recruitment. Only a constant catch policy would avoid long-term fluctuations in catch. However, to have acceptable risk, such a policy would set the TACC at a very low level.

For all of the HCRs it is assumed that catch-at-age data will be collected each year and included in annual stock assessment updates. The frequency of acoustic surveys was found to have little effect on the performance of the HCRs if the stock assessment estimators were assumed to be unbiased. However, if the absence of acoustic survey indices leads to an accumulating bias then, to maintain low risk, acoustic surveys should occur every 2–5 years depending on which HCR is adopted. If the most constrained HCR (C05) is adopted then the simulation results suggest that surveys should occur every 3–5 years. If the least constrained HCR (C20) was adopted then surveys would need to be every 2–4 years.

The MSE should be revised and the "optimal" survey frequency should be reconsidered. when more information is available on southern blue whiting tilt-averaged target strength (which should lead to better information on the scale and productivity of the stock).

Introduction

This document describes a management strategy evaluation (MSE) for Campbell Island Rise southern blue whiting (SBW6I). The objective of the work was to determine a limit reference point, a biomass target range, and a harvest control rule (HCR) which are compatible with both the New Zealand's Harvest Strategy Standard (MFish, 2008) and the Marine Stewardship Council's certification requirements (MSC, 2014). In particular, the reference points and HCR developed in this document aim to be consistent with: PI 1.2.1 Harvest Strategy, and PI 1.2.2 Harvest Control Rules and Tools.

The SBW6I stock was explicitly modelled in the MSE based on a revised stock assessment to the end of the 2013 calendar year (see Appendix B). The greatest uncertainties with regard to the population parameters are the stock-recruitment (SR) relationship and the value of natural mortality (M). The MSE focused on ensuring that the proposed harvest strategy is robust to these uncertainties. In terms of B_{MSY}, the SR relationship is critical, with both the form of the relationship (Beverton-Holt and Ricker were considered) and the level of steepness (h, being the proportion of virgin recruitment at 20% B_0) being important.

Four HCRs with excellent long-term performance were determined by simulation using the SBW6I specific model. The final step was checking that the HCRs also provided good short-term performance for SBW6I. This was done by applying the HCR to projections from the revised stock assessment results.

Methods

An MSE requires a number of components. There must be a population model which keeps track of the true state of the population and incorporates an appropriate level of "reality". In this MSE the model was an age-structured, single-sex, single-area model, tailored to SBW6I and similar to standard stock assessment models. However, the MSE model had some extra features which allow for the specification of parameters that are not usually estimated during a stock assessment (e.g., correlation between annual year class strengths).

The other major component of an MSE is a method whereby the total allowable catch (TAC) is updated. In reality, for SBW6I, this will be by Bayesian stock assessment from time to time in conjunction with a HCR. It is not possible to model full Bayesian stock assessments realistically as the calculation of estimates can take several days for a single assessment (therefore doing thousands of simulated Bayesian assessments is not possible in a reasonable timeframe). In this MSE, the stock assessment was approximated by using estimators based on the true values from the operating model. Two types of estimates were made: current stock status (current mid-season mature biomass divided by virgin mid-season mature biomass) and next year's vulnerable biomass (the beginning of spawning-season biomass available to the fishery). The two estimates were calculated from a matrix of estimated numbers-at-age that was maintained within the population model. This ensured that the estimators were correlated with each other and also correlated across years (as is the case in a real stock assessment).

The population model and the method of updating TACs are part of what can be termed the "operating model". It represents "reality" at any time during a simulation. The testing of various HCRs requires that the properties of each HCR are determined by very long-term simulations. This requires that thousands of years are simulated to accurately calculate the average performance. An alternative approach, that is often used, is to calculate the performance of HCRs over the short to medium term working from a current stock assessment. The problem with this approach is that the results could be very dependent on current stock status and have little to do with whether the rules are intrinsically conservative or aggressive. Good long-term performance ensures that the rules are appropriate provided that the current stock status is within the range at which the HCR maintains the stock.

The objective of the MSE is to find a HCR that maintains the mid-season mature biomass within a biomass range that is consistent with B_{MSY} and allows little possibility of recruitment overfishing. The HCR must perform well over a wide range of assumptions; it should perform very well when the operating model is consistent with the assumptions under which the HCR was defined, but it must also be robust to errors in a wide range of assumptions (e.g., the form of the SR relationship, different values of natural mortality (M) and SR steepness).

The MSE was performed using purpose written code in the statistical package R.

The operating model

Full details of the operating model equations are given in Appendix A. A summary is given below.

The population model keeps track of fish in a single stock according to age (1-30 years with no plus group) and maturity (i.e., mature or immature). Therefore, the model is single-sex, single-area, and age-structured. The annual cycle was: ageing, recruitment (into age class 1), maturation, and then a full-year of natural mortality followed by an instantaneous end-of-year fishery on the mature/spawning fish. The SR relationship was either Beverton-Holt or Ricker and average recruitment was calculated according to mid-season stock status (i.e., after half the fishing mortality). Year class strengths (YCS) were log-normally distributed with a specified recruitment variability (sigmaR = s.d. of log YCS) and correlation (rho = 1-year lag correlation of log YCS). In a sensitivity, a mixture distribution was used for YCS with "weak" YCS being lognormal and correlated and "strong" YCS being lognormal and uncorrelated.

Maturation was constant from year-to-year with first maturation at age 2 years and full maturation at age 6 years. Fishing was independent of age and only on the mature fish.

The population was initialised in deterministic equilibrium and virgin mid-season mature biomass is denoted as B_0. The average unfished mid-season mature biomass was calculated from a long-term simulation with no fishing. If this was not equal to B_0 then a correction factor was applied (this was generally small except when a Ricker SR relationship was used, see Appendix A and also Cordue, 2001).

Two main estimates were produced for each year of a simulation: current stock status and next year's vulnerable biomass. As already described, the estimators were highly correlated within year and across years. The estimate of stock status was available to be used in a HCR to calculate the exploitation rate (U) to be applied to the estimate of vulnerable biomass: $\text{TACC} = U\hat{B}_{vul}$ (subject to constraints on how much the TACC is allowed to change from year to year). A HCR need not update the TACC each year, but the estimates are available to be used if needed. In the base model the control rule does update the TACC every year. The total catch was assumed equal to the TACC subject to a maximum exploitation rate of 80%.

Ground-truthing of the operating model

The results from the revised SBW6I stock assessment (Appendix B) were used for specifying parameter values and/or ranges used in the operating model:

Parameter	Median	95% CI
M	0.25	0.19–0.31
h (BH)	0.95	0.84–0.99
h (Ricker)	2.23	1.57–3.10
sigmaR	1.17	1.06–1.32
rho	0.25	0.09–0.40

To represent the uncertainty in M and h a random sample of 5000 was taken from their joint posterior distribution for use in the MSE (BH in the base model, Ricker in a sensitivity). In the base model sigmaR and rho were fixed at the median values (and sensitivities were performed for higher and lower values).

For the sensitivity that used a mixture distribution for the YCS the marginal posterior distributions for the three very strong cohorts (1991, 2006, and 2009) were used to define a "strong" distribution and the other cohorts were used to define a "weak" distribution (both lognormal). The parameters for the mixture distribution were (where "prob" is the probability of getting either a strong or weak cohort in a single year):

	prob	mean	rsd	rho
weak	0.91	0.6	0.98	0.25
strong	0.09	5.0	0.27	0.00

Maturation was estimated for ages 2–5 years inclusive:

Age (years)	**Median**	**95% CI**
2	0.047	0.034–0.064
3	0.58	0.49–0.68
4	0.78	0.60–0.95
5	0.73	0.15–0.99

The corresponding proportions mature at age in the virgin population were:

Age (years)	**Median**	**95% CI**
2	0.047	0.034–0.064
3	0.60	0.52–0.70
4	0.91	0.83–0.98
5	0.98	0.92–1.00

These are fairly tightly defined and the median values were fixed in the operating model. The above are the estimates for the base model that used Beverton-Holt. For Ricker the estimates were almost identical.

Growth parameters consistent with the average cohort specific length-at-age values used in the revised assessment (see the CASAL population.csl file in Appendix B) were used in the operating model: L_{inf} = 48 cm, k = 0.38, t_0 = –0.1. The length (cm) to weight (gm) parameters were an average across sexes from MPI (2014): a = 0.0045, b = 3.12.

The effect of the number of acoustic surveys available on the precision of MCMC estimates was investigated by successively deleting acoustic survey observations from the revised assessment:

Last survey	**CV (%)**			**Median**		
used	B_0	B_{2013}	*Stock status*	B_0 (000 t)	B_{2013} (000 t)	*Stock status* (%)
2013	23	38	16	390	380	97
2011	21	36	15	400	400	100
2009	23	39	17	400	390	99
2006	21	54	35	300	160	54

The improvement in CV by adding acoustic data appears minimal (which is not surprising as there is only a *weakly* informed prior on the mature acoustic *q*). The only change in CVs is when the strong 2006 cohort enters the spawning population in 2009 (seen in the acoustic survey indices and the catch-at-age data) – the CVs drop because of the large increase in mean/medians. Nevertheless, it was assumed in the simulations that the addition of an acoustic survey resulted in a small reduction in the CV of the estimator of current spawning biomass (see Appendix A).

The CVs in the above table were used as a proxy for the precision of the estimators in the operating model. The simulations are over the long term which means there will be large quantities of data available and the CVs of the estimators are likely to be quite low. However, to be conservative, the "stabilized" proxy values (2009, 2011, 2013) were rounded down a little with the base *target* for average CVs being: CV(B_0^+) = 20%, CV(B_{cur}^+) = 35%, CV(SS^+) = 15% (where "+" denotes that it is an estimator of the parameter and "SS" denotes stock status). The details of how the average CVs of these estimators were tuned is given in Appendix A. The resulting CVs for the stock status and next-year's vulnerable biomass estimators were 15% and 38% respectively (with CV(B_0^+) = 19% and CV(B_{cur}^+) = 35%).

Estimation of B_{MSY} and the LRP

Bayesian estimation of B_{MSY} and the LRP was performed to account for uncertainty in h and M. This was achieved by calculating B_{MSY} and the LRP as a function of h and M over a two-dimensional grid of values and then obtaining a posterior distribution by using the given posterior samples of h and M (see above). For each pair of posterior samples (h, M) the value of B_{MSY} or the LRP was calculated by interpolation using the corresponding "grid function". The "spline" and "splinefun" functions in R were used to provide the interpolated values (these are cubic splines). Hence, the 5000 samples from the joint posterior of h and M provided 5000 samples from the posteriors of B_{MSY} and the LRP.

For given values of h and M, B_{MSY} was calculated by running the base model (or the Ricker model) with deterministic recruitment and constant U over a range of U values to determine the yield curve. The model was run for 5000 years at each value of U (to ensure deterministic equilibrium was reached) and U_{MSY} was determined to two significant figures. The LRP was defined to be the greater of 20% B_0 or 50% B_{MSY}.

Estimation of performance indicators for harvest control rules

Six performance indicators (for a given HCR) were estimated in each run: mean annual mid-season mature biomass; mean annual yield; mean exploitation rate; and the probability of the mid-season mature biomass being below 10% B_0 or being below the LRP (denoted LRP_p), or being below the lower bound of the biomass target range (denoted LB_p).

Bayesian estimation was used to account for the uncertainty in h and M. This was achieved in the same fashion as for B_{MSY} and the LRP, using interpolation via cubic splines over the grid of calculated values for fixed h and M. For each fixed pair (h, M) the HCR was applied for 10,000 years. The first 1000 years were ignored and the statistics were calculated from the remaining 9,000 years. As a check on stochastic equilibrium, the median biomass was calculated for each 3000 year segment after the initial 1000 years were discarded. The CV of the three medians was required to be less than 5% otherwise a warning was issued. Warnings were rare and in those cases the CV was just over the 5% level (and no action was taken).

The Bayesian posteriors of LRP_p and LB_p were used to derive two summary measures:

- **LRP risk**: the probability that the HCR will allow mid-season mature biomass to be below the LRP more than 5% of the time

- **depletion risk**: the probability that the HCR will allow mid-season mature biomass to be below the lower bound of the biomass target range, LB, more than 30% of the time

The probabilities are the proportion of *h*, *M* pairs where the HCR allows the poor performance with respect to the LRP or LB. The choices of 5% and 30% were not entirely arbitrary.

The mid-season mature biomass should rarely go below the LRP in the long-term; the choice is perhaps between 1% and 5%. The rarer the event the harder it is to estimate the actual probability so 5% was chosen rather than 1% (if 1% had been chosen, the simulation period of 10,000 years would probably had to have been increased).

The 30% level for the LB ensures that the spawning biomass is maintained above the LB "most of the time" (using the MSC definition of that phrase).

Robustness testing of control rules

The main robustness testing focused on just two of a set of four HCRs. The main focus of the testing was robustness to uncertainty in *h* and *M* but in addition to this, various assumption violations were laid on top of the uncertainty testing. For example, the proposed HCR was tested over the whole plausible range of *h* and *M* with a Beverton-Holt SR relationship and alternatively with a Ricker SR relationship. Also, the base model assumed unbiased estimators of stock status and vulnerable biomass. As this is unlikely to be the case, the robustness of the proposed HCRs were tested for estimators with positive biases. A higher assumed CV for the stock assessment estimators was also tested; as were higher values of sigmaR and rho.

Results

Bayesian estimates of steepness and natural mortality

The estimates of *M* were very similar for the base model (Beverton-Holt stock-recruitment relationship) and the Ricker model (Table 1). However, the estimates of steepness were very different. The Ricker model had a very high level of compensation estimated to be 160–300% of the virgin recruitment at 20% B_0 (Table 1). The Beverton-Holt model had a high estimated steepness of 85–100% R_0 (Table 1). The results are driven by the very strong year class that was estimated in 1991 when SSB was at about 20% B_0 (see Figures B18 and B19).

Table 1: Bayesian estimates of natural mortality and steepness for revised assessment models that assumed a Beverton-Holt or a Ricker stock-recruitment relationship. The median and 95% CIs are given as percentages.

	Natural mortality (*M*)(%)		Steepness (*h*) (%R_0)	
	Median	**95% CI**	**Median**	**95% CI**
Beverton-Holt	25	19–31	95	84–99
Ricker	26	20–32	223	157–310

Bayesian estimates of B_{MSY}

For the base model, estimates of B_{MSY} were highly dependent on the form of the SR relationship and the level of *h* (Tables 2 and 3). For Beverton-Holt, B_{MSY} does reduce somewhat for increasing *M* provided that *h* is high (Table 2). However, for Ricker, B_{MSY} hardly changes with increasing *M* (Table 3). In both cases, increasing *h* reduces B_{MSY}, but the reduction is far less for the Ricker relationship than for the Beverton-Holt relationship (Tables 2 and 3).

Table 2: B_{MSY} ($\%B_0$) as a function of *h* and *M* when a Beverton-Holt stock recruitment relationship was assumed (base model).

	Natural mortality (*M*)							
Steepness (*h*)	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**
0.80	26	25	25	25	25	25	25	25
0.82	25	25	25	25	24	24	24	24
0.85	24	24	24	23	23	23	23	22
0.90	22	22	21	21	21	20	20	20
0.95	19	19	18	18	18	17	17	17
1.00	15	14	14	13	13	12	11	10

Table 3: B_{MSY} ($\%B_0$) as a function of *h* and *M* when a Ricker stock-recruitment relationship was assumed (sensitivity on the base model).

	Natural mortality (*M*)							
Steepness (*h*)	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**
1.3	38	38	38	38	37	37	37	37
1.8	36	35	35	35	35	35	34	34
2.3	33	33	33	33	33	32	32	32
2.8	32	32	31	31	31	31	30	30
3.1	31	31	30	30	30	30	30	30
3.5	30	30	29	29	29	29	29	29

The Bayesian estimates of B_{MSY} were obtained from the implicit functions in Tables 2 and 3 weighted by the *h* and *M* posterior distributions. The B_{MSY} estimates for Beverton-Holt were much lower than for Ricker with the 95% CIs not overlapping (Table 4).

Table 4: Bayesian estimates of B_{MSY} for the base model assuming a Beverton-Holt or a Ricker stock-recruitment relationship. The median and 95% CIs are given as a percentage of virgin mid-season mature biomass (B_0).

	B_{MSY} ($\%B_0$)	
	Median	**95% CI**
Beverton-Holt	18	13–23
Ricker	33	30–36

Bayesian estimates of the limit reference point

The limit reference point was defined to be the greater of 20% B_0 and 50% B_{MSY}. The rationale for this definition is that the stock should not be too far below B_{MSY} and ideally never be below 20% B_0. Allowing the stock to be below 20% B_0 could (perhaps) impair recruitment, alter the role of the fish in the ecosystem and possibly result in a regime shift to a much lower carrying capacity (i.e., niche replacement).

As B_{MSY} is always less than 40% B_0 the Bayesian estimates of the LRP are, by definition, 20% B_0 with complete certainty, irrespective of the stock-recruit relationship.

Determination of a suitable target range

A suitable biomass target range has to ensure that biomass will be maintained well above the LRP for the majority of the time and that it is consistent with B_{MSY}. A number of runs were done with the base model assuming the marginal-posterior medians for h and M (Table 5). It is apparent that SSB is highly variable for SBW6I. For example, even with no fishing, SSB is below 30% B_0 for 1% of the time (Table 5). If 45% B_0 is targeted (with perfect knowledge of exploitation rates) then SSB is occasionally below 10% B_0 and is below the LRP (20% B_0) more than 10% of the time (Table 5).

Table 5: Stock status statistics for the base model (assuming M=0.25 and h=0.95) when fishing at constant exploitation rates with perfect knowledge (i.e., these results assume no error in exploitation rates). "Deterministic" means no recruitment variability while "stochastic" has the base model sigmaR (1.17) and rho (0.25).

	Deterministic		Stochastic (perfect knowledge)					
	U	Yield ($\%B_0$)	Mean B ($\%B_0$)	Mean Y ($\%B_0$)	P($B <$ $10\%B_0$)	P($B <$ $20\%B_0$)	P($B <$ $30\%B_0$)	CV(B) (%)
	0.00	0.00	100	0.0	0.00	0.00	0.01	57
$U_{30\%B0}$	0.31	11.5	30	10.8	0.08	0.41	0.66	80
$U_{35\%B0}$	0.26	10.0	35	10.4	0.04	0.29	0.55	77
$U_{40\%B0}$	0.22	9.9	40	9.9	0.02	0.20	0.45	74
$U_{45\%B0}$	0.19	9.3	44	9.3	0.01	0.14	0.37	72

The lower bound of the target range (LB) was chosen to be 30% B_0. This is well above the LRP. The upper bound on the target biomass range was chosen to be 60% B_0 which gives a mid-point for the range of 45% B_0. This range is conservative in terms of deterministic B_{MSY} but is consistent with "real world" B_{MSY} as is demonstrated by the results below for the proposed HCRs (in that SSB is maintained above the LB most of the time).

The proposed harvest control rules

Numerous HCRs were investigated but this report covers four main HCRs and variations on them which investigate acoustic survey frequency and stock assessment frequency. Each of the HCRs uses the same functional relationship between estimated stock status and exploitation rate (Figure 1). For a given stock assessment, the estimated stock status is mapped to an exploitation rate (using the functional relationship) which is then applied to the estimate of next year's vulnerable biomass to calculate a provisional TACC. The final TACC is the provisional TACC subject to minimum and maximum allowable changes from the previous TACC. The four HCRs are defined by different levels of constraint on the year-to-year changes in TACC. The total catch is assumed equal to the TACC.

The four proposed HCRs are named according to the parameter that controls the maximum allowable increase from the previous TACC:

HCR	**Up par (%)**	**Down par (%)**	**Minimum change (%)**
C05	5	10	5
C10	10	15	10
C15	15	20	10
C20	20	25	10

The minimum change is to avoid making very small changes in the TACC. If the provisional TACC is inside the previous TACC plus/minus the minimum change then no change is made. The "Up par" and "Down par" define a function which maps estimated stock status to the maximum allowable change in TACC up or down (Figure 2). For these HCRs, the Down par is always 5% greater than the Up par. This ensures that TACCs can go down faster than they can go up. It was apparent from numerous simulations that this was a necessary property for a HCR to deal with periods of poor recruitment (without a high risk of the SSB going below the LB and/or the LRP).

The constraint functions (Figure 2) are hyperbolic which allow large proportional changes in TACC when estimated stock status is low but are very restrictive (proportionally) when stock status is high (see Appendix A for the equations). The parameter value (of the hyperbolic function) is equal to the stock status at which a TACC can be changed by a factor of 2. For example, in HCR10 the Up par is 10% and the Down par is 15%. If estimated stock status was 10% B_0 then the maximum new TACC allowed is double the old TACC. If stock status was 15% B_0, then the minimum new TACC allowed is half the old TACC.

Some results are presented for other HCRs that use simpler constraints: a constant limiting factor for maximum increases and decreases (e.g., maximum new TACC no more than 1.4 times the previous TACC; minimum new TACC no less than the old TACC divided by 1.8).

Performance of the harvest control rules

Six performance indicators were estimated: mean annual mid-season mature biomass; mean annual yield; mean exploitation rate; and the probability of the mid-season mature biomass being below 10% B_0 or being below the LRP, or being below the lower bound of the biomass target range. Also, two risks were estimated from the Bayesian posteriors: LRP risk and depletion risk (see above).

Early in the study, the effect of different frequencies of acoustic surveys was examined for a HCR that had constant limiting factors on the allowable changes in TACC (Table 6). It was found that survey frequency was not important having virtually no effect on the performance indicators for a constrained HCR (Table 6). The reason for this is that improvements in the precision of the estimators of stock status and vulnerable biomass (brought about by increased survey frequency) does not substantially change the TACCs that are set by the HCR. If a HCR is unconstrained the changes in TACC are frequent and large. The imposition of constraints means that often the maximum changes are made and having more precise estimates of stock status and vulnerable biomass does not alter this. Later in this report, in the robustness testing, we look at what happens if there is an increasing bias as survey frequency diminishes and what happens when the estimators are very imprecise.

Table 6: Performance indicators for a HCR using the base functional relationship with annual assessments and constant limiting factors on TACC changes (1.4 up; 1.8 down). Medians and 95% CIs are shown for three different acoustic survey frequencies (every year, every 3 years, or every 5 years).

Survey frequency	Mean B ($\%B_0$)		Mean Y ($\%B_0$)		Mean U (%)		P($B <$ $10\%B_0$) (%)		P($B <$ $20\%B_0$) (%)		P($B <$ $30\%B_0$)(%)	
1	56	51-61	7.2	6.5-7.7	12	11-12	0	0-0	3	3-5	20	18-24
3	56	50-61	7.3	6.5-7.8	12	12-12	0	0-0	3	3-4	20	18-24
5	56	50-61	7.2	6.5-7.8	12	12-12	0	0-0	3	3-4	20	18-24

The frequency of stock assessment updates is important for HCRs with constraints because the more updates that are made the more opportunity there is to change the TACC. If assessments are done every year then yield is higher and risk is lower than if assessments are done less frequently (Table 7). The problem with less frequent assessments is that TACCs cannot be brought down fast enough if there is a period of poor recruitment (hence increased risk).

Table 7: Performance indicators for a HCR using the base functional relationship and constant limiting factors on TACC changes (1.4 up; 1.8 down). Medians and 95% CIs are shown for three different combinations of survey and assessment frequency.

Survey, assessment frequency	Mean B ($\%B_0$)		Mean Y ($\%B_0$)		Mean U (%)		P($B <$ $10\%B_0$) (%)		P($B <$ $20\%B_0$) (%)		P($B <$ $30\%B_0$)(%)	
3, 1	56	50-61	7.3	6.5-7.8	12	12-12	0	0-0	3	3-4	20	18-24
3, 3	63	58-67	6.0	5.4-6.5	12	12-13	2	2-3	9	8-11	23	21-26
5, 5	63	58-67	5.8	5.1-6.3	14	14-15	5	4-8	13	12-16	25	23-28

The four proposed HCRs keep SSB above the LB most of the time and rarely allow it to go below the LRP and never allow it to go below 10% B_0 (Table 8). The effect of the different constraints is particularly apparent in the average SSB and average yield. The tighter the constraints the higher the average SSB and the lower the average yield (Table 8). LRP risk and depletion risk are almost zero for all of the HCRs (Table 9).

Table 8: Performance indicators for the four proposed HCRs. Medians and 95% CIs are shown for acoustic surveys every 3 years with annual stock assessment updates.

HCR	Mean *B* ($\%B_0$)		Mean Y ($\%B_0$)		Mean U (%)		P(*B* < $10\%B_0$) (%)		P(*B* < $20\%B_0$) (%)		P(*B* < $30\%B_0$)(%)	
C05	72	67-77	4.5	4.3-4.5	8	7-8	0	0-0	3	3-4	14	13-16
C10	66	59-71	5.5	5.3-5.6	10	9-10	0	0-0	3	3-4	17	16-21
C15	61	54-66	6.4	5.9-6.6	11	11-11	0	0-0	4	3-5	20	18-24
C20	58	52-63	6.8	6.3-7.2	12	11-12	0	0-0	4	3-5	21	19-25

Table 9: LRP risk and depletion risk for the four proposed HCRs (for acoustic surveys every 3 years with annual stock assessment updates).

HCR	LRP risk	Depletion risk
C05	0.00	0.00
C10	0.00	0.00
C15	0.01	0.00
C20	0.01	0.00

The small LRP risks that exist for C15 and C20 (Table 9) are associated with the lowest values of *h* (e.g., Figure 3). The proportion of time that SSB spends below the LB under the HCRs does increase for lower values of *h* and *M* but it never exceeds 30% and therefore the depletion risk is zero for all of the HCRs (see the performance of C20 in Figure 4).

Robustness of the proposed HCRs

Many assumptions are made in the base model and the robustness of the proposed HCRs to most of these assumptions was tested. To save time, only C05 and C20 were given full robustness testing as the performance indicators for the other two HCRs will be bounded by the performance indicators of these two rules (since C05 is the most conservative and C20 is the least conservative).

C05 is robust to the use of the median values for recruitment variability (sigmaR) and correlation (rho)(Table 10). Depletion risk is zero for all tested values (from the 95% CIs in Table 10). The LRP risk is positive for the high values of rho and sigmaR but it is highly dependent of the use of 5% as a cutoff. If 6% was used the LRP risk would be very close to zero (from the 95% CIs in Table 10). For C20 the results are very similar with the high values of rho and sigmaR producing LRP risk but zero depletion risk (Table 11). And again, the LRP risk is highly sensitive to the percentage cutoff used.

For the alternative assumption about YCS (the mixture distribution rather than lognormal) the performance indicators are almost identical for C05 (Table 12) and C20 (Table 13). The same is true for the higher and lower levels of mean length/weight (via L_{inf})(Tables 12 and 13).

Interestingly, when much higher CVs are assumed for the stock status and vulnerable biomass estimators the HCRs become more conservative with higher mean biomass, lower yield, and less risk (Tables 12 and 13). This is because the HCRs have constraints which allow the TACC to come down faster than it can go up. That is, the constraints are "negatively biased" and increased observation error will cause more unnecessary reductions than it will cause erroneous increases.

Table 10: Performance indicators for HCR C05 for the base model (rho=0.25, sigmaR=1.17) and higher and lower rho and sigmaR. Medians and 95% CIs are shown assuming acoustic surveys every 3 years with annual stock assessment updates.

Rho, sigmaR	Mean *B* ($\%B_0$)	Mean Y ($\%B_0$)	Mean U (%)	P(*B* < $10\%B_0$) (%)	P(*B* < $20\%B_0$) (%)	P(*B* < $30\%B_0$)(%)
0.25, 1.17	72 67-77	4.5 4.3-4.5	8 7-8	0 0-0	3 3-4	14 13-16
0.09, 1.17	70 64-74	4.9 4.7-5.0	8 8-9	0 0-0	2 2-2	12 10-14
0.40, 1.17	75 69-79	3.9 3.7-4.0	7 6-7	0 0-0	5 4-5	16 15-19
0.25, 1.06	70 63-74	5.0 4.8-5.1	8 8-9	0 0-0	2 2-2	12 10-14
0.25, 1.32	75 70-79	3.7 3.5-3.8	7 6-7	0 0-0	5 5-5	17 16-20

Table 11: Performance indicators for HCR C20 for the base model (rho=0.25, sigmaR=1.17) and higher and lower rho and sigmaR. Medians and 95% CIs are shown assuming acoustic surveys every 3 years with annual stock assessment updates.

Rho, sigmaR	Mean *B* ($\%B_0$)	Mean Y ($\%B_0$)	Mean U (%)	P(*B* < $10\%B_0$) (%)	P(*B* < $20\%B_0$) (%)	P(*B* < $30\%B_0$) (%)
0.25, 1.17	58 52-63	6.8 6.3-7.2	12 11-12	0 0-0	4 3-5	21 19-25
0.09, 1.17	57 51-62	7.1 6.4-7.5	12 12-12	0 0-0	2 2-3	18 16-21
0.40, 1.17	60 53-65	6.5 6.0-6.8	11 11-11	0 0-0	6 6-7	25 23-29
0.25, 1.06	56 50-62	7.2 6.5-7.7	12 12-13	0 0-0	2 2-3	17 15-20
0.25, 1.32	61 55-66	6.2 5.8-6.4	11 10-11	0 0-0	7 6-8	26 24-30

The only concern for the HCRs is when there is a constant and positive 20% bias in the estimators. C05 is almost robust to this assumption; it still has zero depletion risk, but LRP risk becomes substantial for the 5% cutoff definition (Table 12). C20 is less robust and shows some depletion risk and 100% LRP risk for the 5% cutoff (Table 13).

Table 12: Performance indicators for HCR C05 for the base model and alternative assumptions: a mixture distribution for YCS; lower and higher mean length/weight; a constant positive bias; and much more imprecise estimators. Medians and 95% CIs are shown assuming acoustic surveys every 3 years with annual stock assessment updates.

	Mean *B* ($\%B_0$)	Mean Y ($\%B_0$)	Mean U (%)	P(*B* < $10\%B_0$) (%)	P(*B* < $20\%B_0$) (%)	P(*B* < $30\%B_0$) (%)
Base	72 67-77	4.5 4.3-4.5	8 7-8	0 0-0	3 3-4	14 13-16
Mix. YCS	75 68-79	4.4 4.3-4.5	7 7-8	0 0-0	3 3-4	14 13-16
L_{inf} = 44	72 67-77	4.5 4.3-4.5	8 7-8	0 0-0	3 3-4	14 13-16
L_{inf} = 52	72 67-77	4.5 4.3-4.5	8 7-8	0 0-0	3 3-4	14 13-16
Bias=20%	71 65-75	4.7 4.5-4.8	9 8-9	0 0-0	5 5-6	18 16-21
CV + 20%	73 68-77	4.3 4.1-4.3	7 7-8	0 0-0	3 2-3	13 12-15
CV + 30%	75 70-79	4.0 3.8-4.1	7 6-7	0 0-0	2 2-3	12 11-14

Table 13: Performance indicators for HCR C20 for the base model and alternative assumptions: a mixture distribution for YCS; lower and higher mean length/weight; a constant positive bias; and much more imprecise estimators. Medians and 95% CIs are shown assuming acoustic surveys every 3 years with annual stock assessment updates.

	Mean B ($\%B_0$)		Mean Y ($\%B_0$)		Mean U (%)		P($B <$ 10%B_0) (%)		P($B <$ 20%B_0) (%)		P($B <$ 30%B_0) (%)	
Base	58	52-63	6.8	6.3-7.2	12	11-12	0	0-0	4	3-5	21	19-25
Mix. YCS	59	51-65	7.2	6.6-7.5	12	12-12	0	0-0	4	4-5	22	20-26
L_{inf} = 44	58	52-63	6.8	6.3-7.2	12	11-12	0	0-0	4	3-5	21	19-25
L_{inf} = 52	58	52-63	6.8	6.3-7.2	12	11-12	0	0-0	4	3-5	21	19-25
Bias=20%	54	48-60	7.4	6.7-7.9	14	14-14	0	0-0	8	7-10	30	26-36
CV + 20%	60	53-65	6.6	6.1-6.9	11	11-11	0	0-0	4	3-5	20	17-23
CV + 30%	62	55-67	6.3	5.8-6.5	10	10-11	0	0-0	3	3-4	17	15-21

The bias in the estimators will not be constant and will depend very much on the true values of the parameters. The bias may also depend, to some extent, on how many years it has been since an acoustic survey index was obtained. This was modelled by assuming that there was an annual increase in a positive bias for the estimators. For example, with an annual bias of 5%, the estimates in the first year without a survey were multiplied by 1.05, and in the second year without a survey by 1.05^2, and so on. When a survey did occur, the bias was reduced to zero.

C05 is very robust to this "increasing bias" assumption with no depletion risk and LRP risk only becoming large for a 10% annual bias and surveys every 5 years (Table 14). For C20, the LRP risk starts becoming large for a 5% annual bias and surveys every 3 years; and for 10% annual bias and surveys every 5 years there is substantial depletion risk (Table 15).

Table 14: Performance indicators for HCR C05 for the base model (no bias, surveys every 3 years) and alternatives with higher bias and less frequent surveys. Medians and 95% CIs are shown assuming annual stock assessment updates.

Annual bias, survey frequency	Mean B ($\%B_0$)		Mean Y ($\%B_0$)		Mean U (%)		P($B <$ 10%B_0) (%)		P($B <$ 20%B_0) (%)		P($B <$ 30%B_0) (%)	
0%, 3	72	67-77	4.5	4.3-4.5	8	7-8	0	0-0	3	3-4	14	13-16
5%, 3	72	66-76	4.5	4.4-4.6	8	8-8	0	0-0	3	3-4	15	13-18
5%, 5	72	66-76	4.5	4.3-4.6	8	8-8	0	0-0	4	4-5	16	14-19
10%, 3	72	66-76	4.5	4.3-4.6	8	8-8	0	0-0	4	4-5	16	14-19
10%, 5	72	67-76	4.5	4.2-4.6	8	8-8	0	0-0	5	5-6	17	15-20

Table 15: Performance indicators for HCR C20 for the base model (no bias, surveys every 3 years) and alternatives with higher bias and less frequent surveys. Medians and 95% CIs are shown assuming annual stock assessment updates.

Annual bias, survey frequency	Mean *B* (%B_0)		Mean Y (%B_0)		Mean U (%)		P(*B* < 10%B_0) (%)		P(*B* < 20%B_0) (%)		P(*B* < 30%B_0) (%)	
0%, 3	58	52-63	6.8	6.3-7.2	12	11-12	0	0-0	4	3-5	21	19-25
5%, 3	57	51-62	7.0	6.4-7.4	12	12-12	0	0-0	5	4-6	23	20-28
5%, 5	57	50-62	7.1	6.5-7.5	13	13-13	0	0-0	6	6-7	25	22-30
10%, 3	57	50-62	7.1	6.4-7.5	13	13-13	0	0-0	6	6-7	25	22-30
10%, 5	55	49-61	7.2	6.5-7.6	14	14-14	0	0-0	9	8-11	30	26-35

Application of the proposed HCRs to the revised stock assessment

Projections at the current TACC of 39,200 t for the revised assessment (including the catch in the 2014 calendar year of just 25,000 t) show that there is very little risk of SSB falling below the LRP (20% B_0) until the 2018 calendar year (Figure 5, Table 16). This is also the case if the "worst case" scenario from the virgin biomass profile is assumed with B_0 = 300,000 t (Figure 6, Table 16). It is also true for projections using each of the four proposed HCRs assuming no acoustic surveys until 2017 but with annual assessment updates (Table 16).

Table 16: Estimated risks of spawning biomass in 2017 being below 10%, 20%, or 30% B_0 for a constant catch equal to the current TACC (39,200 t) for the revised assessment and when B_0 is assumed to be 300,000 t; and for the revised assessment under each of the four proposed HCRs.

	P(B_{2017} < 10%B_0)	P(B_{2017} < 20%B_0)	P(B_{2017} < 30%B_0)
Constant 39,200 t	0.00	0.00	0.02
B_0 = 300,000 t	0.00	0.02	0.16
HCR C05	0.00	0.00	0.03
HCR C10	0.00	0.01	0.05
HCR C15	0.00	0.01	0.06
HCR C20	0.00	0.02	0.07

Expected variability of TACCs under the proposed HCRs

For each of the proposed HCRs, projections of the TACC were done for the revised stock assessment incorporating the actual TACC and catch in 2014 (Table 17). The point of the projections is to illustrate the scale of increases and between-year changes in TACC that are likely under the different HCRs (although it should be noted that the 2015 TACC is already fixed at the time of writing this report). The level of variability in TACCs and the average TACC over the period increase as the constraints are relaxed (Table 17). The actual TACCs that will result from applying the HCRs will depend on new data and the methods used in the annual stock assessments (and, in particular, on the average level of recruitment during the period).

Table 17: Projected TACCs for the four HCRs from the revised assessment. The average TACC for 2015 to 2019 inclusive is also given.

	TACC (000 t)			
Calendar year	**C05**	**C10**	**C15**	**C20**
2014	39	39	39	39
2015	41	43	45	48
2016	44	48	53	58
2017	47	55	53	58
2018	49	48	47	43
2019	42	37	35	33
Av. 2015-19	44.5	46.1	46.8	47.9

Discussion and conclusion

Revised stock assessment

The confounding of M and B_0 makes it difficult, or perhaps impossible, to provide a risk-neutral stock assessment for SBW6I. A fairly strongly informed prior for B_0, M, or the mature acoustic q is required to stabilize the stock assessment estimates. It would be inappropriate to strengthen the prior on the acoustic q without additional information and *a priori* we know very little about B_0 (there are early trawl survey data, but we know very little about the trawl survey qs). We know little about M and there do not appear to be any good estimates of M from other blue whiting stocks.

When a uniform prior is used on M (which would be the best attempt at a risk-neutral assessment) the model does not produce useful estimates because of the confounding. The profile across B_0 demonstrated the problem: for B_0 at 300,000 t and higher, estimates of M increase as B_0 increases (see Figure B21). For a fixed B_0, M is relatively well estimated, but across all values of B_0, M is estimated as anything from 0.2 up to 0.4 (Figure B21). The previous assessment fixed M at 0.2 following Hanchet (1991). There is almost no support for such a low value of M from the current data given the model structure and assumptions. In the B_0 profile, the lowest estimates of M were obtained for B_0 = 300,000 t and in that case the probability that $M \leq 0.2$ is just 3%.

The revised assessment used an informed prior on M that was normally distributed with a mean of 0.2 and a CV of 15%. This is a strong prior assumption that asserted M is in the range 0.14–0.26 with 95% probability. The posterior for M was shifted to the right of the prior with a 95% probability range of 0.19–0.31. Because the prior is fighting against the data and constrains M and B_0, compared to a uniform prior, the revised assessment should be considered to be conservative (i.e., it very likely contains negative biases for M and B_0; that is, a tendency to produce estimates lower than the true values).

Proposed HCRs and acoustic survey frequency

With the functional relationship between stock status and exploitation rate that the four HCRs share, the highest long-term yield is achieved when no constraints are placed on annual changes in TACC. However, without any constraints, the annual variation in TACCs would be far too high to be practical for the Industry (e.g., fishing capacity might have to very high one year and then substantially reduced the next). The four HCRs presented here have contrasting outcomes in terms of the likely variability of TACCs and the possible increases in TACC over the next few years. There is a trade-off between variability and yield; the lower the variability, the lower the average yield; the higher the variability the higher the average yield.

All four of the HCRs have acceptable risk profiles and will very likely meet MSC requirements and MPI’s HSS. All of the rules, over the long term, will lead to substantial changes in TACC as SSB fluctuates due to natural changes in recruitment. Only a constant catch policy would avoid long-term fluctuations in catch. However, to have acceptable risk, such a policy would set the TACC at a very low level.

The HCR with the tightest constraints (C05) is the most robust of the four rules. It has very little risk even when increasing annual positive bias of 5% is assumed and acoustic surveys are conducted only every 5 years (see Table 14). The LRP risk does become large when the annual bias is assumed to be 10% and surveys are only every 5 years (Table 14) but this is driven by the 5% definition and LRP risk would be zero if 6% was used (instead of 5%). If C05 was adopted the results suggest that acoustic surveys need only be done every 3 to 5 years.

The results for increasing annual bias for C20 suggest that acoustic surveys would need to be more frequent than every 5 years if rules C10, C15, or C20 were adopted. Certainly for C20, it appears that surveys would need to be every 2 to 4 years (see Table 15, for 10% annual bias and surveys every 5 years the risks of going below the LRP are too high).

The MSE should be revised and the “optimal” survey frequency should be reconsidered. when more information is available on southern blue whiting tilt-averaged target strength (which should lead to better information on the scale and productivity of the stock).

Acknowledgements

This work was guided by MPI’s Deepwater Fisheries Assessment Working Group over a period of months that involved several meetings. The work was greatly improved by comments made and questions asked by members of the WG. Thanks also to NIWA for allowing the use of their stock assessment package CASAL and for supplying the CASAL input files for the previous stock assessment of SBW6I.

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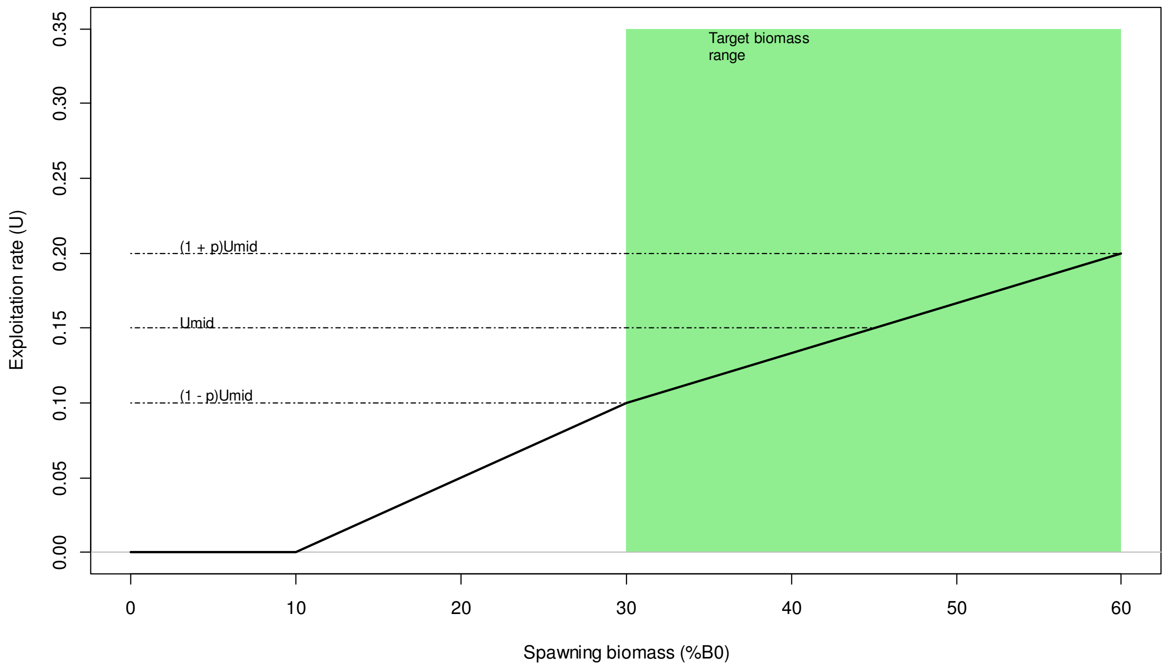

Figure 1: The functional relationship used to provide a provisional TACC for each of the proposed HCRs (estimated stock status is mapped to an exploitation rate). U_{mid} = 0.15 and p = 1/3. The target biomass range is 30–60% B_0.

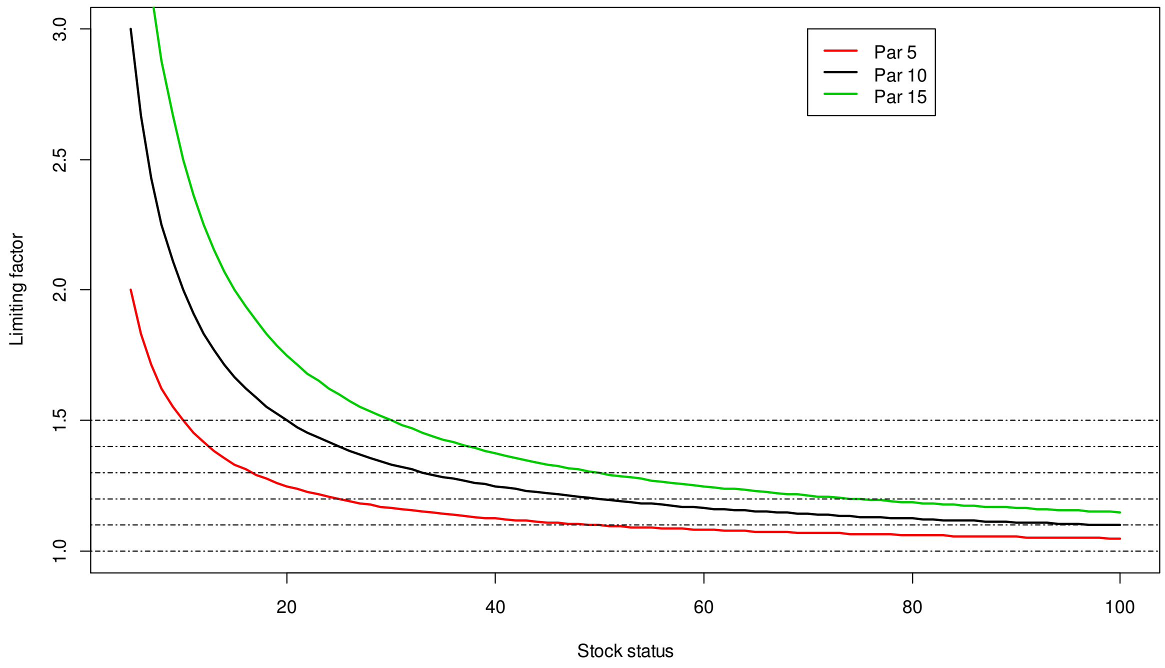

Figure 2: Three examples of the hyperbolic functions which define constraints that are used in the proposed HCRs. Each function has a single parameter (par) that is equal to the stock status (% B_0) at which the limiting factor is 2. Equivalently, at a stock status of 100% B_0 the limiting factor is 1 + par/100.

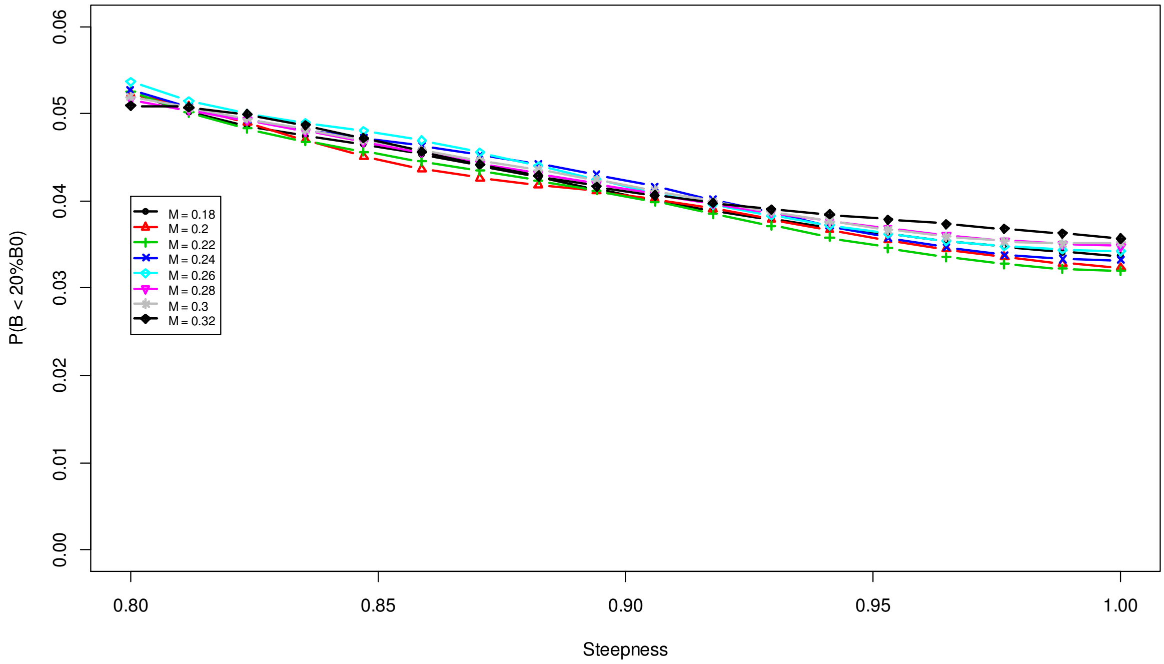

Figure 3: An example "grid function" for C20 showing the proportion of time that SSB spends below 20% B_0 for given values of steepness (h) and natural mortality (M).

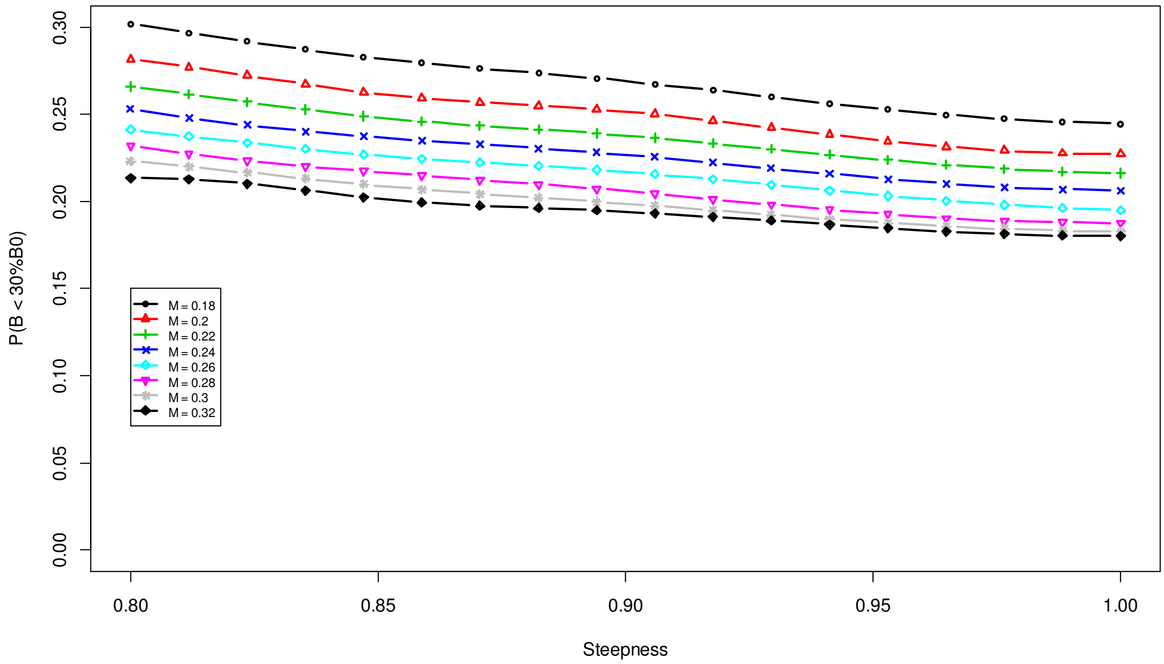

Figure 4: An example "grid function" for C20 showing the proportion of time that SSB spends below 30% B_0 for given values of steepness (h) and natural mortality (M).

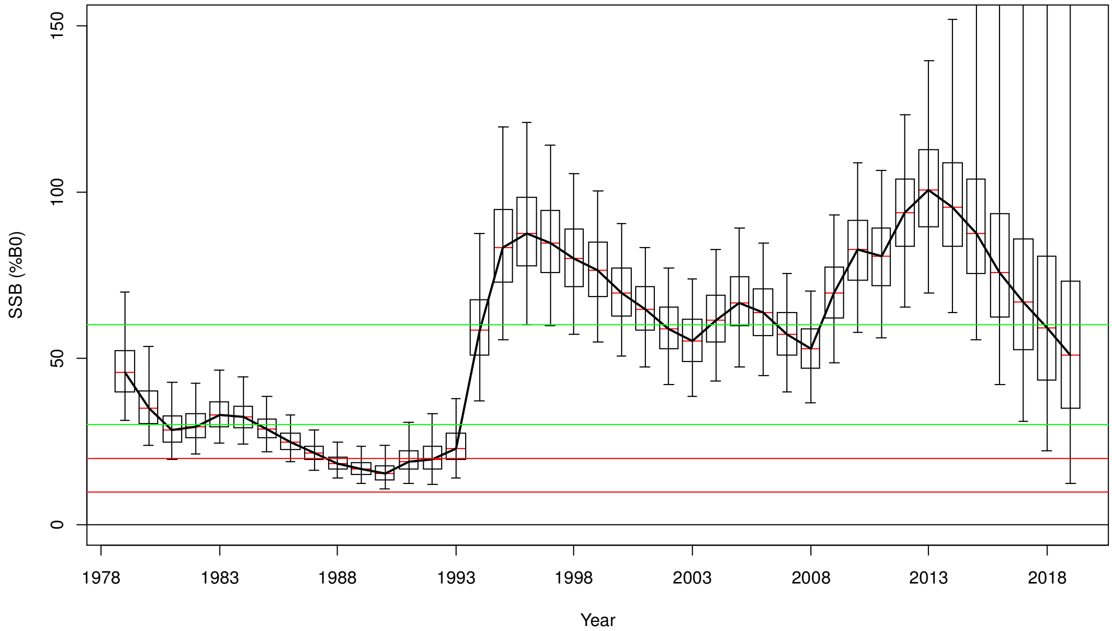

Figure 5: Box and whiskers plot of spawning stock biomass (%B_0) from 1979 to 2019 for the revised stock assessment assuming projected catches at the level of the current TACC (39 200 t). Each box covers 50% of the posterior distribution and the whiskers cover 95% of the distribution. Lines shown at 10%, 20%, 30%, and 60% B_0.

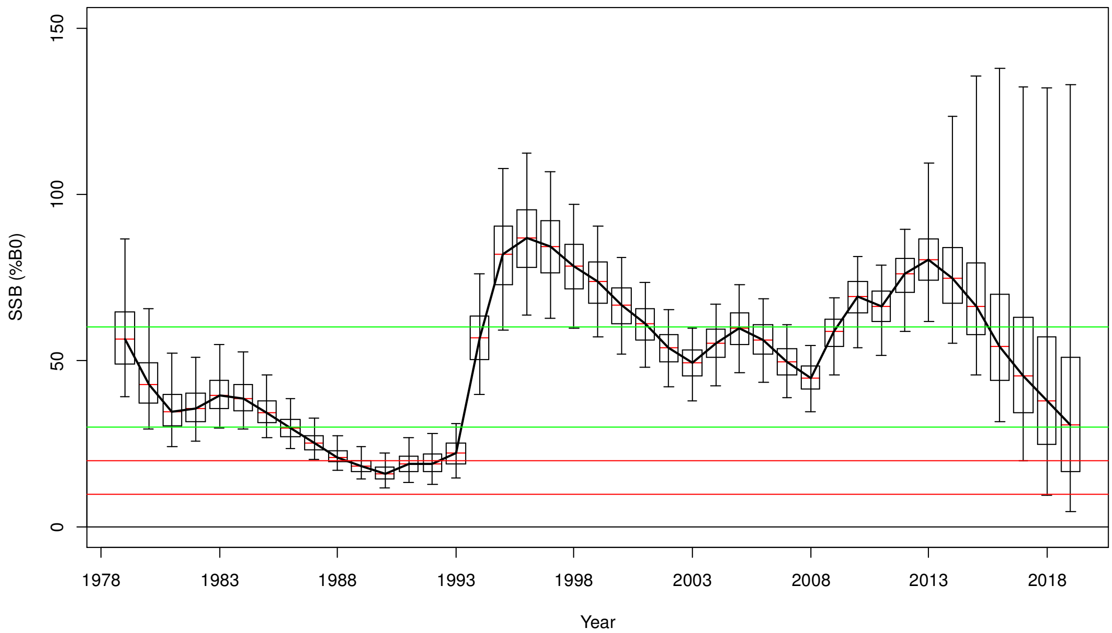

Figure 6: Box and whiskers plot of spawning stock biomass (%B_0) from 1979 to 2019 for when B_0 = 300,000 t is assumed with projected catches at the level of the current TACC (39 200 t). Each box covers 50% of the posterior distribution and the whiskers cover 95% of the distribution. Lines shown at 10%, 20%, 30%, and 60% B_0.

Appendix A: Model equations

Population dynamics

A standard age-structured population dynamics model was used in the simulations: single sex, single area, "instantaneous" catch equation (at the end of the year), with fish numbers tracked by age and maturity state (mature: "*mat*", or immature: "*imm*"). The model was started in deterministic equilibrium with the end-of-year total numbers at age a = 1, …, 30 years, $N_{0,a}$:

$$N_{0,a} = R_0 e^{-aM}$$

where R_0 is the number of recruits at age 1 in the virgin population (an arbitrary value of R_0 = 100 fish was used). The proportion mature at age a (in the virgin population) was set equal to the median of the posterior distribution from the base MCMC:

Age (years)	**Median**	**95% CI**
2	0.047	0.034–0.064
3	0.60	0.52–0.70
4	0.91	0.83–0.98
5	0.98	0.92–1.00

The annual cycle consisted of ageing, recruitment, maturation, and mortality (a full year of natural mortality followed by instantaneous fishing mortality) in that order. The total number of fish in year y+1 at age a+1 were obtained from the previous end-of-year numbers:

Ageing: a = 1,…,30 years $N_{y+1,a+1} = N_{y,a}$

The recruitment at age 1, in year y+1, was the product of virgin recruitment (R_0), the response from the stock-recruitment relationship ($p_{SR}(B_y)$, where B_y is the mid-season mature biomass in year y (see below)) and the "year class strength" (Y_y) of the cohort:

Recruitment: $N_{y+1,1} = Y_y p_{SR}\left(B_y\right) R_0$

A fixed proportion of immature fish were matured at each age in each year. The fixed maturation ogive was calculated from the proportions mature-at-age in the virgin population:

Maturation: a = 2,…,6 years

$$N_{new,mat,a} = \left(\frac{p_{mat,a} - p_{mat,a-1}}{1 - p_{mat,a-1}}\right) N_{y+1,imm,a}$$

$$N_{y+1,mat,a} = N_{y+1,mat,a} + N_{new,mat,a}$$

$$N_{y+1,imm,a} = N_{y+1,imm,a} - N_{new,mat,a}$$

This formulation ensures that the proportions mature-at-age are in deterministic equilibrium in the virgin population (i.e., do not change when there is no fishing and all YCS are equal to 1).

Mortality was modelled as a full-year of natural mortality followed by an instantaneous non-age-selective fishery on mature fish.

Mortality: $$N_{y,a,end} = (1 - U_y)e^{-M}N_{y,a,begin}$$

where M is natural mortality (independent of age or maturity) and U_y is the exploitation rate in year y. The "N" terms refer to mature or immature numbers at the beginning and end of the year and $U_y = 0$ for immature fish.

The catch was calculated in the usual way:

Catch: $$C_{y,a} = U_y e^{-M} N_{y,a,begin}$$
$$C_y = \sum_a w_a C_{y,a}$$

where w_a is the mean fish weight at age a years (calculated from given von Bertalanffy growth and length-weight relationships which are independent of maturity).

Stock status or depletion in year y, D_y, is defined to be the mid-season mature biomass divided by the mid-season unfished mature biomass: $D_y = B_y/B_{unfished}$. Mid-season occurs when half of the fishing mortality has been applied. The unfished biomass is the average mid-season mature biomass in the virgin population which is almost equal to the deterministic mid-season virgin mature biomass (B_0):

$$B_0 = \sum_a w_a \, p_{mat,a} R_0 e^{-aM}$$
$$B_{unfished} = cB_0.$$

c is a correction factor which depends on many of the parameters in the population model (particularly the variability and correlation driving the year class strengths, M, and steepness, h, in the stock-recruitment relationship). The correction factors were calculated, as needed, by running the virgin population over 10,000-30,000 years (depending on what was required to make the result independent of the random number seed). The correction factors for the base model ranged from 0.97–1 (over the grid of h and M values used)(Table A1). For the Ricker model, the curvature goes the other way so the correction factors are greater than 1 (Table A2). In the main text, "B_0" is used to denote "$B_{unfished}$" as the distinction is obscure for the general reader.

Table A1: Correction factors required in the base model (Beverton-Holt) to scale deterministic mid-season virgin mature biomass to the average mid-season virgin mature biomass.

	Natural mortality (*M*)							
Steepness (*h*)	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**
0.80	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.97
0.82	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
0.85	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
0.90	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
0.95	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table A2: Correction factors required in the Ricker model to scale deterministic mid-season virgin mature biomass to the average mid-season virgin mature biomass.

	Natural mortality (*M*)							
Steepness (*h*)	**0.18**	**0.20**	**0.22**	**0.24**	**0.26**	**0.28**	**0.30**	**0.32**
1.30	1.03	1.03	1.04	1.04	1.04	1.04	1.04	1.05
1.80	1.06	1.06	1.07	1.08	1.08	1.09	1.09	1.10
2.30	1.08	1.09	1.10	1.11	1.11	1.12	1.13	1.14
2.80	1.10	1.11	1.12	1.13	1.14	1.16	1.17	1.18
3.10	1.11	1.12	1.14	1.15	1.16	1.17	1.19	1.20
3.50	1.12	1.14	1.15	1.17	1.18	1.20	1.21	1.23

In the stock-recruitment relationship the uncorrected depletion level (B_y/B_0) was used because that is what gives rise to $B_{unfished}$. In the base model the Beverton-Holt relationship was used:

$$p_{SR}(B_y) = \frac{B_y/B_0}{\left[1 - \dfrac{(5h-1)}{4h}\left(1 - B_y/B_0\right)\right]}$$

and in some sensitivities the Ricker relationship was used:

$$p_{SR}(B_y) = \frac{B_y}{B_0}(5h)^{\frac{5}{4}(1-B_y/B_0)} .$$

The year class strengths, Y_y, were assumed to follow an AR(1) process in log space:

$$Y_y \sim \mathrm{LN}(\mu, \sigma_R),\ Y_y = e^{X_y} \text{ where } X_y = d + \rho X_{y-1} + \epsilon_y,\ \ \epsilon_y \sim \mathrm{N}(0, \sigma^2),\ \text{and } X_0 = 0.$$

It follows that: $\mu = d/(1-\rho)$ and $\sigma_R = \sigma/\mathrm{sqrt}(1-\rho^2)$. The constant d is defined by the requirement that $\mathrm{E}(Y_y) = 1$. There appears to be no analytical solution for d but a good approximation can be found by solving the following equation iteratively:

$$d = \log\left[\frac{1-\rho}{1-\rho+\rho d+\dfrac{\rho^2}{2}\left(\dfrac{\sigma^2}{1+\rho}+\dfrac{d^2}{1-\rho}\right)}\right] - \frac{\sigma^2}{2}$$

The above equation is derived by noting that

$$E(Y_y) = E(e^{X_y}) = E(e^d e^{\rho X_{y-1}} e^{\epsilon_y}) = e^d E(e^{\rho X_{y-1}}) e^{\frac{\sigma^2}{2}} = 1$$

and approximating $\mathrm{E}(e^{\rho X_{y-1}})$ with a second order Taylor approximation:

$$\mathrm{E}(e^{\rho X_{y-1}}) \cong 1 + \rho\left(\frac{d}{1-\rho}\right) + \frac{\rho^2}{2}\left(\frac{\sigma^2}{1+\rho} + \frac{d^2}{1-\rho}\right)$$

Note that ρ is the correlation coefficient for successive YCS and that when $\rho = 0$ we have $\sigma_R = \sigma$ and the familiar $d = -\sigma^2/2$.

Simulation of assessments

To apply a HCR the current stock status and next year's vulnerable biomass must be estimated. Also, when an acoustic survey is done there must be a boost to the precision of the estimators of stock status and current mid-season spawning biomass. Two mechanisms were used to simulates the estimators.

The first mechanism was to maintain a matrix of *estimated* numbers at age and maturity. This was set up to mimic the accumulation of observations of a cohort as it aged from 2 years (first observation) through to 30 years (as occurs with annual catch-at-age data). The variance of the estimator of the numbers at age a was designed to be proportional to $1/(a - 1)$. At the end of each year, the estimated numbers at age $a + 1$ was updated via:

$$new\ \hat{N}_{a+1} = \frac{(a-1)\hat{N}_{a+1} + N_{a+1}\epsilon}{a}$$

where N_{a+1} is the actual numbers at age $a + 1$ (either mature or immature), the "hat" denotes the estimated value and ε is a lognormal random variable with mean = 1 and CV = CV_{cohort}. The matrix of estimated numbers at age and maturity was passed through the same annual cycle as the actual numbers at age and maturity with all other parameters assumed known so that the unbiased nature of the estimators was maintained. (When biased estimators were used the bias was introduced explicitly by multiplying the unbiased estimators by the given bias.)

The second mechanism was the use of "shrinkage" to adjust the precision of some estimators with a proportion of the true value being used in a weighted average:

$$B_{est} = p\hat{B} + (1-p)B$$

where B_{est} is the more precise version of $\hat{B}$ (both of them being unbiased estimators of B). From the above equation it follows that p can be chosen to give a required improvement in the CV of the estimators:

$$p = \frac{CV(B_{est})}{CV(\hat{B})}$$

This mechanism was used to boost the information contained in the estimators and the estimated numbers-at-age matrix in every year that there was an acoustic survey. In particular, the estimator of mid-season spawning biomass was updated whenever there was a survey using $p_{surv} = 0.73$. This reflects an approximately 9% improvement in CV for each survey (given the target CV of 35% for the estimator of current mid-spawning biomass from the CV of the marginal posterior of B_{13} from the revised assessment). The matrix of estimated numbers at age was also updated whenever there was a survey by scaling the matrix to match the new estimate of mid-spawning season biomass (i.e., it was multiplied by $B_{est}/\hat{B}$).

The shrinkage mechanism was also used to tune the average CVs of the estimators of B_0, B_{mid}, and stock status (to hit targets of 20%, 35%, and 15% respectively). The four parameters used were:

$p_{surv} = 0.73$
$p_{B0} = 0.49$
$p_{ss} = 0.65$
$CV_{cohort} = 1.45$

where the "p"s are the shrinkage proportions and CV_{cohort} is the CV of the lognormal errors used in the generation of estimated numbers-at-age matrix (see above). The tuning was done using the base HCR without any constraints and surveys every 3 years. The average CVs from the run were calculated from the CV of the estimates divided by their true values (and these ratios were checked to make sure they averaged to 1 as expected for unbiased estimators).

The errors were introduced into the estimators via the estimated numbers-at-age matrix. The estimate of next year's vulnerable biomass was calculated from the estimated numbers projected forward to the start of next year's spawning season. The error in B_{vul} was then borrowed for the estimator of B_0 (i.e., B_0 was multiplied by the same proportional error and then the shrinkage mechanism was applied). The B_{mid} estimate came from applying the annual cycle to the estimated numbers at age (in the previous year). Finally, stock status was estimated using the ratio of the B_{mid} and B_0 estimates with shrinkage applied (to the estimator of stock status).

Application of harvest control rules (HCRs)

Each HCR specified an assessment frequency n. In a simulation run, with a given HCR, an assessment was performed in the first year and then every n years after that. In a non-assessment year, the TACC was unchanged. In an assessment year, the provisional TACC was calculated from the HCR using the *estimates* of stock status and vulnerable biomass (see above) and the associated U from the HCR: $\mathrm{TACC}_y = U\hat{B}_{vul,y}$.

The final TACC was determined subject to the constraints. Let m be the minimum change and p_{up} be the up par and p_{down} be the down par (*not* expressed as percentages). Then:

For $\mathrm{TACC}_{old} /(1 + m) < \mathrm{TACC}_{provisional} < (1 + m)\ \mathrm{TACC}_{old}$ $\quad \mathrm{TACC} = \mathrm{TACC}_{old}$
and
For $\mathrm{TACC}_{provisional} > (1 + p_{up}/s)\ \mathrm{TACC}_{old}$ $\quad \mathrm{TACC} = (1 + p_{up}/s)\ \mathrm{TACC}_{old}$
and
For $\mathrm{TACC}_{provisional} < \mathrm{TACC}_{old}/ (1 + p_{down}/s)$ $\quad \mathrm{TACC} = \mathrm{TACC}_{old} / (1 + p_{down}/s)$

where s is the estimated stock status.

The total catch was assumed equal to the TACC and in each year it was removed from the stock by calculating the actual fishing mortality required to remove the TACC (i.e., $U_y = \mathrm{TACC}_y/B_{vul,y}$) subject to an 80% maximum exploitation rate.

Appendix B: Revised Campbell Island Rise SBW stock assessment

The most recently reported stock assessment for Campbell Island Rise SBW was to the end of the 2013 calendar year (MPI, 2014). That assessment was not suitable to be used to ground-truth an MSE as it had a fixed $M = 0.2$ and used a faulty prior on the mature acoustic q (MPI, 2014). New assumptions for a prior were developed for the Bounties SBW assessment in 2015 and these assumptions were borrowed to construct a mature acoustic q prior for the revised Campbell Island Rise assessment. Also, M and h were estimated and other minor changes were made. This appendix describes the methods and results for the revised assessment.

Summary of the previous assessment

The assessment is partly documented in the Plenary report (MPI, 2014) and there is another document detailing all SBW input data (Cole et al., 2013). The key points, in terms of model structure were:

- The model started at non-equilibrium in 1979 (early catch history is very uncertain)
- Two-sexes and two areas (home and spawning)
- Ages 2–15 years with a plus-group
- Two time steps with 0.9 natural mortality in the first time step and 0.1 in the second
- The fishery operates in the spawning ground during the second time step
- Fish enter the model at age 2 in the home ground
- Some fish migrate from the home ground to the spawning ground each year (and never return).

The migration is a proxy for maturation. The model structure is equivalent to having age, sex, and maturity in the partition (with just a single area). It was set up with migration instead of maturity to allow for possible annual variation in migration/maturation rates. However, in the base model, migration/maturation rates were constant over time.

The key input data were:

- Wide-area acoustic surveys:
    - 1993-95, 1998, 2000, 2002, 2004, 2006, 2009, 2011, 2013
    - Split into mature biomass and immature biomass
- Catch at age: proportions by age and sex
    - 1979-2013

The key points with regard to estimation were:

- Initial age-structure in 1979 estimated
- Year class strengths from 1977 to 2010 estimated with Haist parameterisation and lognormal priors on the free parameters (mean = 1, CV = 1.3)
- The acoustic indices were relative and so mature and immature acoustic qs were estimated

- An informed prior was used for the mature acoustic q (lognormal, mean=0.87, CV=0.3)
- Migration/maturation at age and sex was estimated.

In the base model $M = 0.2$ was assumed based on an early estimate of 0.21 which was rounded down to reflect the imprecision in the estimate (Hanchet 1991). Also, a Beverton-Holt stock-recruit relationship was assumed with a fixed $h = 0.9$. The main changes to the base model were the estimation of M and h and the use of an updated prior for the mature acoustic q.

Summary of the revised assessment model

The CASAL files for the base run in the revised assessment are given in the Annex to this appendix. A summary of the changes made to the previous assessment is given below.

The model structure and the input data were not changed. The only changes related to the estimation methods which were introduced in a step-by-step procedure to see how the changes affected the (MCMC) results.

First, there were two minor changes: fixing the migration proportion at age and sex equal to 1 for ages 6 years and older (this had previously been fixed at 0.5 but the change should make almost no difference as most of the fish have migrated/matured by age 5 years); and using free qs in the MCMC (nuisance qs had been used which gives an approximation to the correct results obtained by free qs – although in this case it may make little difference).

An important change was the use of the Bounties SBW prior for the mature acoustic q. The previous (lognormal) prior did not include a factor for tilt-angle distribution and had mean=0.87 and CV=0.3. The tilt-angle factor that was introduced had a range from 0.25–1.0 with a best guess of 0.66 (this was to allow for the unknown tilt-angle distribution of the fish when they were surveyed compared to the near-horizontal distribution of the fish when their target strength was measured). When this factor was included, with minor adjustments to the other factors, the new prior had mean=0.68 and CV=0.77 (from equating the best guess of 0.53 to the median of a lognormal and equating the lower bound of 0.092 to the 0.05 percentile). The changes produce a moderate decrease in the mean and a very large increase in the spread of the prior.

Another minor change was made to use near-uniform priors for the free parameters from which the YCS are derived (under the Haist parameterisation the YCS are the free parameters divided by the mean of the free parameters – which ensures that the estimated YCS average to 1). The previous prior was lognormal with mean=1 and CV=1.3. It is mainly a matter of taste, but as there is no basis for choosing a particular CV for a lognormal prior on the YCS free parameters, it was preferred to use a less informed prior (the near-uniform prior on the free parameters implies a prior on the YCS that is fairly flat between 0 and 2 but also allows much higher values).

The final changes were to estimate *M* and then *h* so that the primary uncertainty in the drivers of productivity could be used in the MSE. The prior on *M* was normal with mean=0.2 and CV=0.15 (which is fairly tight). The prior on *h* was set to have a mean=0.85 and to eliminate weight below 0.6 to reflect that SBW is *a priori* believed to be resilient (a Beta(10, 1.76) distribution was used). A Ricker informed prior for *h* was constructed from the Beverton-Holt prior assuming that the distribution of the slopes at the origin were identical for the Beverton-Holt and Ricker relationships (this gave an approximately lognormal prior with mean=2.7, CV=0.5). Also, the MSE operating model was a single-sex model so in the base MCMC non sex-specific parameters were estimated for migration/maturation and natural mortality.

Many additional runs were performed to explore the estimation of *M*. These included using different means for the prior on *M* and conditional estimation of *M* (and the other parameters) for fixed values of B_0.

For all runs, MCMC estimates were obtained by running 3 independent chains starting at a random jump from the MPD estimate. Chains were run out to a minimum of 2,000,000 and a maximum of 15,000,000 samples with every 1000th sample retained. A burn-in of 1000 retained samples was applied. Chains were stopped when convergence appeared adequate on the basis of plots comparing the posterior distributions of the three chains. For some graphing purposes a random subsample of 3000 was taken from the concatenated chains (excluding each burn-in). Medians and 95% CIs were calculated using the full concatenated chains.

Development of the base MCMC for the revised assessment

The base and the "estimate M" models reported in MPI (2014) were re-run without any changes to the CASAL files except for the choice of step-size, proposal distribution, number of chains, and length of chains. The changes were made to obtain more accurate results as only a single chain had been used previously and the results were obtained from a sub-sample of only 1000 posterior samples.

For the base model, the almost-identical runs gave results that were almost identical (Table B1). For the "estimate M" model the results were very close but the repeat run had slightly lower B_0 and slightly higher stock status (Table B1).

Table B1: A comparison of the stock assessment results reported in MPI (2014) and results from almost identical runs. Medians and 95% CIs from the posterior distributions of virgin biomass (B_0) and 2013 spawning biomass (B_{13}) are given for the base and "estimate M" models.

	B_0 (000 t)	95% CI	B_{13} (000 t)	95% CI	B_{13} (% B_0)	95% CI
Plenary (base)	342	308-391	206	146-285	60	48-74
Repeat (base)	335	300-383	206	146-289	61	48-76
Plenary (est *M*)	347	298-434	263	168-406	76	54-97
Repeat (est *M*)	337	289-420	261	170-410	78	56-100

The step-wise changes that were made to the original base model to get a run suitable for ground-truthing the MSE produced increasing larger estimates of B_{13} and stock status (Table B2). Individually the use of the new prior on the mature acoustic q and the estimation of M only produced small to moderate increases to estimated stock status (65% and 78% B_0 respectively compared to 60% B_0). However, when both changes were present, estimated stock status was much higher at 94% B_0 (Table B2).

Table B2: A comparison of the stock assessment results reported in MPI (2014) and results from this study. Medians and 95% CIs from the posterior distributions of virgin biomass (B_0) and 2013 spawning biomass (B_{13}) are given for the original base model and runs with a succession of changes. (Changes were cumulative as indicated by "+"; "n. unf. prior" denotes a nearly-uniform prior on the free parameters from which the YCS are derived.)

	B_0 (000 t)	95% CI	B_{13} (000 t)	95% CI	B_{13} (%B_0)	95% CI
Plenary (base)	342	308-391	206	146-285	60	48-74
Repeat (base)	335	300-383	206	146-289	61	48-76
+ New q prior	345	305-402	222	155-317	65	50-80
+ YCS n. unf. prior	356	312-423	256	180-371	72	57-88
+ est M	393	316-677	368	212-818	94	65-124
+ est h	374	303-606	351	206-723	94	65-123
+ est h (Ricker)	228	168-447	248	154-535	109	87-129

The final change was to estimate non sex-specific migration/maturation parameters for use in the single-sex operating model. There are small differences between the estimates by sex with males maturing earlier but such differences would not be expected to have any effect on the performance of HCRs. The use of a single-sex maturation/migration pattern caused only minor changes in the estimates of B_0 and B_{13} (Table B3).

Table B3: A comparison of the results for the two-sex and single-sex migration parameterisations. Medians and 95% CIs from the posterior distributions of virgin biomass (B_0) and 2013 spawning biomass (B_{13}) are given for the Beverton-Holt (BH) and Ricker runs.

	B_0 (000 t)	95% CI	B_{13} (000 t)	95% CI	B_{13} (% B_0)	95% CI
Est *M, h* (BH, 2-sex)	374	303-606	351	206-723	94	65-123
Est *M, h* (BH, 1-sex)	390	308-689	378	216-842	97	68-126
Est *M, h* (Ricker, 2-sex)	228	168-447	248	154-535	109	87-129
Est *M, h* (Ricker, 1-sex)	236	171-563	259	159-692	109	88-130

The Beverton-Holt model with the full suite of changes, including the single-sex parameterisation for M and migration/maturity, is the base model for the revised assessment.

Revised assessment: base MCMC model diagnostics

A comprehensive check of the diagnostics for the revised base model was made to ensure that it was an acceptable assessment that could be used to ground-truth the MSE.

The three chains delivered almost identical marginal posterior distributions for B_0, B_{13}, stock status, *M*, and *h* (Figures B1-B5).

The MCMC "fit" to the mature acoustic indices was good with the marginal posterior distributions following the general trend of the indices (Figure B6). The normalised residuals were also adequate showing that the mature indices had an appropriate data weighting (Figure B7). The same cannot be said for the immature acoustic indices. Although the "fit" was not too bad (Figure B8) it was clear from the normalised residuals that the indices were given too much weight (Figure B9). The data weights (CVs and sample sizes) from the original base model were used in all the runs. In the next assessment it would be best to down-weight the immature acoustic indices (but this is very unlikely to affect the results of the assessment as they are only a weak relative index for immature fish).

The Pearson residuals for the catch-at-age data show no patterns across years (Figure B10). However, there is the expected pattern in residuals by sex at ages 2 and 3 years (Figures B11 and B12). This is caused by males maturing in higher proportions than females at ages 2 and 3 years.

Revised assessment: base MCMC model results

The marginal posterior distribution for the mature acoustic q is shifted and contracted to the left of the prior distribution (Figure B13). It has a mode at 0.25 with very little weight above 0.5. This suggests that the tilt-averaged target strength in the spawning aggregations is much lower than the estimated target strength from the AOS recordings (fish herded by the trawl net). The marginal posterior distribution for the immature acoustic q is much tighter than its uniform prior (Figure B14). It has a mode at 0.15 with very little weight above 0.4.

The marginal posterior distribution for M is shifted to the right of the prior but has a similar spread (Figure B15). The median and 95% CI are 0.25 and 0.19–0.31. For Beverton-Holt h, the posterior is shifted to the right of the prior and is much tighter with little weight below 0.8 (Figure B16). The median and 95% CI are 0.95 and 0.84–0.99.

The cumulative proportions migrating/maturing at age are tightly defined with median estimates of 0.047, 0.60, 0.91, and 0.98 at ages 2–5 years respectively (Figure B17). The YCS shows the same pattern as the original assessment with very strong cohorts estimated for 1991, 2006, and 2009 (Figure B18). The SSB trajectory also shows the same pattern as the original assessment except that it finishes at a much higher level (~ 100% B_0 rather than ~60% B_0)(Figure B19).

Estimation of M in the model is problematic because the estimates are dependent on the prior used (Table B4). As the mean of the prior on M is increased so are the estimates of M and of B_0. The problem with estimating M within the model is that information on M comes from the right-hand limbs of the catch-at-age data. These provide information for $Z = F + M$ and because B_0 is uncertain then F is uncertain and the estimation of M and B_0 is confounded.

However, estimation of M externally to the model is an even worse option as allowances cannot be made for catch, the maturity ogive, and highly variable YCS. As an example, consider the use of catch curves to estimate Z from the earliest known part of the fishery (Figure B20). From 1979 to 1984 one would have to estimate Z (and hence M) at something less than 0.1; while from 1985 to 1989 an estimate of M at about 0.2 would be the likely choice. Of course, these estimates of Z are just driven by the variation in recruitment rather than fishing and natural mortality. This becomes obvious when Z ~ 1.7 when the very strong 1991 cohort is 6 years old and produces a very steep slope in the right-hand limb of the catch curve (see Figure B20 for the Z estimate).

From a pragmatic viewpoint, the mean of the prior on M cannot be larger than about 0.2 because at higher values the estimates of the mature acoustic q become untenable (Table B4). Essentially as M becomes large so does B_0 and hence SSB biomass is very large during the period of the acoustics surveys and the q becomes far too small (e.g., Figure B21).

Table B4: Population parameter estimates for the base MCMC (N(20)) and variations with alternative priors on *M* (normal with the given mean and a CV of 15%, and uniform from *M*=0.05 to 0.5). Medians and 95% CIs are given for virgin biomass (B_0), natural mortality (*M*), stock-recruitment steepness (*h*), recruitment variability (Rsd), recruitment correlation (Rho), and the mature acoustics *q* (Aco. *q*).

M prior (%)	B_0 (000 t)		*M* (%)		*h* (%)		Rsd (%)		Rho (%)		Aco. *q* (%)	
N(15)	350	310-420	18	14-22	97	88-100	110	100-130	19	5-33	40	27-55
N(20)	390	310-690	25	19-31	95	84-99	120	110-130	25	9-40	24	11-41
N(25)	590	360-810	31	25-35	94	80-99	120	110-130	27	11-41	12	9-27
N(30)	660	410-820	33	28-37	93	79-99	120	110-130	26	9-40	11	9-20
N(35)	680	450-830	34	30-39	93	78-99	120	110-130	24	8-39	10	9-17
Unf. (5, 50)	700	450-840	35	29-39	93	78-99	120	100-130	23	7-39	10	9-17

The question of whether a mean of something less than 0.2 should be used for the prior is answered by a series of MCMC runs for given values of B_0. The confounding of B_0 and *M* is of course eliminated when B_0 is known. In this case a uniform prior can be used for *M* and the data contain excellent information on *M* (for given B_0). The results show that the lowest estimates of *M* are obtained for B_0 ~ 300,000 t (Figure B21, median and 95% CI: 0.25, 0.2–0.3). For B_0 values lower than 300,000 t the estimates of *M* increase because higher productivity is needed to support the historical catches (since B_0 is so low). When a prior on *M* with mean 0.15 is used the posterior distribution has a median of 0.18 and 95% CI of 0.14–0.22 (Table B4). This is inconsistent with the range on *M* from the conditional estimates (~ 0.18–0.4). It is not a pure Bayesian approach, but of the priors used for *M* only N(mean=0.2) gives results that are consistent with the plausible range of *M* ~ 0.18–0.4 and doesn't estimate the mature acoustics *q* to be too low.

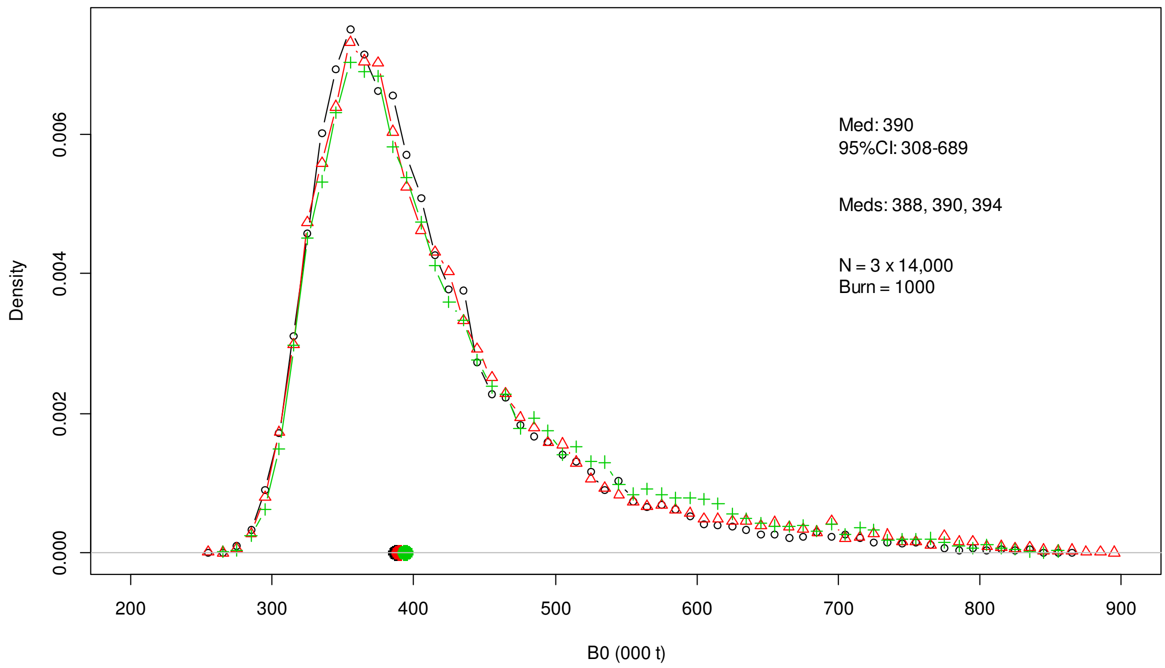

Figure B1: The marginal posterior distributions of B_0 for the three independent chains used for the revised base model. The median and 95% CI are given for the combined chains after burn-in together with the individual medians (000 t).

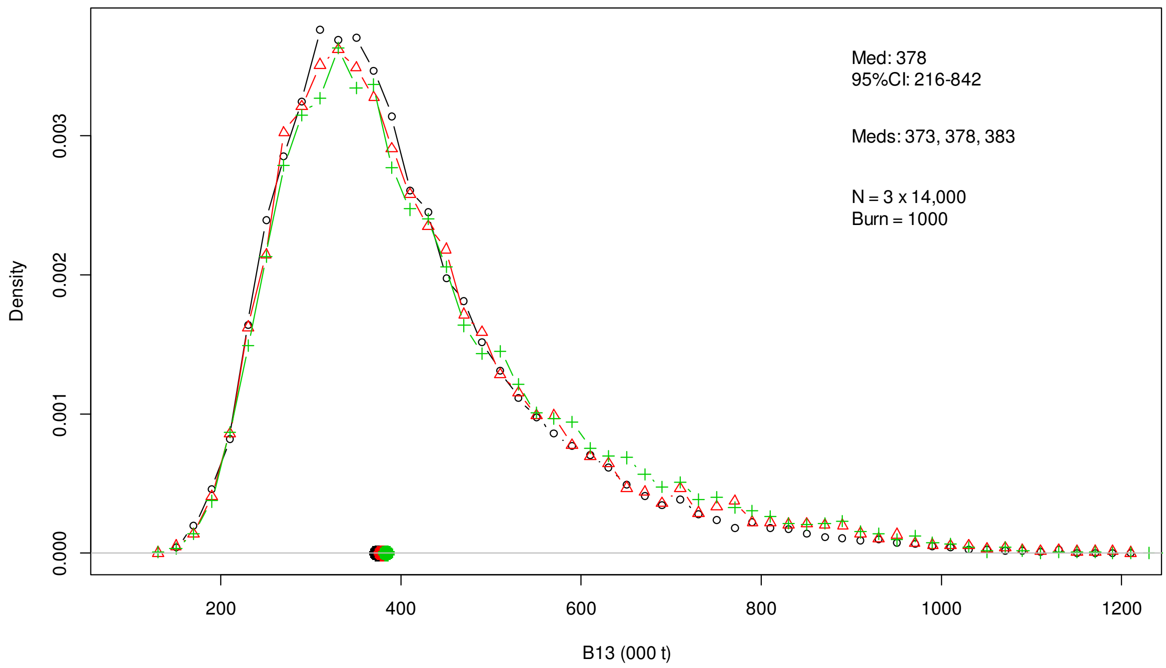

Figure B2: The marginal posterior distributions of B_{13} for the three independent chains used for the revised base model. The median and 95% CI are given for the combined chains after burn-in together with the individual medians (000 t).

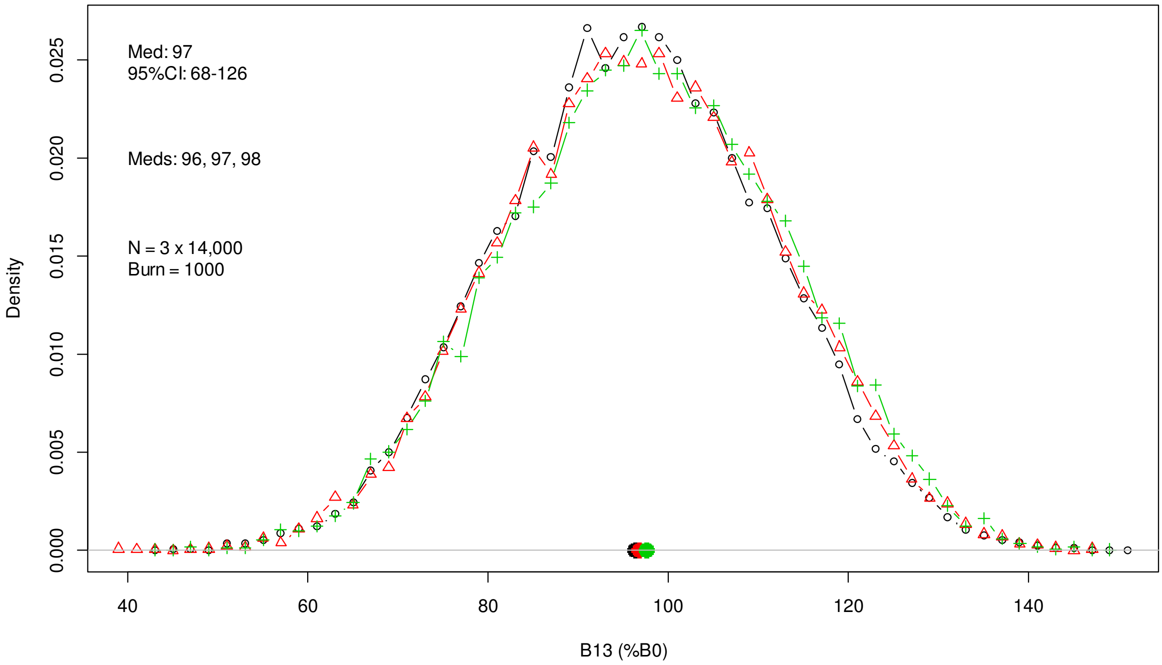

Figure B3: The marginal posterior distributions of stock status (B_{13}/B_0) for the three independent chains used for the revised base model. The median and 95% CI are given for the combined chains after burn-in together with the individual medians (%B_0).

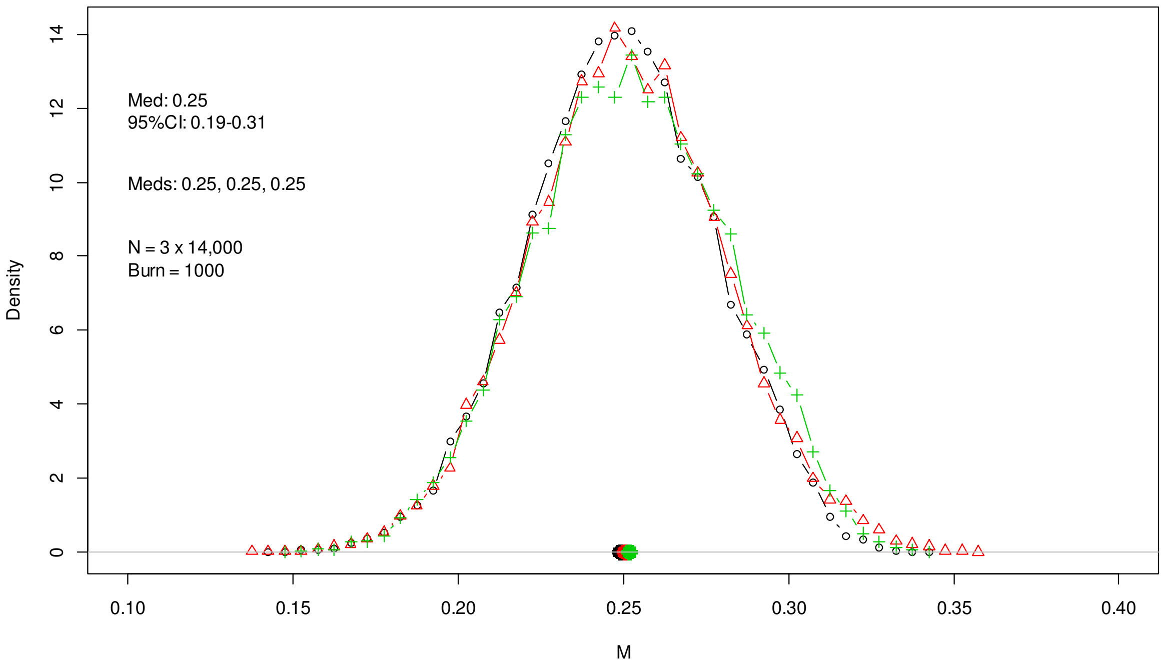

Figure B4: The marginal posterior distributions of M for the three independent chains used for the revised base model. The median and 95% CI are given for the combined chains after burn-in together with the individual medians.

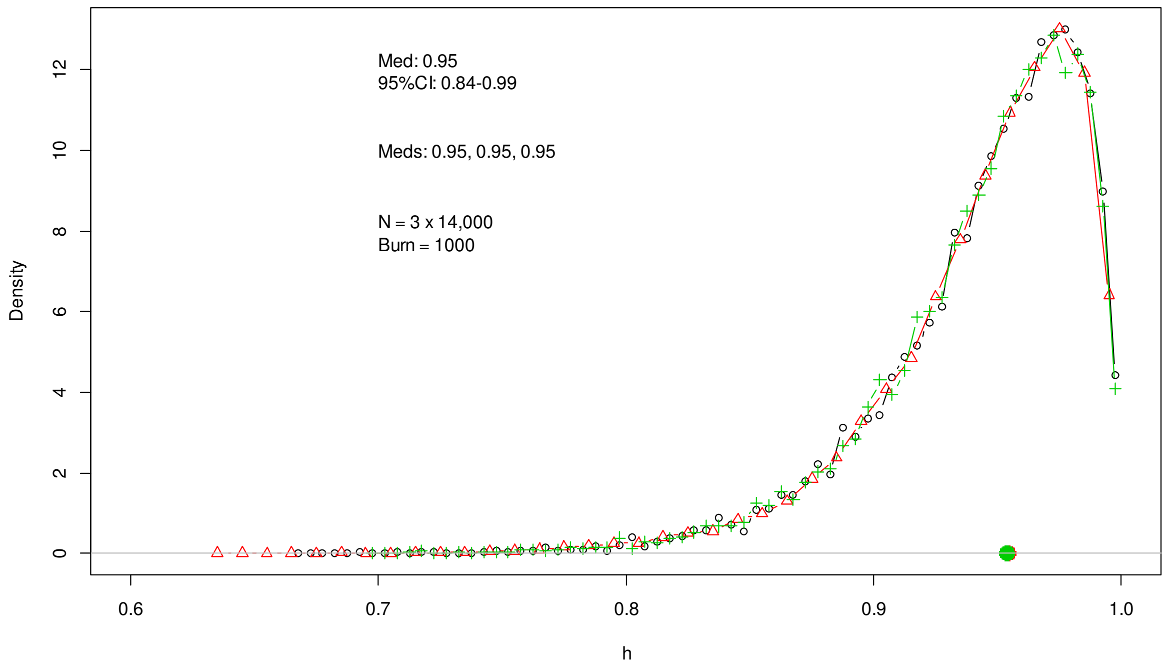

Figure B5: The marginal posterior distributions of h for the three independent chains used for the revised base model. The median and 95% CI are given for the combined chains after burn-in together with the individual medians.

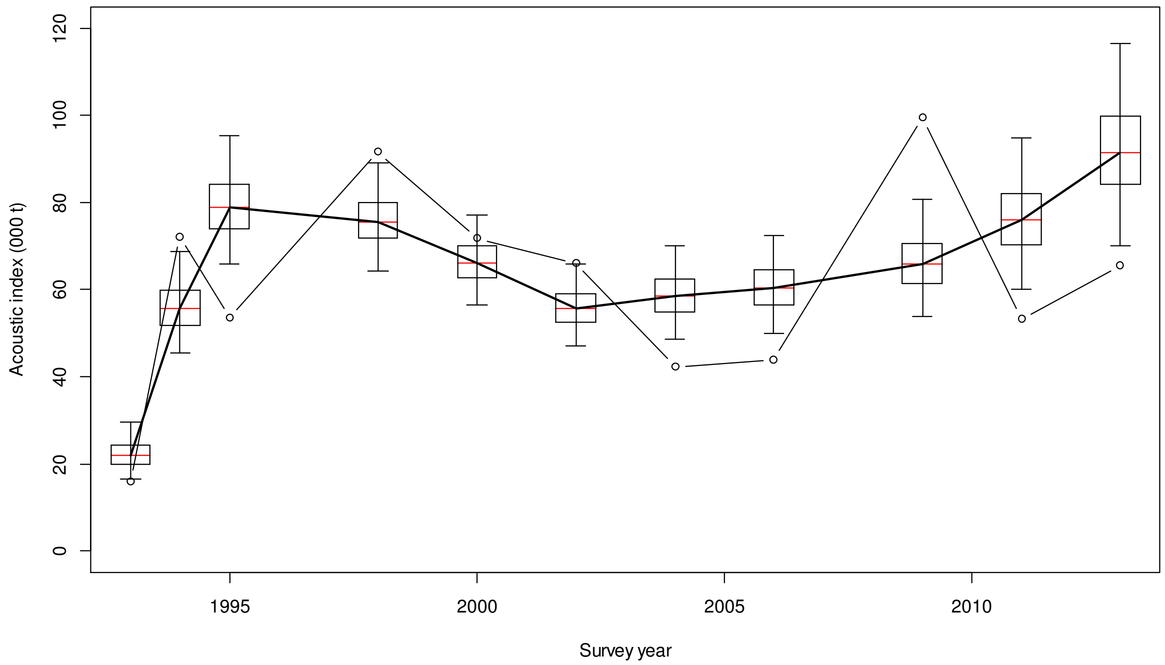

Figure B6: The MCMC "fit" to the mature acoustic indices. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers) for the marginal posterior distribution of each predicted average index. The observed indices are the open circles.

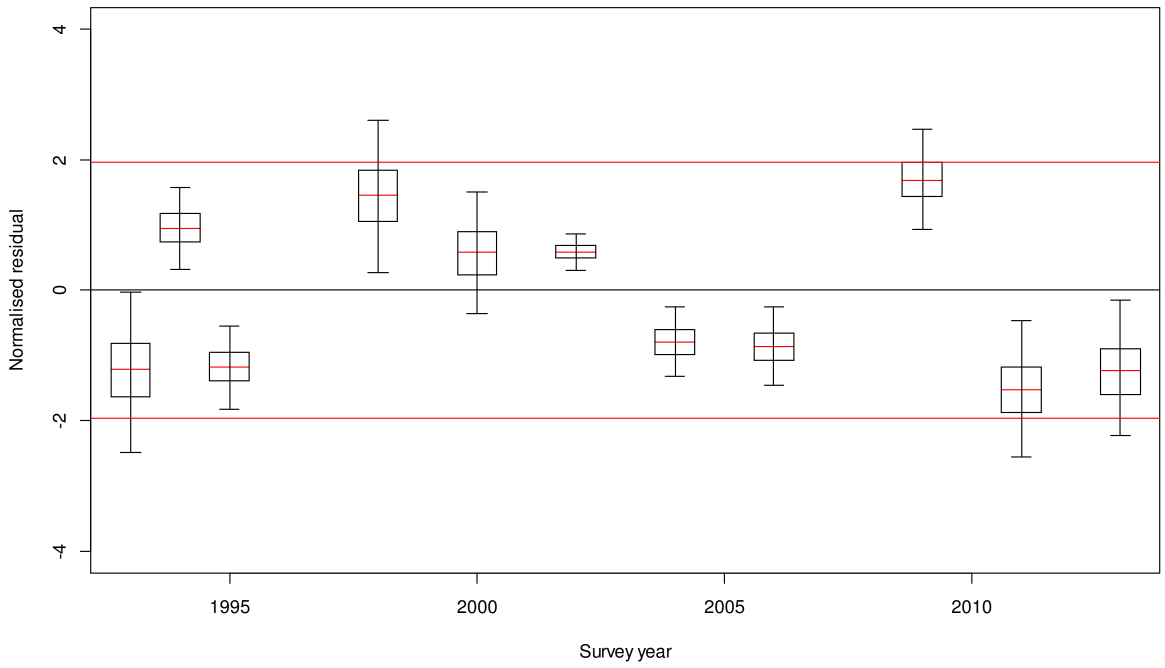

Figure B7: The normalised residuals for the mature acoustic indices. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers). The red horizontal lines are at ± 1.96 which represents 95% of a standard normal distribution.

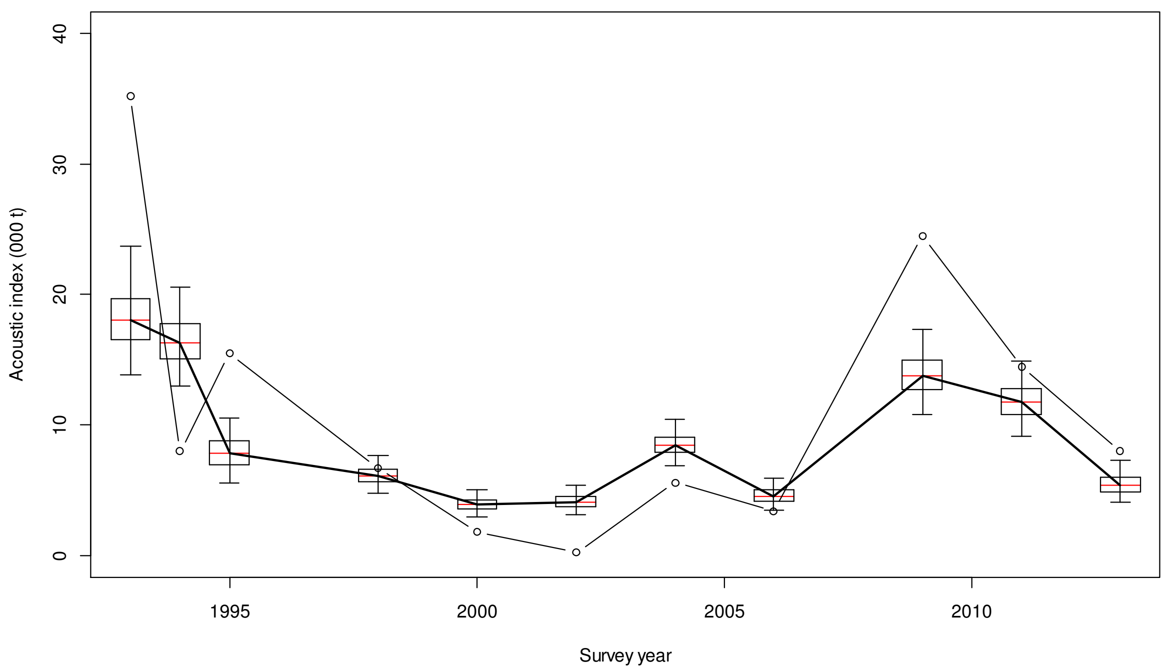

Figure B8: The MCMC "fit" to the immature acoustic indices. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers) for the marginal posterior distribution of each predicted average index. The observed indices are the open circles.

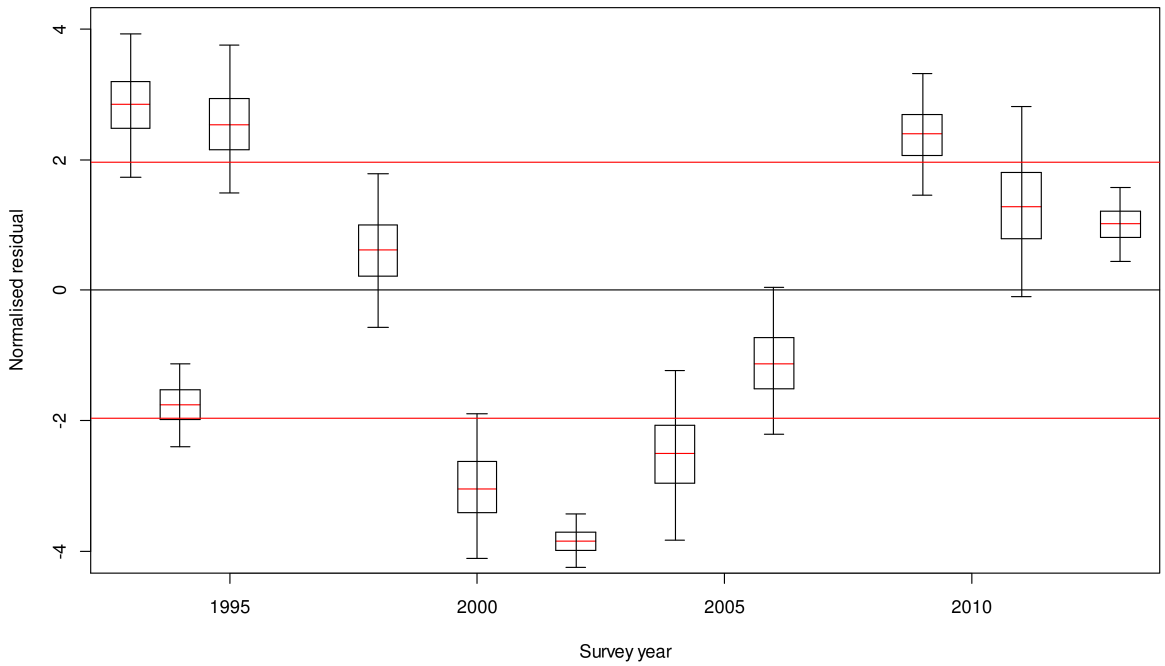

Figure B9: The normalised residuals for the immature acoustic indices. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers). The red horizontal lines are at ± 1.96 which represents 95% of a standard normal distribution.

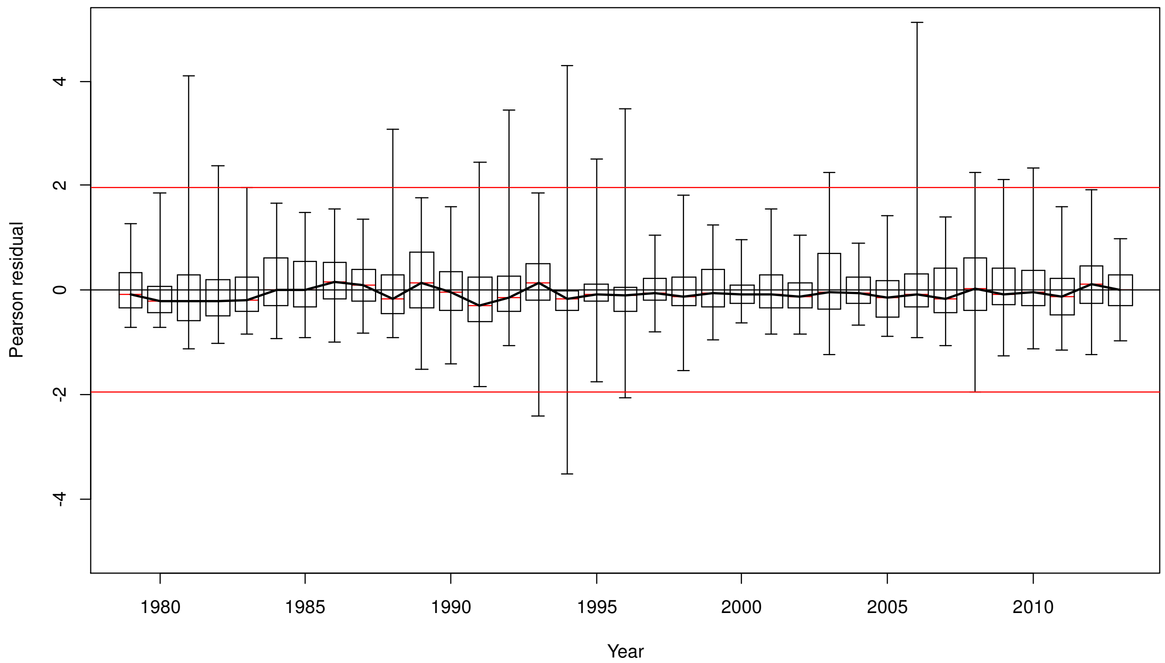

Figure B10: The Pearson residuals for the catch-at-age data (over both sexes) by year. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers). The red horizontal lines are at ± 1.96 which represents 95% of a standard normal distribution.

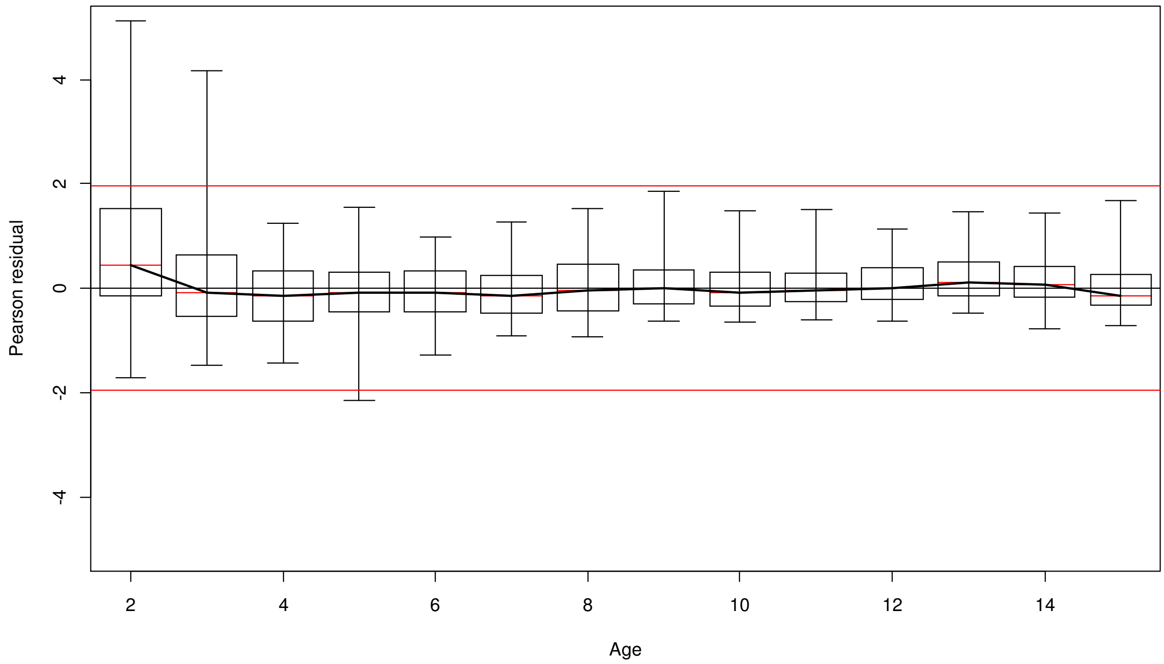

Figure B11: The Pearson residuals for the male catch-at-age data by age. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers). The red horizontal lines are at ± 1.96 which represents 95% of a standard normal distribution.

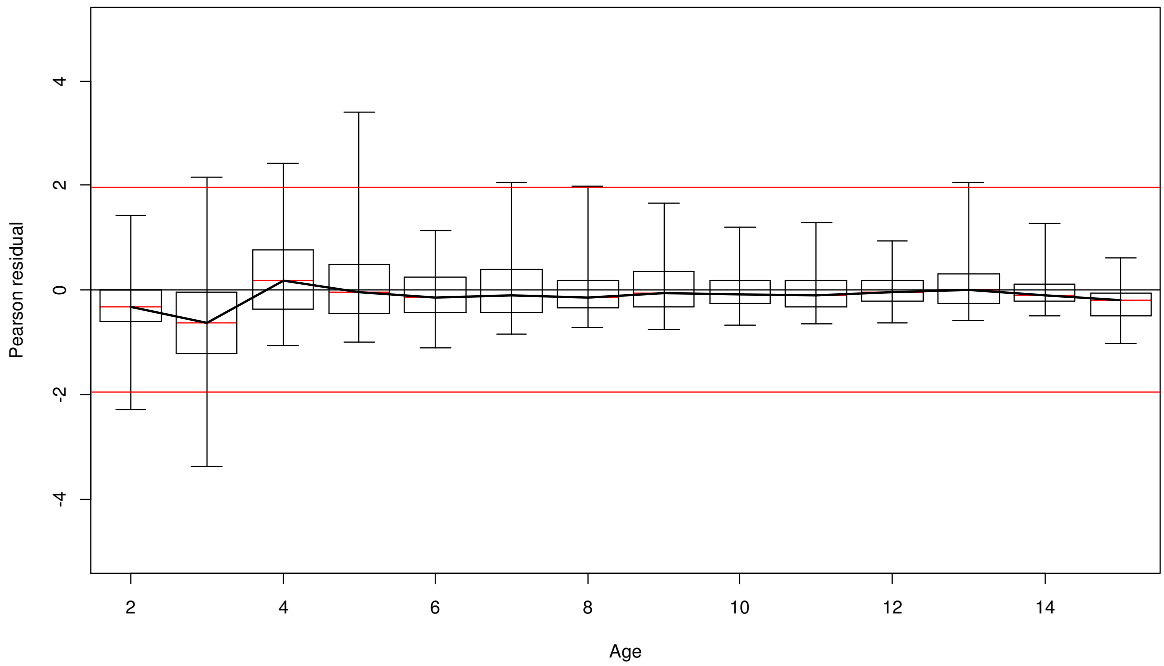

Figure B12: The Pearson residuals for the female catch-at-age data by age. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers). The red horizontal lines are at ± 1.96 which represents 95% of a standard normal distribution.

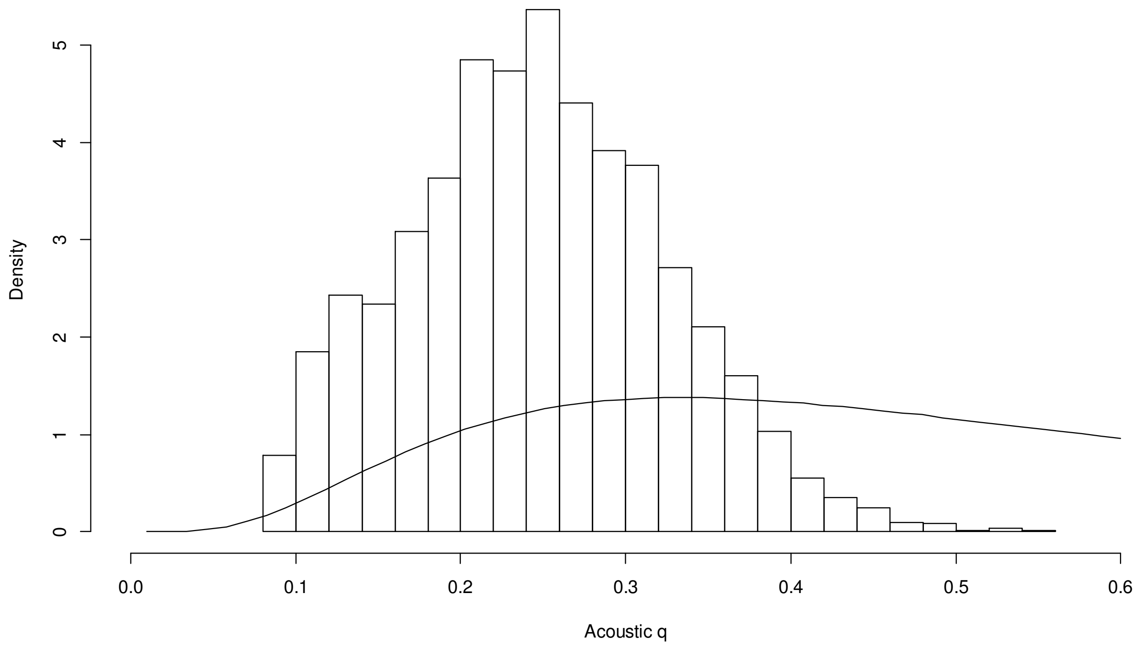

Figure B13: The marginal posterior distribution (histogram) and prior (smooth line) for the mature acoustic q.

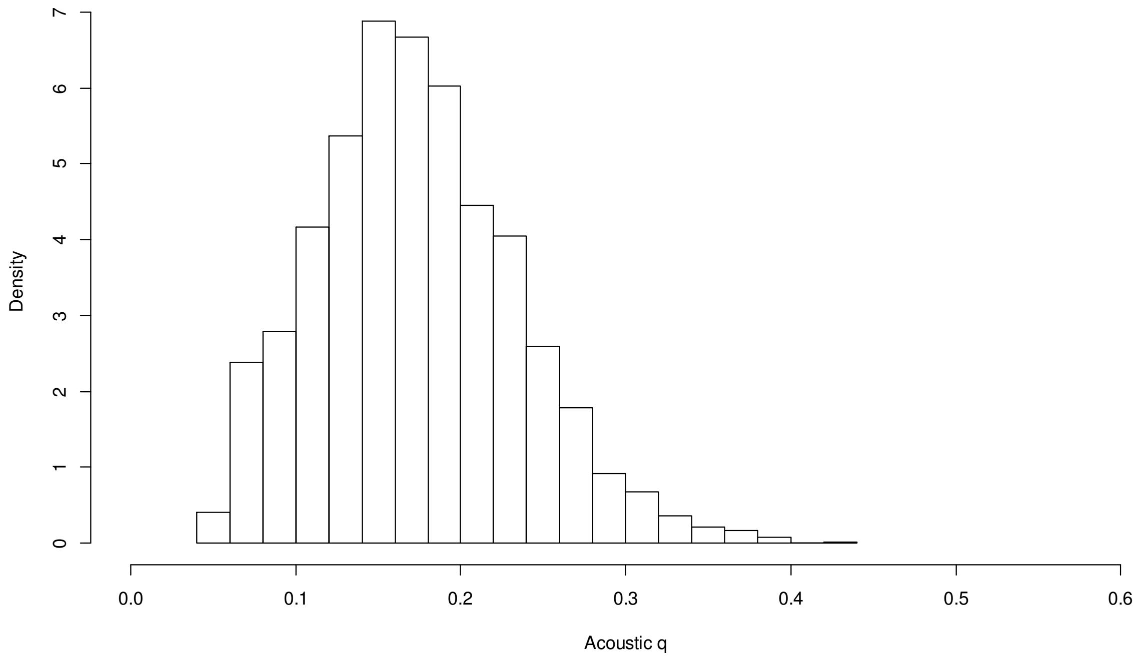

Figure B14: The marginal posterior distribution for the immature acoustic q. The prior was uniform.

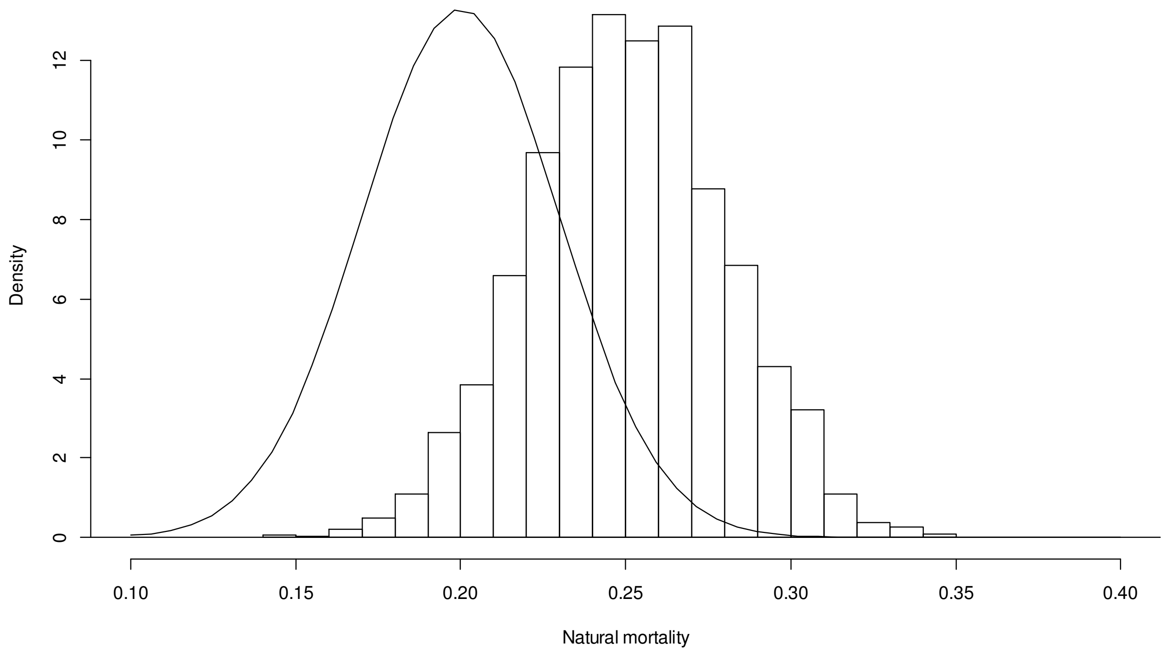

Figure B15: The marginal posterior distribution (histogram) and prior (smooth line) for M.

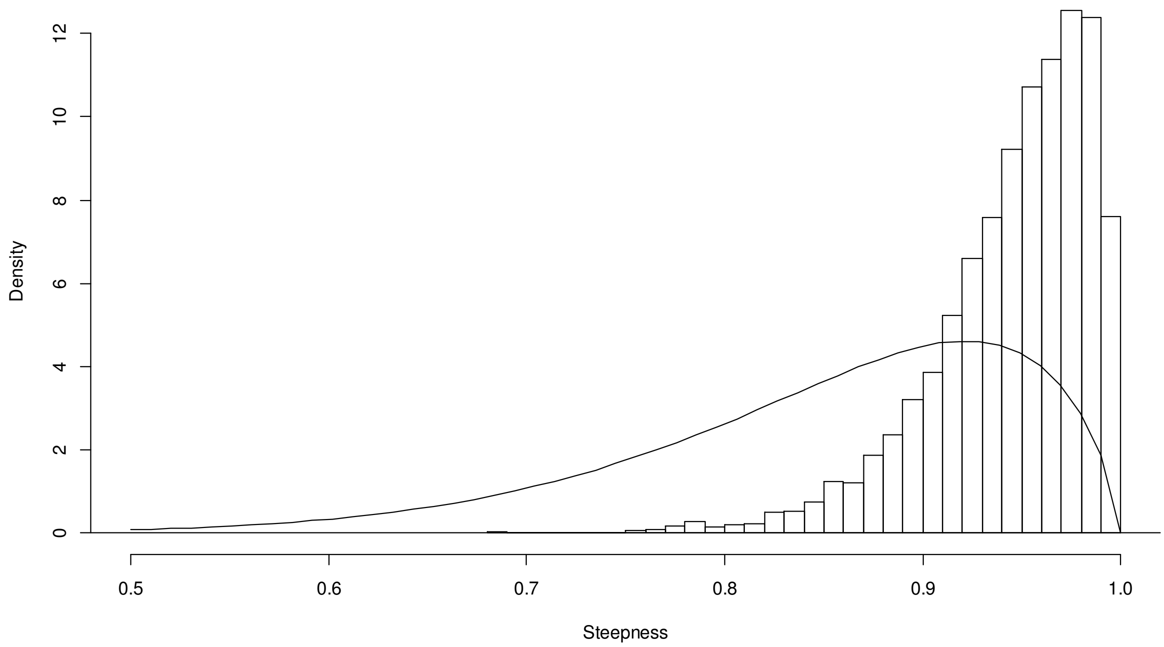

Figure B16: The marginal posterior distribution (histogram) and prior (smooth line) for h.

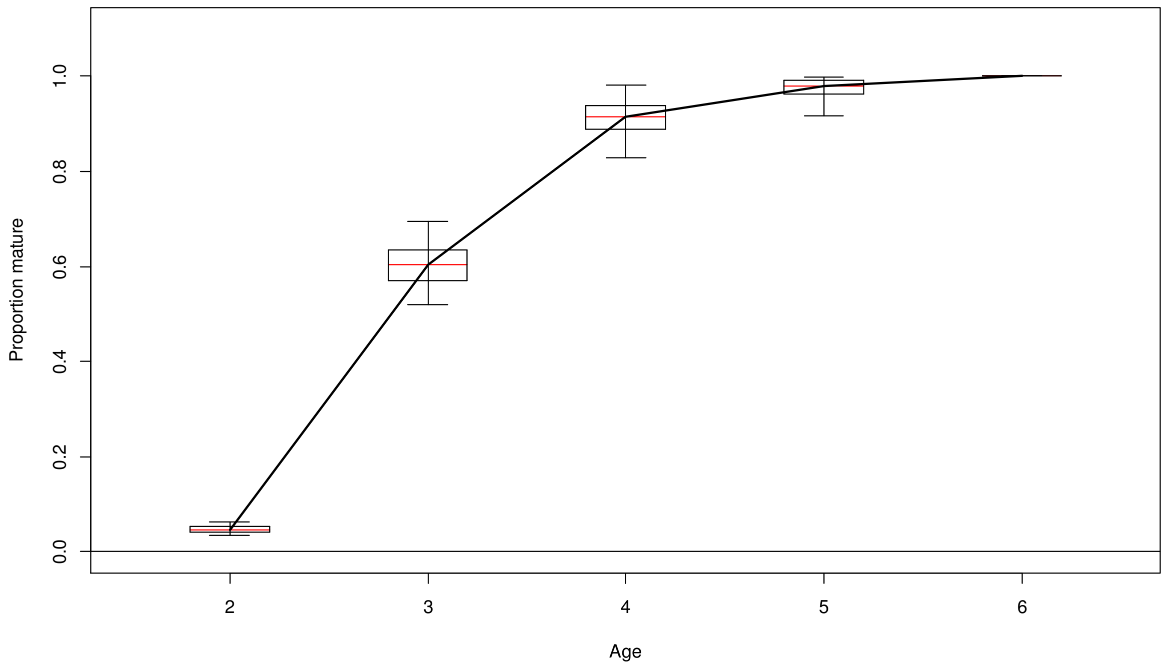

Figure B17: The MCMC estimates of the cumulative migration (maturation) proportion at age. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers) for the marginal posterior distribution. The proportion was fixed at 1 for ages 6 years and older.

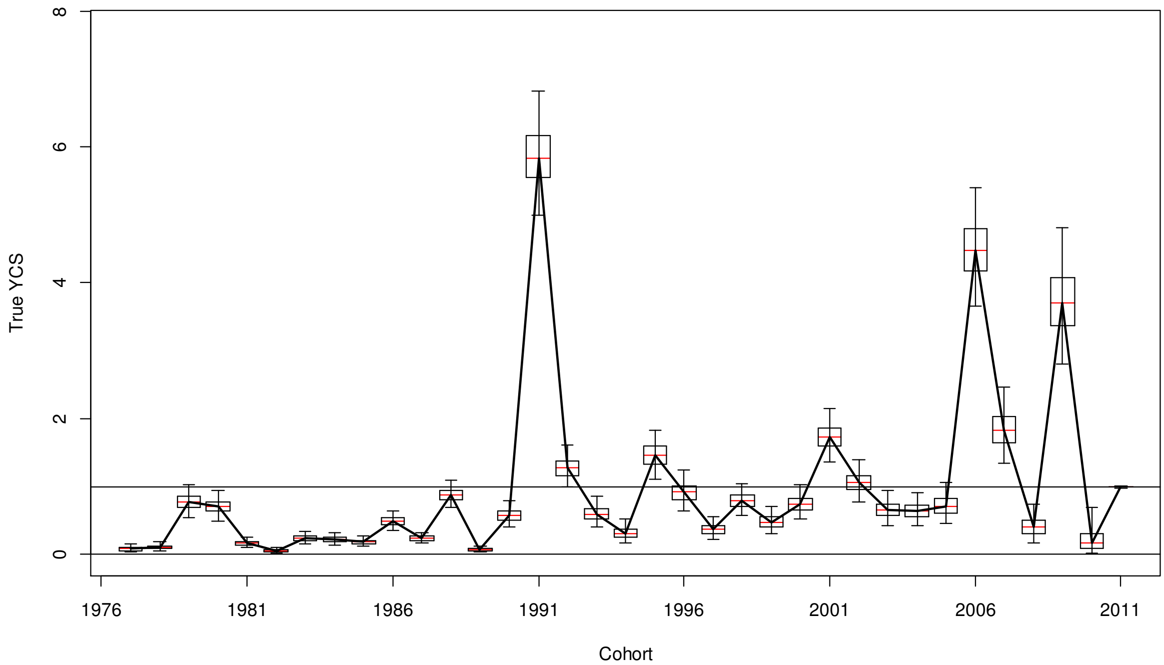

Figure B18: The MCMC estimates of the "true" YCS (R_y/R_0) for cohorts spawned in 1977 to 2010 inclusive. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers) for the marginal posterior distribution.

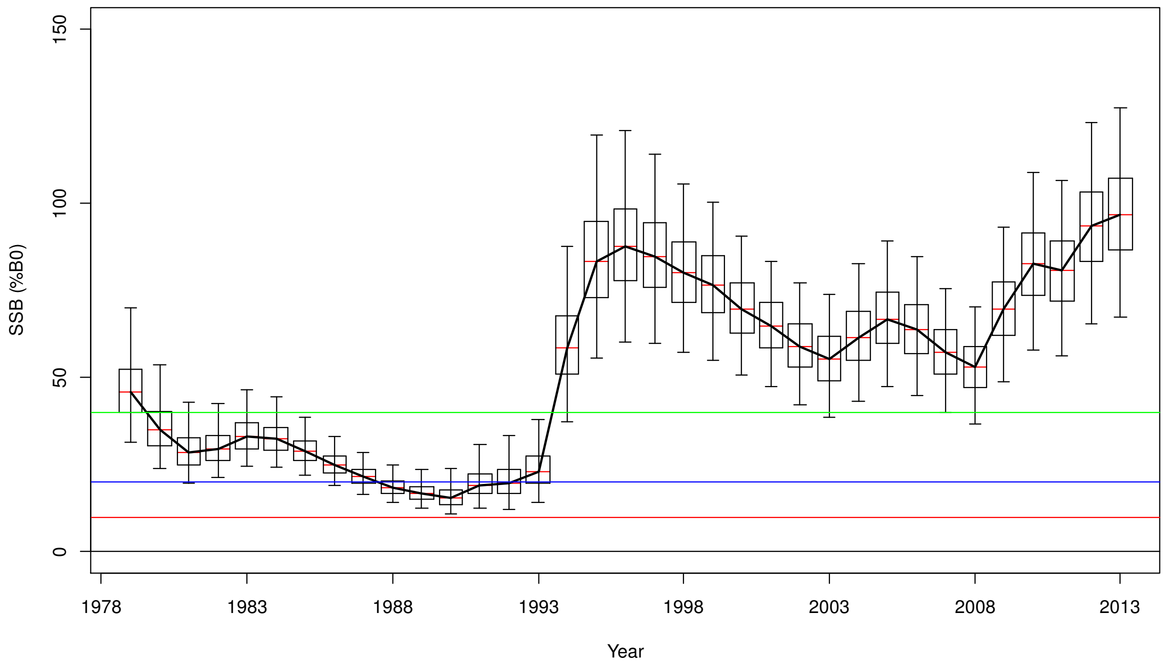

Figure B19: The MCMC estimate of the stock status trajectory (B_y/B_0). Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers) for the marginal posterior distribution. The red, blue, and green horizontal lines are at 10%, 20%, and 40% B_0 respectively.

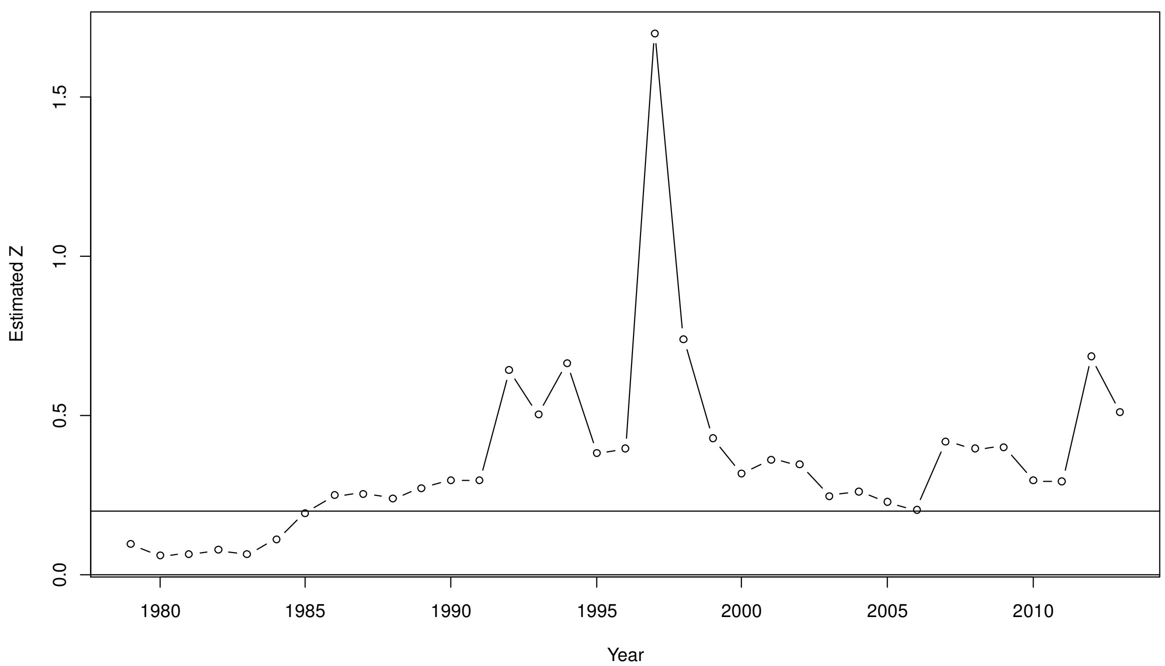

Figure B20: Maximum likelihood estimates of Z from the annual catch-at-age data assuming full recruitment at 6 years of age. The horizontal line is at 0.2.

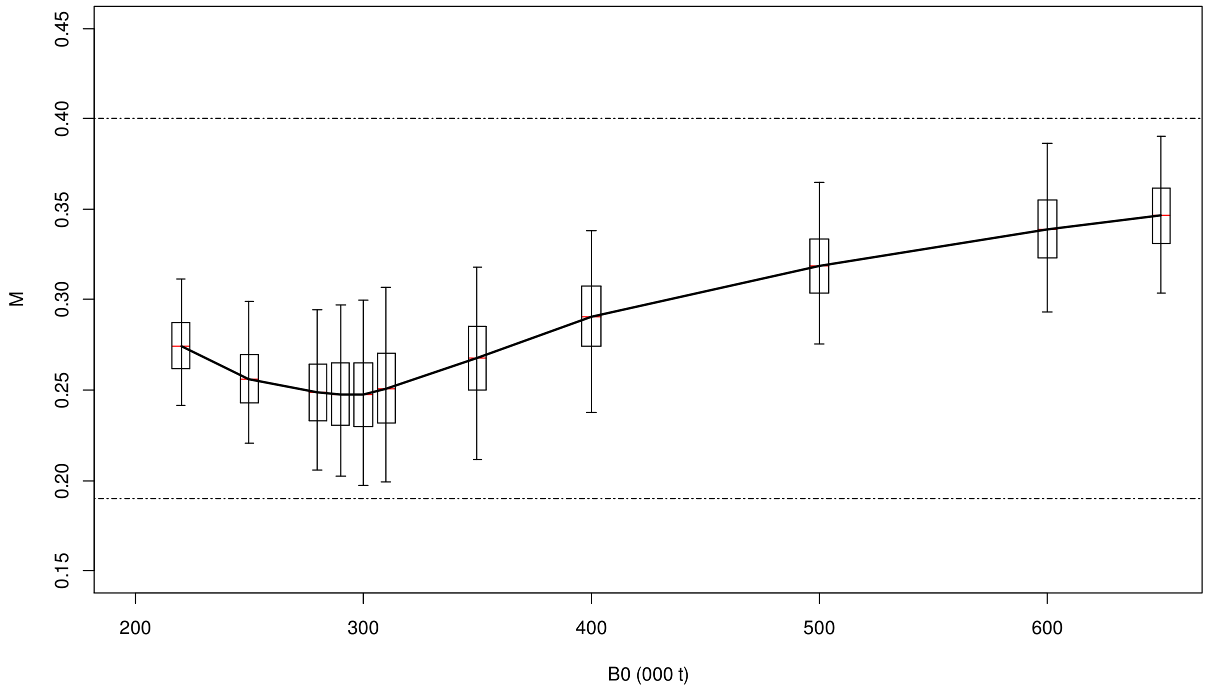

Figure B21: The MCMC estimates of M when B_0 is fixed and a uniform prior is used for M. Each box and whiskers plot gives the median (red line), middle 50% (box) and 95% CI (whiskers) for the marginal posterior distribution. Horizontal dashed lines are at 0.18 and 0.4.

Annex to Appendix B: The CASAL files for the base MCMC

Population.csl

```
# Note all years are calendar years, not fishing years, because
fishery happens in August

@initialization
B0 60000
#Binitial 1e5
Cinitial_male allvalues   5e7 5e7 7e6 6e6 5e6 4e6 3e6 2e6 1e6 1e6
1e1 1e1 1e1 1e1
Cinitial_female allvalues 5e7 5e7 7e6 6e6 5e6 4e6 3e6 2e6 1e6 1e6
1e1 1e1 1e1 1e1
@size_based False
@min_age 2
@max_age 15
@plus_group True
@sex_partition True
@mature_partition False
@n_areas 2
@n_stocks 1
@area_names spawn nonspawn

@initial 1979
@current 2013
@final 2019

@annual_cycle
time_steps 2
recruitment_time 2
maturation_times 2
n_migrations 1
migration_times 2
migrate_from nonspawn
migrate_to   spawn
migration_names toSpawn
spawning_areas spawn
recruitment_areas nonspawn
spawning_time 2
spawning_part_mort 0.5
spawning_ps 1.0
ageing_time 2
M_props 0.9 0.1
baranov False
fishery_names Trawl
fishery_times     2
fishery_areas spawn
growth_props 0 0
spawning_use_total_B True

@y_enter 2
@standardise_YCS True
@recruitment
```

```
YCS_years 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011
YCS           1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1    1    1    1    1    1
1    1    1    1    1    1    1    1    1    1
SR BH
steepness 0.9
p_male 0.5
sigma_r 1.0
first_free 1977
last_free 2010
year_range 1977 2010

@randomisation_method lognormal
@first_random_year 2010

@natural_mortality
all 0.20

@maturity_props
all constant 1

@migration toSpawn
migrators all
rates_all   allvalues_bounded 2 6  0.15 0.7 0.95 0.50 1

@fishery Trawl
years    1979  1980  1981 1982 1983  1984  1985 1986  1987  1988
1989  1990  1991  1992  1993 1994  1995  1996  1997  1998  1999
2000  2001  2002  2003  2004  2005  2006  2007  2008  2009  2010
2011  2012  2013
catches 25305 12828 5989 7915 12803 10777 7490 15252 12804 17422
26611 16542 21314 14208 9316 11668 10436 16504 18923 27164 27205
18052 28232 33445 23718 19799 26190 19763 20996 20483 19040 20224
30982 21321 28607
U_max 0.8
selectivity TrawlSel

@selectivity_names TrawlSel TangaroaMatureSel TangaroaImmatureSel
@selectivity TrawlSel
all constant 1
@selectivity TangaroaMatureSel
all constant 1
@selectivity TangaroaImmatureSel
all logistic 2 3

@size_at_age_type  data
@size_at_age_years 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988
1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
2015 2016 2017 2018 2019
@size_at_age_step 2
@size_at_age_dist normal
@size_at_age_miss mean
@size_at_age
```

```
cv 0.1
# age         2     3     4     5     6     7     8     9     10
11    12    13    14    15
male_1979 30.31 35.70 39.36 41.92 42.76 43.85 43.51 43.07 42.57
43.06 42.91 42.71 42.85 43.02
male_1980 30.21 35.38 38.84 41.11 42.44 43.37 44.00 43.62 43.36
43.85 43.84 43.51 43.44 43.45
male_1981 30.31 35.26 38.34 40.15 42.24 43.26 44.22 44.24 43.98
44.38 44.64 44.14 44.03 43.92
male_1982 30.48 35.33 38.18 40.06 42.18 43.13 44.15 44.63 44.56
44.77 45.36 44.62 44.67 44.40
male_1983 30.65 35.54 38.21 40.25 42.21 43.11 44.10 44.85 44.98
45.13 45.92 45.16 45.39 44.93
male_1984 30.78 35.79 38.35 40.48 42.32 43.16 44.11 45.05 45.33
45.51 46.37 45.75 46.05 45.49
male_1985 30.91 35.96 38.54 40.70 42.45 43.20 44.17 45.29 45.67
45.84 46.64 46.27 46.52 46.02
male_1986 31.02 36.11 38.61 40.91 42.55 43.31 44.34 45.55 46.19
46.09 46.70 46.68 46.83 46.46
male_1987 31.00 36.21 38.66 41.03 42.69 43.66 44.58 45.66 46.70
46.09 46.72 47.02 47.12 46.84
male_1988 30.52 36.30 38.80 41.14 42.91 44.04 44.91 45.69 46.97
46.11 46.88 47.34 47.45 47.26
male_1989 30.01 36.09 39.13 41.38 43.16 44.38 45.23 45.82 47.16
46.57 47.12 47.54 47.80 47.72
male_1990 29.79 36.11 39.39 41.79 43.46 44.76 45.63 46.25 47.35
47.10 47.62 47.78 48.24 48.15
male_1991 29.45 35.72 40.19 42.10 43.97 45.09 45.97 46.67 47.42
47.53 48.25 48.15 48.67 48.57
male_1992 28.27 34.99 39.76 42.13 44.37 45.64 46.24 46.94 47.47
47.87 48.76 48.52 49.04 48.96
male_1993 28.02 32.81 38.71 41.75 44.42 46.18 46.40 47.18 47.59
48.18 49.06 48.87 49.36 49.39
male_1994 28.34 31.29 36.36 40.63 44.13 45.98 46.57 47.25 47.61
48.35 49.20 49.33 49.60 49.81
male_1995 28.98 31.19 34.41 38.27 43.07 45.31 46.55 47.20 47.53
48.49 49.21 49.81 49.84 50.01
male_1996 29.30 31.66 34.36 36.35 40.67 44.02 46.13 46.98 47.44
48.46 49.11 49.95 50.05 49.98
male_1997 28.81 32.05 35.12 36.32 38.66 41.77 44.40 46.38 47.24
48.10 48.80 49.66 50.04 49.82
male_1998 28.01 32.12 35.71 37.18 38.45 39.90 42.47 44.93 46.67
47.59 48.08 49.10 49.74 49.56
male_1999 27.67 32.25 35.75 37.94 39.10 39.69 40.80 43.06 45.40
46.93 47.14 48.06 49.26 49.23
male_2000 28.06 32.66 35.76 38.31 39.80 40.36 40.48 41.67 43.87
45.93 46.30 46.73 48.42 48.83
male_2001 28.67 33.36 36.13 38.72 40.25 41.13 40.99 41.35 42.89
44.78 45.61 45.74 47.35 48.05
male_2002 29.03 33.99 37.03 39.24 40.70 41.77 41.71 41.73 42.95
44.05 45.02 45.22 46.50 46.96
male_2003 29.18 34.20 37.95 39.84 41.67 42.28 42.77 42.26 43.57
44.09 44.71 44.95 46.20 46.13
male_2004 29.37 33.91 38.25 40.21 41.83 42.43 43.74 42.82 44.04
44.55 44.83 44.93 46.27 45.76
```

```
male_2005 29.42 33.37 37.66 40.05 41.61 42.34 43.91 43.35 43.99
44.93 45.21 45.32 46.45 45.62
male_2006 29.24 32.73 36.63 39.20 40.65 41.98 43.61 43.62 43.85
45.03 45.51 45.93 46.67 45.54
male_2007 28.85 31.85 35.58 38.02 39.64 41.24 43.02 43.67 43.67
45.05 45.71 46.23 46.91 45.58
male_2008 27.97 30.80 34.43 36.97 39.06 40.59 41.82 43.38 43.28
44.81 45.74 45.77 46.89 45.81
male_2009 27.13 29.96 33.22 36.05 38.57 40.08 40.78 42.70 42.86
44.32 45.24 45.19 45.87 46.14
male_2010 26.81 29.41 32.49 35.25 38.00 39.62 40.51 42.22 42.24
43.86 44.49 44.66 44.80 46.47
male_2011 26.73 29.00 32.35 34.91 37.59 39.29 40.47 42.30 41.95
43.80 43.92 43.96 44.44 46.70
male_2012 26.97 28.95 32.33 35.32 37.54 39.03 40.53 42.61 42.91
44.18 44.06 43.57 44.15 46.72
male_2013 27.87 29.32 32.58 36.08 38.20 39.13 40.78 42.91 43.91
44.79 44.78 43.80 44.10 46.62
male_2014 27.87 29.32 32.58 36.08 38.20 39.13 40.78 42.91 43.91
44.79 44.78 43.80 44.10 46.62
male_2015 27.87 29.32 32.58 36.08 38.20 39.13 40.78 42.91 43.91
44.79 44.78 43.80 44.10 46.62
male_2016 27.87 29.32 32.58 36.08 38.20 39.13 40.78 42.91 43.91
44.79 44.78 43.80 44.10 46.62
male_2017 27.87 29.32 32.58 36.08 38.20 39.13 40.78 42.91 43.91
44.79 44.78 43.80 44.10 46.62
male_2018 27.87 29.32 32.58 36.08 38.20 39.13 40.78 42.91 43.91
44.79 44.78 43.80 44.10 46.62
male_2019 27.87 29.32 32.58 36.08 38.20 39.13 40.78 42.91 43.91
44.79 44.78 43.80 44.10 46.62
female_1979 29.94 36.67 40.26 42.43 43.25 44.13 45.66 46.00 46.23
45.79 46.06 45.82 46.19 46.89
female_1980 30.80 36.34 40.30 42.53 43.86 45.32 46.03 46.44 46.73
46.79 46.53 46.51 46.46 47.01
female_1981 30.93 36.03 40.07 42.60 44.25 45.95 46.25 46.70 46.91
47.44 46.88 46.86 46.73 47.21
female_1982 30.68 36.15 39.86 42.67 44.68 46.27 46.45 46.82 47.15
47.96 47.36 47.21 47.04 47.47
female_1983 30.51 36.38 39.90 42.68 44.95 46.51 46.70 46.94 47.38
48.49 47.85 47.76 47.45 47.85
female_1984 30.54 36.64 39.95 42.53 44.88 46.64 46.94 47.07 47.66
48.94 48.22 48.32 48.16 48.36
female_1985 31.11 37.03 39.75 42.30 44.58 46.52 47.25 47.27 48.00
49.15 48.58 48.70 48.89 48.93
female_1986 31.93 37.39 39.70 41.80 44.30 46.24 47.32 47.77 48.35
49.12 49.10 49.01 49.39 49.50
female_1987 32.23 37.73 40.12 41.52 43.94 46.11 47.33 48.21 48.79
49.25 49.50 49.47 49.83 50.04
female_1988 31.08 37.86 40.75 42.21 43.83 46.34 47.37 48.55 49.30
49.68 49.89 50.03 50.29 50.58
female_1989 29.81 37.40 41.26 43.39 44.57 46.75 47.67 48.92 49.88
50.15 50.28 50.74 50.89 51.06
female_1990 29.77 36.72 41.55 44.32 45.72 47.21 48.05 49.40 50.49
50.84 50.67 51.45 51.61 51.51
female_1991 29.62 36.52 41.51 44.70 46.54 47.71 48.60 49.89 51.13
51.57 51.41 52.02 52.28 51.95
```

```
female_1992 28.52 36.01 41.00 44.65 46.76 48.02 49.27 50.21 51.66
52.29 52.12 52.52 52.72 52.33
female_1993 27.71 34.57 39.97 44.19 46.64 48.35 49.73 50.40 51.86
52.86 52.56 52.87 52.81 52.62
female_1994 27.79 33.40 37.88 43.18 46.31 48.41 50.13 50.48 51.82
52.91 52.65 53.09 52.70 52.77
female_1995 28.19 33.27 36.17 40.82 45.44 47.97 50.18 50.56 51.59
52.78 52.64 52.90 52.63 52.85
female_1996 28.48 33.63 36.15 38.79 43.37 46.62 49.59 50.47 51.21
52.45 52.55 52.90 52.67 52.94
female_1997 28.25 33.88 36.91 38.60 41.59 44.33 47.74 49.87 50.66
51.98 51.79 52.92 52.82 53.10
female_1998 27.77 33.65 37.47 39.21 41.26 42.49 45.63 48.24 49.83
51.18 51.04 52.70 52.95 53.24
female_1999 27.59 33.37 37.50 39.74 41.59 42.50 43.98 46.20 48.36
50.19 50.63 52.30 52.95 53.33
female_2000 27.80 33.51 37.52 39.99 42.05 43.30 44.12 44.91 46.66
48.75 49.96 51.56 52.71 53.29
female_2001 28.07 34.28 37.87 40.37 42.36 44.08 45.14 45.16 45.70
47.84 49.24 50.54 52.11 53.08
female_2002 28.20 35.20 38.65 40.90 42.75 44.63 46.00 46.29 46.07
47.39 48.53 49.67 51.29 52.52
female_2003 28.11 35.66 39.41 41.53 43.61 45.10 46.29 47.07 46.84
47.68 48.19 49.09 50.55 51.71
female_2004 27.93 35.59 39.68 41.98 44.03 45.30 46.38 46.82 47.71
48.23 48.68 48.77 50.22 51.02
female_2005 27.77 35.33 39.23 41.91 44.06 45.28 46.38 46.26 47.74
49.03 49.38 49.15 50.10 50.66
female_2006 27.61 34.92 38.37 41.11 43.11 45.01 46.30 45.86 47.43
49.26 50.15 49.87 50.14 50.42
female_2007 27.39 34.22 37.50 39.96 42.17 44.21 46.03 45.38 47.32
49.01 50.47 50.49 50.36 50.21
female_2008 27.17 33.36 36.62 38.98 41.60 43.50 45.35 45.02 46.95
48.77 50.17 50.60 50.50 50.05
female_2009 27.04 32.70 35.76 38.12 41.07 42.97 44.71 44.85 46.48
48.51 49.64 50.38 50.44 49.94
female_2010 27.06 32.05 35.22 37.29 40.45 42.52 44.37 44.70 45.72
48.24 48.71 50.03 50.43 49.85
female_2011 27.35 32.34 34.88 36.86 39.95 42.19 44.08 44.67 45.04
47.71 47.83 48.84 50.38 49.79
female_2012 28.12 33.02 35.32 36.94 39.78 41.87 43.95 44.93 44.64
47.21 47.72 47.68 50.17 49.79
female_2013 29.16 33.90 36.13 37.83 40.30 41.87 44.18 45.33 45.13
47.10 47.98 47.87 49.97 49.87
female_2014 29.16 33.90 36.13 37.83 40.30 41.87 44.18 45.33 45.13
47.10 47.98 47.87 49.97 49.87
female_2015 29.16 33.90 36.13 37.83 40.30 41.87 44.18 45.33 45.13
47.10 47.98 47.87 49.97 49.87
female_2016 29.16 33.90 36.13 37.83 40.30 41.87 44.18 45.33 45.13
47.10 47.98 47.87 49.97 49.87
female_2017 29.16 33.90 36.13 37.83 40.30 41.87 44.18 45.33 45.13
47.10 47.98 47.87 49.97 49.87
female_2018 29.16 33.90 36.13 37.83 40.30 41.87 44.18 45.33 45.13
47.10 47.98 47.87 49.97 49.87
female_2019 29.16 33.90 36.13 37.83 40.30 41.87 44.18 45.33 45.13
47.10 47.98 47.87 49.97 49.87
```

```
@size_weight
a_male 0.00000000515
b_male 3.092
a_female 0.00000000407
b_female 3.152
verify_size_weight 50 0.8 1 # 50 cm fish weighs between 0.8 and 1 kg
```

Estimation.csl

```
@estimator Bayes
@max_iters  4000
@max_evals 10000
@grad_tol 0.0002 #The default is 0.002

@MCMC
start 0.2
length 15000000
keep 1000
stepsize 0.02
proposal_t True
df 2
burn_in 1000
subsample_size 3000
systematic False

@profile
parameter initialization.B0
n      15
l  200000
u  600000

@relative_abundance TangaroaAcousticMature
biomass True
q TangaroaMatureq
years 1993 1994 1995 1998 2000 2002 2004 2006 2009 2011 2013
step 2
area spawn
ogive TangaroaMatureSel
proportion_mortality 0.5
1993 16060
1994 72168
1995 53608
1998 91639
2000 71749
2002 66034
2004 42236
2006 43843
2009 99521
2011 53299
2013 65487 # ROD revised to 65801 (jan 2013)
cvs_1993 0.24
cvs_1994 0.34
cvs_1995 0.30
```

```
cvs_1998 0.14
cvs_2000 0.17
cvs_2002 0.68
cvs_2004 0.35
cvs_2006 0.32
cvs_2009 0.27
cvs_2011 0.22
cvs_2013 0.25
dist lognormal
cv_process_error 0.001

@relative_abundance TangaroaAcousticImmature
biomass True
q TangaroaImmatureq
years 1993 1994 1995 1998 2000 2002 2004 2006 2009 2011 2013
step 2
area nonspawn
ogive TangaroaImmatureSel
proportion_mortality 0.5
1993 35208
1994  8018
1995 15507
1998  6759
2000  1864
2002   247
2004  5617
2006  3423
2009 24479
2011 14454
2013  8004
cvs_1993 0.25
cvs_1994 0.38
cvs_1995 0.29
cvs_1998 0.20
cvs_2000 0.24
cvs_2002 0.76
cvs_2004 0.16
cvs_2006 0.24
cvs_2009 0.26
cvs_2011 0.17
cvs_2013 0.55
dist lognormal
cv_process_error 0.001

@catch_at ObserverProportionsAtAge
years 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990
1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013
fishery Trawl
sexed True
plus_group True
#        M2     M3     M4     M5     M6     M7     M8     M9     M10
M11    M12    M13    M14    M15     F2      F3     F4     F5     F6
F7     F8     F9     F10    F11    M12    M13    M14    M15
1979 0.0059 0.0139 0.1321 0.0439 0.0066 0.0065 0.0570 0.0087 0.0130
0.0358 0.0657 0.0601 0.0931 0.1649 0.0028 0.0079 0.0800 0.0240
```

0.0093 0.0029 0.0154 0.0000 0.0082 0.0082 0.0144 0.0198 0.0374
0.0626
1980 0.0019 0.0100 0.0254 0.0381 0.0031 0.0260 0.0146 0.0266 0.0000
0.0213 0.0659 0.0517 0.0824 0.3443 0.0003 0.0025 0.0041 0.0334
0.0074 0.0064 0.0095 0.0114 0.0046 0.0130 0.0031 0.0214 0.0358
0.1360
1981 0.1238 0.0080 0.0096 0.0147 0.0227 0.0182 0.0050 0.0235 0.0248
0.0053 0.0212 0.0423 0.0427 0.2575 0.0326 0.0015 0.0116 0.0037
0.0359 0.0075 0.0070 0.0215 0.0170 0.0071 0.0165 0.0206 0.0240
0.1744
1982 0.0648 0.2994 0.0346 0.0024 0.0117 0.0432 0.0039 0.0036 0.0088
0.0178 0.0037 0.0019 0.0019 0.1078 0.0505 0.1348 0.0279 0.0229
0.0020 0.0228 0.0063 0.0048 0.0116 0.0085 0.0075 0.0048 0.0120
0.0781
1983 0.0239 0.2128 0.1646 0.0043 0.0055 0.0108 0.0202 0.0029 0.0000
0.0179 0.0135 0.0000 0.0035 0.1003 0.0094 0.1773 0.1145 0.0076
0.0102 0.0015 0.0218 0.0067 0.0000 0.0038 0.0022 0.0000 0.0015
0.0631
1984 0.0017 0.0287 0.1417 0.1876 0.0297 0.0244 0.0192 0.0415 0.0128
0.0044 0.0039 0.0185 0.0061 0.0951 0.0005 0.0276 0.1280 0.1285
0.0100 0.0038 0.0049 0.0167 0.0056 0.0009 0.0036 0.0095 0.0045
0.0405
1985 0.0202 0.0082 0.0861 0.1896 0.1193 0.0033 0.0063 0.0130 0.0212
0.0157 0.0038 0.0229 0.0119 0.0892 0.0031 0.0036 0.0493 0.1134
0.1250 0.0116 0.0020 0.0018 0.0103 0.0000 0.0055 0.0174 0.0180
0.0283
1986 0.0255 0.0680 0.0264 0.0414 0.1421 0.1195 0.0180 0.0078 0.0112
0.0151 0.0000 0.0089 0.0089 0.0922 0.0065 0.0465 0.0264 0.0218
0.0916 0.1089 0.0121 0.0092 0.0137 0.0112 0.0085 0.0042 0.0050
0.0494
1987 0.0200 0.0949 0.0905 0.0133 0.0244 0.1115 0.0787 0.0093 0.0074
0.0052 0.0115 0.0034 0.0077 0.0501 0.0102 0.0958 0.1099 0.0125
0.0288 0.0765 0.0727 0.0079 0.0058 0.0075 0.0055 0.0035 0.0043
0.0314
1988 0.0813 0.0943 0.0866 0.0704 0.0000 0.0202 0.1200 0.0571 0.0006
0.0110 0.0013 0.0115 0.0055 0.0248 0.0033 0.0750 0.0823 0.0627
0.0038 0.0315 0.0759 0.0404 0.0055 0.0031 0.0043 0.0027 0.0000
0.0249
1989 0.0038 0.1440 0.0758 0.0617 0.0554 0.0000 0.0356 0.0864 0.0637
0.0172 0.0040 0.0077 0.0061 0.0189 0.0007 0.0923 0.0633 0.0543
0.0595 0.0089 0.0152 0.0609 0.0349 0.0133 0.0014 0.0052 0.0013
0.0084
1990 0.0198 0.1070 0.2107 0.0457 0.0405 0.0459 0.0034 0.0104 0.0260
0.0240 0.0062 0.0000 0.0058 0.0099 0.0039 0.0450 0.2625 0.0318
0.0268 0.0210 0.0046 0.0062 0.0193 0.0129 0.0019 0.0024 0.0026
0.0037
1991 0.0000 0.2668 0.0517 0.0428 0.0161 0.0104 0.0061 0.0027 0.0049
0.0074 0.0035 0.0020 0.0001 0.0022 0.0007 0.3521 0.0870 0.0836
0.0178 0.0120 0.0048 0.0021 0.0035 0.0064 0.0052 0.0020 0.0018
0.0044
1992 0.0814 0.0086 0.2553 0.0648 0.0739 0.0142 0.0111 0.0077 0.0024
0.0025 0.0035 0.0038 0.0024 0.0012 0.0141 0.0054 0.2586 0.0684
0.0859 0.0102 0.0094 0.0042 0.0004 0.0036 0.0039 0.0015 0.0000
0.0013
1993 0.0293 0.1831 0.0299 0.1551 0.0295 0.0386 0.0095 0.0000 0.0000
0.0000 0.0020 0.0061 0.0033 0.0000 0.0008 0.1981 0.0258 0.1399

0.0438 0.0759 0.0046 0.0064 0.0021 0.0015 0.0014 0.0116 0.0002
0.0014
1994 0.0240 0.5952 0.0198 0.0018 0.0185 0.0011 0.0105 0.0000 0.0005
0.0000 0.0000 0.0000 0.0008 0.0000 0.0064 0.2378 0.0487 0.0017
0.0179 0.0049 0.0075 0.0009 0.0003 0.0005 0.0000 0.0000 0.0006
0.0007
1995 0.0037 0.0791 0.3109 0.0124 0.0018 0.0156 0.0020 0.0071 0.0006
0.0002 0.0002 0.0000 0.0000 0.0013 0.0002 0.0291 0.4778 0.0277
0.0011 0.0150 0.0029 0.0082 0.0005 0.0008 0.0003 0.0002 0.0002
0.0010
1996 0.0039 0.0425 0.0728 0.2360 0.0046 0.0007 0.0051 0.0011 0.0009
0.0004 0.0003 0.0002 0.0000 0.0005 0.0017 0.0251 0.1035 0.4724
0.0090 0.0024 0.0098 0.0019 0.0026 0.0010 0.0002 0.0004 0.0000
0.0010
1997 0.0094 0.0203 0.0461 0.0890 0.3210 0.0095 0.0070 0.0094 0.0029
0.0037 0.0002 0.0010 0.0000 0.0002 0.0110 0.0228 0.0483 0.0595
0.3134 0.0115 0.0046 0.0035 0.0020 0.0020 0.0003 0.0009 0.0000
0.0006
1998 0.0136 0.1025 0.0289 0.0343 0.0826 0.2160 0.0041 0.0112 0.0014
0.0044 0.0000 0.0000 0.0005 0.0000 0.0022 0.0335 0.0271 0.0381
0.0734 0.3085 0.0059 0.0031 0.0062 0.0005 0.0019 0.0000 0.0000
0.0000
1999 0.0094 0.0680 0.1257 0.0037 0.0219 0.0433 0.1596 0.0122 0.0024
0.0016 0.0044 0.0040 0.0000 0.0023 0.0026 0.0739 0.1812 0.0075
0.0340 0.0325 0.1908 0.0087 0.0039 0.0028 0.0027 0.0000 0.0000
0.0008
2000 0.0136 0.0598 0.0810 0.1064 0.0150 0.0178 0.0160 0.1426 0.0061
0.0000 0.0063 0.0009 0.0023 0.0014 0.0010 0.0227 0.1447 0.1452
0.0147 0.0210 0.0308 0.1396 0.0038 0.0034 0.0026 0.0008 0.0007
0.0000
2001 0.0192 0.1308 0.0449 0.0687 0.0746 0.0017 0.0200 0.0396 0.0861
0.0040 0.0036 0.0060 0.0018 0.0003 0.0041 0.1179 0.0345 0.0791
0.1085 0.0058 0.0150 0.0458 0.0775 0.0069 0.0014 0.0010 0.0002
0.0012
2002 0.0088 0.0330 0.1523 0.0397 0.0878 0.0621 0.0000 0.0104 0.0192
0.0608 0.0026 0.0000 0.0000 0.0011 0.0000 0.0169 0.1483 0.0195
0.0772 0.0785 0.0083 0.0129 0.0504 0.1004 0.0077 0.0012 0.0000
0.0010
2003 0.0266 0.0504 0.0595 0.1068 0.0321 0.0345 0.0287 0.0057 0.0081
0.0168 0.0586 0.0123 0.0016 0.0022 0.0003 0.0554 0.0674 0.1063
0.0246 0.0696 0.0616 0.0231 0.0080 0.0099 0.0973 0.0254 0.0039
0.0035
2004 0.0225 0.2053 0.0419 0.0336 0.0420 0.0172 0.0155 0.0295 0.0042
0.0000 0.0139 0.0539 0.0000 0.0012 0.0000 0.1590 0.0958 0.0385
0.0564 0.0356 0.0174 0.0274 0.0162 0.0007 0.0134 0.0549 0.0020
0.0020
2005 0.0000 0.1409 0.1645 0.0460 0.0109 0.0221 0.0067 0.0105 0.0127
0.0040 0.0031 0.0074 0.0089 0.0052 0.0000 0.1235 0.2360 0.0665
0.0212 0.0169 0.0121 0.0071 0.0213 0.0121 0.0057 0.0049 0.0273
0.0026
2006 0.0927 0.0473 0.1319 0.1360 0.0544 0.0222 0.0059 0.0228 0.0165
0.0169 0.0107 0.0031 0.0000 0.0361 0.0000 0.0207 0.0728 0.1494
0.0371 0.0345 0.0161 0.0123 0.0085 0.0096 0.0010 0.0000 0.0027
0.0386
2007 0.0189 0.0482 0.0494 0.0993 0.1396 0.0308 0.0322 0.0085 0.0064
0.0066 0.0083 0.0059 0.0000 0.0121 0.0000 0.0290 0.1283 0.1365

```
0.1028 0.0659 0.0104 0.0087 0.0096 0.0066 0.0042 0.0026 0.0018
0.0275
2008 0.0182 0.0175 0.0749 0.0605 0.0935 0.1132 0.0540 0.0204 0.0078
0.0048 0.0046 0.0030 0.0027 0.0190 0.0001 0.0046 0.0861 0.0791
0.0583 0.1286 0.0762 0.0274 0.0101 0.0050 0.0035 0.0019 0.0004
0.0246
2009 0.0532 0.2327 0.0000 0.1067 0.0174 0.0576 0.0516 0.0136 0.0096
0.0003 0.0044 0.0000 0.0020 0.0078 0.0055 0.1474 0.0000 0.1083
0.0584 0.0383 0.0198 0.0501 0.0067 0.0005 0.0007 0.0017 0.0009
0.0047
2010 0.0000 0.1160 0.2388 0.0474 0.0128 0.0153 0.0195 0.0250 0.0217
0.0044 0.0022 0.0022 0.0021 0.0048 0.0002 0.0551 0.2382 0.0857
0.0174 0.0187 0.0222 0.0172 0.0179 0.0067 0.0033 0.0003 0.0011
0.0040
2011 0.0026 0.0023 0.0910 0.2497 0.0262 0.0019 0.0155 0.0064 0.0311
0.0024 0.0050 0.0012 0.0009 0.0048 0.0007 0.0225 0.1213 0.3280
0.0225 0.0092 0.0163 0.0055 0.0163 0.0043 0.0052 0.0027 0.0016
0.0029
2012 0.0020 0.1542 0.0214 0.0728 0.1642 0.0222 0.0095 0.0014 0.0071
0.0164 0.0055 0.0021 0.0033 0.0013 0.0022 0.1236 0.0346 0.0759
0.1835 0.0479 0.0046 0.0103 0.0089 0.0110 0.0064 0.0042 0.0011
0.0023
2013 0.0049 0.0006 0.2520 0.0143 0.0787 0.0828 0.0154 0.0087 0.0002
0.0034 0.0129 0.0031 0.0000 0.0012 0.0059 0.0000 0.2590 0.0223
0.0681 0.0904 0.0233 0.0190 0.0107 0.0047 0.0093 0.0040 0.0014
0.0038
N_1979  12  # 150
N_1980  16  # 200
N_1981  41  # 495
N_1982  41  # 494
N_1983  35  # 423
N_1984  47  # 571
N_1985  33  # 404
N_1986  47  # 568
N_1987  58  # 705
N_1988  54  # 656
N_1989  55  # 664
N_1990  60  # 724
N_1991  161 # 1941
N_1992  72  # 872
N_1993  40  # 488
N_1994  122 # 1474
N_1995  135 # 1632
N_1996  133 # 1598
N_1997  69  # 833
N_1998  48  # 584
N_1999  61  # 734
N_2000  26  # 318
N_2001  47  # 574
N_2002  28  # 343
N_2003  58  # 704
N_2004  24  # 296
N_2005  62  # 745
N_2006  26  # 318
N_2007  46  # 562
N_2008  55  # 670
```

```
N_2009  20  # 246
N_2010  75  # 908
N_2011  56  # 675
N_2012  69  # 832
N_2013  55  # 669
dist multinomial

@estimate
parameter q[TangaroaMatureq].q
lower_bound 0.09
upper_bound 3.00
prior lognormal
mu 0.68
cv 0.77

@estimate
parameter q[TangaroaImmatureq].q
lower_bound 0.01
upper_bound 3.00
prior uniform

@estimate
parameter initialization.B0
lower_bound  30000
upper_bound 1500000
prior uniform-log

# Q METHOD

@q_method free

@q TangaroaMatureq
q .5

@q TangaroaImmatureq
q .3


@estimate
parameter initialization.Cinitial_male
same initialization.Cinitial_female
lower_bound  2e2  2e2  2e2  2e2  2e2  2e2  2e2  2e2  2e2  2e2  2e0
2e0  2e0  2e0
upper_bound  2e9  2e9  2e9  2e9  2e9  2e9  2e9  2e9  2e9  2e9  2e9
2e9  2e9  2e9
prior uniform

@estimate
parameter migration[toSpawn].rates_all
lower_bound 0.001 0.001 0.001 0.001 1
upper_bound 0.999 0.999 0.999 0.999 1
prior uniform


@estimate
parameter recruitment.YCS
```

```
#YCS_years   1977  1978  1979  1980  1981  1982  1983  1984  1985
1986  1987  1988  1989  1990  1991  1992  1993  1994  1995  1996
1997  1998  1999  2000  2001  2002  2003  2004  2005  2006  2007
2008  2009  2010  2011
lower_bound 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 1
upper_bound   10   10  10   10   10   10   10   10   10   10   10
10   10   10   10   10   10   10   10   10   10   10   10   10   10
10   10   10   10   10   10   10   10   10     1
prior lognormal
mu              26489122130 26489122130 26489122130 26489122130
26489122130 26489122130 26489122130 26489122130 26489122130
26489122130 26489122130 26489122130 26489122130 26489122130
26489122130 26489122130 26489122130 26489122130 26489122130
26489122130 26489122130 26489122130 26489122130 26489122130
26489122130 26489122130 26489122130 26489122130 26489122130
26489122130 26489122130 26489122130 26489122130 26489122130
26489122130
cv            2980.958 2980.958 2980.958 2980.958 2980.958 2980.958
2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958
2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958
2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958
2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958
2980.958


@catch_limit_penalty
label Penalty-CatchLimitTrawl
log_scale True
fishery Trawl
multiplier 100

@estimate
parameter recruitment.steepness
lower_bound     0.21
upper_bound     1
prior beta
mu 0.85
stdev 0.1

@estimate
parameter natural_mortality.all
prior normal
mu 0.20
cv 0.15
lower_bound 0.1
upper_bound 0.4
```