SCIENTIFIC COMMITTEE

FIFTH REGULAR SESSION

10-21 August 2009

Port Vila, Vanuatu

GENERAL STRUCTURAL SENSITIVITY ANALYSIS FOR THE YELLOWFIN TUNA STOCK ASSESSMENT

WCPFC-SC5-2009/SA- IP-3

S. J. Harley[1], S. D. Hoyle[1], F. Bouyé[1]

---

[1] Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia

General structural sensitivity analysis for the yellowfin tuna stock assessment

Shelton Harley, Simon Hoyle, and Fabrice Bouyé

Oceanic Fisheries Programme – Secretariat of the Pacific Community

Summary

Given the numerous untested assumptions and uncertainties contained within most stock assessments, it is important to evaluate the resulting key management quantities that come from a range of plausible model structures. Using the 2007 yellowfin assessment, we examined the influence of seven sources of structural uncertainty (i.e. we undertook a Structural Sensitivity Analysis (SSA)), using two options for each factor, to give a total of 128 model runs (2^7). Unlike the bigeye analysis undertaken in 2008, there was no need to use a partially confounded factorial design to reduce the number of model runs required. However, we still used the distributed computing system (Condor), which reduced the expected runtime from 85 to 6 days.

The purpose of this work was to identify the key (and plausible) sources of uncertainty that should be considered in the 2009 YFT stock assessment. Based on the results of the SSA and recommendation from the previous assessment, we have provided some recommendations for sensitivity analyses that should be considered for inclusion 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 regularly run as part of each stock assessment. For example, the 2006 yellowfin stock assessment considered the effects of lower and higher effective sample sizes for size frequency data, and using seven regions instead of six (Hampton et al. 2006). The 2007 assessment carried out 13 structural sensitivity analyses relating to growth, size frequency data re-weighted by catch, Indonesian catch, longline effort penalty weights in region 3, newly defined fisheries, steepness, and modelling region 3 alone (Langley et al. 2007).

However, the complexity of the stock assessments means that many structural assumptions remain to be examined. In particular, interactions among structural assumptions are potentially important, but have not been examined in detail to date. In this paper we continue the approach described in Hoyle et al (2008) for running multiple MFCL stock assessments to test a range of structural assumptions, and combining the assumptions to examine the effects of interactions. We apply this approach to the 2007 YFT assessment considering seven factors which combine to give 128 plausible model structures. The goals of the analysis are to better understand the uncertainty in the overall assessment and the results are expected to guide the 2009 YFT assessment.

Methods

A series of seven pairs of alternative hypotheses (each pair designated R, M, G, C, N, X, or B, see Table 1) was established about selected factors that may affect the results of the MFCL YFT 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. weighting of effort deviates and 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 seven of these hypotheses were also tested by combining scenarios.

Testing all possible combinations of scenarios (128 runs) on a single fast machine would take, assuming sixteen hours per run, twelve 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 one week. The setup of files is described below in more detail. The condor submit script and related files are available from the authors.

Setting up each of the 128 runs as a combination of seven scenarios involved altering 4 MFCL input files: the batch script (doitall.yft), the data file (yft.frq), the tag data file (yft.tag), and the initial values file (yft.ini). To facilitate this process we wrote a program, MFCLCC.jar, which took an input matrix of all the jobs as a series of codes (e.g. R0M0G1C0N1X1B0), generated input files, set up the job directory, and submitted the job to condor.

Scenarios for general structural sensitivity analysis.

The seven assumptions examined are detailed below, and summarized in Table 1 and Figures 1a-1f, 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 (R) (par, doitall)

Steepness was given alternative values of 0.62 (estimate from the 2007 assessment) and 0.90 (Figure 1a).

In MFCL the stock recruitment relationship can be parameterised using steepness, which 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. To set this parameter we changed the par file after the first run. Note for future: need to include specs for S in the .ini file so that initial values can be easily set.

2. 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. We compared the effect of the base case assumption, i.e., an ogive based on the values used by the IATTC which came from an analysis which considered growth, maturity, sex ratio and natural mortality data, with an ogive modified to take into account the different patterns observed in these processes in the WCPO (Figure 1c). Natural mortality was adjusted by changing values in the yft.ini file.

3. Growth curve (G)

The growth curve is estimated in the MFCL yellowfin base case (Hampton et al. 2006), but recent analyses (Langley et al. 2007) suggest that estimates of growth within the model may be driven largely by length frequency data from region 1. There are also indications that growth rates vary among regions.

We therefore modelled growth under two alternative scenarios: 1) the growth curve estimated in the 2007 base case, and 2) an alternative growth curve representing one of many alternative plausible growth scenarios, rather than a definitive alternative scenario. The alternative growth curve was that estimated in the 2007 analysis with the MFCL Region 3 model (Adam Langley unpublished data) (Figure 1b).

For each growth curve, natural mortality at age and sex ratio at age (modelled using maturity at age in MFCL) may be adjusted for the growth curve. This is because the observed decline in yellowfin sex ratio with length is assumed to reflect increased natural mortality of females with age (Harley and Maunder 2003). Fecundity at age may also be adjusted to reflect changes in growth rate, since fecundity at age is estimated from fecundity at length (Itano 2000; Schaefer 1998). Therefore the alternative assumption for the natural mortality ogive (M) was adjusted for the growth curve used. Similarly, the alternative assumption for the maturity ogive (B) was adjusted for the growth curve. In each case the ogives for the base assumptions were not adjusted for the growth curve.

4. *CPUE CV (C) – trial alternative weightings (doitall)*

The penalty weight on the effort deviates reflects assumptions about how much variability there is in the relationship between the catch per unit effort (CPUE) and the vulnerable population (or, more precisely, between effort and fishing mortality). The base case assumption in MFCL is to set the penalty weight (via fish flag 13) on standardized longline fisheries to -50, implying a prior distribution with standard deviation of 0.1, but with the penalty scaled by the square root of the quarterly effort within the fishery. Most non-longline fisheries are given a penalty of -10, implying an effort-scaled prior distribution with standard deviation of 0.22. Penalty on the Indonesia-Philippines mixed fishery in region 3 is set to 10 implying a standard deviation of 0.22, not scaled by effort.

The alternative assumption trialed was to use the same prior standard deviation on effort deviates as the IATTC use for their fisheries in A-SCALA (Maunder et al. 2003). This involves standard deviation of 0.2 on standardized longline fisheries, 0.3 on un-standardized longlines and purse-seine fisheries involving school sets, and 0.4 on purse-seine fisheries involving FAD sets.

MFCL uses only integer flags so fish flags(13) for standardized longline fisheries were set to 13 (SD = 0.20), unstandardized longline, and purse-seine sets on schools and miscellaneous were set to 6 (SD = 0.29), and purse-seine sets on logs and FADS were set to 3 (SD=0.41). Fish flags(13) for other fisheries were set to 1 (SD = 0.7).

5. *Alternative Re-weighted length frequency data (N) (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. The MFCL yellowfin base case uses effective sample size of n/10 for both length frequency and weight frequency data, with maximum sample size of 100. We used an alternative value of n/50, resulting in maximum sample size of 20. This change involved setting age_flags(49) and age_flags(50) equal to 50.

6. *Effort creep (X) (frq)*

Increasing trend in catchability in all fisheries. Increase in longline fishery catchability by 0.5% per year before 1990 and 2% per year post-1990 (Figure 1d). Increase purse seine fisheries by 2% per year throughout (Figure 1e). These are equivalent to 0.00125 and 0.005 per quarter. Change effort series for all fisheries to match this assumption – progressively increase quarterly effort.

7. *Spawning biomass (B) (doitall, ini)*

Spawning biomass, an important output of the model, is defined in MFCL by the product of numbers at age, mean weight at age, and maturity at age. Maturity at age has not been re-calculated to take into account the effects of updated growth curves, which it should be given that maturity data are obtained at length. In addition, it models the mature biomass of both sexes rather than the reproductive potential of the population.

The base case used the standard approach, with maturity 0 for ages 0-6 quarters, 0.25, 0.5, and 0.75 for age 7, 8, and 9 quarters respectively, and 1 for all older ages.

The updated maturity schedule was re-parameterised in terms of relative egg production per unit weight, as equal to the product of sex ratio, maturity, batch fecundity, and spawning fraction (q.v. Hoyle and Nicol 2008) (Figure 1f). These were all estimated based on observations at length (Itano 2000), and translated into age based on the growth curve. Spawning fraction was not available for the WCPO, so the EPO estimate of spawning fraction at length was used (Schaefer et al. 2005).

Results

The results are described in two stages, first the one-change sensitivity analyses and second the full grid of 128 model runs.

Single model changes

All model runs had the same number of parameters. Two runs involved changes to data weightings, therefore it was not possible to directly compare the objective function values (length frequency data samples size (N) and the CPUE CV (C)). Compared to the base model, better fits to the data were obtained with the natural mortality and effort creep scenarios (Table 2). With the effort creep, it was the effort deviate likelihood that showed the greatest improvement, but it could not be determined if this was for the longline or purse seine fisheries. The alternative growth curve led to a far worse fit mostly due to the worse fit to the Region 1 and 2 size frequency data, and the alternative steepness value gave a slightly worse fit.

Values for the key management quantities were also compared (Table 3 and Figure 2) with MSY larger with the steepness, growth, effort creep, and spawning biomass scenarios and decreased with the natural mortality and CPUE CV scenarios. F_{CURR}/F_{MSY} increased with the CPUE CV and effort creep scenarios, and decreased with the steepness and growth scenarios. B_{CURR}/B_{MSY} increased with the natural mortality and steepness scenarios and decreased under effort creep. B_{MSY}/B_0 was relatively stable across the runs except that it was much lower for the steepness scenario. The reference point $SB_{CURR}/SB_{CURR,F=0}$ incorporates a variety of factors and was higher for the steepness and growth scenarios and lower for the length frequency sample size and effort creep scenarios.

In terms of the view on overall stock status, the base case model indicated that the stock was close to both the overfished and overfishing thresholds. However, four of the plausible scenarios indicated that overfishing was occurring and one even had the stock in an overfished state as well (effort creep).

Full grid

The general patterns in the single-change model runs was followed through in the full grid. A series of runs containing a combination of scenarios that led to changes in the same direction when done individually, led to greater changes when combined. Figures 3 to 7 provide boxplots showing the distribution of estimates of key management quantities.

An interesting result was the comparison of the effect of each scenario on the status against two alternative spawning biomass based reference points SB_{CURR}/SB_{MSY} (Figure 3) and $SB_{CURR}/SB_{CURR,F=0}$ (Figure 7). Current status was worse based on SB_{CURR}/SB_{MSY} for the alternatives for length frequency sample size and spawning biomass calculation method, but better under $SB_{CURR}/SB_{CURR,F=0}$. Further, while there was little difference in SB_{CURR}/SB_{MSY} for the options for natural mortality and CPUE CV (effort deviate penalties), stock status in terms of $SB_{CURR}/SB_{CURR,F=0}$ was worse under the alternative options. These types of patterns may be important to discussions within the Commission on MSY-based and other reference points and will be further examined prior to SC-5.

Figures 8 and 9 provide scatter plots of F_{CURR}/F_{MSY} versus some of the biomass-based reference points. The distributions of results from the full grid indicate plausible model results in the overfished and overfishing quadrants of the Kobe-style plot.

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 upcoming assessment.

We will discuss the various sources of uncertainty and provide our recommendations as to their inclusion, both in developing the stock assessment and in structural sensitivity analyses to estimate remaining structural uncertainty.

Steepness

The steepness of the Beverton Holt spawner recruitment model has a large impact on both the levels of MSY-related reference points and current stock status in relation to them. Based on experience with other assessments and simulation studies, it is recognized that it is very difficult to reliably estimate steepness from the data available for a single stock. It is recommended that at least two values be considered in the assessment, and that these values should be determined independently of the steepness estimated by the model. It is noted that when steepness is fixed, subsequent likelihood profiles will be much tighter than if steepness is estimated within the model run.

Natural mortality

It is recommended that the alternative natural mortality curve be used as the previous base case was not internally consistent with assumptions of growth and other biological parameters. It is noted that the work of Hoyle et al. (2009) will be the best source of estimates for the biological parameters. It is possible that there will only be one option for consideration in the assessment.

Growth curve

There is currently a difference between the growth curve estimated for the overall assessment and that estimated just for region 3 where 80% of the biomass is estimated to occur. When the region 3 curve was used it improved the fit in the region 3 small fish fisheries, but at the expense of fits elsewhere. Given the effect that the growth options have on assessment results, it is recommended that spatial variation in growth and its effects on model parameters are further investigated. For example, the assessment could be run for individual regions, with growth either estimated or fixed at plausible alternative levels. Several alternative options should be considered in the assessment to address growth – how these options are implemented is to be determined.

CPUE and size frequency weights

The weighting of different data sources is often quite arbitrary and important model results can be sensitive to alternative assumed values. It is recommended that at least two options be considered for each data type. One of these options may be the traditional weights, but consideration should also be given to several alternatives. For CPUE, the weights estimated in the standardization process may be used, potentially also adjusted for overdispersion. For both CPUE and size frequency data, we should consider weights based on iterative reweighting of both data sources simultaneously. For both data types, residuals should be examined to determine how appropriate the weights are. The specification of these penalty weights is also likely to affect the estimates of statistical uncertainty obtained from individual runs using either likelihood profile or the inverse-hessian-delta method.

Effort creep

There is no question that effort in purse seine fisheries is becoming more efficient and the stock assessment estimates of catchability reflect this. What is more controversial is increases in efficiency in the key longline fisheries for which we assume a fixed catchability. There can be no doubt that longline vessels have become more efficient over time in aspects of their operations – the key question is whether this increase can be reflected in the catch per thousand hooks of yellowfin tuna. Because many WCPFC members still do not submit operational level catch and effort data to the WCPFC, there are very few variables available for CPUE standardization. For this reason it is very unlikely that we can standardize for changes in the operation of longline fishing that could influence catchability of yellowfin and that there will be changes in catchability reflected in CPUE trends that we cannot explain.

It is possible that longliners could have improved their efficiency in the following types of ways:

- Increased number of hooks set per day (possibly a negative impact on CPUE expressed as catch per 1,000 hooks because of reduced soak time per hook)
- Crew required on the boat
- Reduced gear breakages
- More predictable behavior of the gear (e.g. use of monofilament mainline materials)
- Less fishing in unproductive areas (e.g. through use of real-time oceanographic data)
- Increased catches of the target species – perhaps increasing catch per day, but what about catch per 1000 hooks
- Increased catches of a suite of desirable species - perhaps increasing catch per day, but what about catch per 1000 hooks and what might the impacts be on individual species

- Reduced catches of undesirable species

It is recognized that while effort creep might be a reality it could be either positive or negative for YFN, since increased ability to target bigeye tuna (often the preference of Japanese longline fisheries) may have unpredictable effects on catch rates of yellowfin tuna.

Given the sensitivity of the results to an alternative assumption it is recommended that if a defensible alternative scenario can be defined it be included as a sensitivity analysis. Therefore, further examination of the CPUE data for these fisheries is proposed. Currently, operational logsheet data is available for a large proportion of the fishery operations that are undertaken within the zones of PICTs. Following from the work of Langley (2007), we will continue to examine these data to see if alternative CPUE series can be defined or if particular variables, not available in the 5x5 aggregated data, have an influence on CPUE trends. The output from this work will either be an alternative CPUE series or some information on which to formulate an effort creep scenario.

Spawning biomass calculation

The best estimate of the reproductive potential should be included in the YFT assessment. Currently this will be the alternative values used in the SSA, but this will likely be updated based on the outcomes of the work in the Hoyle et al. (2009).

Others

There are some other sources of uncertainty that should be considered. Both alternative estimates of purse seine catches and alternative estimates of catches from the ID/PH fisheries are likely to have an important impact on estimated stock status and relative contributions of different fisheries to stock depletion. In consultation with the OFP-SPC data experts, alternative scenarios for each will be developed.

The new option of length-specific selectivity available in MFCL should also be considered and, in particular, it may improve the fit to size data for some fisheries with very tight modal structure.

Another structural option will be included to try and examine the impact of the rapid declines in the early periods of the longline CPUE series. It could be done through running the model over a shorter time period, or through excluding the early effort data (possibly preferable to keep the same fundamental model structure).

Summary

The following sources of uncertainty should be considered in the YFT assessment:

- Steepness
- Growth
- Data weightings
- Longline CPUE / catchability
- Purse seine catches

- IND/PHI catches
- Early CPUE trends in longline fisheries
- Length-specific catchability

References

Hampton, J., Langley, A., and Kleiber, P. (2006). Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options. WCPFC SC2 SA WP-1, (Secretariat of the Pacific Community: Noumea, New Caledonia.)

Harley, S. J. and Maunder, M. N. (2003). A simple model for age-structured natural mortality based on changes in sex ratios. IATTC, 4th Meeting of the Scientific Working Group, La Jolla, USA, May 19-21 2003.

Hoyle, S. D., Bouyé, F., Langley, A., and Hampton, J. (2008). Sensitivity of the bigeye stock assessment to alternative structural assumptions. WCPFC-SC4 SA-WP-3 (Secretariat of the Pacific Community: Noumea, New Caledonia.)

Hoyle, S. D. and Nicol, S. (2008). Sensitivity of bigeye stock assessment to alternative biological and reproductive assumptions. No. WCPFC-SC4-2008/ ME-WP-1 (Secretariat of the Pacific Community: Noumea, New Caledonia.)

Hoyle, S. D., Nicol, S. and Itano, D. G. (2009). Adjusted biological parameters and spawning biomass calculations for yellowfin tuna in the WCPO. WCPFC-SC5-2009/ BI-WP-xx (Secretariat of the Pacific Community: Noumea, New Caledonia.)

Itano, D. G. (2000). 'The Reproductive Biology of Yellowfin Tuna (*Thunnus albacares*) in Hawaiian Waters and the Western Tropical Pacific Ocean: Project Summary.' (University of Hawaii, Joint Institute for Marine and Atmospheric Research.)

Langley, A. D., (2007). Analysis of yellowfin and bigeye catch and effort data from Japanese and Korean longline fleet collected from regional logsheets. WCPFC-SC3, SA WP-6 (Secretariat of the Pacific Community: Noumea, New Caledonia.)

Langley, A. D., Hampton, J., Kleiber, P. M., and Hoyle, S. D. (2007). Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options. WCPFC-SC3, SA WP-1 (Secretariat of the Pacific Community: Noumea, New Caledonia.)

Schaefer, K. M.(1998). Reproductive biology of yellowfin tuna (*Thunnus albacares*) in the eastern Pacific Ocean. Bulletin. Inter-American Tropical Tuna Commission. Vol. 21. 205-272.

Schaefer, K. M., Fuller, D. W., and Miyabe, N. (2005). Reproductive biology of bigeye tuna (*Thunnus obesus*) in the eastern and Central Pacific Ocean. Inter-American Tropical Tuna Commission Bulletin 23, 1-31.

Tannenbaum, T., Wright, D., Miller, K., and Livny, M. (2001). Condor - A Distributed Job Scheduler. In 'Beowulf Cluster Computing with Linux'. pp. 307-350.(The MIT Press).

Tables and Figures

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

Assumptions	**Hypothesis 1**	**Hypothesis 2**
R - Recruitment steepness	0.62	0.9
M – Natural mortality function (see figure)	Standard approach	Recalculated based on sex ratio
G – Growth curve. M(age) and sex ratio adjusted to match growth curve?	2006 approach	SPC growth curve
C - CPUE CV	2006 approach	IATTC approach
N - length/wt sample size assumption	10	50
X - Effort creep (catchability trend)	No creep	LL & other: 0.5%/yr to 1990, then 2%/yr PS: 2%/yr throughout
B - Spawning biomass	2006 approach	Egg production

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	5458	0.04672	1100632	0
Steepness = 0.90	5458	0.008799	1100624	-8.55014
Natural mortality	5458	0.000296	1100694	61.99128
Growth curve	5458	0.020245	1087193	-13439
Effort deviate penalties	5458	0.000886	1102544	1911.9
Length frequency N	5458	0.000992	863763.7	-236869
Effort creep	5458	0.000929	1100656	24.01148
Reproductive potential	5458	16.43053	1100598	-34.677

Table 3: Estimates of management quantities for the single option runs versus the SSA base model. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	**Units**	**Base**	**Steepness = 0.90**	**Natural mortality**	**Growth curve**	**Effort deviate penalties**	**Length frequency N**	**Effort creep**	**Reproductive potential**
$\widetilde{Y}_{F_{current}}$	mt per year	411,600	490,000	376,520	426,400	344,440	379,960	482,400	431,600
MSY	mt per year	412,800	556,000	376,600	468,000	346,680	380,080	484,000	438,400
$\widetilde{B}_0$	mt	3,898,000	3,770,000	3,512,000	3,770,000	3,444,000	3,561,000	4,738,000	3,866,000
$\widetilde{B}_{F_{current}}$	mt	1,754,000	2,083,000	1,474,000	2,237,000	1,307,000	1,493,000	1,873,000	1,837,000
$\widetilde{B}_{MSY}$	mt	1,654,000	1,381,000	1,497,000	1,671,000	1,441,000	1,523,000	1,997,000	1,591,000
$S\widetilde{B}_0$	mt	2,307,000	2,231,000	2,107,000	2,792,000	2,038,000	2,110,000	2,804,000	2,111,000
$S\widetilde{B}_{F_{current}}$	mt	830,000	985,200	660,800	1,459,000	602,300	691,300	866,300	904,100
$S\widetilde{B}_{MSY}$	mt	771,000	541,000	674,400	1,011,000	679,800	708,800	938,900	763,600
$B_{current}$	mt	1,921,472	1,916,710	1,743,982	2,266,337	1,639,681	1,763,241	1,753,908	1,918,748
B_{latest}	mt	2,250,529	2,284,016	2,070,439	4,507,281	1,932,952	2,209,483	2,010,266	2,292,394
$SB_{current}$	mt	911,230	907,622	788,053	1,427,087	742,244	802,815	825,861	921,039
SB_{latest}	mt	1,147,789	1,149,235	994,096	1,940,677	949,124	1,161,727	998,927	1,219,280
$B_{current,F=0}$	mt	3,684,287	3,228,310	3,530,225	3,718,950	3,882,679	3,466,628	3,707,646	3,593,605
$SB_{current,F=0}$	mt	2,115,401	1,875,239	2,035,451	2,663,127	2,238,223	1,972,446	2,127,061	1,907,649
$B_{latest,F=0}$	mt	4,091,346	3,522,938	4,014,778	6,244,042	4,108,883	4,070,198	4,122,091	4,004,914
$SB_{latest,F=0}$	mt	2,499,364	2,140,698	2,432,232	3,252,306	2,526,945	2,528,370	2,500,887	2,293,984

Management quantity	Units	Base	Steepness = 0.90	Natural mortality	Growth curve	Effort deviate penalties	Length frequency N	Effort creep	Reproductive potential
$B_{current}/\tilde{B}_0$		0.49	0.51	0.50	0.60	0.48	0.50	0.37	0.50
$B_{current}/\tilde{B}_{F_{current}}$		1.10	0.92	1.18	1.01	1.25	1.18	0.94	1.04
$B_{current}/\tilde{B}_{MSY}$		1.16	1.39	1.16	1.36	1.14	1.16	0.88	1.21
$B_{current}/B_{current,F=0}$		0.52	0.59	0.49	0.61	0.42	0.51	0.47	0.53
$B_{latest}/B_{latest,F=0}$		0.55	0.65	0.52	0.72	0.47	0.54	0.49	0.57
$SB_{current}/SB_{current,F=0}$		0.43	0.48	0.39	0.54	0.33	0.41	0.39	0.48
$SB_{latest}/SB_{latest,F=0}$		0.46	0.54	0.41	0.60	0.38	0.46	0.40	0.53
$SB_{current}/\tilde{SB}_0$		0.39	0.41	0.37	0.51	0.36	0.38	0.29	0.44
$SB_{latest}/\tilde{SB}_0$		0.50	0.52	0.47	0.70	0.47	0.55	0.36	0.58
$SB_{current}/\tilde{SB}_{F_{current}}$		1.10	0.92	1.19	0.98	1.23	1.16	0.95	1.02
$SB_{current}/\tilde{SB}_{MSY}$		1.18	1.68	1.17	1.41	1.09	1.13	0.88	1.21
$SB_{latest}/\tilde{SB}_{MSY}$		1.49	2.12	1.47	1.92	1.40	1.64	1.06	1.60
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.45	0.55	0.42	0.59	0.38	0.42	0.40	0.48
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.36	0.44	0.31	0.52	0.30	0.33	0.31	0.43
$\tilde{B}_{MSY}/\tilde{B}_0$		0.42	0.37	0.43	0.44	0.42	0.43	0.42	0.41

$S\tilde{B}_{MSY}/S\tilde{B}_0$	0.33	0.24	0.32	0.36	0.33	0.34	0.33	0.36
$\tilde{F}_{MSY}$	0.06	0.10	0.06	0.07	0.06	0.06	0.06	0.07
$F_{current}/\tilde{F}_{MSY}$	0.94	0.57	1.02	0.62	1.10	1.02	1.07	0.85
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$	1.06	1.51	0.98	1.34	0.91	0.98	0.94	1.15
$S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$	1.08	1.82	0.98	1.44	0.89	0.98	0.92	1.18
$\tilde{Y}_{F_{current}}/MSY$	1.00	0.88	1.00	0.91	0.99	1.00	1.00	0.98

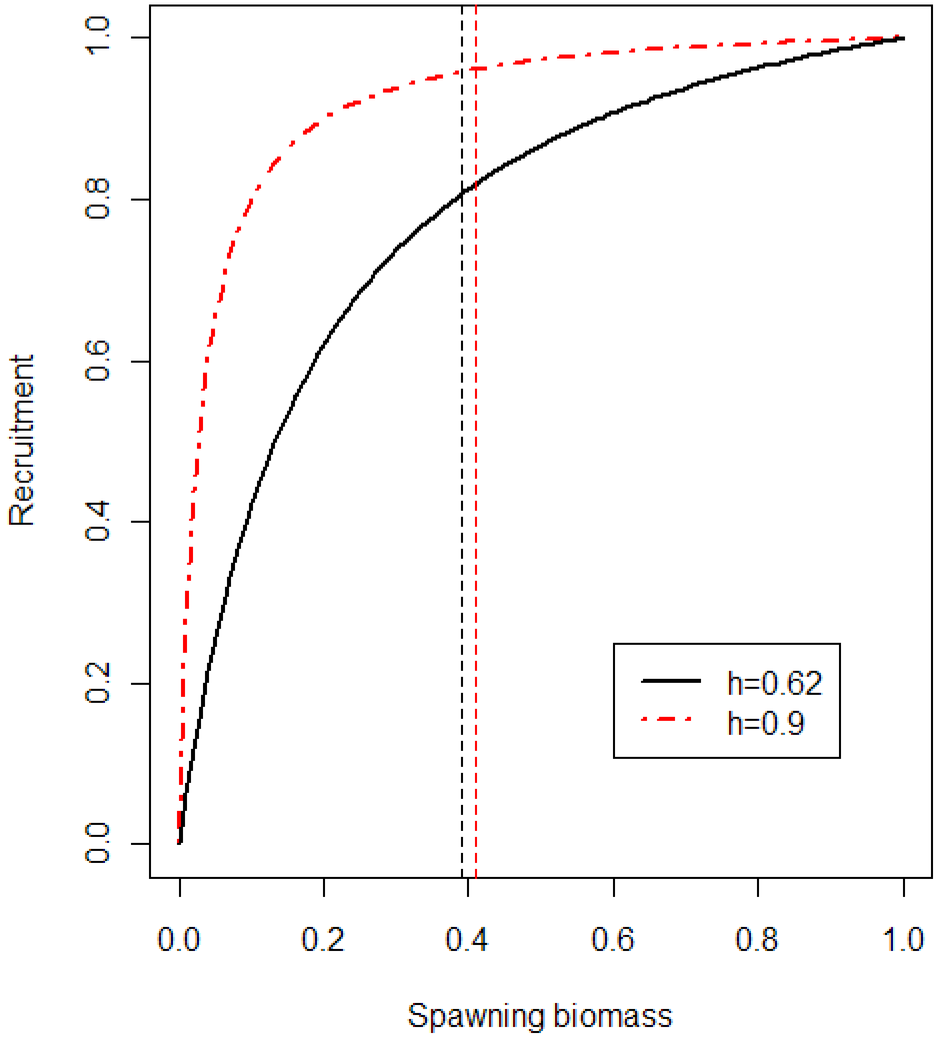

Figure 1a: Spawner recruitment curves for the two values of steepness included in the structural sensitivity analysis. The current levels of spawner depletion for each case are indicated with the vertical lines.

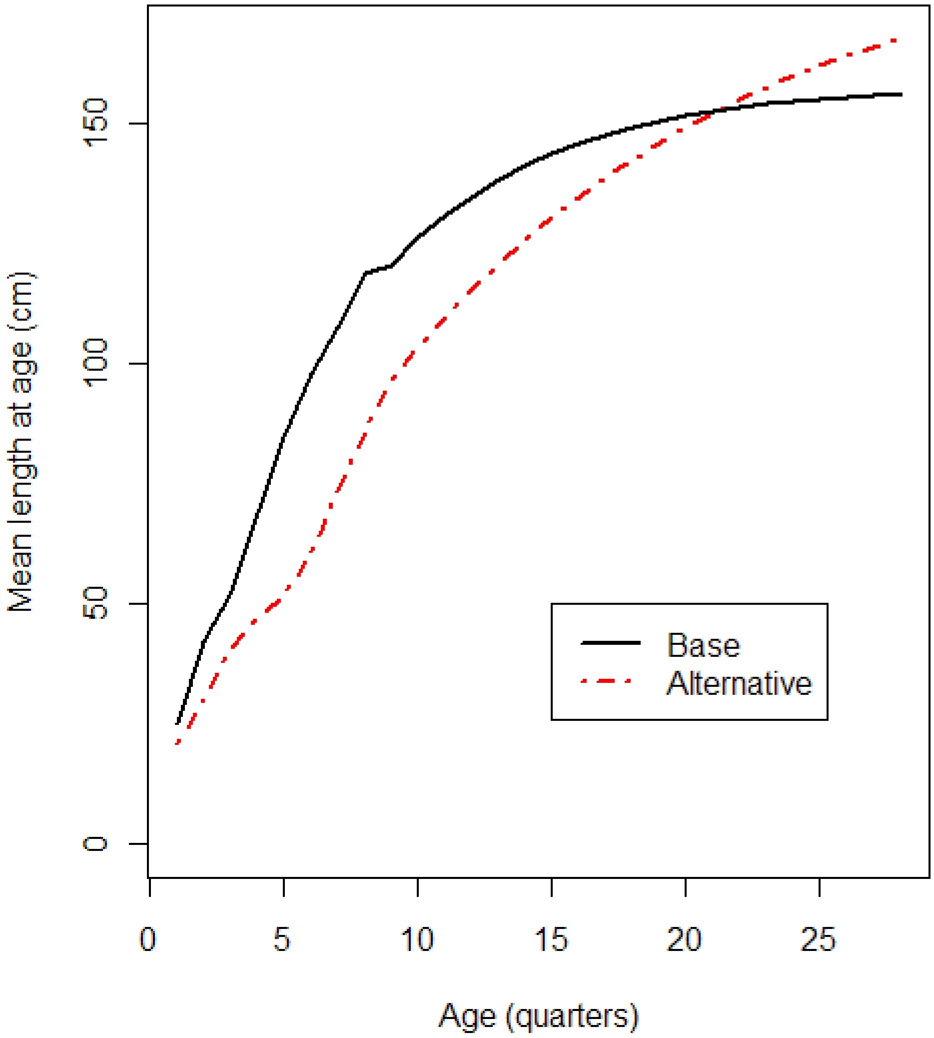

Figure 1b: Growth curves included in the structural sensitivity analysis.

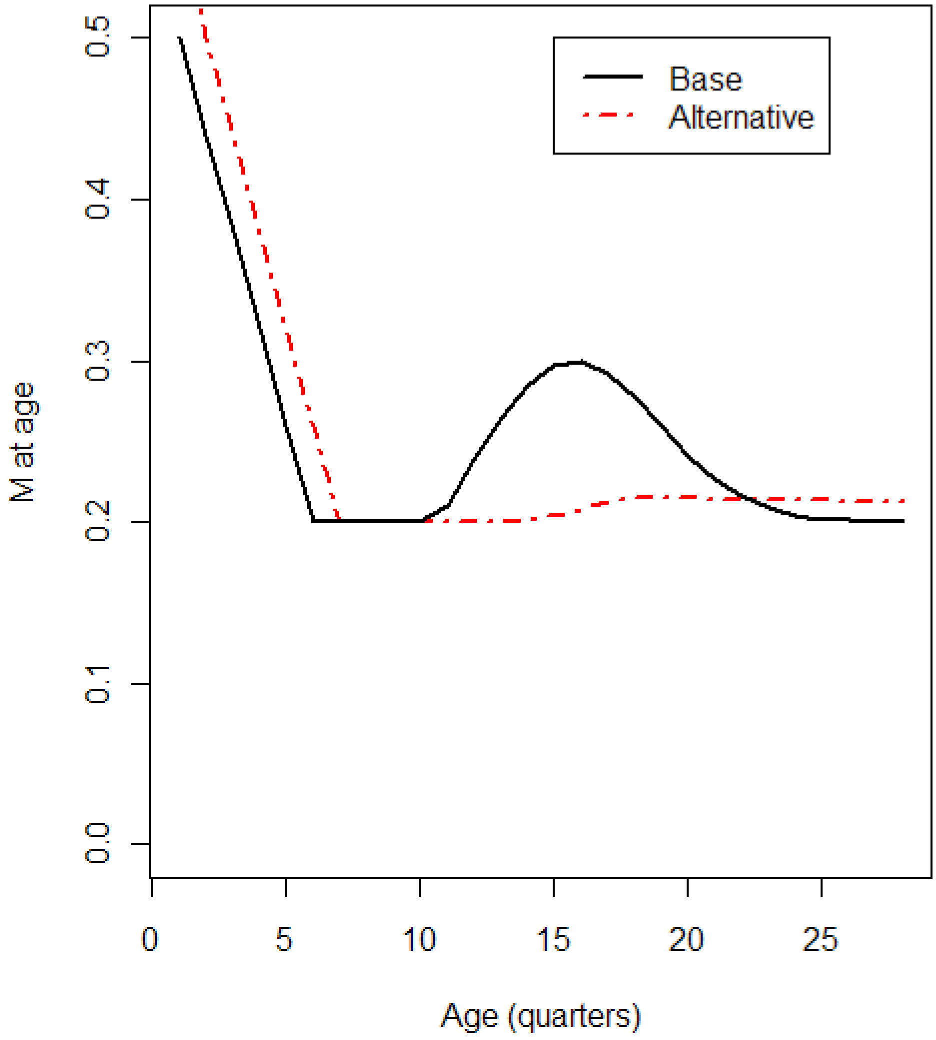

Figure 1c: Natural mortality at age curves included in the structural sensitivity analysis.

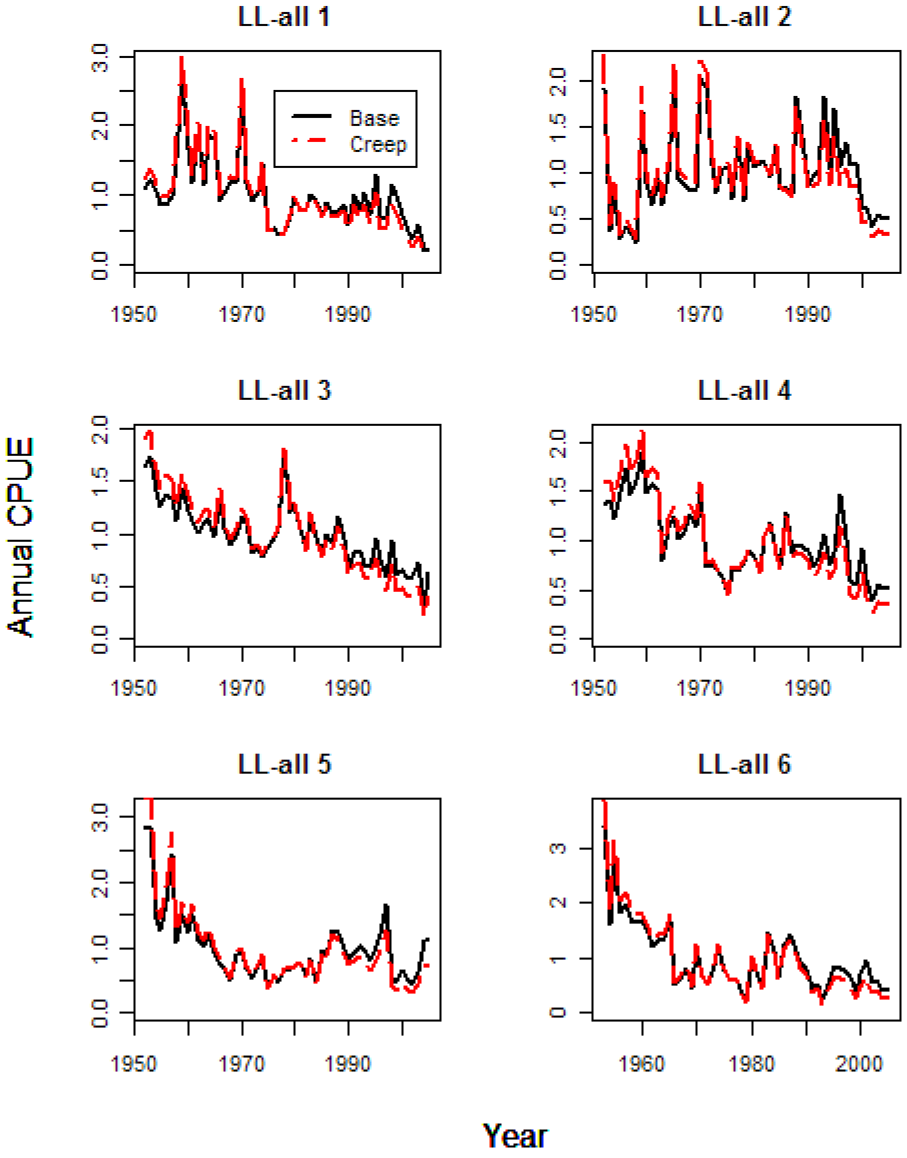

Figure 1d: CPUE series included in the structural sensitivity analysis for the key longline fisheries.

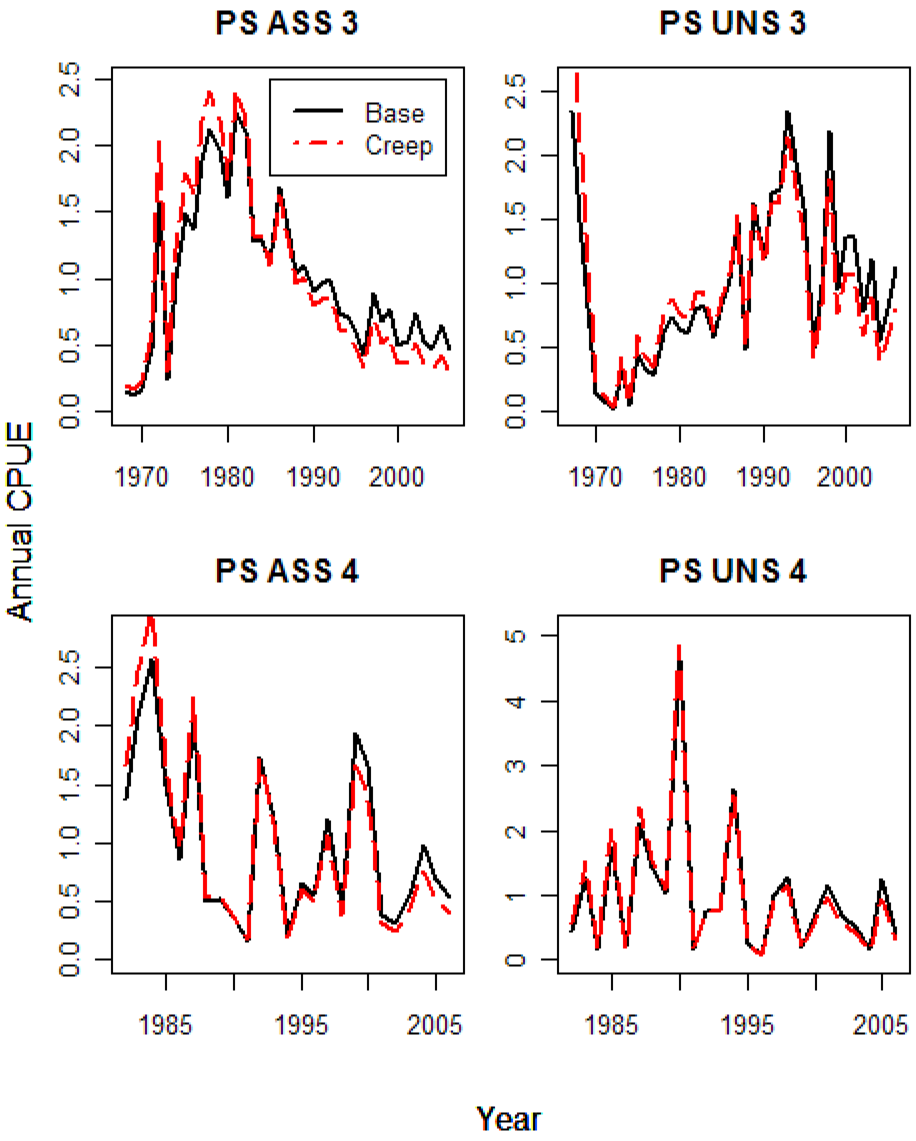

Figure 1e: CPUE series included in the structural sensitivity analysis for the key purse seine fisheries.

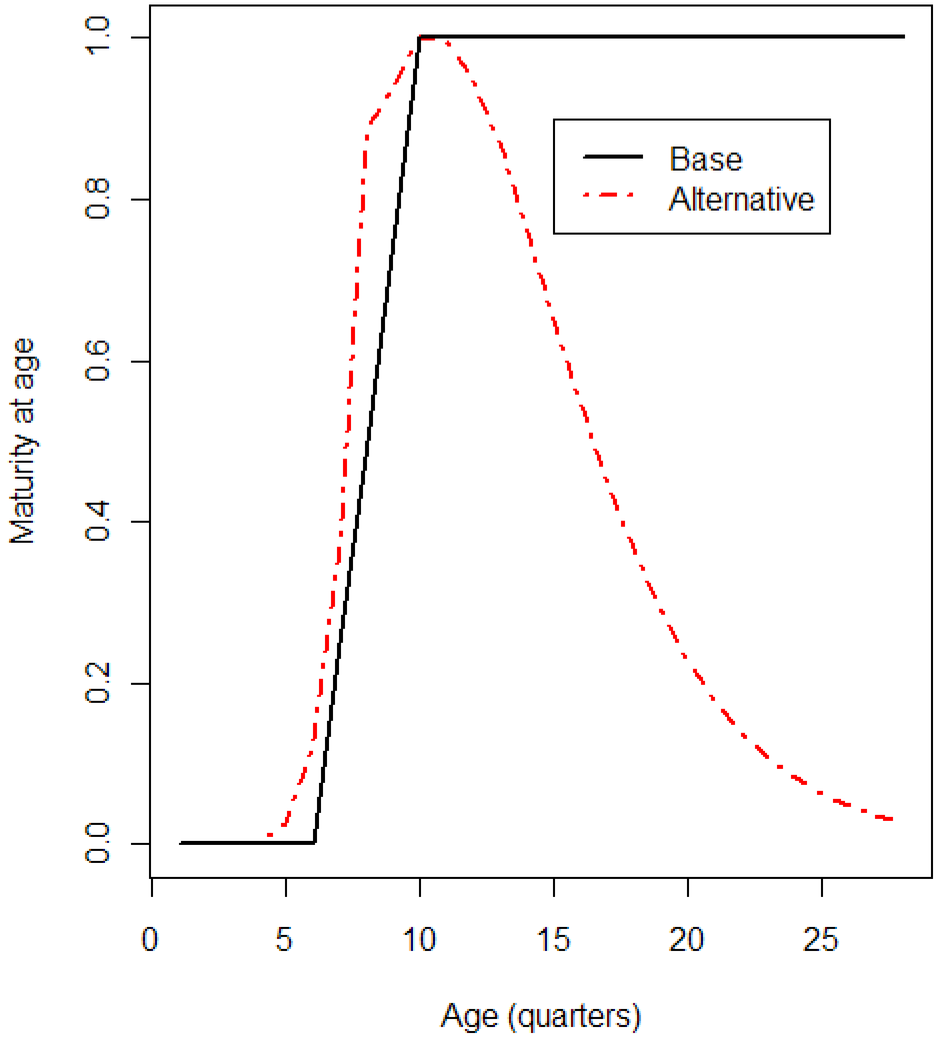

Figure 1f: Maturity-at age curves included in the structural sensitivity analysis.

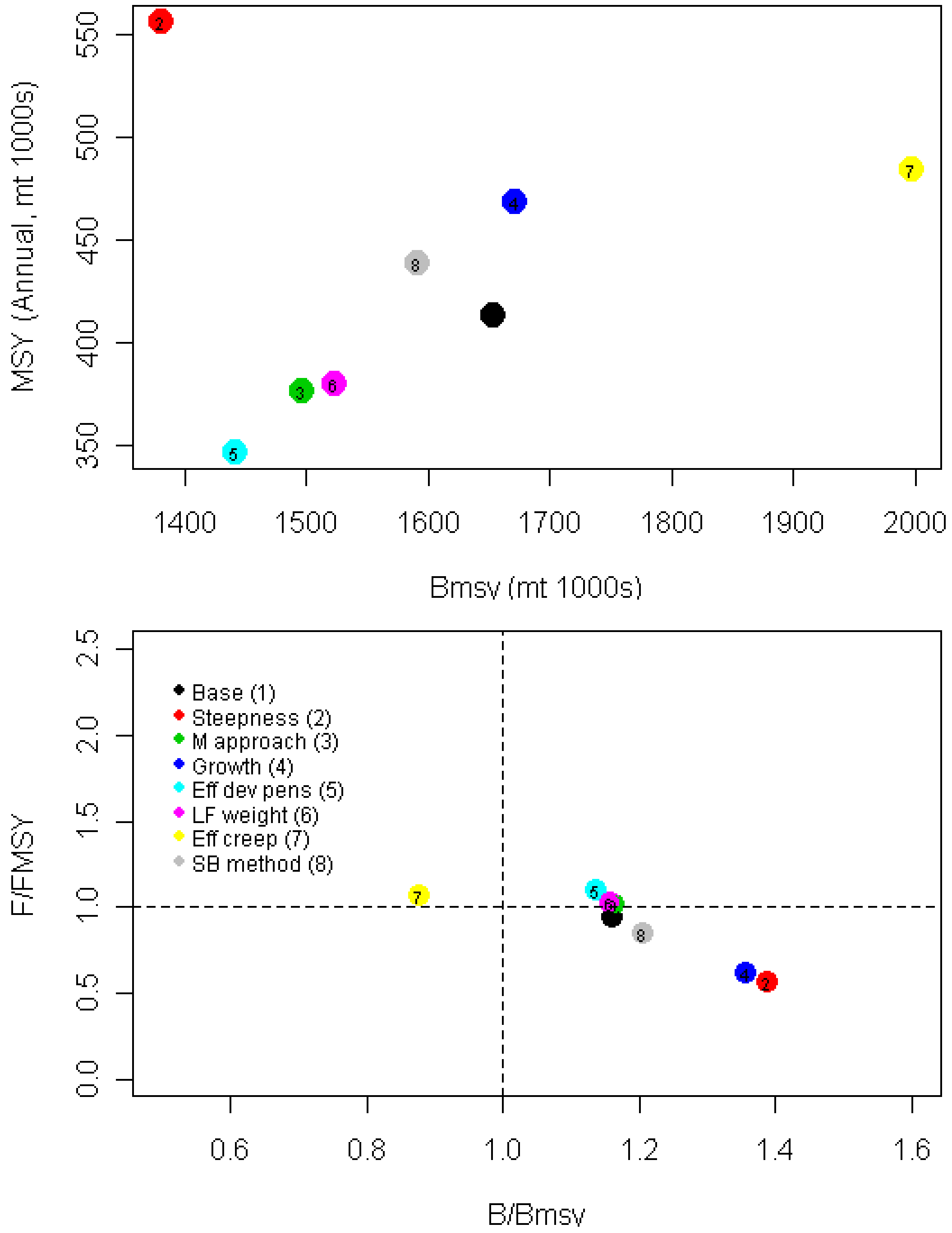

Figure 2: BMSY versus MSY and B/BMSY versus F/FMSY for each single-change scenario.

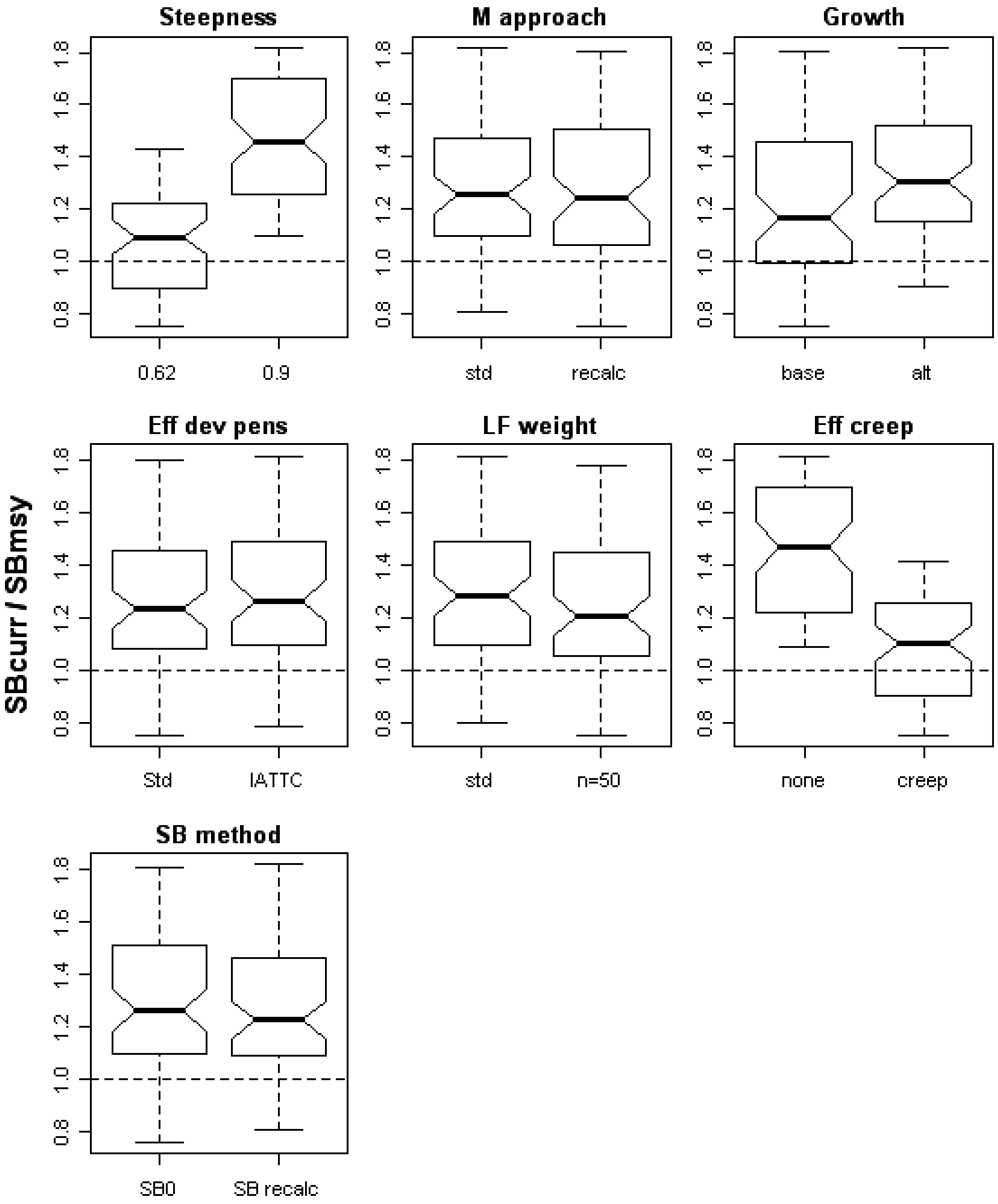

Figure 3: Distribution of SBCURR / SBMSY from 128 runs, grouped by factor. When the notches in the sides of the boxes within a pair do not overlap, this is strong evidence that the two medians differ. The box encloses the upper and lower quartiles, divided by the median, and whiskers extend to either the extreme values or 1.5 times the inter-quartile range from the box, whichever is smaller.

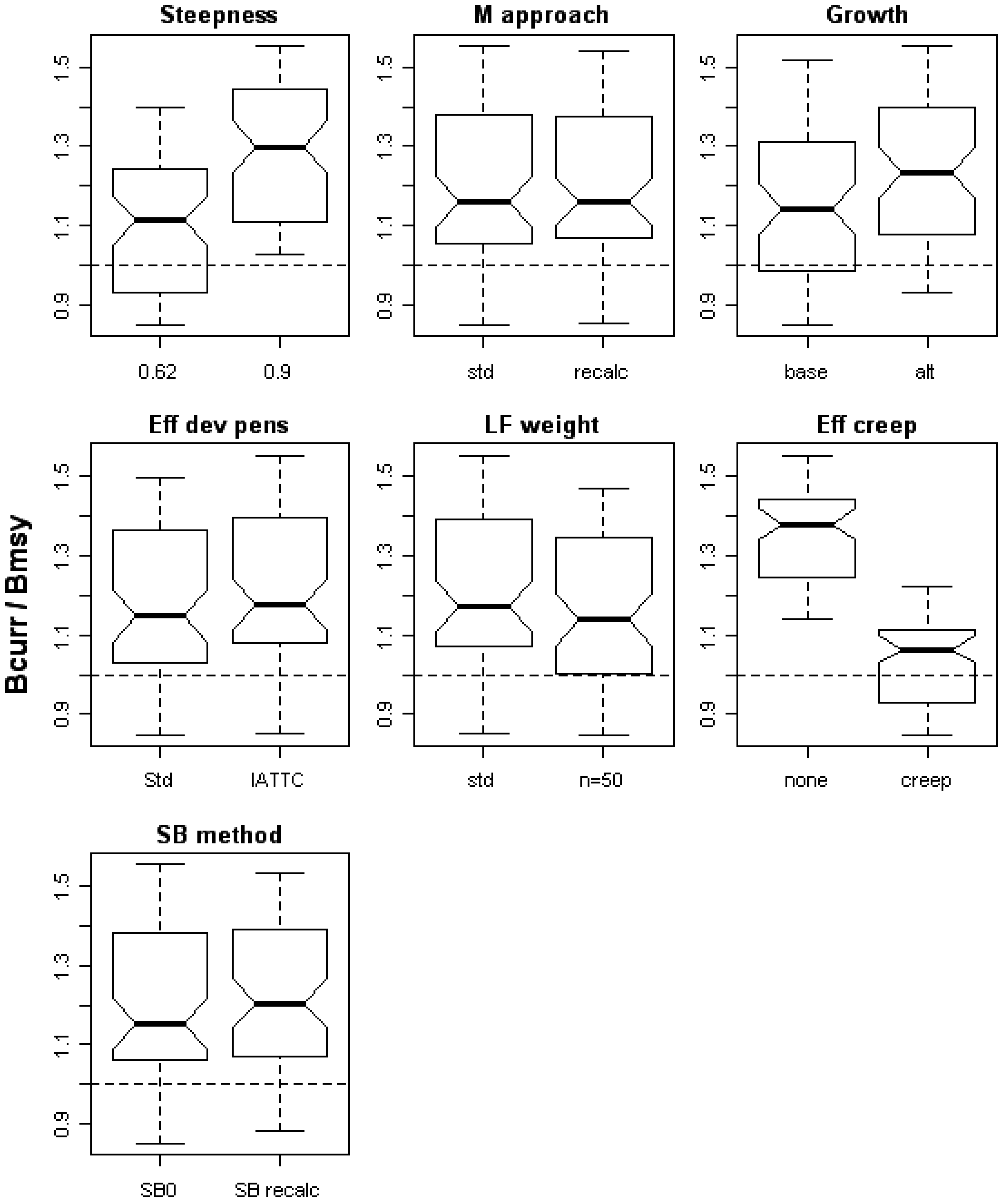

Figure 4: Distribution of BCURR / BMSY from 128 runs, grouped by factor.

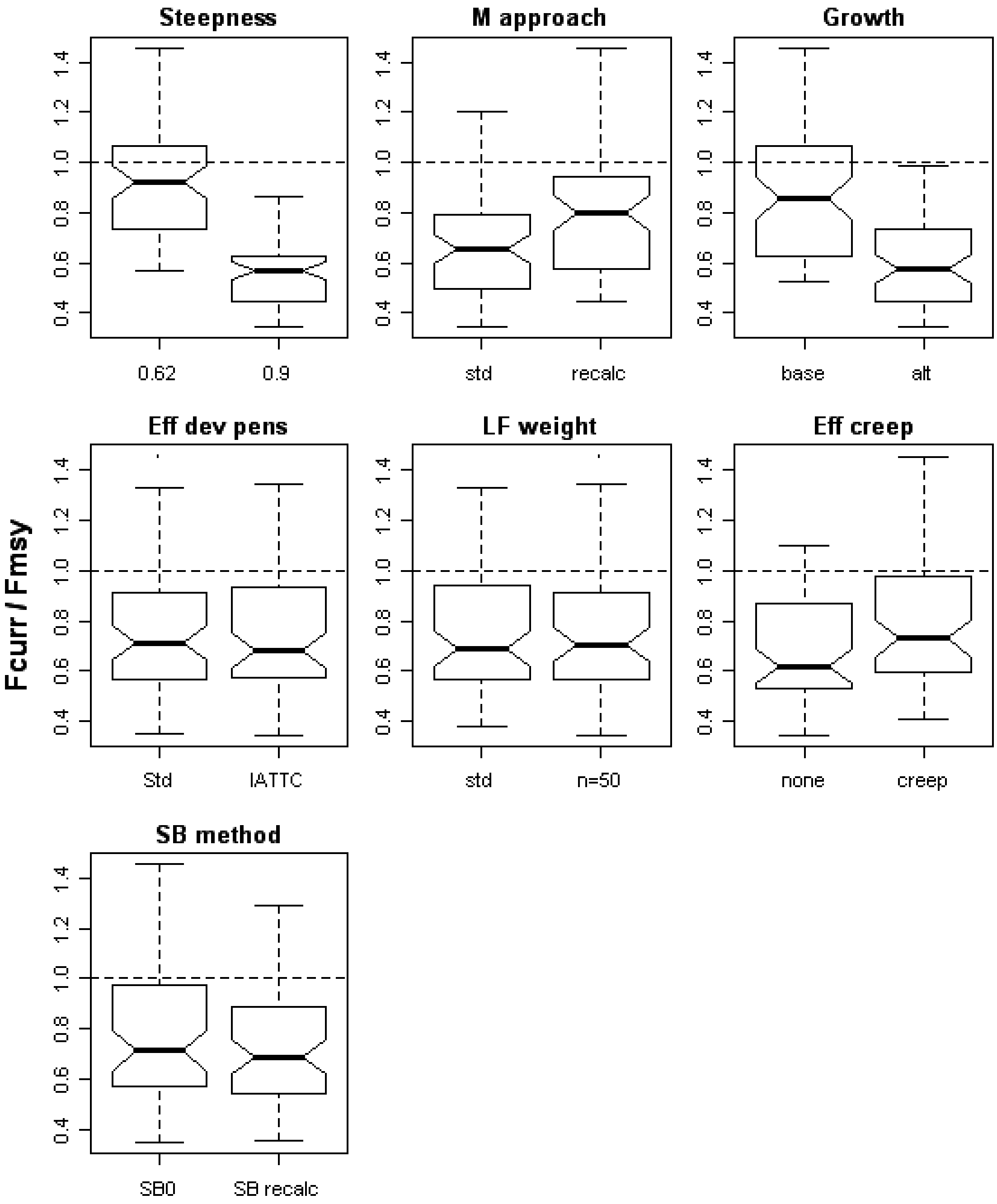

Figure 5: Distribution of FCURR / FMSY from 128 runs, grouped by factor.

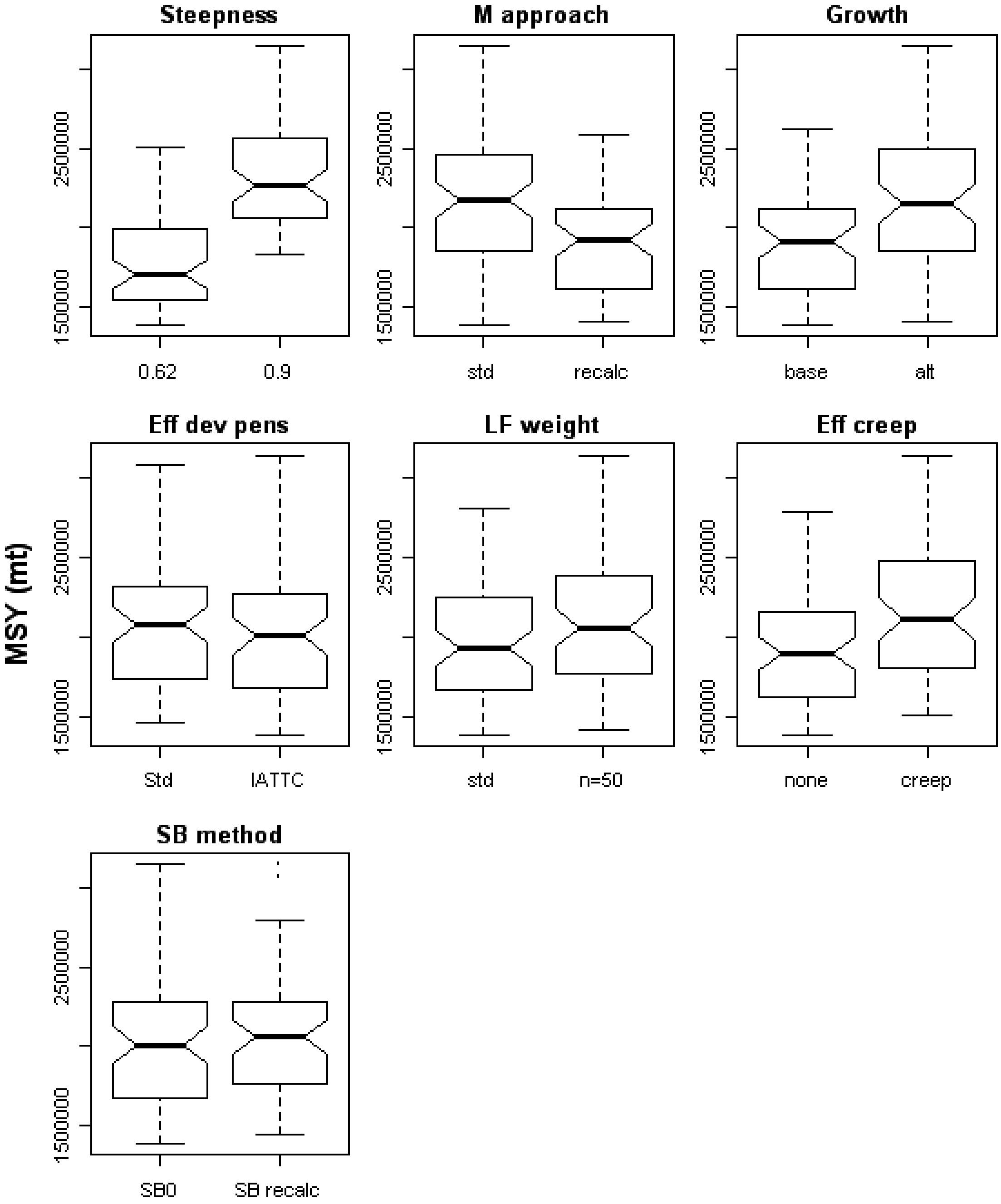

Figure 6: Distribution MSY from 128 runs, grouped by factor.

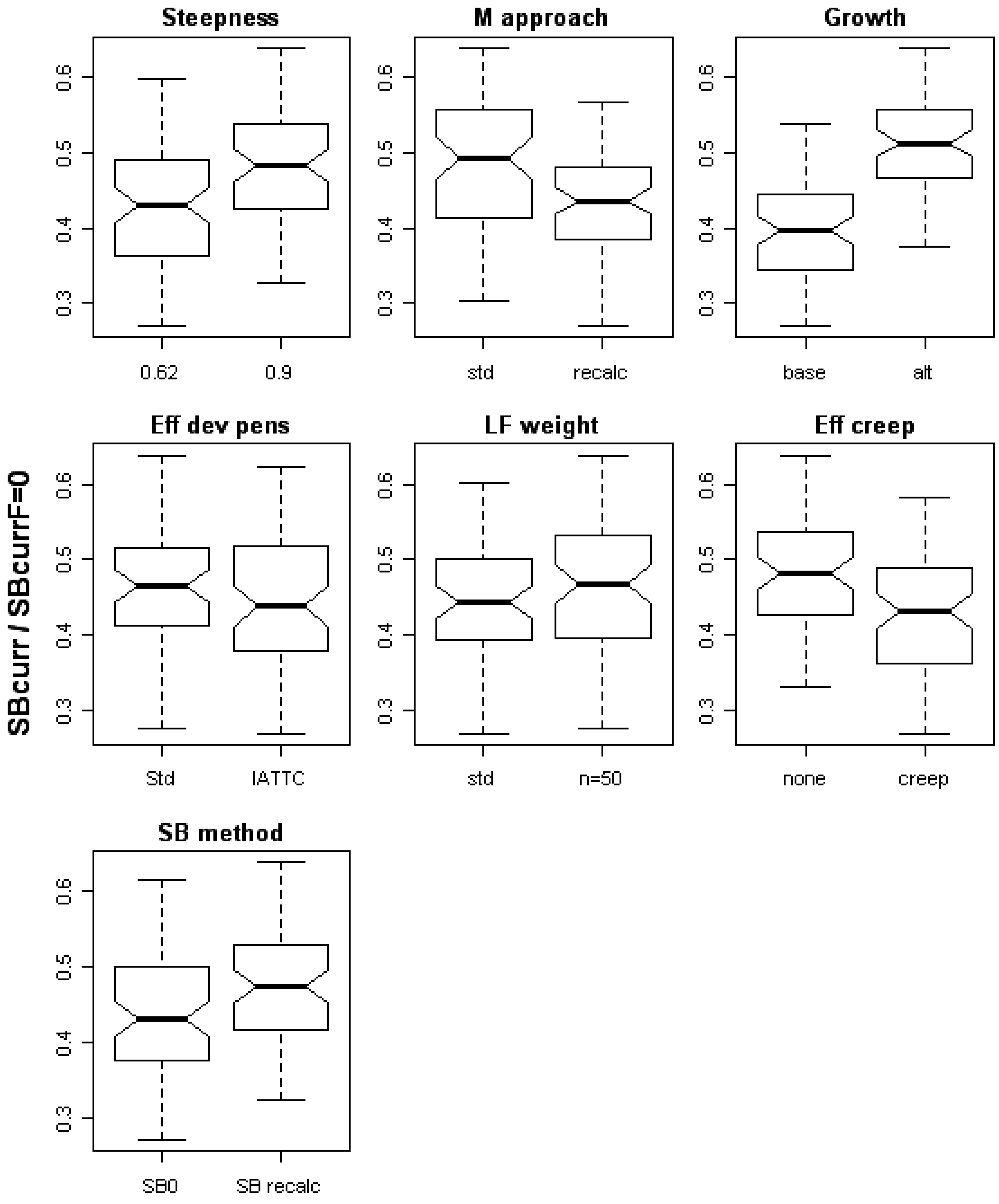

Figure 7: Distribution of SBCURR / SBCURR, F=0 from 128 runs, grouped by factor.

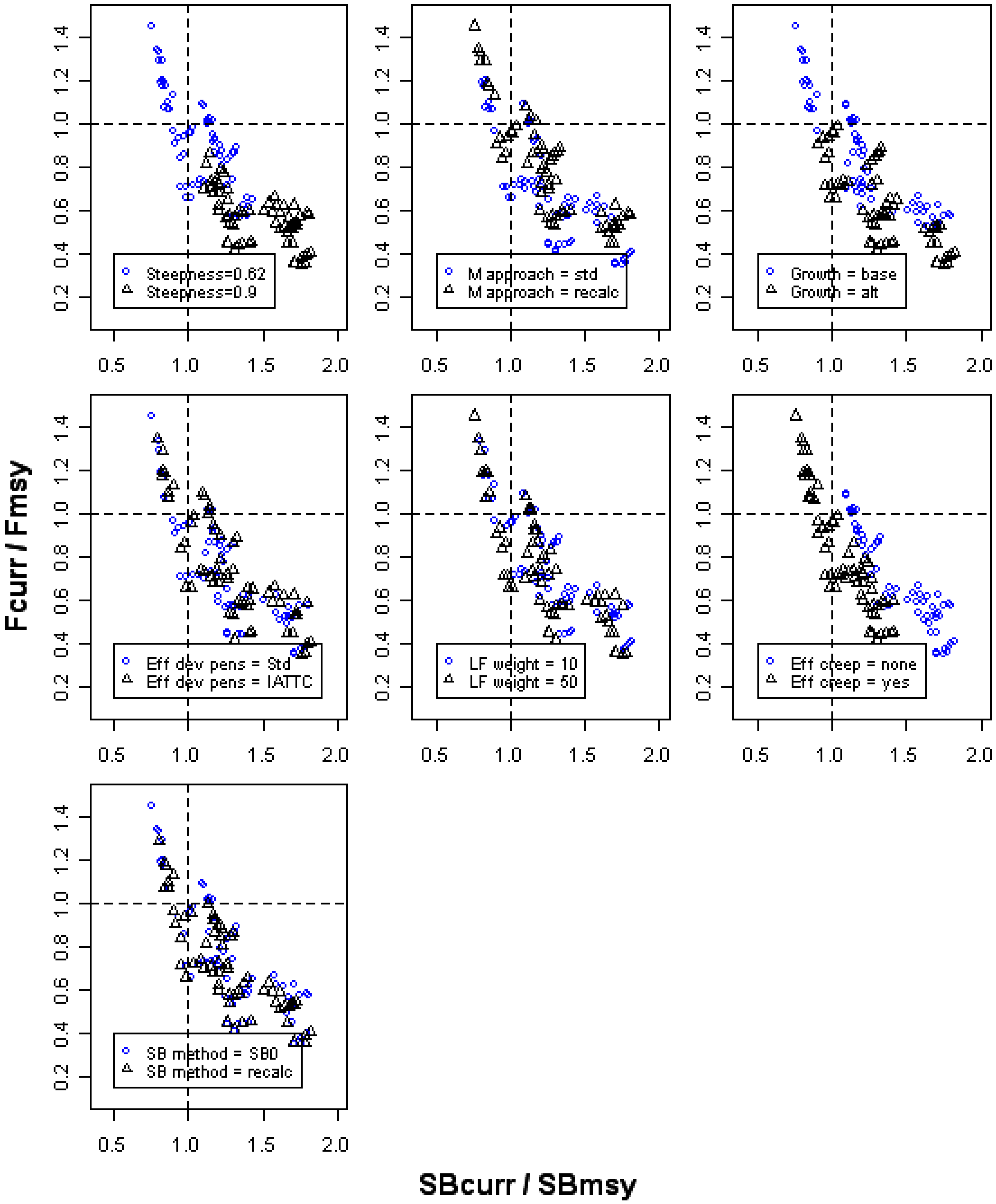

Figure 8: SBCURR / SBMSY versus FCURR / FMSY from 128 runs, grouped by factor.

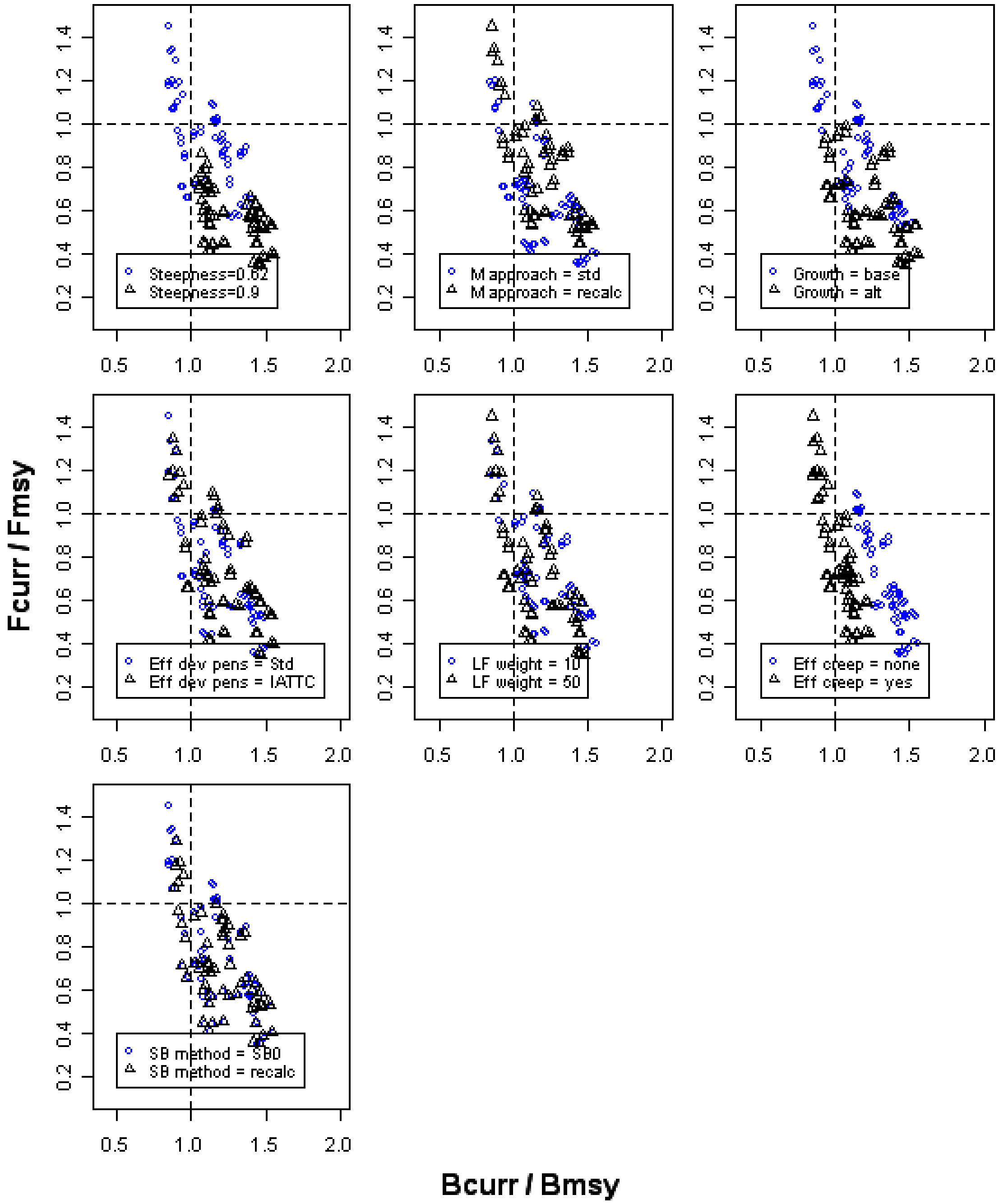

Figure 9: BCURR / BMSY versus FCURR / FMSY from 128 runs, grouped by factor.