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General structural sensitivity analysis for the albacore tuna stock assessment in the south Pacific Ocean.

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Summary

For the 2008 albacore stock assessment, a version of the final model was tested for a large number of assumptions and uncertainties to evaluate the effects on a range of management quantities (Hoyle et al. 2008). In examining these sources of uncertainty more closely, these tests were repeated, using a slightly revised version of the 2008 model input files, an updated version of MULTIFAN-CL, and an expanded and improved range of uncertainty factors. We examined the influence of eight sources of structural uncertainty (i.e. we undertook a Structural Sensitivity Analysis (SSA)), with two options for each factor, comprising a total of 256 model runs (2^8). Using the distributed computing system (Condor), the complete uncertainty grid was estimated in about 33 hours.

The purpose of this work was to identify the key (and plausible) sources of uncertainty that should be considered in the 2009 ALB stock assessment. Based on the results of the SSA, and recommendations from the previous assessment, we offer guidance for sensitivity analyses to be undertaken in the 2009 assessment.

Introduction

Many sources of uncertainty affect the results of stock assessment models. It is important to examine their influence, and to consider overall assessment results in the light of this uncertainty. Including structural uncertainty in the assessment, using multiple combinations of structural uncertainties, has advantages over the standard approach of using a base case and sensitivity runs. Integrating across these structural uncertainties can improve understanding of the overall level of uncertainty in the stock assessment. Interactions among sources of uncertainty can also be important.

Sensitivity analyses to aspects of model structure are a routine element in fisheries stock assessments. In developing a base model for the 2008 albacore stock assessment, a wide range of sources of bias and uncertainty were investigated including: moving the central latitudinal boundary north by 5° to 25°S; separating data from the Japanese and Korean longline fisheries; including standardised CPUE data as relative abundance indices for the Japanese, Korean and Chinese Taipei longline fisheries, and the New Zealand troll fishery; reducing the weight given to length frequency data; making the selectivity of longline fisheries seasonal; removing length frequency data collected in Pago Pago before 1971;

changing the biological parameters for natural mortality and reproductive potential; reducing the influence of CPUE from non-standardized fisheries; and permitting declining (i.e. dome-shaped) selectivity to be estimated for most longline fisheries (Hoyle et al. 2008).

In addition to these developments, a number of structural assumptions were tested for the 2008 stock assessment, including the interactions among them, for: the stock-recruitment relationship, growth, time-variant selectivity, increased fishing efficiency, natural mortality, relative weight of the catch at length frequency data, and the choice of the model start-year. In this paper, we further develop this approach for assessing structural uncertainty in the 2008 albacore stock assessment model that combines the assumptions to examine the effects of interactions. We have considered six of the factors used previously with two additional factors (estimating length-based selectivity and offsets to the von Bertalanffy growth curve for young fish) which combine to give 256 plausible model structures. The goal of this analysis is to better understand the uncertainty in the overall assessment and the results are expected to guide the 2009 albacore stock assessment.

Methods

A series of eight pairs of alternative hypotheses (each pair designated S, G, C, M, X, L, V or P, see Table 1) was established about selected factors that may affect the results of the MFCL albacore stock assessment. The focus was on factors where there was either recognized uncertainty that should be considered (e.g. steepness and growth), or factors where assumptions were made without a strong basis and alternative assumptions should be considered (e.g. relative weighting on length frequency data). All of the hypotheses were considered to be plausible, but at this stage no attempt was made to determine the relative plausibility.

Each hypothesis was examined using a scenario established in the MFCL input files. Interactions among hypotheses are likely to be important, so multi-way interactions among eight of these hypotheses were also tested by combining scenarios.

Testing all possible combinations of scenarios (256 runs) on a single fast machine would take, assuming 3.5 hours per run, 5.3 weeks. However, this type of simulation can be run with many jobs in parallel, which we achieved by setting up a Condor cluster (Tannenbaum et al. 2001); http://www.cs.wisc.edu/condor) at the Secretariat of the Pacific Community. Once established, Condor clusters can be expanded relatively easily to include hundreds of computers. This cluster was limited by MFCL's requirement, when running under Condor, for computers to have more than 1GB of RAM. The jobs were submitted to over 25 personal computers, running both Linux and Windows XP operating systems, and the entire set ran in approximately 33 hours. The setup of files is described below in more detail. The condor submit script and related files are in the Appendix.

Setting up each of the 256 runs as a combination of eight scenarios involved altering 4 MFCL input files: the batch script (doitall), the data file (alb.frq), the tag data file (alb.tag), and the initial values file (alb.ini). To facilitate this process we wrote a program, R setup runs.r, which generated input files, set up the job directories, and submitted the jobs to condor.

Scenarios for general structural sensitivity analysis (SSA).

The eight assumptions examined are detailed below, and summarized in Table 1 and Figures 1a-1c display the different model inputs for various scenarios. All options included the same number of model parameters, though this obviously does not have to be the case.

1. *Recruitment constraints (S) (par, doitall)*

Steepness is unknown and very difficult to estimate from fisheries data, and so constitutes a relatively intractable source of uncertainty. Alternative values should always be considered in a stock assessment. The albacore stock assessment is very sensitive to assumptions about steepness (Hoyle et al. 2008) because the spawning biomass at maximum sustainable yield is very low for albacore, at 18% of spawning biomass at MSY. Steepness was given alternative values of 0.7 and 0.9 (the fixed value assumed for the 2008 assessment), (Figure 1a).

In MFCL the stock recruitment relationship can be parameterised using steepness, by setting age_flag(163)=0 and age_flags(153 and 154) to 0. Steepness was fixed, by setting age_flag(162)=0. The steepness parameter is stored in sv(29), which is the 29th column in the “Seasonal growth” section of the par file. This requires a change to the par file after the first run.

2. *Growth curve (G)(ini. Doitall)*

The growth curve was estimated in the 2008 albacore base case model, and the rates were higher than the established growth parameters used as starting values in the model, and higher than growth rates estimated in previous assessments. The estimates were close to the Australian (Farley & Clear 2008) growth curve estimate, with most differences occurring for young fish below about six years. The estimated variability of length at age reduces with age, and was very low for the older age classes. This appears unrealistic and suggests a problem fitting to the length frequency data.

The base option for the growth curve in the sensitivity analysis runs was to fix the growth rate parameter K of the growth curve to the value estimated for the Australian curve (Figure 1b). The alternative option was to estimate all parameters. The parameters for variability of length at age were estimated in both cases. The parameter values were adjusted in the alb.ini file and the associated flag values in the doitall file.

3. *Effort creep (C) (frq)*

An increasing trend in catchability in fisheries is analogous to an “invisible creep” in fishing effort as fishing operations improve in efficiency. This may occur when technological improvements, such as remote sensing equipment, GPS, better communication equipment, and/or higher vessel speeds, allow vessels to improve their ability to find and catch fish. At some life stages, albacore tend to aggregate at oceanographic fronts (Chen et al. 2005, Langley 2004, Langley 2006, Laurs et al. 1977), and the technology to detect fronts has improved dramatically in recent years. Preferred environmental conditions also vary with age, and improved ability to target larger fish may help to explain the increasing average size of albacore caught in recent years. Such technological advances may be capable of generating quite large increases in fishing catchability.

Effort creep is very likely to be affecting even the standardized longline effort for south Pacific albacore, and further work should be carried out to determine an appropriate level to include in the model. This change would primarily affect the fisheries with standardized CPUE, and not those fisheries in which temporal catchability deviates are estimated.

The alternative option to no effort creep was examined through an increase in catchability by 0.5% per year since 1960 for all fisheries. This is equivalent to 0.00125 per quarter and was achieved by changing the effort series for all fisheries to match this assumption, i.e. progressively increasing the quarterly effort. This was achieved by adjusting the effort time series for all fisheries in the alb.frq file.

4. M with alternative mean value (M) (ini)

Natural mortality is a difficult parameter to estimate in a model, and it is often fixed at a 'reasonable' value. Fishery data are usually uninformative about natural mortality, and attempts to estimate the mean annual value for the 2008 assessment resulted in unrealistic values greater than 0.9. Mean natural mortality was therefore fixed at a value of 0.4, with variation at age as estimated from analysis of sex ratio at length data. The increasing skew in the sex ratio towards males (SPC unpublished data) is hypothesised to be due to higher natural mortality of sexually mature females than for males of the same age or size (although other possible explanations should be considered) (Harley and Maunder 2003). This increase in female natural mortality and the subsequent loss of females from the population, are implemented in the single sex model via an increase in the combined M for both sexes (since MFCL is a single sex model) at the age of female sexual maturity, and subsequent decline towards the constant male value.

An alternative option of adjusting the mean natural mortality to a fixed value of 0.45, instead of 0.4, was examined in the SSA (Figure 1c). Natural mortality was adjusted by changing values in the alb.ini file.

5. Time split (X) (frq,tag,doitall)

Changing selectivity through time has been suggested as a reason for the increasing mean length of fish observed in longline fisheries (Langley and Hampton 2005, Langley and Hampton 2006). Multifan-CL does not have the facility to vary selectivity through time within a fishery; selectivity is constrained to be constant. However, time-variant selectivity may be emulated by sub-dividing an individual fishery into discrete fisheries over several time periods and estimating unique selectivities for each, which we have termed as a "time split". This approach involved splitting each of the seasonal and regional Japanese, Korean and Chinese Taipei longline fisheries into period-specific fisheries, and estimating selectivity and catchability (which is confounded with selectivity) separately for each fishery-period. In order to retain the long-term index of abundance over the periods, the splits by fishery were offset from one another in time. The divided fisheries shared tag return rates and length frequency sample size weighting.

The alternative option to time-invariant selectivity, entailed two splits, north and south: fisheries in regions 1 and 4 were each split into three periods, at 1971 and 1990, while fisheries in regions 2 and 3 were split at 1975 and 1986. The timing of the selectivity splits was chosen arbitrarily, rather than by observing the timing of length changes. Selectivity changes are likely to occur as a trend rather than in jumps, and an approach that takes this into account is likely to be more successful. For example, it may be possible to use hooks between floats as an indicator of gear configuration, and use it to as a covariate in the model.

Time splits in the fisheries were applied by adding new fisheries in the alb.frq, alb.tag, and doitall files.

6. *Alternative Re-weighted length frequency data (L) (frq)*

The sample sizes of length and weight frequency data determine the amount of influence that the samples have in the likelihood. Raw sample sizes cannot be used however, because individual fish within a sample are not independent of one another. Sample sizes are therefore adjusted, and down-weighted. For the 2008 assessment, attempts were made to reduce the impact of the increasing size of fish in the catch-at-length time series by reducing the weight of the length frequency data. The MFCL albacore base case uses effective sample size of n/20 for length frequency data, with maximum sample size of 1000. An alternative value of n/40 was considered. This change involved setting fish_flag(49) to specify the relative weighting scalar in the doitall file.

7. *Von Bertalanffy growth offsets (V) (doitall)*

It became apparent in the 2008 albacore assessment the quality of fit to length frequencies in the small size classes was relatively poor. In MFCL size at age for specified age classes (starting from the youngest age) can be modified from von Bertalanffy by activating independent parameters for the average lengths of young age classes. The number of age classes to be modified is set by parest flag(173) in the doitall file. For the 2008 albacore base case model no offsets were estimated. An alternative was examined in which growth offsets for the first 3 age classes were estimated.

8. *Length-based selectivity (P) (doitall)*

The 2008 albacore base model assumed age-based fishing selectivity. However, the variability of length at age in the growth function declined with age and was very low for the older age classes. This was apparently unrealistic and suggested a problem in the model fit to the length frequency data. Consequently, it was recommended that length-based selectivity be investigated as a model development. This alternative was achieved by adjusting the fish flag(26) using the upgraded version of MFCL.

Results

The results are described in two stages, firstly the one-change sensitivity analyses, and secondly, the full grid of 256 model runs.

Single model changes

In the first stage, 9 models were examined: the base model, and eight models with the alternative hypothesis considered for each of the eight structural assumptions examined. Including the base model, 6 runs had the same number of parameters, with 3 runs having more parameters (estimated growth, time split, von Bertalanffy offsets). The run with lower relative weight assigned to length-frequency observations involved changes to the likelihood function (length frequency effective sample size (N)) and therefore the objective function value was not directly comparable. Compared to the base model, better fits to the data were obtained with the estimated growth, natural mortality, time split, von Bertalanffy offset, and length-selectivity scenarios (Table 2). For the time split scenario the fit was improved to both the CPUE and length-frequency likelihood terms, while for the von Bertalanffy offset scenario the improvement in fit to the length-frequency was accompanied by a worse fit to the CPUE. The steepness and effort creep scenarios produced roughly equivalent fits (Table 2).

The length-based selectivity scenario produced a substantial improvement in both the model fit and in estimating variation in mean length at age (Figure 2). However, for a length-based selectivity scenario in which growth was estimated, the model estimated an implausible flat growth curve that started high and grew little. This indicates a model fitting problem. Length-based selectivity may permit the model to fit the data better, but it represents a substantial change in model structure, so some changes to the doitall file may be needed to help the model find the best solution.

Values for the key management quantities were also compared (Table 3 and Figure 3). MSY was larger for the higher steepness, length-based selectivity, and effort creep scenarios, and smaller for the length-frequency weight and (in particular) time split scenarios. The time-split scenario also predicted substantially higher current fishing mortality (F_{CURR}/F_{MSY}), and B_{CURR}/B_{MSY}. The key reference point $SB_{CURR}/SB_{CURR,F=0}$ was also sensitive to this scenario. Higher B_{CURR}/B_{MSY} was estimated for the time split, length-based selectivity, length frequency weight, and higher steepness runs, with lower B_{CURR}/B_{MSY} estimated for the effort creep run.

In terms of overall stock status, the base model indicated that the stock was not exceeding the overfished and overfishing thresholds.

Full grid

The general patterns in the one change model runs were reflected in the results from the full uncertainty grid estimation. Runs containing a combination of scenarios that led to changes in the same direction when done individually lead to greater changes when combined. Figures 4 to 7 provide boxplots showing the distribution of estimates of key management quantities.

Intuitive results were obtained for scenarios having lower steepness and natural mortality, with effort creep that produced more pessimistic estimates of stock status. Consistent with the one change model runs, the von Bertalanffy offset and length frequency relative weight scenarios had little effect.

The fixed growth, steepness, time split and length-based selectivity scenarios produce large effects, with the latter three producing more pessimistic estimates of stock status. SB_{CURR}/SB_{MSY} was substantially lower for the lower steepness scenario (Figures 4 and 8). Similarly, length-based selectivity results in lower values for SB_{CURR}/SB_{MSY} and B_{CURR}/B_{MSY} (Figures 4 and 5), with higher F_{CURR}/F_{MSY} (Figure 6), . Although SB_{CURR}/SB_{MSY} was lower for the time split scenario, higher B_{CURR}/B_{MSY} was obtained (Figures 4, 5 and 8). This is due to the substantially lower value of B_{MSY} for this scenario compared to the base model, as was indicated in the single model changes (Table 3). The low SB_{CURR}/SB_{MSY} most likely reflects the effects of time-variant selectivity that may reduce adult biomass relative to total biomass. This result warrants closer examination in the 2009 assessment. Fixing growth to the Australian curve produced more optimistic results, while most of the pessimistic runs, in terms of F_{CURR}/F_{MSY} and $SB_{CURR}/SB_{MSY,}$ were obtained when growth was estimated. It was noted that some of these model runs, the growth curves were implausible.

Figures 8 and 9 provide scatter plots of F_{CURR}/F_{MSY} versus some of the biomass-based reference points, indicating the effects of the scenario factors in terms of the overfished and overfishing quadrants of the Kobe-style plot. Generally the runs with the estimated growth, time split, and length-based selectivity predict a more pessimistic stock status relative to the alternative scenarios.

Discussion

The purpose of the analysis described in this paper was to indicate which potential sources of uncertainty were likely to impact on the important management quantities and therefore warranted consideration in the 2009 assessment. Based on the results of the analysis, a number of topics were identified for discussion at a workshop held before undertaking the assessment, so as to focus attention on the main sources of uncertainty to be considered.

It was recommended that this approach can produce robust advice on the main sources of model uncertainty in respect of the structural assumptions that potentially cause mis-specification of model processes, and hence, bias in the estimates. This approach is similar to that used initially for southern bluefin tuna assessments (Polacheck et al. 2001), and more recently for south-west Pacific swordfish (Kolody et al. 2006). A main advantage of this method over “one-dimensional” sensitivity tests relative to a base case model, is that it illustrates the effects of interactions among assumptions on model uncertainty. Since the approach effectively gives equal relative weight to each assumption, methods for assigning non-uniform weight according to each assumption’s reliability could usefully be developed in the future. This is particularly important if the approach is used for quantifying model uncertainty due to structural assumptions, i.e., a structural uncertainty analysis (SUA). This differs from the method presented here which has the main aim of identifying the main sources of uncertainty.

A number of the models in the grid illustrated substantial structural uncertainty which prompted a set of recommendations for topics needing closer examination during the 2009 assessment.

i) Growth

A number of runs produced implausible growth functions, especially when length-based selectivity was estimated, with the mean length for the younger age classes being poorly determined. This highlights growth estimation as being very influential and warrants attention for the 2009 assessment as a major source of uncertainty. In future SSA, it is advised that feasibility criteria be determined for identifying and removing runs from the analysis having biologically unrealistic growth estimates, similar to the approach used for the south-west Pacific swordfish assessment (Kolody et al. 2006). Although, estimating von Bertalanffy offsets improved the model fit to length frequency observations, it appears to have little effect on model uncertainty.

ii) Steepness

This parameter is influential and warrants close attention for the 2009 assessment, and it is recommended that it be included in SUA for estimating model structural uncertainty. Since little is known of the relationship between the albacore spawning stock and absolute annual recruitments, it is difficult to determine whether a steepness value of 0.7 is plausible. This uncertainty should underpin the specification of an appropriate prior distribution for the model.

iii) Length-based selectivity

Applying fishery-specific selectivity to fish lengths rather than their ages clearly improved the model fit and also the estimation of growth variability, i.e., the variance around mean lengths at age. Applying this assumption had a large effect on model results and will be a substantial feature of the 2009 assessment. Issues usefully highlighted from the SSA included the uncertainty caused by the simultaneous estimation of mean growth and selectivity at length, which often produced implausible growth curves.

iv) Time-split

Time-variance in fishery-specific selectivity was implemented in the model by splitting a particular fishery's time series of a into separate time-segments, i.e., splitting the fishery's history, and estimating a unique selectivity for each. This assumption was one of the four most important sources of uncertainty, having a substantial impact on early recruitment estimates, and hence, on SB_0, SB_{MSY} and their related reference points. Characteristic of this scenario was a higher number of runs for which overfishing occurs – a more pessimistic stock status. Further development of this scenario must take account of related work currently in progress to explore issues with sampling approaches for albacore length frequency data, and in redefining the fisheries by split model regions. Also a useful diagnostic of the plausibility of this assumption is to examine the time series of catchability estimates among the splits.

v) Relative weighting of the length frequency data

It was not clear from the analysis whether the scenario values (n/20 or n/40) sufficiently explored the true structural uncertainty caused by this assumption for the statistical model. It was recommended that alternative hypotheses be explored further for the 2009 assessment. This scenario should take account of the comprehensive review of the LF data proposed for the assessment, including downweighting of domestic longline data, stratifying by spatial distribution and vessel characteristics, etc. The conflict between the CPUE and length frequency data has been a fundamental source of uncertainty in previous albacore assessments. Therefore, the outcomes of the review may be an informative basis for specifying appropriate relative weight for length frequency data.

vi) Effort creep

Similar to point v), it was not clear from the analysis whether the scenario values sufficiently explored the full structural uncertainty caused by this assumption. It substantially affected model uncertainty, but there is little information on which to base an assumed rate of 0.05% per annum. It is recommended that trends in catch per unit effort data be examined for indicators of increased catchability, and rates that are suitable and consistent with those tested in other assessments be specified. In addition, there is the unanswered question whether an assumed increase in catchability is suitable for all the fisheries having fixed catchability.

vii) Natural mortality

This scenario produced a minimal effect on model uncertainty, which prompted the question whether the assumed values (0.4 and 0.45) sufficiently explored the structural uncertainty. It was recommended that a wider range be explored for the 2009 assessment.

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Tables and Figures

Table 1: Summary of the scenario options considered in the albacore structural sensitivity analyses.

Assumptions	**Hypothesis 1**	**Hypothesis 2**
S - Recruitment steepness	0.7	0.9
G – Growth curve	Fixed *K* – Australian curve	Estimated
C – Effort creep	No creep	0.5% per year
M – Natural mortality	0.4	0.45
X – Time split (time-variant selectivity)	No split	Split selected fisheries
L – Length frequency relative weighting	Down-weight by 20	Down-weight by 40
V – von Bertalanffy offsets (juvenile growth)	No offsets estimated	Offsets estimated (1 to 3 years)
P – Length-based Selectivity	Age-based selectivity	Length-based selectivity

Table 2: Individual runs with number of parameters, gradient, objective functions, and offsets of the objective function and number of parameters from the base model.

Run	**Npars**	**gradient**	**objective fn**	**delta Obj**
Base	5255	1.9866	-346426	0.0
Steepness = 0.90	5255	0.7662	-346424	2.2
Growth estimated	5256	1.5928	-346470	-44.0
Effort creep	5255	3.1261	-346422	4.4
Natural mortality	5255	1.7757	-346451	-24.8
Time split	5881	4.7539	-347089	-663.0
LF relative weighting	5255	2.1836	-298606	47819.5
vonB. offsets	5258	0.8242	-346493	-67.1
Length-based Selectivity	5255	1.8666	-346631	-205.0

Table 3: Estimates of management quantities for the single option runs (Hypothesis 2) versus the SSA base model (Hypothesis 1).

Management quantity	**Units**	**Base**	**Steepness = 0.90**	**Growth estimated**	**Effort creep**	**Natural mortality**	**Time split**	**LF relative weighting**	**vonB. offsets**	**Length-based Selectivity**
$\tilde{Y}_{F_{current}}$	mt per year	77610	80620	78900	85440	78460	32670	72850	80020	78820
MSY	mt per year	127500	169400	127300	153300	134000	32810	107000	132900	156400
$\tilde{B}_0$	mt	1907000	1901000	1858000	2304000	1988000	475800	1644000	1953000	2259000
$\tilde{B}_{F_{current}}$	mt	1558000	1612000	1501000	1926000	1664000	241500	1305000	1594000	1898000
$\tilde{B}_{MSY}$	mt	994300	929800	955800	1202000	1072000	256300	875900	1021000	1137000
$S\tilde{B}_0$	mt	627600	625600	603100	751600	573000	159500	501500	661500	814300
$S\tilde{B}_{F_{current}}$	mt	425500	440000	400100	532800	390500	39830	310700	448900	595200
$S\tilde{B}_{MSY}$	mt	173200	107800	164000	206600	151800	44670	133900	182300	221700
$B_{current}$	mt	1073600	1070166.7	1054736.7	1211533.3	1121166.7	368786.7	1028023.3	1111100	1375666.7
B_{latest}	mt	1058900	1067600	1030900	1192000	1128400	323710	1155800	1130100	1414000
$SB_{current}$	mt	331793.3	330026.7	303510	376556.7	302883.3	78117	250700	337680	408810
SB_{latest}	mt	334990	332970	316850	381790	306110	72004	268050	348570	469600
$B_{current,F=0}$	mt	1258133.3	1254700	1239366.7	1395900	1286000	564333.3	1212566.7	1299266.7	1566566.7
$SB_{current,F=0}$	mt	449053.3	447333.3	417883.3	492826.7	409463.3	210950	366833.3	459620	530120
$B_{latest,F=0}$	mt	1243500	1252200	1215900	1376600	1291500	519350	1339800	1318600	1606900
$SB_{latest,F=0}$	mt	462430	460360	441660	508040	421300	215910	392600	481550	602030

Management quantity	Units	Base	Steepness = 0.90	Growth estimated	Effort creep	Natural mortality	Time split	LF relative weighting	vonB. offsets	Length-based Selectivity
$B_{current}/\tilde{B}_0$		0.56	0.56	0.57	0.53	0.56	0.78	0.63	0.57	0.61
$B_{current}/\tilde{B}_{F_{current}}$		0.69	0.66	0.70	0.63	0.67	1.53	0.79	0.70	0.72
$B_{current}/\tilde{B}_{MSY}$		1.08	1.15	1.10	1.01	1.05	1.44	1.17	1.09	1.21
$B_{current}/B_{current,F=0}$		0.85	0.85	0.85	0.87	0.87	0.65	0.85	0.86	0.88
$B_{latest}/B_{latest,F=0}$		0.85	0.85	0.85	0.87	0.87	0.62	0.86	0.86	0.88
$SB_{current}/SB_{current,F=0}$		0.74	0.74	0.73	0.76	0.74	0.37	0.68	0.73	0.77
$SB_{latest}/SB_{latest,F=0}$		0.72	0.72	0.72	0.75	0.73	0.33	0.68	0.72	0.78
$SB_{current}/S\tilde{B}_0$		0.53	0.53	0.50	0.50	0.53	0.49	0.50	0.51	0.50
$SB_{latest}/S\tilde{B}_0$		0.53	0.53	0.53	0.51	0.53	0.45	0.53	0.53	0.58
$SB_{current}/S\tilde{B}_{F_{current}}$		0.78	0.75	0.76	0.71	0.78	1.96	0.81	0.75	0.69
$SB_{current}/S\tilde{B}_{MSY}$		1.92	3.06	1.85	1.82	2.00	1.75	1.87	1.85	1.84
$SB_{latest}/S\tilde{B}_{MSY}$		1.93	3.09	1.93	1.85	2.02	1.61	2.00	1.91	2.12
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.82	0.85	0.81	0.84	0.84	0.51	0.79	0.82	0.84
$S\tilde{B}_{F_{current}}/S\tilde{B}_0$		0.68	0.70	0.66	0.71	0.68	0.25	0.62	0.68	0.73
$\tilde{B}_{MSY}/\tilde{B}_0$		0.52	0.49	0.51	0.52	0.54	0.54	0.53	0.52	0.50
$S\tilde{B}_{MSY}/S\tilde{B}_0$		0.28	0.17	0.27	0.27	0.26	0.28	0.27	0.28	0.27
$\tilde{F}_{MSY}$		0.13	0.18	0.13	0.13	0.13	0.13	0.12	0.13	0.14
$F_{current}/\tilde{F}_{MSY}$		0.24	0.13	0.27	0.21	0.22	1.13	0.30	0.25	0.22

$\tilde{B}_{F_{current}} \big/ \tilde{B}_{MSY}$	1.57	1.73	1.57	1.60	1.55	0.94	1.49	1.56	1.67
$S\tilde{B}_{F_{current}} \big/ S\tilde{B}_{MSY}$	2.46	4.08	2.44	2.58	2.57	0.89	2.32	2.46	2.68
$\tilde{Y}_{F_{current}} \big/ MSY$	0.61	0.48	0.62	0.56	0.59	1.00	0.68	0.60	0.50

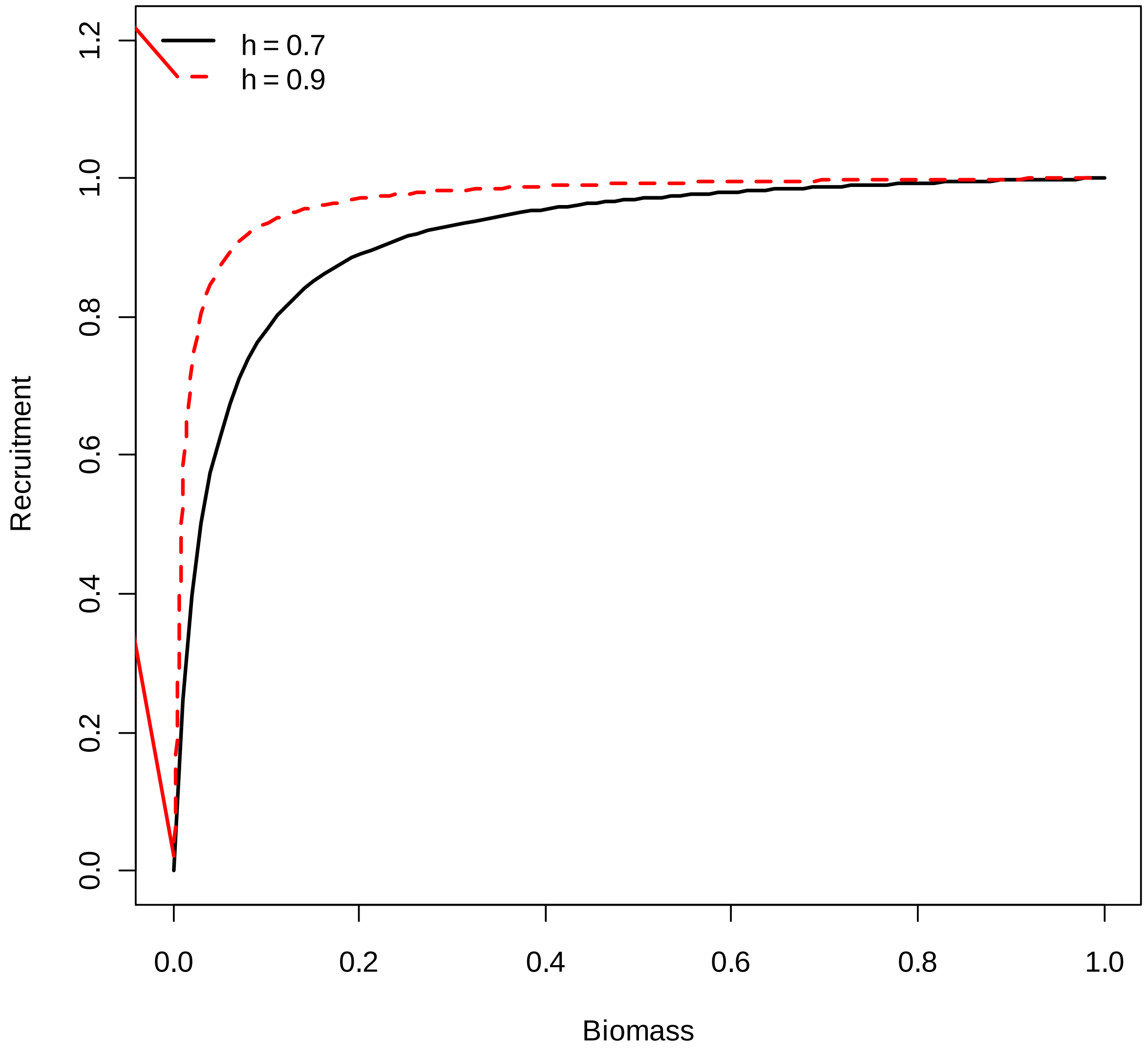

Figure 1a: Spawner recruitment curves for the two values of steepness included in the structural sensitivity analysis. The current levels of spawner depletion for each case are indicated with the vertical lines.

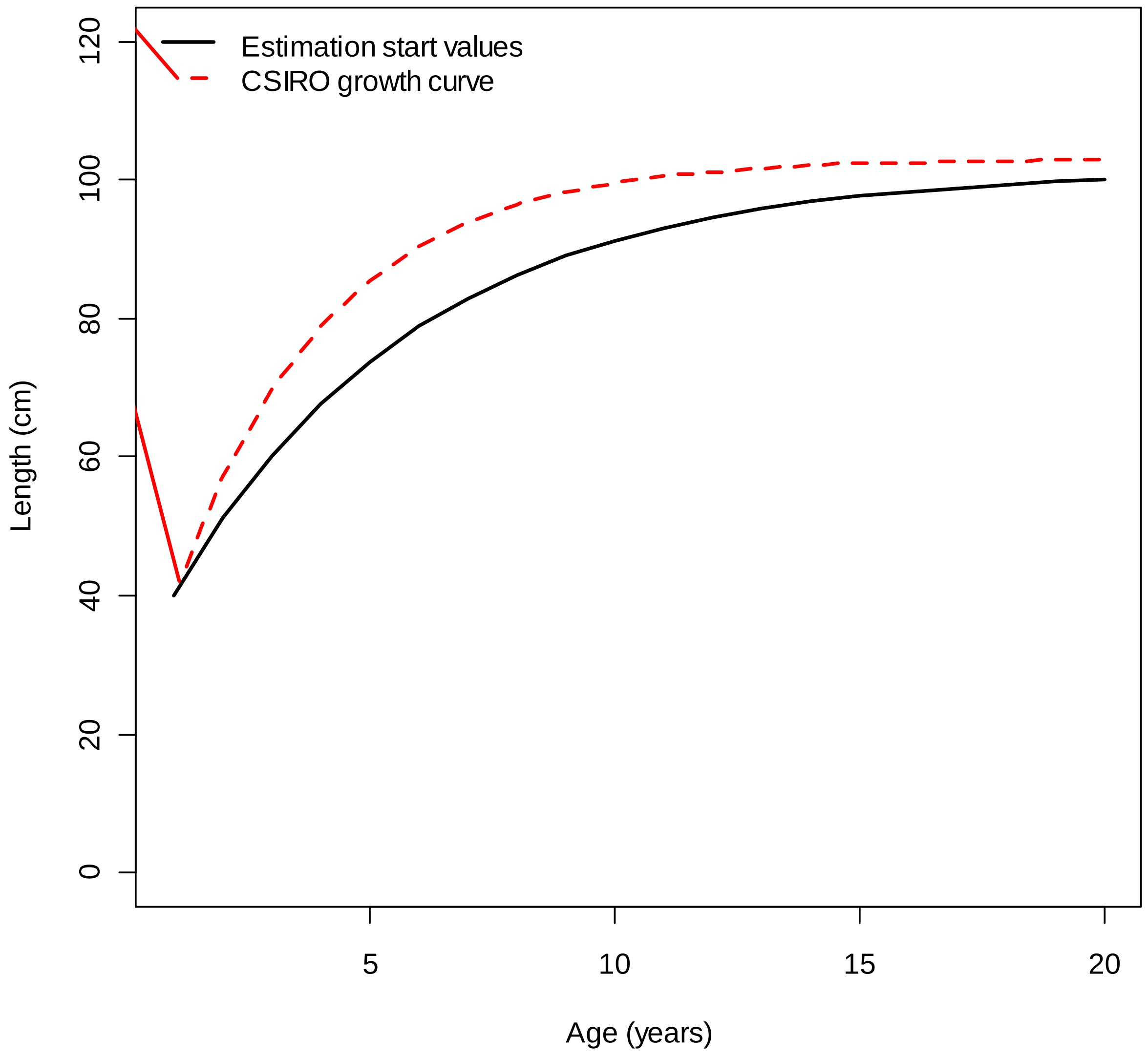

Figure 1b: Growth curves included in the structural sensitivity analysis.

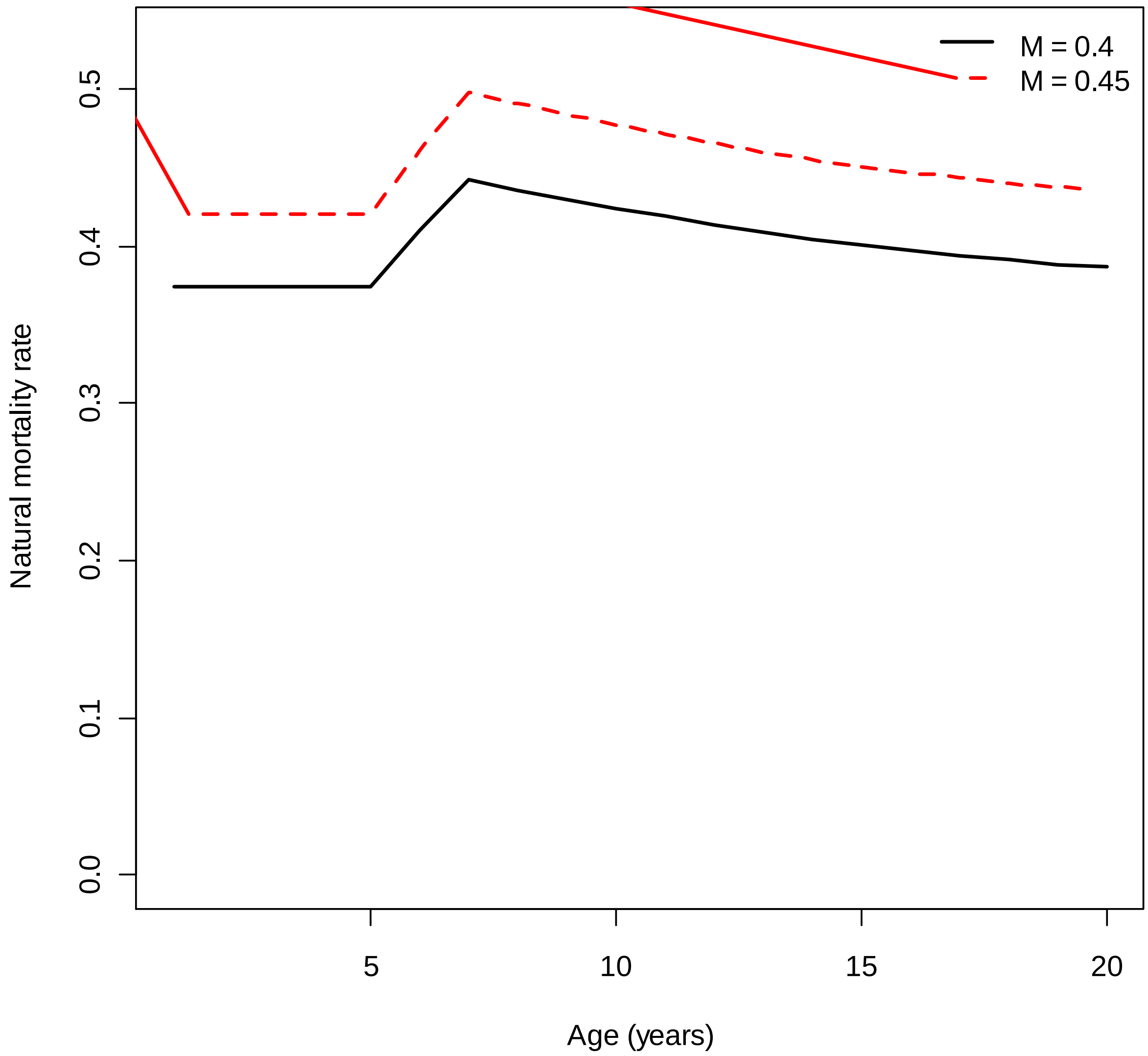

Figure 1c: Natural mortality at age curves included in the structural sensitivity analysis.

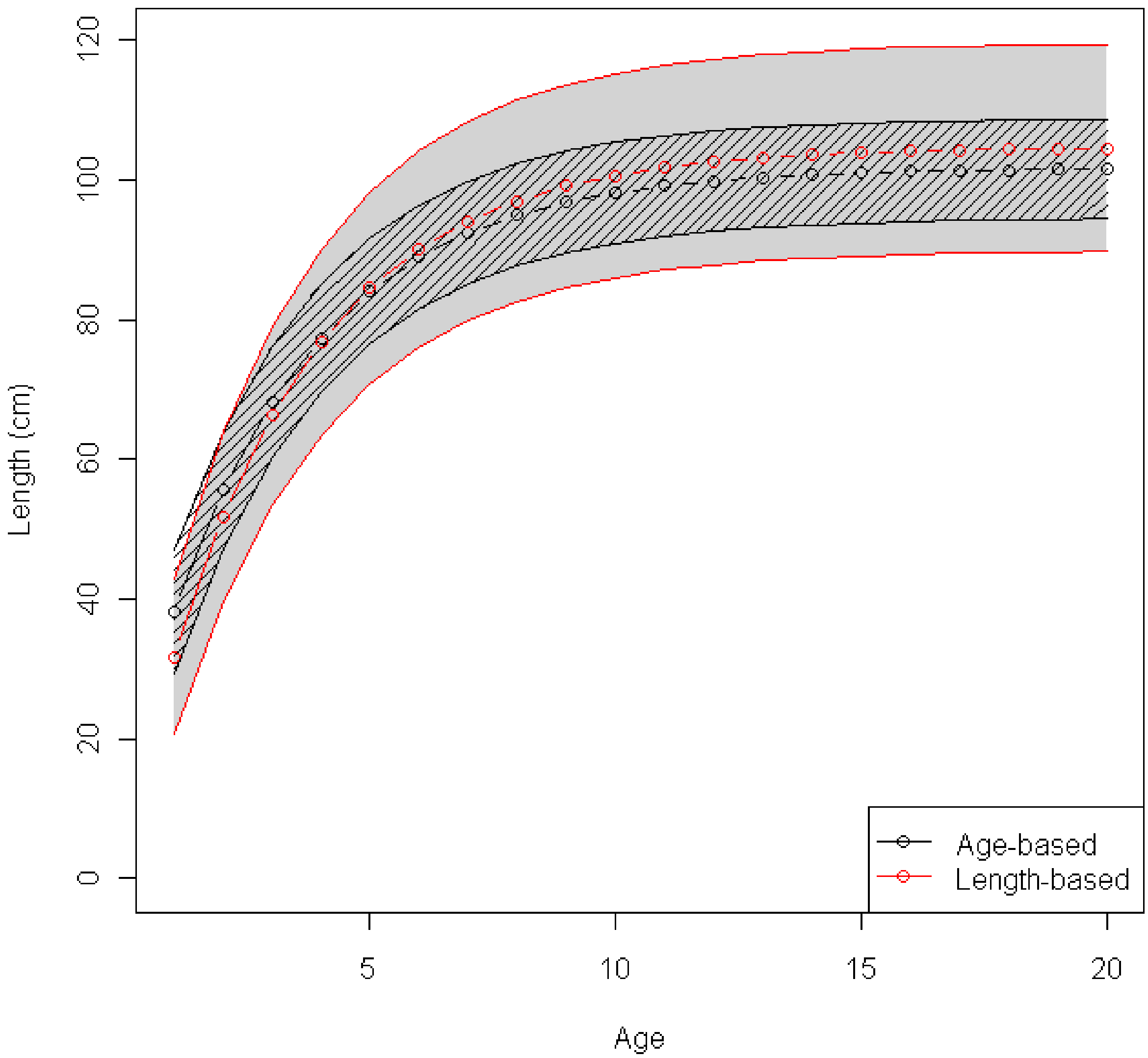

Figure 2: Alternative albacore growth curves estimated from models for which either age- or length-based fishery selectivities were estimated, showing higher variability in mean length-at-age for a model with length-based selectivity. In both models the von Bertalanffy growth parameter *k* was fixed. Total likelihood was -346,425.8 and -346,630.8 for the model fit with either age- or length-based fishery selectivity estimated, respectively.

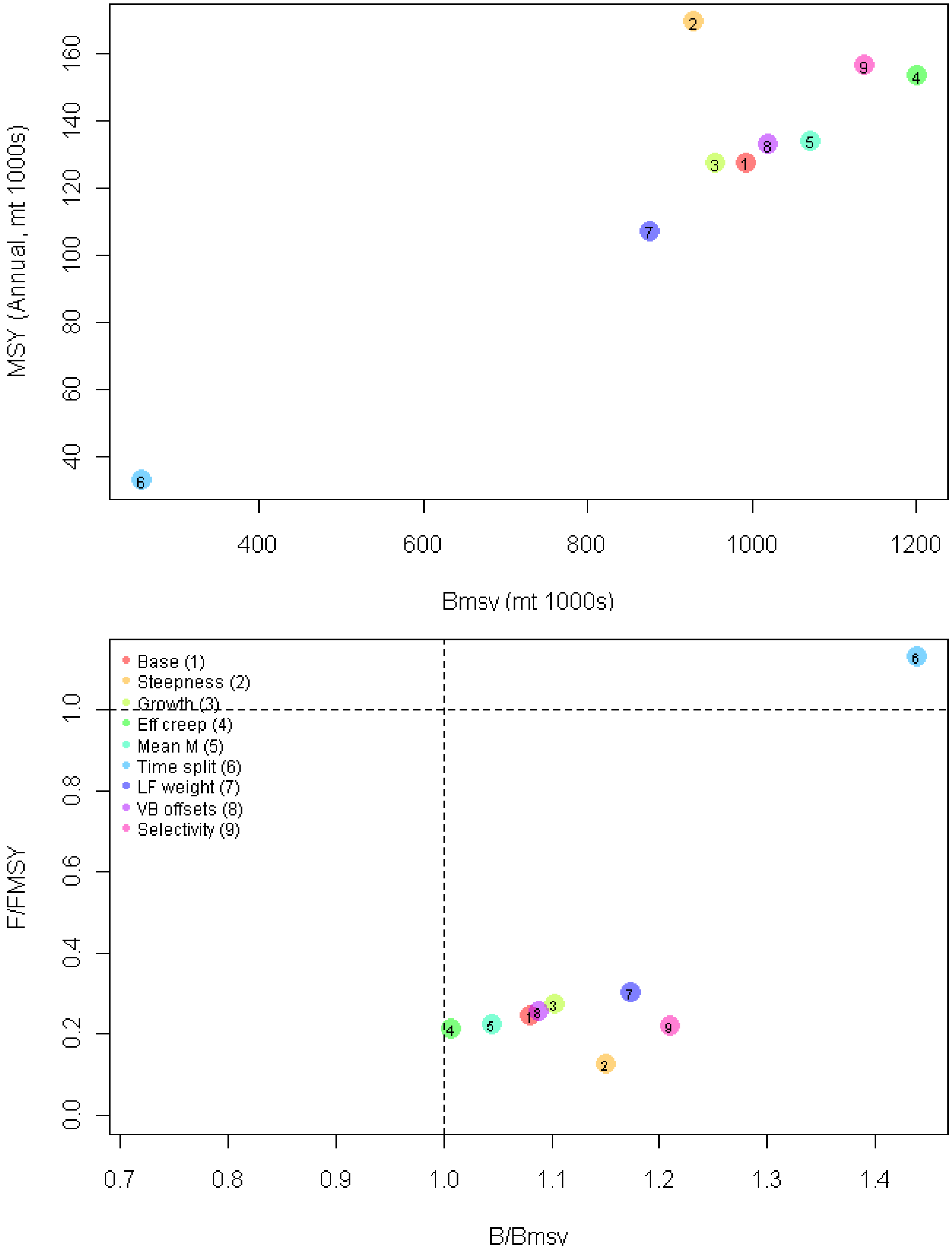

Figure 3: BMSY versus MSY and B/BMSY versus F/FMSY for each single-change scenario.

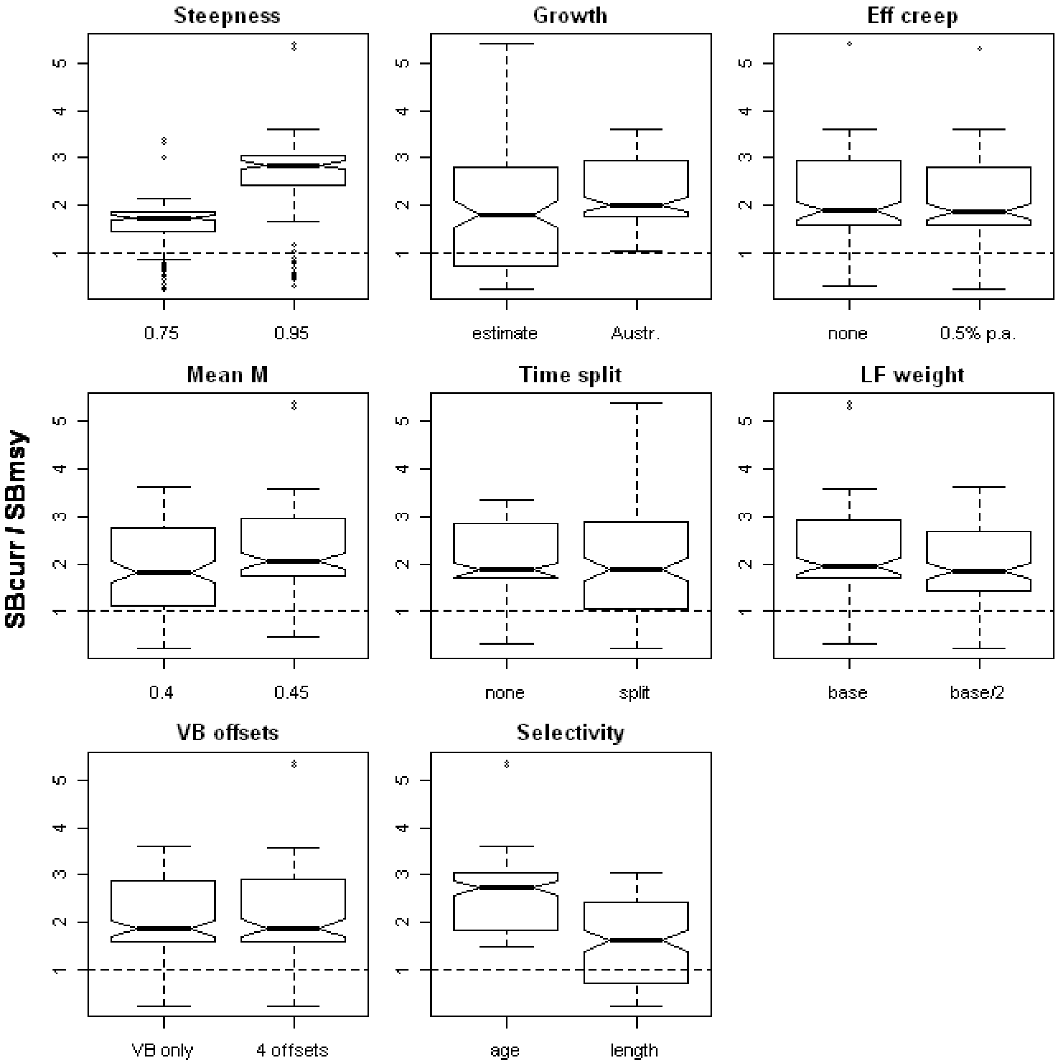

Figure 4: Distribution of SBCURR / SBMSY from 256 runs, grouped by factor. When the notches in the sides of the boxes within a pair do not overlap, this is strong evidence that the two medians differ. The box encloses the upper and lower quartiles, divided by the median, and whiskers extend to either the extreme values or 1.5 times the inter-quartile range from the box, whichever is smaller.

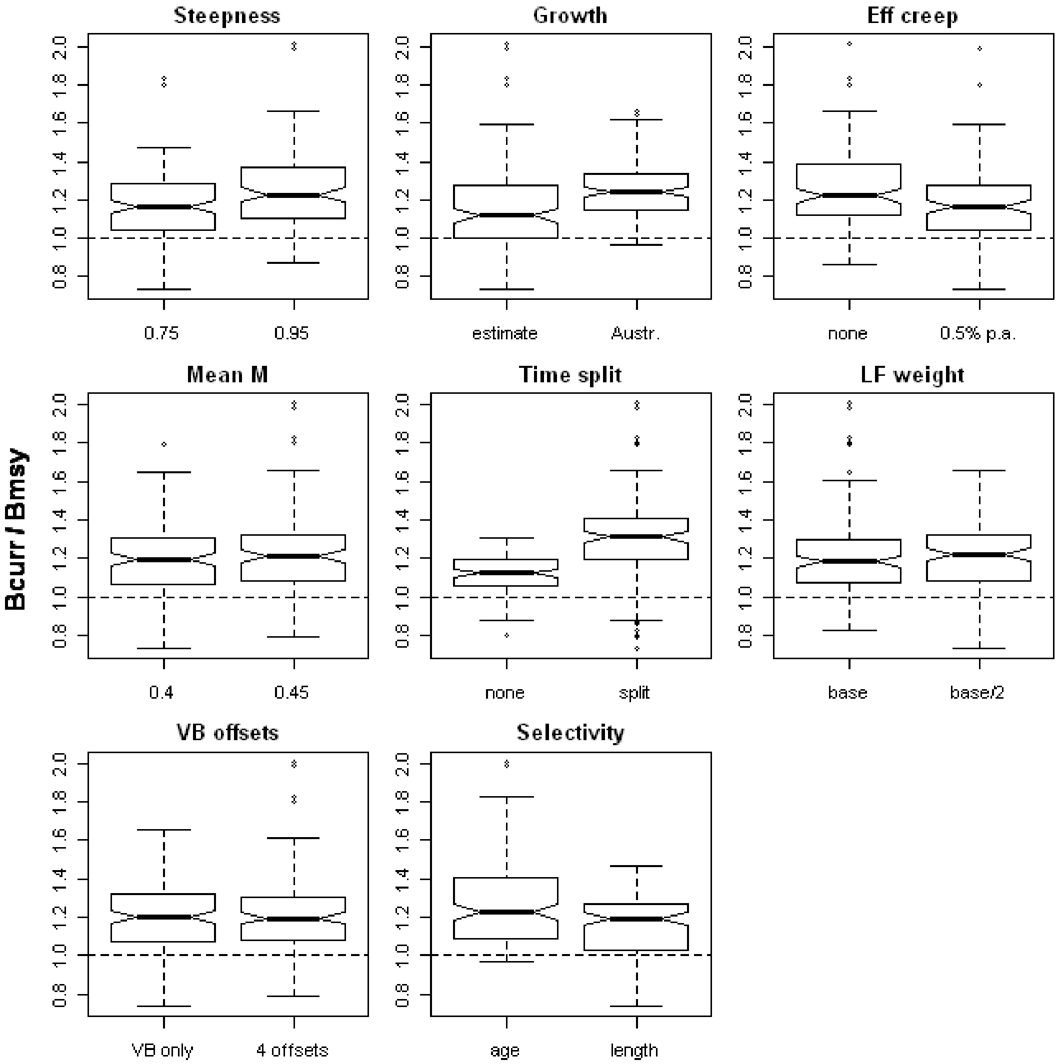

Figure 5: Distribution of BCURR / BMSY from 256 runs, grouped by factor.

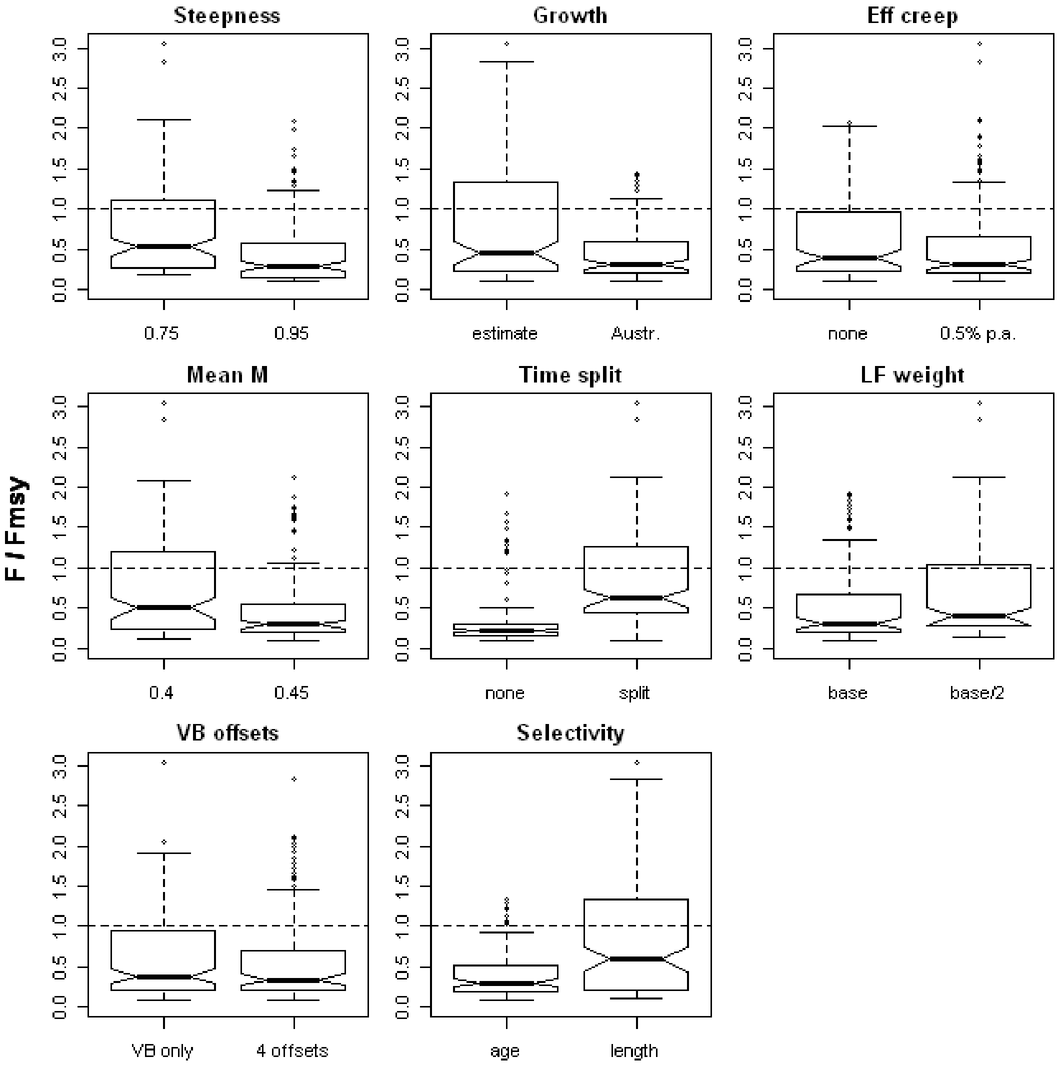

Figure 6: Distribution of FCURR / FMSY from 256 runs, grouped by factor.

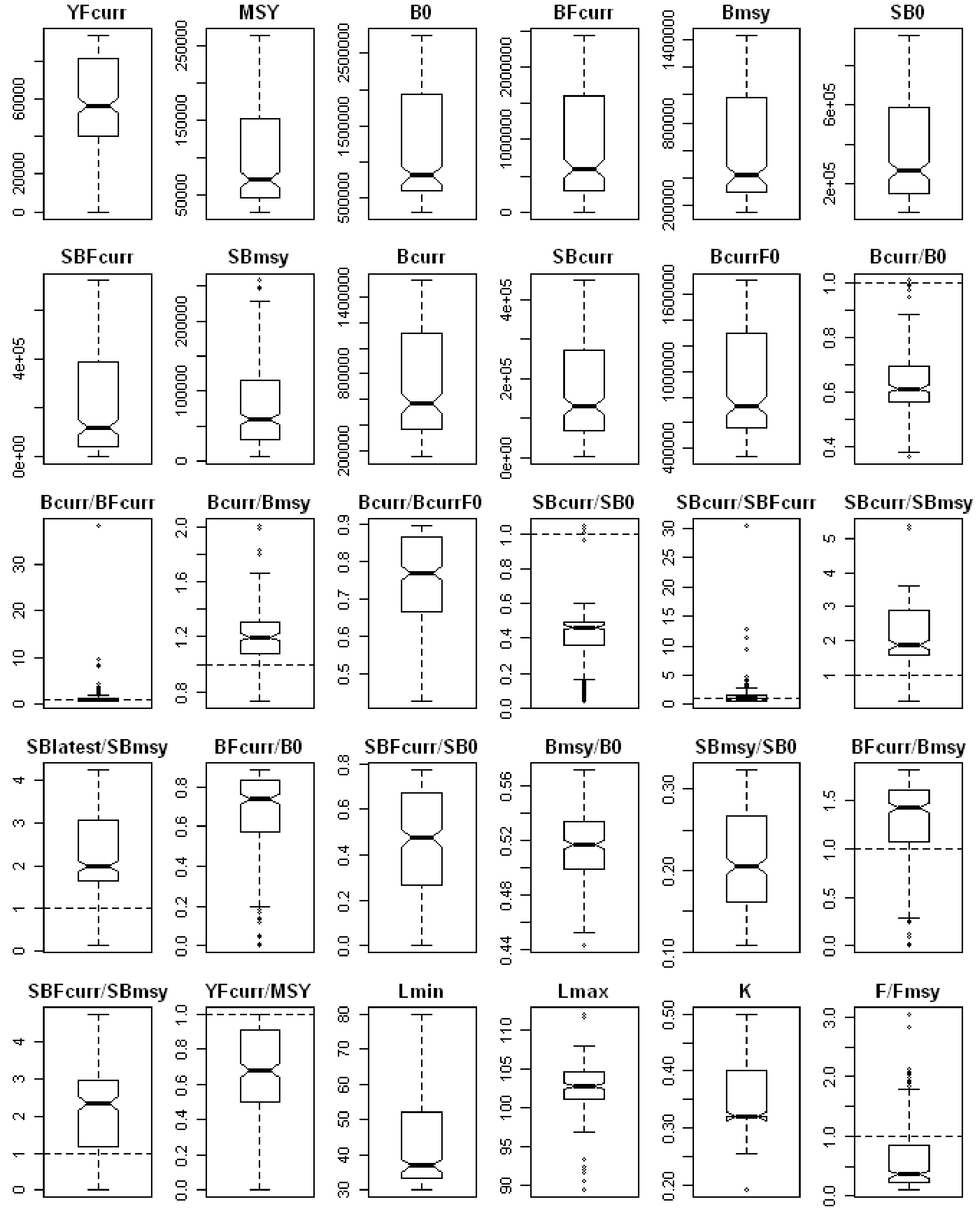

Figure 7: A complete range of management quantities estimated over the complete uncertainty grid of 256 models.

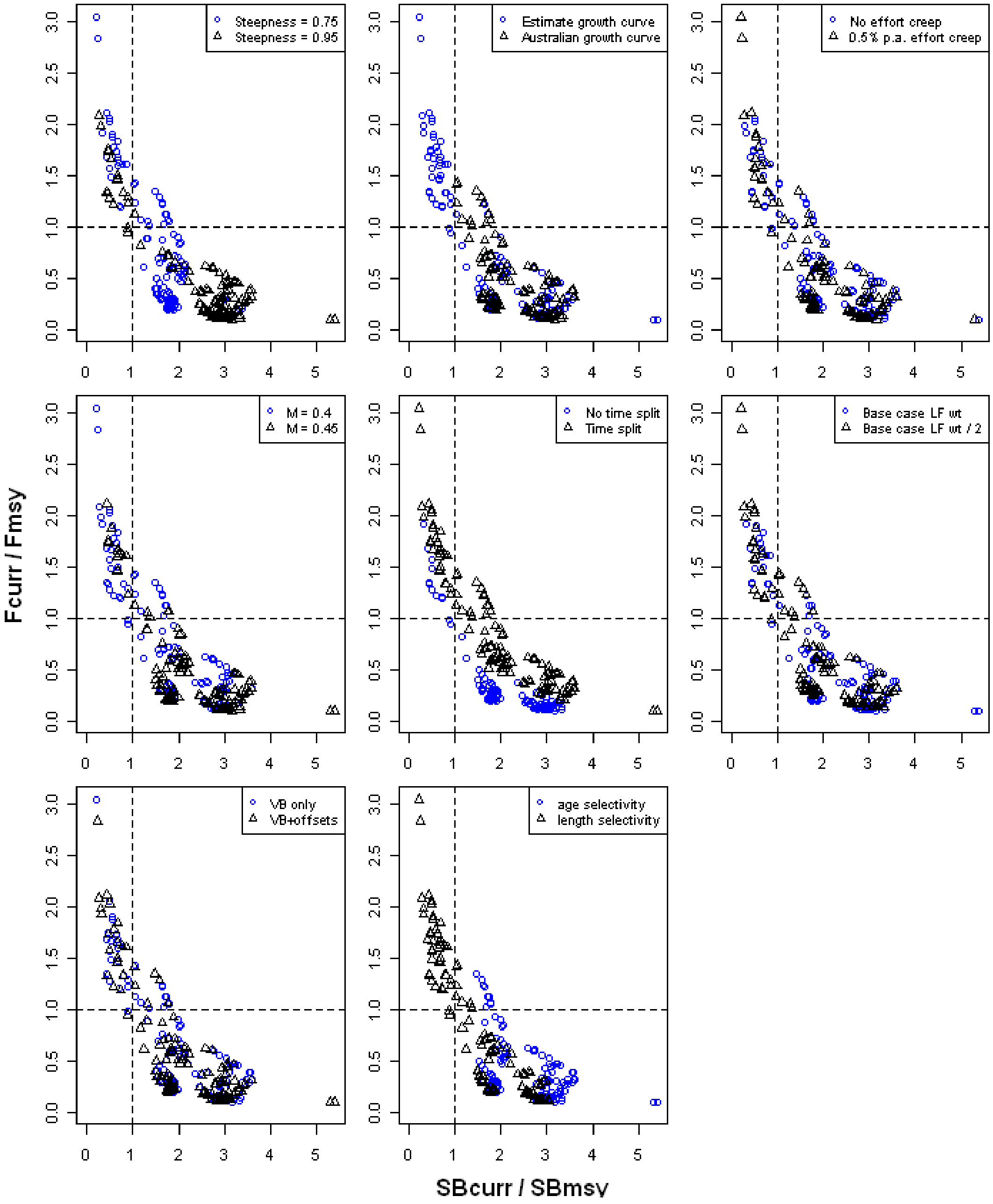

Figure 8: SBCURR / SBMSY versus FCURR / FMSY from 256 runs, grouped by factor.

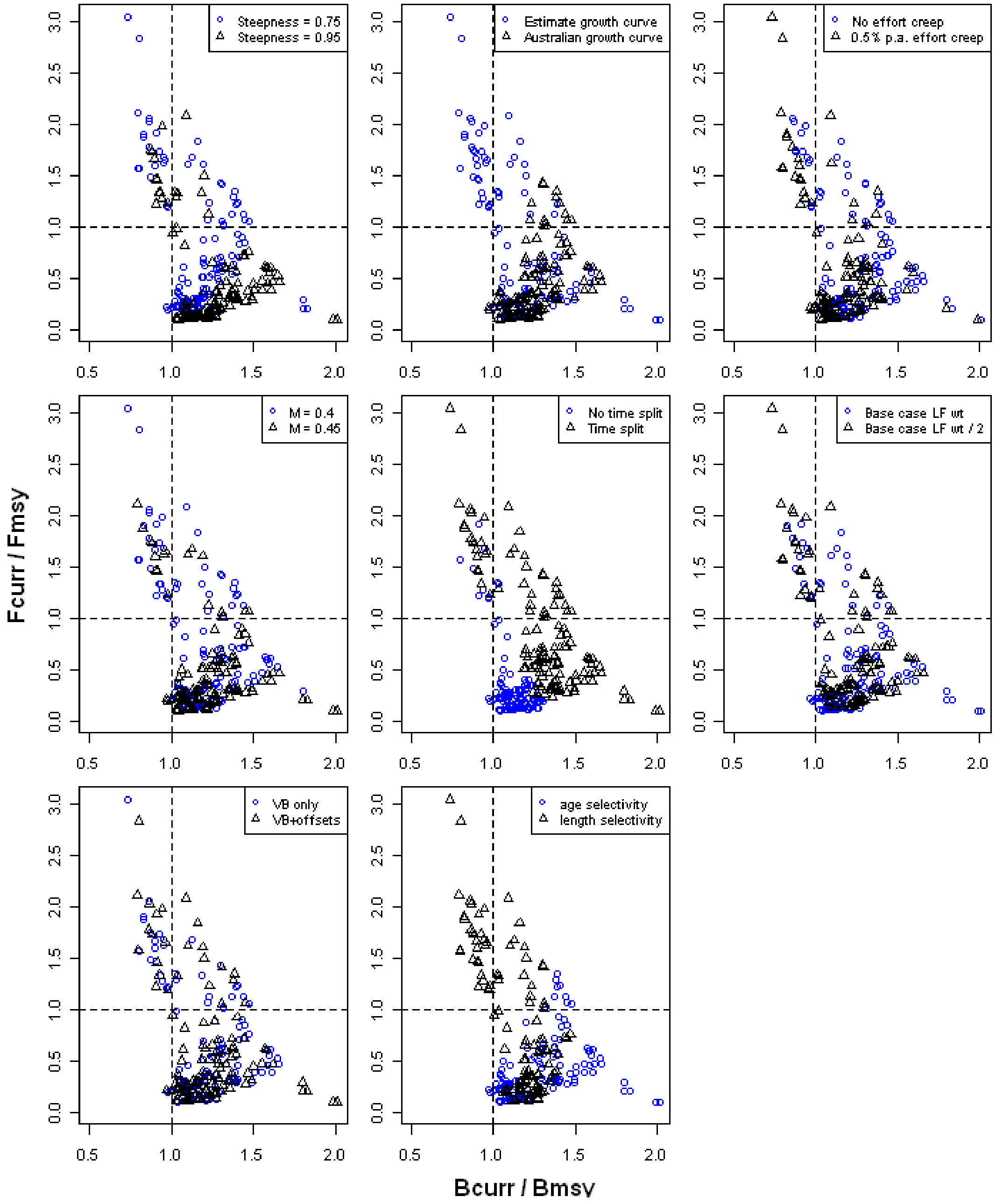

Figure 9: BCURR / BMSY versus FCURR / FMSY from 256 runs, grouped by factor.