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Management strategy evaluation of data limited management procedures for Indian Ocean striped marlin (*Tetrapturus audax*)

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Abstract

Catch of striped marlin in the Indian Ocean has increased markedly over since 2013. According to recent stock assessments the stock was likely to be overfished and subject to overfishing. In this study, the DLMtool package was used to test management procedures (MPs) and calculate catch limits for Indian Ocean striped marlin. Catch data (1950-2015), CPUE data (Japanese longline from 1976 to 2013 and Taiwanese longline from 1980 to 2013) and biological parameters were used to develop the Operating Model (OM) and/or alternative MPs. Twenty-one (21) alternative MPs were tested using simulations based on a 50-year projection.

Twenty-one MPs resulted in stock status with biomass higher than the target reference point (B/B_{MSY}), and 6 MPs resulted in stock status with more than 50% probability of $F/F_{MSY}>1$, in which DD (Delay-difference Stock Assessment in MP), SBT1 (southern bluefin tuna simple MP), CC1 (constant catch) and GB_slope (Geromont and Butterworth index slope) resulted in stock status with more than 80% probability of $F/F_{MSY}>1$. The MPs of AvC (average catch), Islope1 (adjusts catch to maintain a constant CPUE) and Islope4 (adjusts catch to maintain a constant CPUE) led to increasing stock trends from the red zone to the green zones of the Kobe plot. There was almost 0% probability that these MPs would reduce the stock to biomass levels lower than $0.5B_{MSY}$. According to performance metrics and an MP trade-off scheme, DD4010 (Delay-difference Stock Assessment with U_{MSY} and MSY leading coupled with 40-10 harvest control rule) was regarded as the best performing MP. The estimated range of catch limits for Indian Ocean striped marlin was 1,662-4,115 t based on Japanese CPUE data and 1,554-3,415 t based on Taiwanese CPUE data. Sensitivity analyses were also conducted to evaluate the impacts of uncertainty in biological parameters.

1 Introduction

Striped marlin is a large oceanic species that inhabits tropical and subtropical waters of the Indian and Pacific Oceans (Ijima, 2015). It is also considered to be a non-target species of industrial longline fisheries in the Indian Ocean. However, striped marlin in the Indian Ocean is subject to only a few conservation and management measures (adopted by Indian Ocean Tuna Commission, IOTC) and no Total Allowable Catch (TAC) has been estimated. The Indian Ocean striped marlin annual catch trends are variable, ranging from 1 t (1950) to 8,730 t (1986). The highest catch has been recorded since 1986, which was 8,730 t in 1986. Catches of striped marlin have increased in 2012 and 2013, as longline vessels have resumed operations in the northwest Indian Ocean.

The recent assessment using ASPIC indicated that the stock has been subject to overfishing for some years, and the biomass was well below the B_{MSY} level and showed little sign of rebuilding despite of the declining effort trend (Nishida, 2015). The approaches of Bayesian Surplus Production Model and Stock Reduction Analysis (IOTC, 2016) came to similar conclusions with assessment using ASPIC method for stock status of striped marlin. In 2016 the reported catch increased to 4,410 t. On the weight-of-evidence available in 2016, the stock was determined to be overfished and subject to overfishing (IOTC, 2016). It may be necessary to estimate and set a TAC for Indian Ocean striped marlin to control exploitation and conserve the stock.

The DLMtool R-based simulation package that was developed by University of British Columbia (UBC) and Natural Resources Defense Council (NRDC) is open software for conducting MSE of data-limited fisheries (Carruthers and Hordyk, 2015). Some institutions such as US NOAA, Canadian DFO and the California Department of Fish and Wildlife, have used DLMtool to manage more than 20 species in Caribbean, California and Gulf of Mexico waters (SEDAR, 2015; SEDAR, 2016). More than 100 Management Procedures (MPs) contained in DLMtool can be tested (Carruthers and Hordyk, 2015).

Using DLMtool to conduct management strategy evaluation, the objectives of this study were to: (1) evaluate management procedures for Indian Ocean striped marlin; (2) calculate TAC for Indian Ocean striped marlin; and (3) suggest conservation measures for consideration by the IOTC scientific committee.

2 Data

2.1 Fishery data

The data used in this study includes annual catch, CPUE and biological parameters of Indian Ocean striped marlin. Catch data was downloaded from the IOTC secretariat website. Annual catch data was available from 1950 to 2015 (Figure 1).

Nominal CPUE data was downloaded from datasets of IOTC 13th Working party on Billfish, IOTC secretariat website. CPUE data for striped marlin was only available for the fleets of Japan and Taiwan, China. Nominal CPUE data was used because the methods conducted on CPUE standardization of the two fleets were very different. Two scenarios were conducted in MSE process with two CPUE data series, i.e., CPUE of Japanese longline from 1976 to 2013 (Figure 2) and CPUE of Taiwanese longline from 1980 to 2013 (Figure 3), which were used for developing operating models (OMs) and calculating performance trade-offs among MPs. Both CPUE series infer a pronounced declining in vulnerable biomass since 1980 after which it stabilizes at a relatively low level.

2.2 Biological parameters

Biological parameters of Indian Ocean striped marlin have not been well investigated. Parameter M (natural mortality), L_{50} (length at 50% maturity), maximum age, and steepness were borrowed from Pacific striped marlin (Lee et al., 2012) because there was no study conducted on these parameters of Indian Ocean striped marlin, and growth parameters K, t_0, L_{inf} were obtained from striped marlin information on Fish Base (www.fishbase.org). Weight-length relationship parameters a and b were borrowed from IOTC striped marlin supporting information.

These biological parameters were required to specify the operational model and to calculate TACs. In each case a certain degree of uncertainty in each parameter was specified (a coefficient of variation) to evaluate robustness and sensitivity of MPs.

3 Management strategy evaluation

3.1 Overview of the MSE

Management Strategy Evaluation (MSE) is designed to identify fishery rebuilding strategies and ongoing harvest strategies that are robust to uncertainty and natural variation, and that balance biological and socioeconomic objectives (Holland, 2010). The MSE approach involves the following steps to evaluate a set of candidate management strategies:

a) Identification of the objectives that the candidate management strategies are aiming to satisfy, and quantification of these objectives using a small set of performance measures.

b) Specification of the set of alternative management strategies.

c) Development and parameterization of a set of alternative operating models that represent different states of the ‘true’ system being managed.

d) Simulation of the future using each management strategy (Punt, 2007).

In this case we used DLMtool for rapid MSE of MPs for Indian Ocean striped marlin. Data on the stock were used to specify the operating model which was used in MSE to select robust MPs according to various biological reference points and performance trade-off plots. Subsequently MPs that performed satisfactorily were used to calculate TACs from fishery data.

3.2 Management procedures

3.2.1 Operating model

A standard age-structured, special model identical to that of Crruthers et al. (2014) was used to simulate population and fisheries dynamics. The DLMtool operating model contains four distinct components that specify:

1. stock dynamics (Stock)
2. fleet dynamics (Fleet)
3. the observation model (Obs)
4. the implementation model (Imp)

Stock is an operating model component that specifies the parameters of population dynamics model including maxage (maximum age), M (natural mortality), steepness, von Batalanffy growth parameters K, t_0 (von Batalanffy theoretical age at length zero), maximum length (L_{inf}), and weight-length relationship parameters a, b, while Fleet controls fishing dynamics. Obs controls the observation model and Imp specifies the degree of adherence to management recommendations. Almost all of these inputs are vectors with two elements which describe the upper and lower bounds of uniform distribution from which the parameters were sampled.

We constructed operating model using a factorial design encompassing 36 sets of operating model assumptions. The four factors were 1) life history with three levels, 2) temporal autocorrelation in recruitment with two levels, 3) starting stock depletion with two levels and 4) data quality with three levels. We did not simulate implementation error and assumed that prescribed catches would be taken exactly up to a maximum instantaneous fishing mortality rate of 90%. The MPs were rerun and the TAC updated every 3 years to approximate an assessment cycle.

For further details on how operating model parameters were sampled and simulated data were generated we refer readers to Carruthers et al. (2014).

CV inputs for each parameter were the main sources of uncertainties. Most of them are typical, such as CV for von Bertalanffy parameters while some of CVs are highly uncertain, such as CV for steepness.

3.2.2 Estimation method

Biological parameters with normal distribution were summarized in Figure 4. Meanwhile, the projections for the trends of these biological parameters were also showed in Figure 1. Distribution and projection of fleet parameters were summarized in Figure 5. Figures 6 and 7 summarized the observation object imprecise-biased in which observation biases and time series trends were definitely shown.

The specification of the operating model is a critical component of the MSE process. Several important parameters of Indian Ocean striped marlin stock were summarized in Figure 8. Spawning biomass and recruitment seemed constant in historical year while fishing mortality and annual catches increased distinctly with the stock depletion slightly decreased. From the Kobe plot it is apparent that the stock status has a strong trend moving to the red zone. Sample parameters and cross-correlations between parameter M, K, L50 and L_{inf} reflect that K has strong correlativity with L_{inf} (Figure 9).

Forty-eight simulations were conducted for each DLMtool MP for fifty projection years in the MSE process. More complex MPs, similar to conventional stock assessments were not included in MSE due to the lack of reliable, long term relative abundance indices.

3.2.3 Performance measures

Suitable MPs were chosen if they fit the input data as the pre-MPs for further trade-off estimate. Probability of overfishing, probability of $B<B_{MSY}$, probability of $B<0.5B_{MSY}$ and probability of $B<0.1B_{SMY}$ of long term projection were calculated from MSE simulations. Catch and biomass trends were simulated at the same time within the 'real' stock. Afterwards, limitations for B/B_{MSY} and F/F_{MSY} were input and tested until MPs left in the trade-off results performed well in management judging by B/B_{MSY} and F/F_{MSY}. In summary, performance metrics were used to reduce candidate MPs to a subset of the best performing MPs after which we examined more detailed performance trade-offs.

Figure 10 is the results of convergence checking and from these results we find that 48 MSE simulations were sufficient to obtain representative performance estimates. Related yield, probability of $F/F_{MSY}>1$ and probability of $B/B_{MSY}<1$ converged well after twenty MSE simulations while probability of $B/B_{MSY}<0.1$ and probability of $B/B_{MSY}<0.5$ required more numerous MSE simulations to stabilize.

3.2.4 Reference points and harvest control rules

Although IOTC adopted reference points for Swordfish (*Xiphias gladius*) on target and limit reference points and a decision framework, no such interim reference points have been established for striped marlin. Therefore F/F_{MSY} and B/B_{MSY} were widely adopted as the provisional reference points. TAC calculation was based on MPs trade-off results in **Section 3.2.3** together with the harvest control rules with the best performance compared to others. The MPs were used to calculate stochastic TAC recommendations. One hundred TAC samples were calculated for each MP using the real fishery data.

4 Results and discussion

MSE running results were showed in Figure 11. Forty-eight simulations were conducted to each MP over fifty projection years while twenty-one MPs according to data-match test (Table 1). All twenty-one MPs performed well as most simulation results were above 1 on B/B_{MSY} (green lines). Six MPs showed more than 50% probability of $F/F_{MSY}>1$ in which DD, SBT1, CC1 and GB_slope more than 80%. Kobe plot shows that MPs such as AvC, Islope1 and Islope4 indicated that stocks have strong trends of moving from red zone to green zone (Figure 12(a), 12(b)). Figure 13 shows that there was a very low probability that these MPs will drive stock biomass below half of B_{MSY}. Fifteen of the twenty-one MPs have a possibility of 20% to 50% for overfishing while more than 75% of MPs have a possibility of less than 40% for $B/B_{MSY}<1$.

Trade-off plots of long term yields show a wide range of performance among the candidate MPs (Figure 14). The DD4010 MP provided arguably the best performance achieving an 85% probability of providing over half MSY yield and over an 85% probability of keeping the stock above $0.5B_{MSY}$ (Figure 15).

TAC calculating results are shown in Figure 16 and Figure 17 with the only 5 output control, DD, CC1, SBT1, GB_slope and DD4010 were selected from the two scenarios. According to MPs trade-off result, DD4010 was chosen to be the best MP which performed well in MSE running result. It was not surprising because this MP implemented the least catch for the stock. The TAC recommendation for Indian Ocean striped marlin is 1662 t to 4115.08 t with Japan CPUE data and 1554.47 t to 3415.38 t with Taiwan, China CPUE data (Table 1, Table 2). Concerning about the average catch which is 3731 t from 2006 to 2015 and 4819 t from 2012 to 2015, the TAC recommendation matches the catch trend well and will contribute to conservation and management for Indian Ocean striped marlin if it is adopted. Meanwhile, sensitivity analyses for each of 5 MPs are taken and the results are shown in Figure 18-22. All five MPs are sensitive to parameter Cat (catch).

Acknowledgement

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Table1 Alternative MPs in Indian Ocean striped marlin MSE

MPs	**Description**
Avc	A simple average catch MP that is included to demonstrate a 'status quo' management option
CC1	Constant catch management procedures of Geromont and Butterworth (2014) (yrsmth years)
CC4	Constant catch management procedures of Geromont and Butterworth (2014) (yrsmth years reduced by 30)
DD	A simple delay-difference stock assessment with UMSY (U, total catch relative to the total biomass) and MSY leading which estimates the TAC using a time-series of catch and a relative abundance index
DD4010	A simple delay-difference stock assessment that estimate the OFL using a time-series of catch and a relative abundance index with a 40-10 rule imposed over the OFL recommendation
GB_slope	Geromont and Butterworth index slope Harvest Control Rule which modifies a time-series of catch recommendation and aims for a stable catch rates
Islope1	A management procedure that incrementally adjusts the TAC to maintain a constant CPUE or relative abundance index which is the least biologically precautionary of two constant index/CPUE methods
Islope4	A management procedure that incrementally adjusts the TAC to maintain a constant CPUE or relative abundance index which is the most biologically precautionary of two constant index/CPUE methods
Nfref	No Fishing Reference MP used for looking at variability in stock with no fishing
SBT1	A simple MP that makes incremental adjustments to TAC recommendations based on the apparent trend in CPUE
SPMSY	Catch trends Surplus Production MSY MP which uses Martell (2012)and Froese method for estimating MSY to determine the OFL with the approach estimates stock trajectories based on catches and a rule for intrinsic rate increase it also returns depletion
curE	Fishing at current effort levels in which constant fishing effort set at final year of historical simulations subjects to changes in catchability determined by OM @ qinc and interannual variability in catchability determined by OM @ qcv
curE75	Fishing at 75% of current effort levels in which constant fishing effort set at 75% of final year of historical simulations subjects to changes in catchability determined by OM @ qinc and interannual variability in catchability determined by OM @ qcv
DDe	Effort control version of DD-Delay-Difference Stock Assessment with UMSY and MSY leading which estimates and recommends FMSY using a time-series of catch and a relative abundance index
EtargetLopt	Effort MP: adjust effort up/down if mean length above/below L target
matlenlim	A data-limit method in which selectivity-at-length is set equivalent to maturity-at-length
matlenlim2	A data-limit method in which selectivity-at-length is set slightly higher than maturity-at-length
minlenLopt1	This input control sets the minimum length of fish caught to a fraction of the length that maximises the biomass, Lopt
MRnormal	A marine reserve in area 1 with no spatial reallocation of fishing effort which prevents fishing in area 1 and does not reallocates this fishing effort in area 2
MRreal	A marine reserve in area 1 with full reallocation of fishing effort which prevents fishing in area 1 and reallocates this fishing effort in area 2
slotlim	An data-limited method which sets a slot limit in which selectivity-at-length is set using a slot limit (minimum and maximum legal length)

Table 2 TAC calculating results using Japan CPUE

MP	Median	SD	TAC (50% CI)
DD4010	2802.77	3776.26	1662.70-4115.08
GB_slope	3910.38	660.82	3528.00-4132.89
SBT1	4355.34	1441.89	3386.93-4450.40
CC1	4552.82	663.59	4195.23-4544.90
DD	5986.77	8417.79	3785.29-8599.76

Table 3 TAC calculating results using Taiwan, China CPUE

MP	Median	SD	TAC (50% CI)
DD4010	2694.41	2545.10	1554.47-3415.38
SBT1	4169.96	1388.16	3351.89-4406.15
CC1	4414.70	644.69	4103.07-4569.13
GB_slope	4886.29	666.44	4129.66-4675.34
DD	7983.89	7983.89	2850.87-7481.17

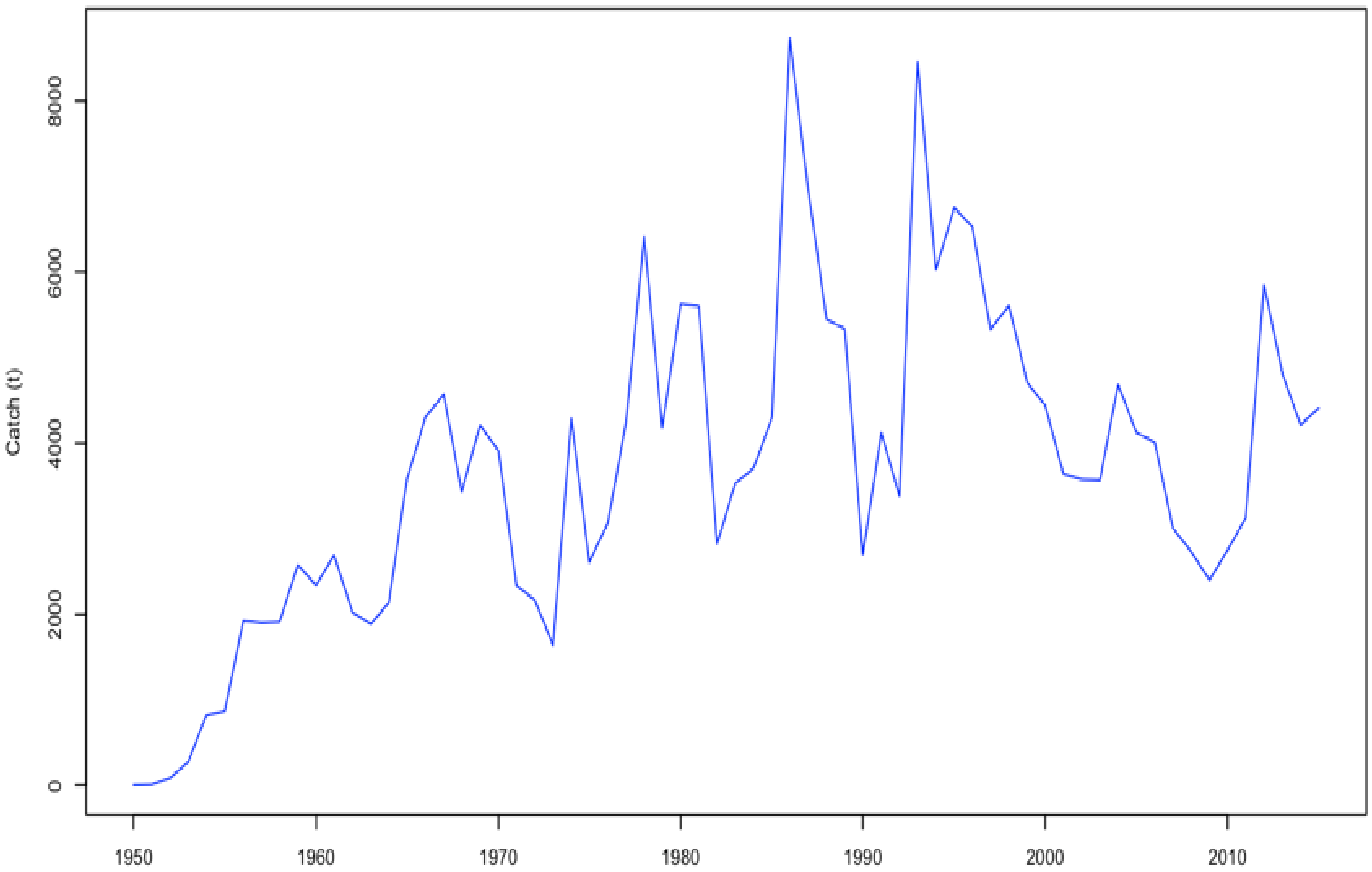

Figure 1 Catch trend from 1950 to 2016 for Indian Ocean striped marlin.

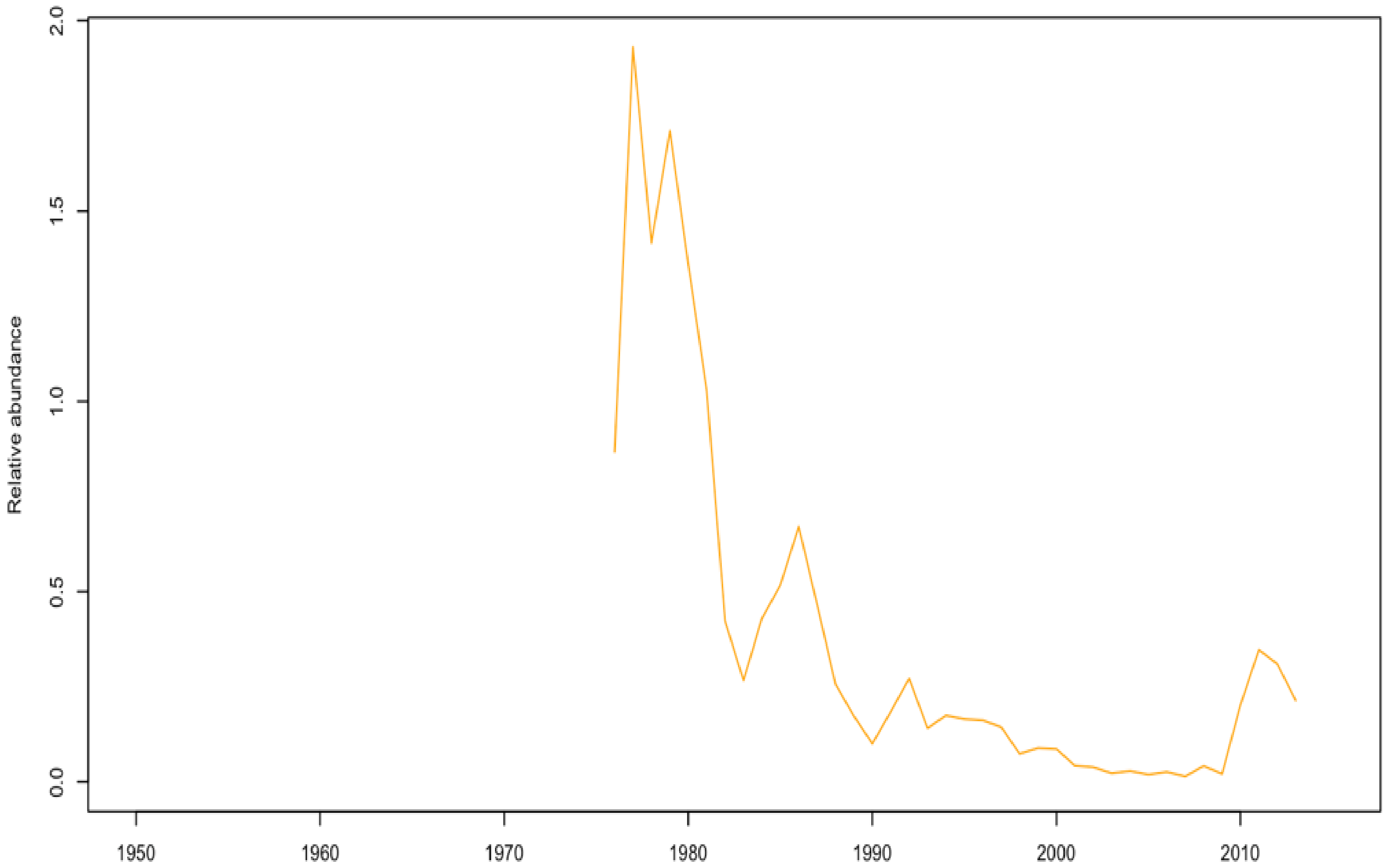

Figure 2 Relative abundance trend of Japan from 1976 to 2013 for Indian Ocean striped marlin.

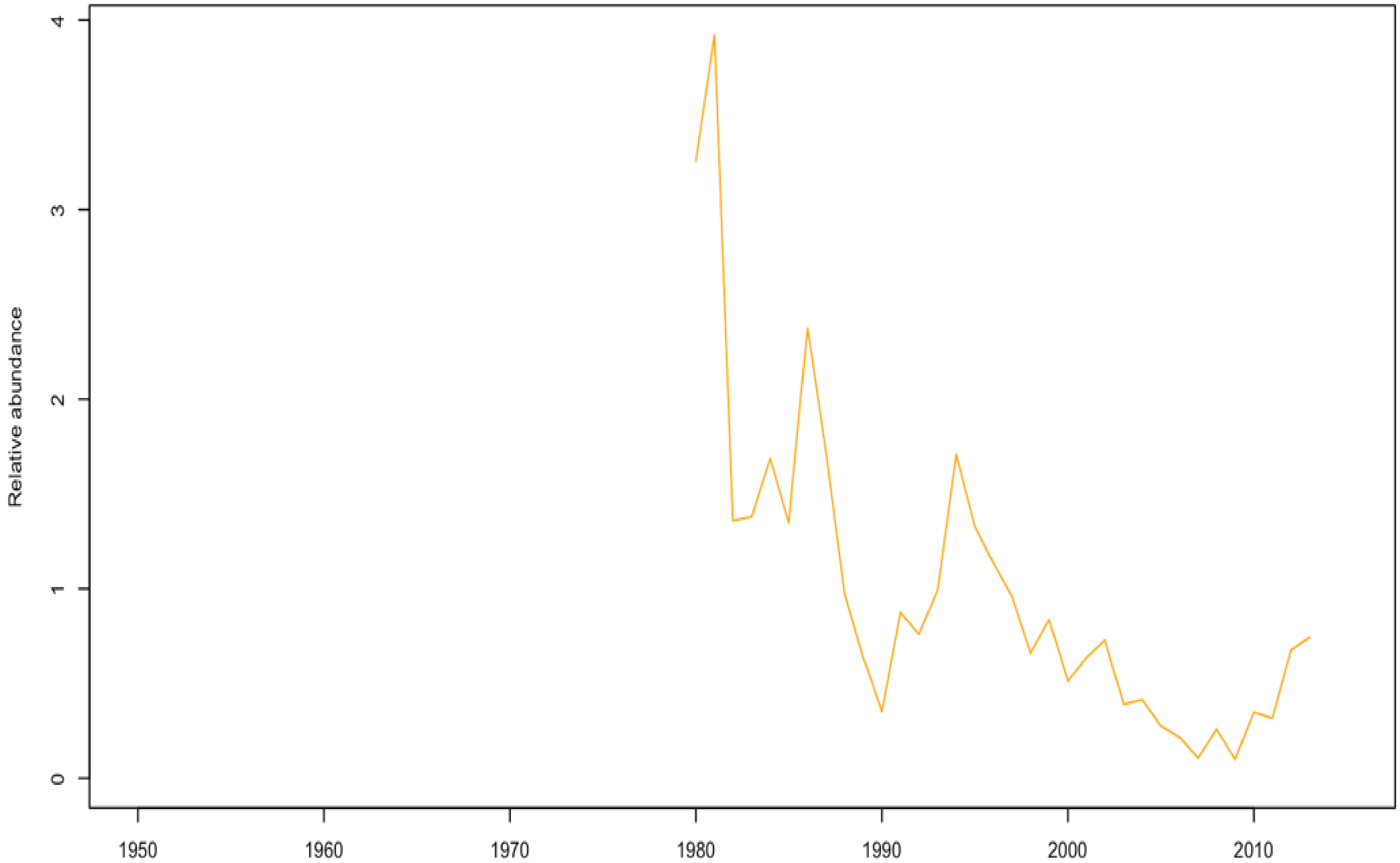

Figure 3 Relative abundance trend of Taiwan, China from 1980 to 2013 for Indian Ocean striped marlin.

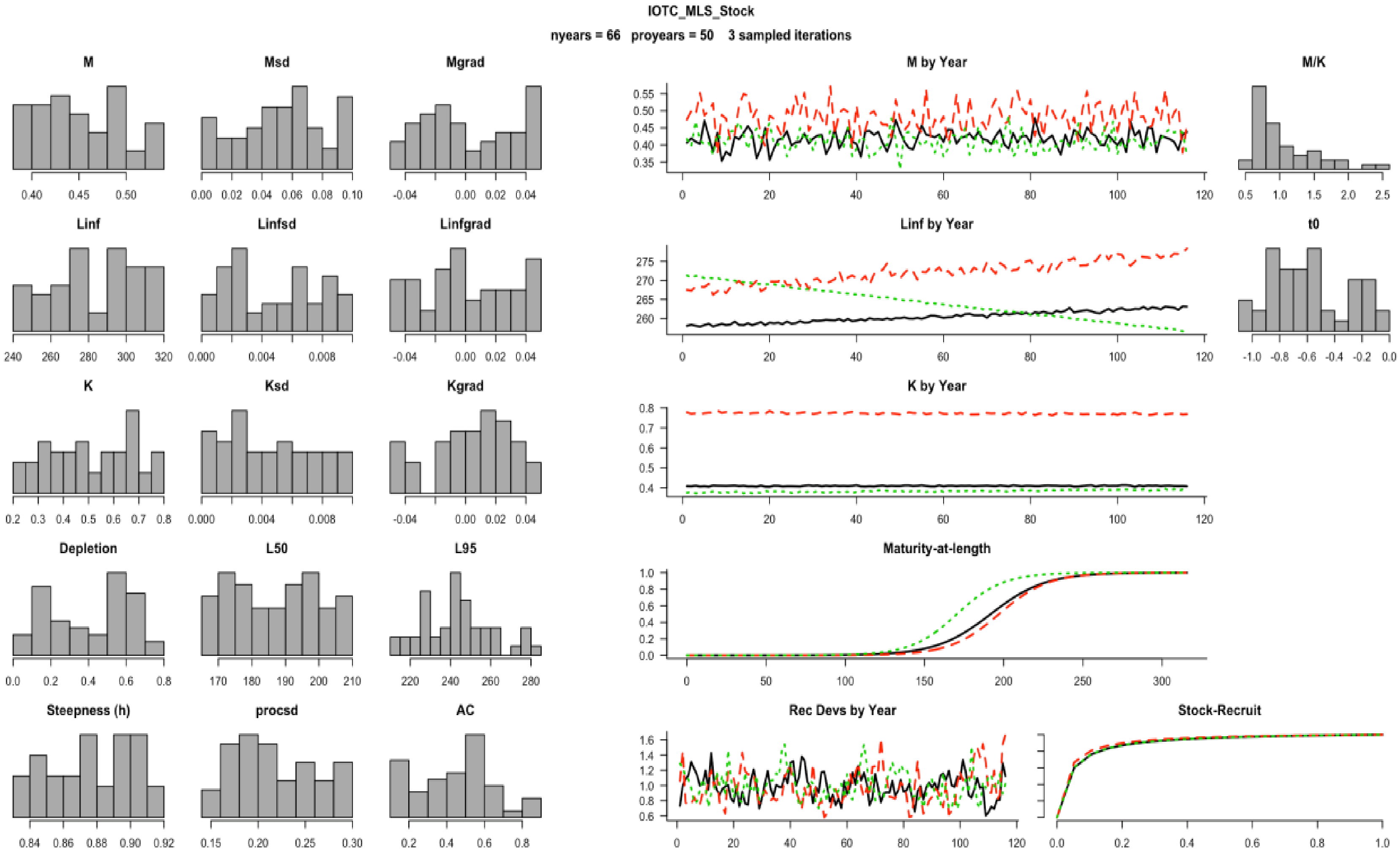

Figure 4 Summary of biological parameters. Biological parameters were all in uniform distribution. Parameter M, L_{inf}, K and Rec Devs show the stable trend in historical and projection years.

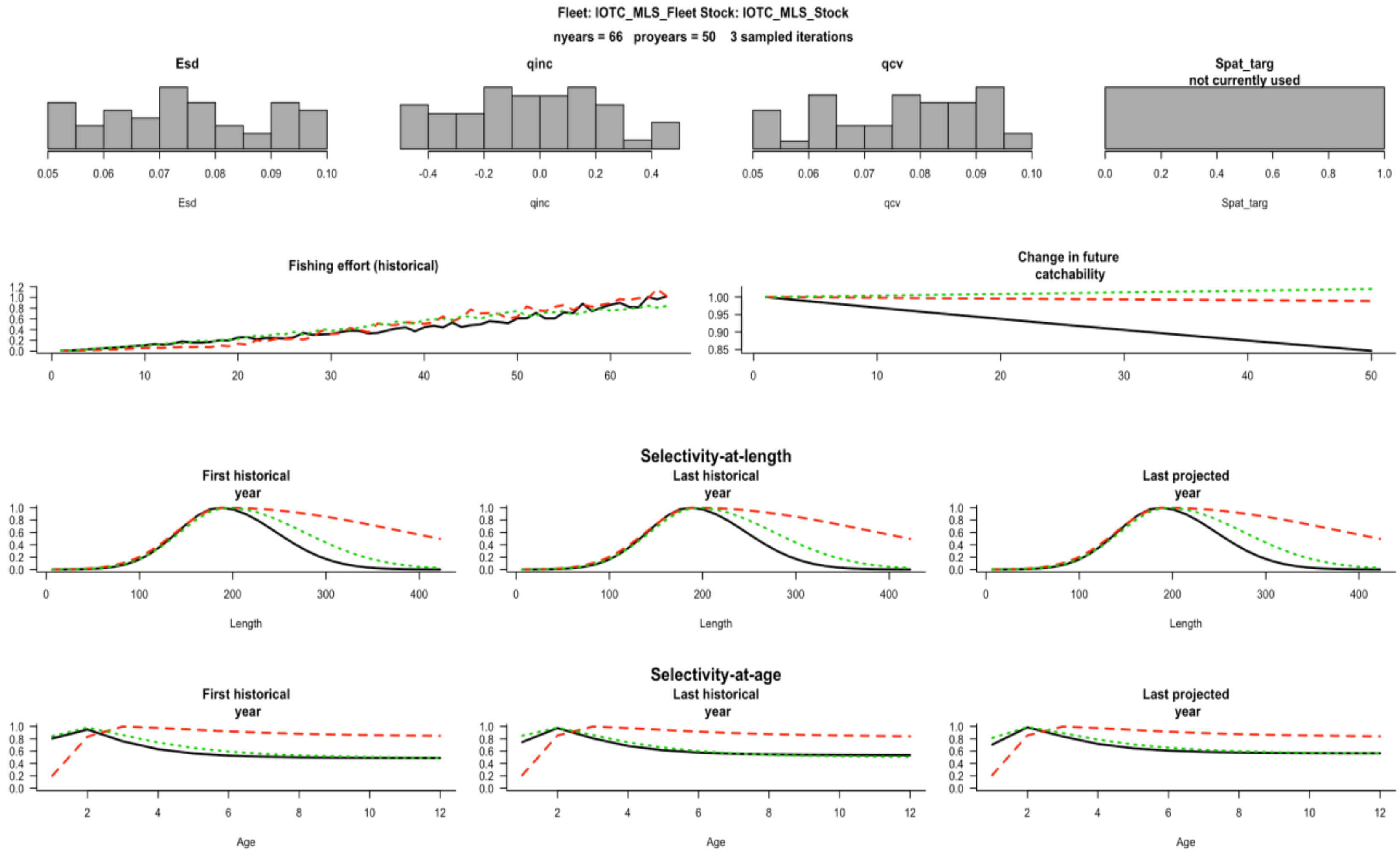

Figure 5 Summary of fleet parameters. Fishing effort increased continuously in historical years while it shows the stable status in 50 projection years. Selectivity-at-length and selectivity-at-age did not make any change in historical and projection years.

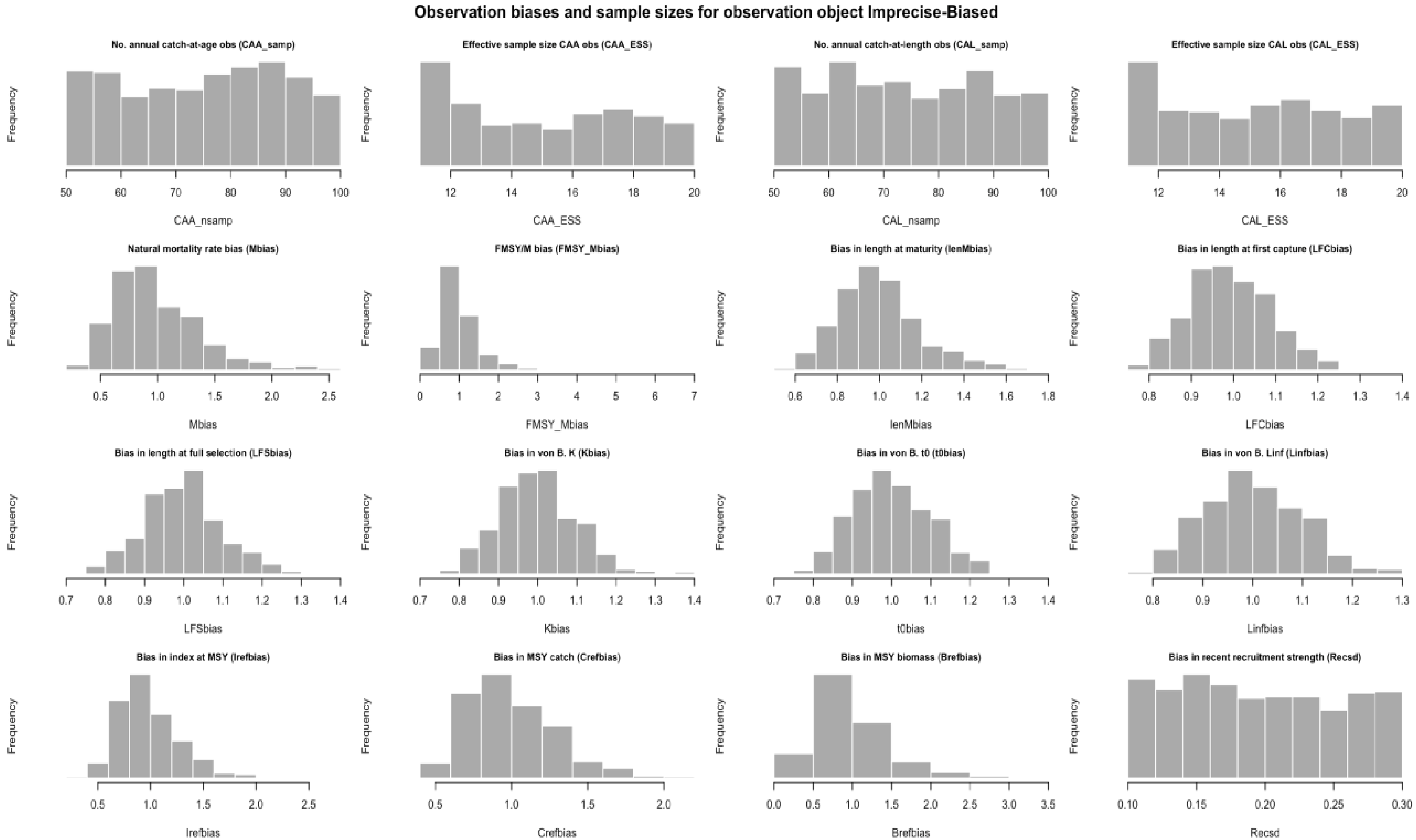

Figure 6 Observation biases and sample size for observation object imprecise-biased.

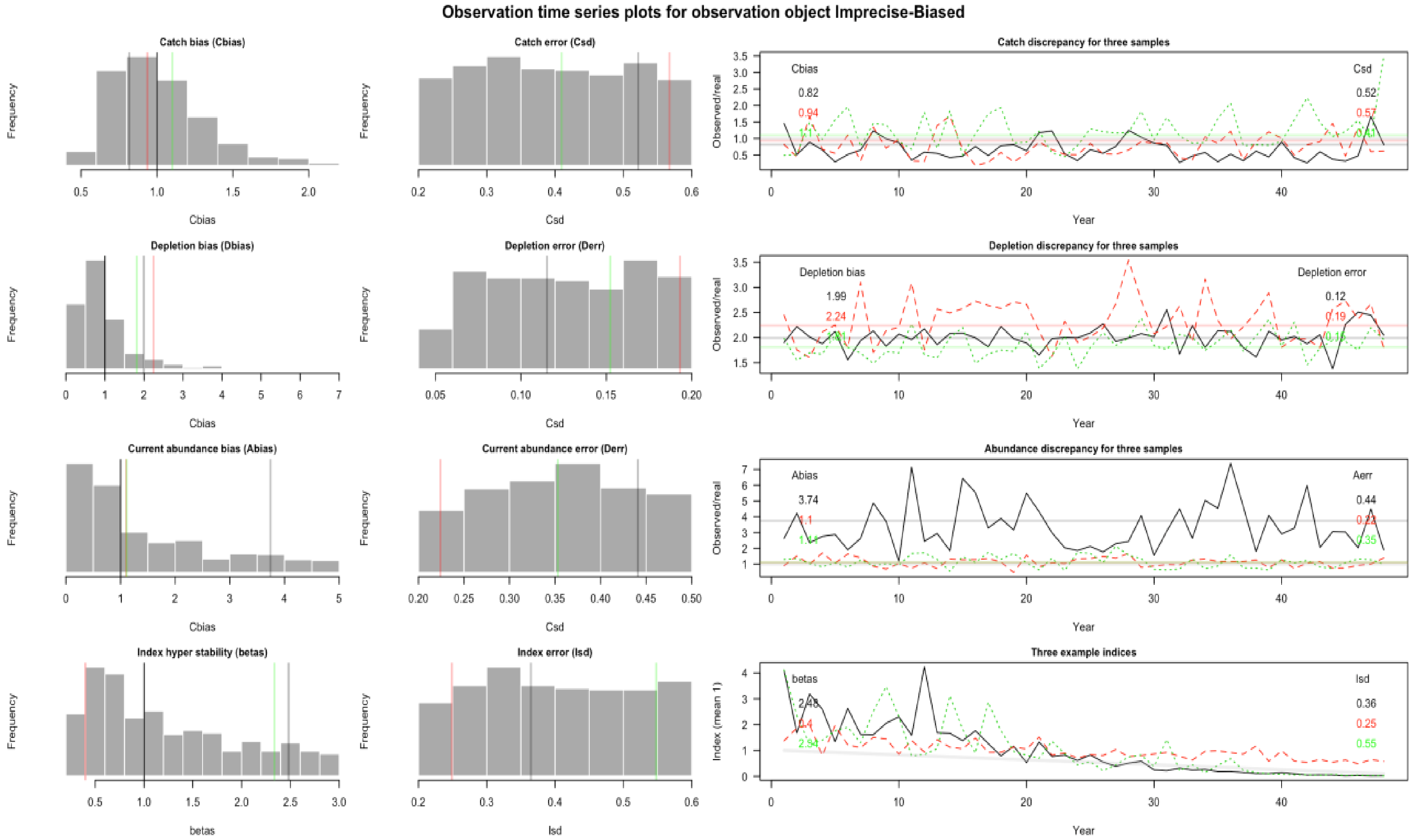

Figure 7 Observation time series plots for observation object imprecise-biased.

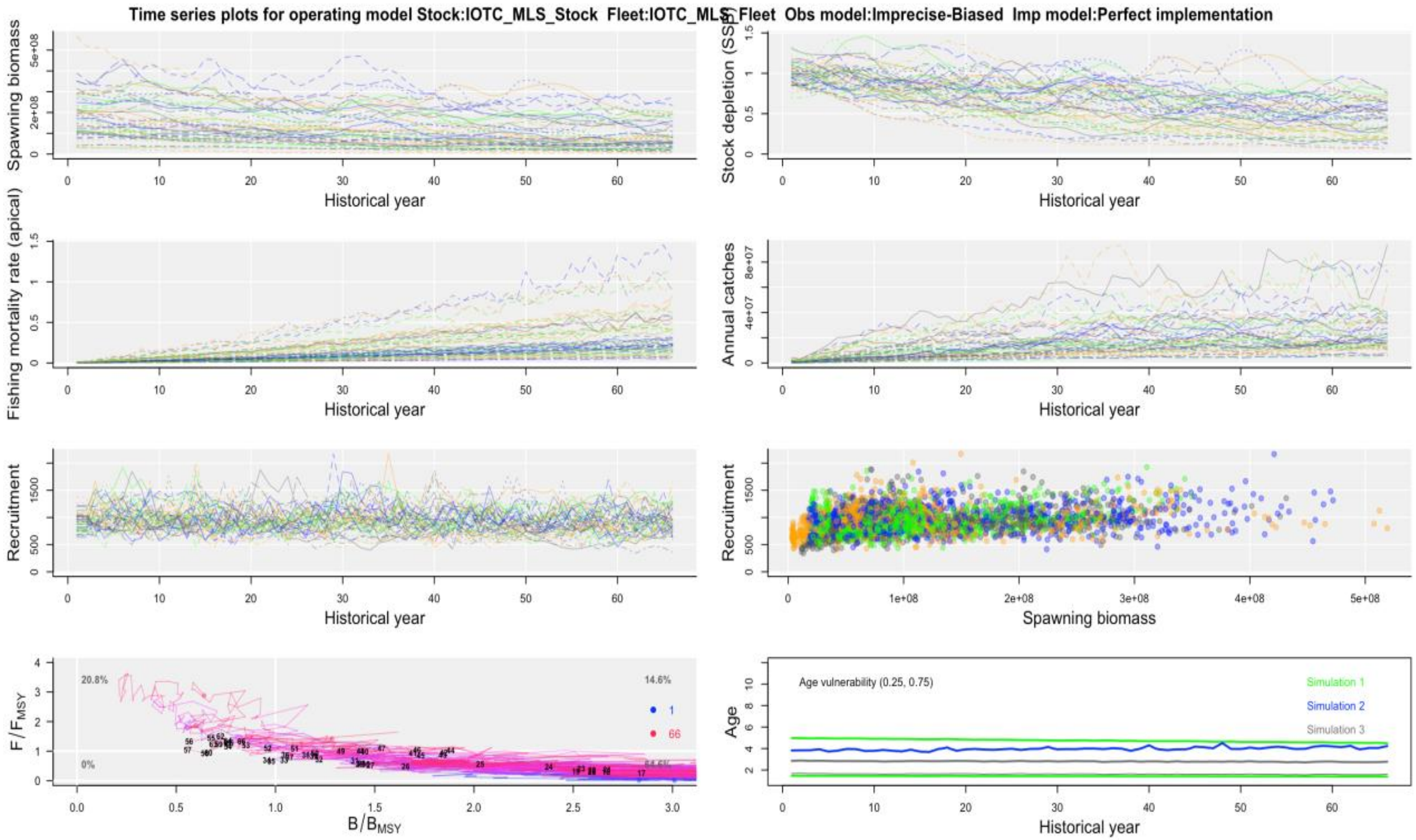

Figure 8 Time series plots for operating model. Spawning biomass and recruitment seem stable in historical years while fishing mortality, annual catches have a trend of increasing. Kobe plot shows that there is a strong trend that stock moved from the green area to red area in historical years.

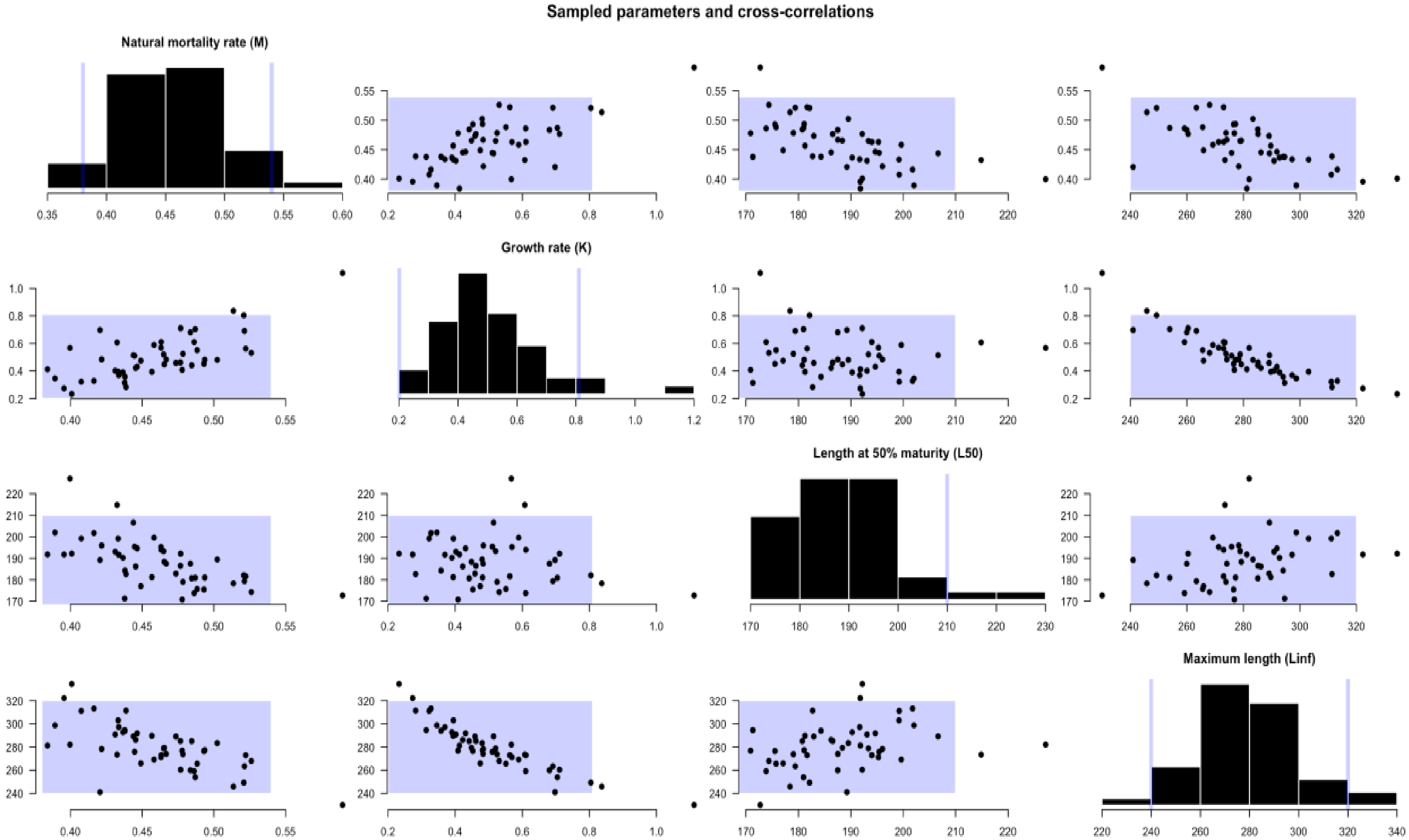

Figure 9 Sample parameters and cross-correlations. Some parameters have correlativity such as K and L_{inf}.

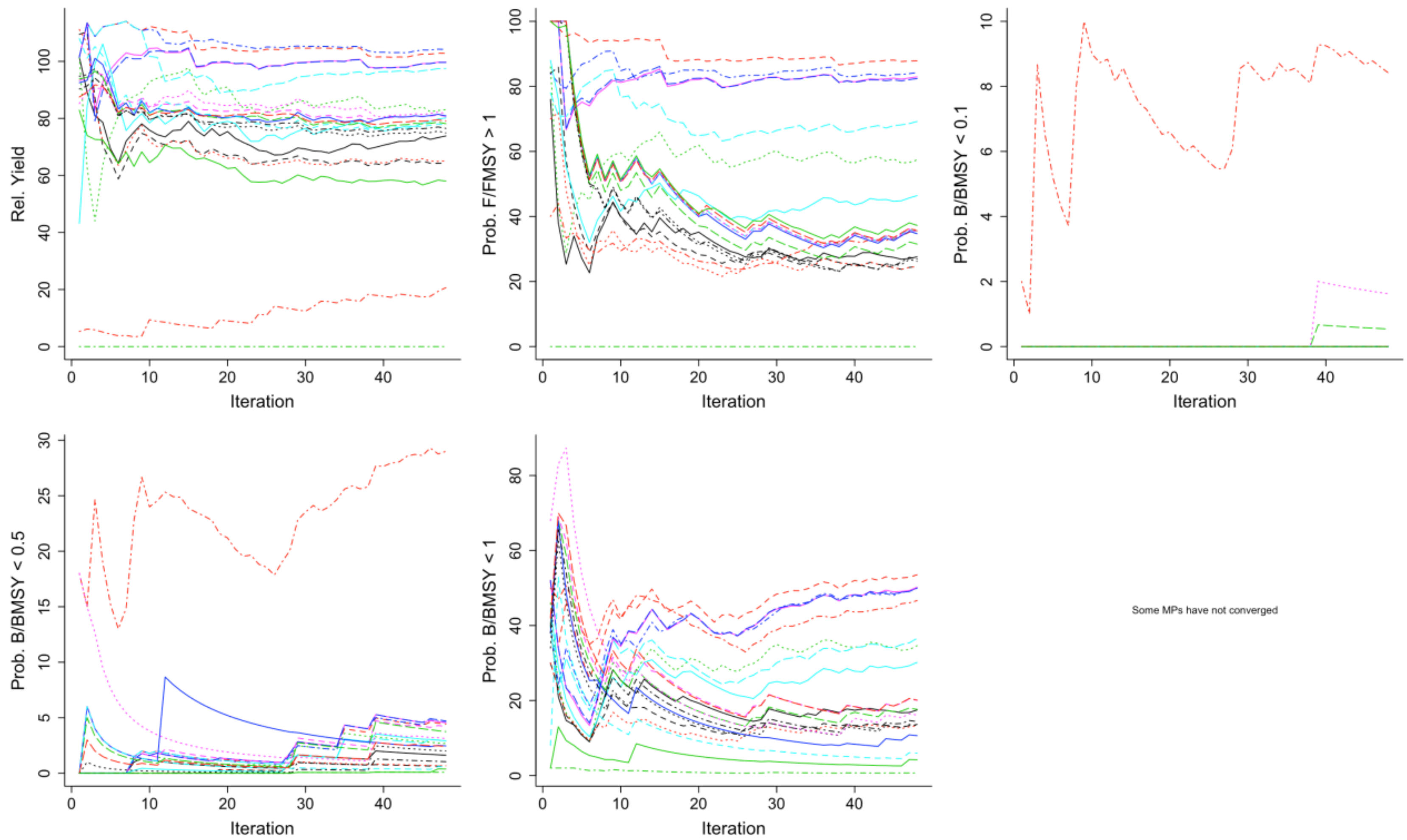

Figure 10 Convergence check result. Relative yield, probability of F/FMSY > 1 and probability of B/BMSY < 1 converge after twenty iterations while others converge after more iterations.

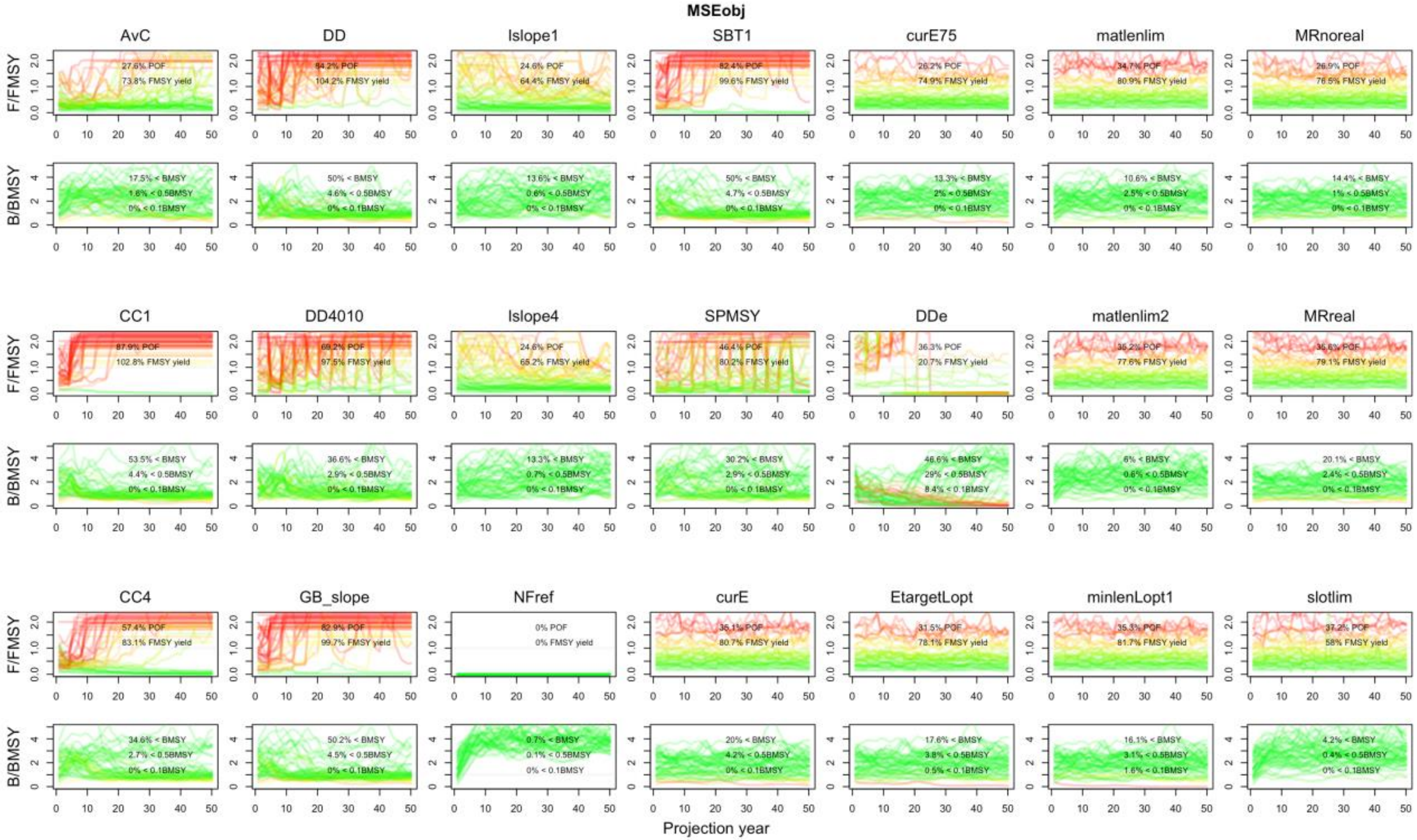

Figure 11 MSE running results. Forty-eight simulations for each MP (Green lines: good performance; yellow lines: normal performance; red lines: bad performance).

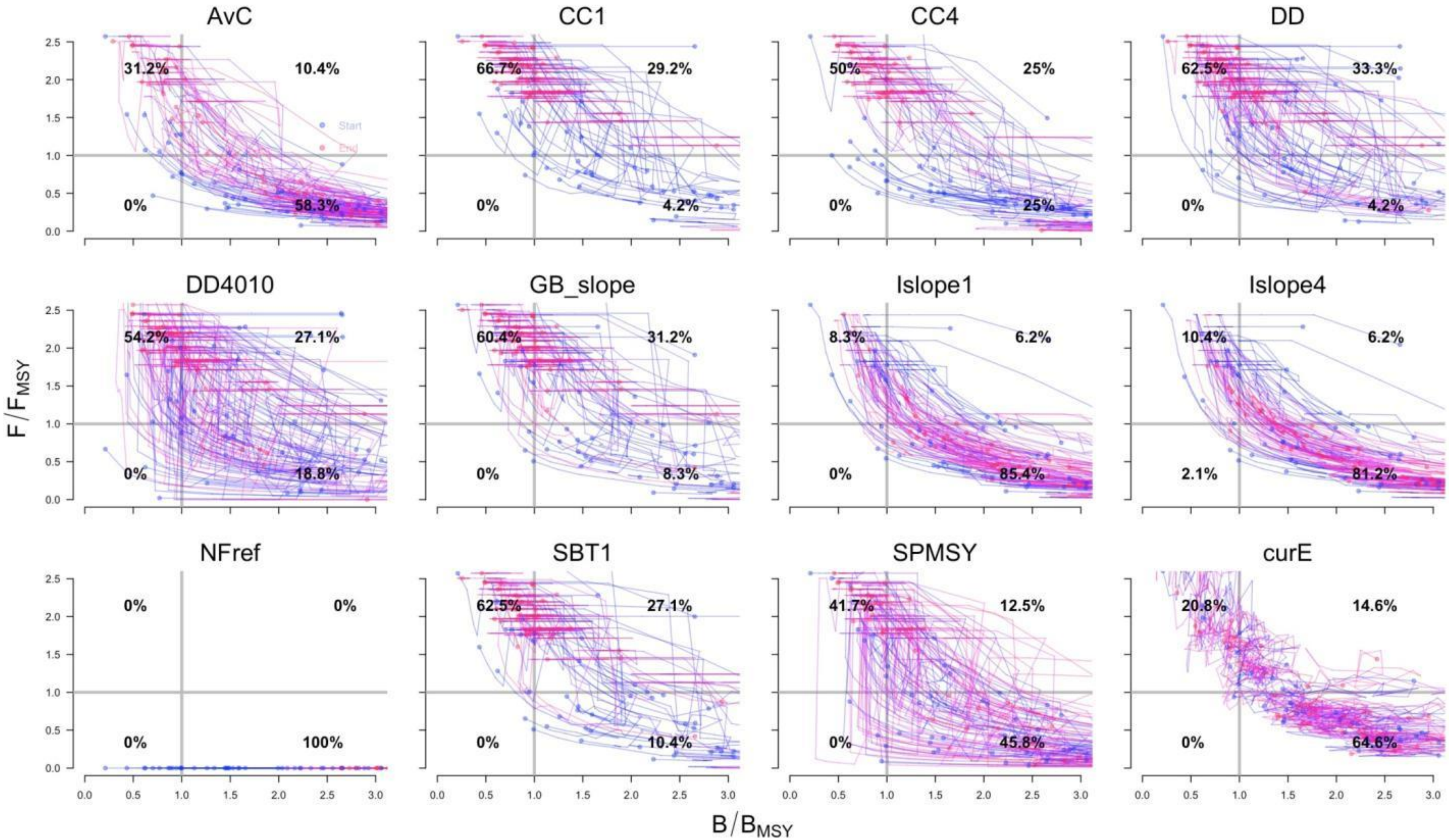

Figure 12(a) Kobe plot results (blue points/lines: start year; purple points/lines: end year). AvC, Islope1, Islope4 and curE shows stock moves to ‘green area’ .

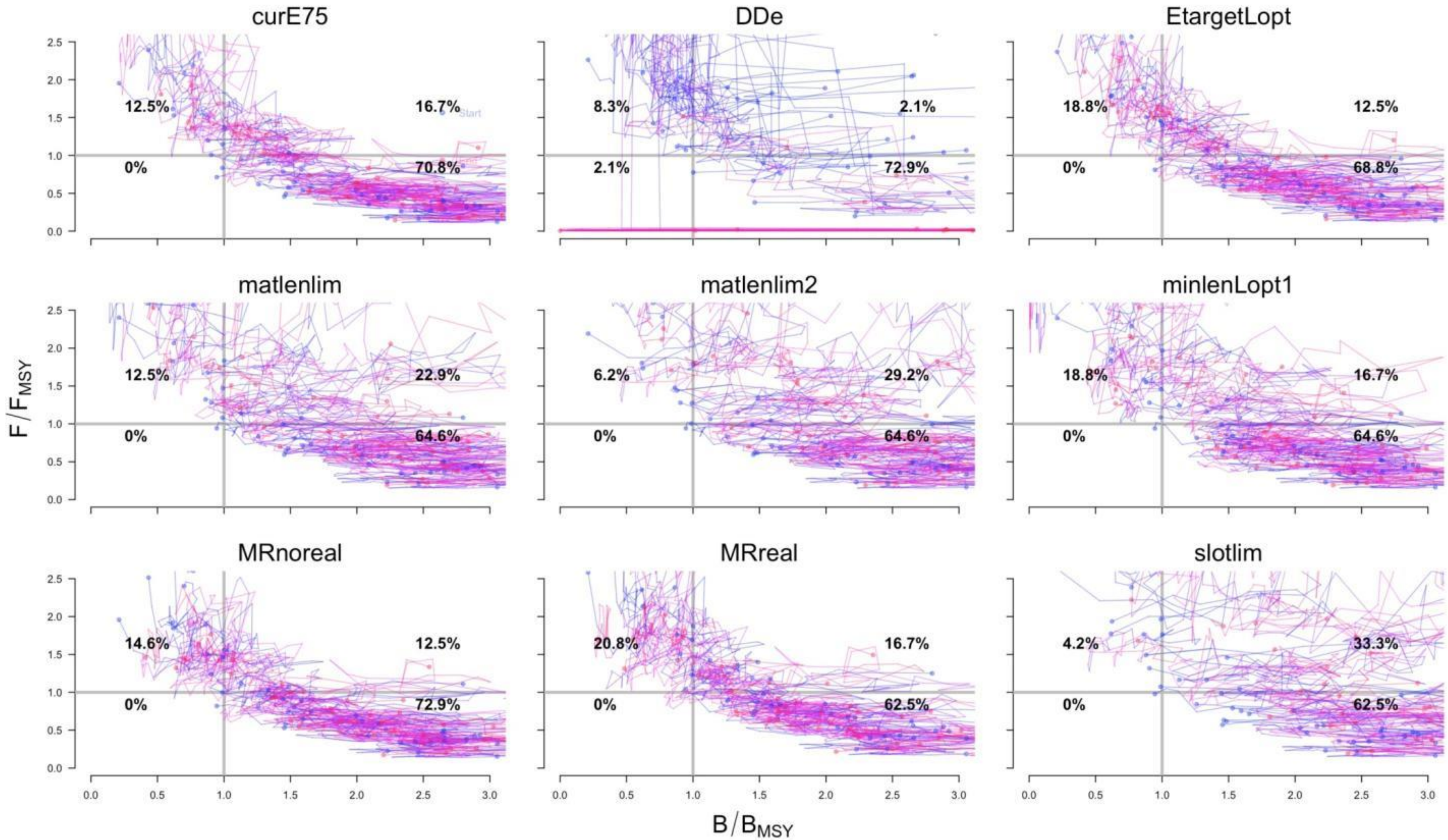

Figure 12(b) Kobe plot results (blue points/lines: start year; purple points/lines: end year). All MPs except DDe shows stock moves to 'green area'.

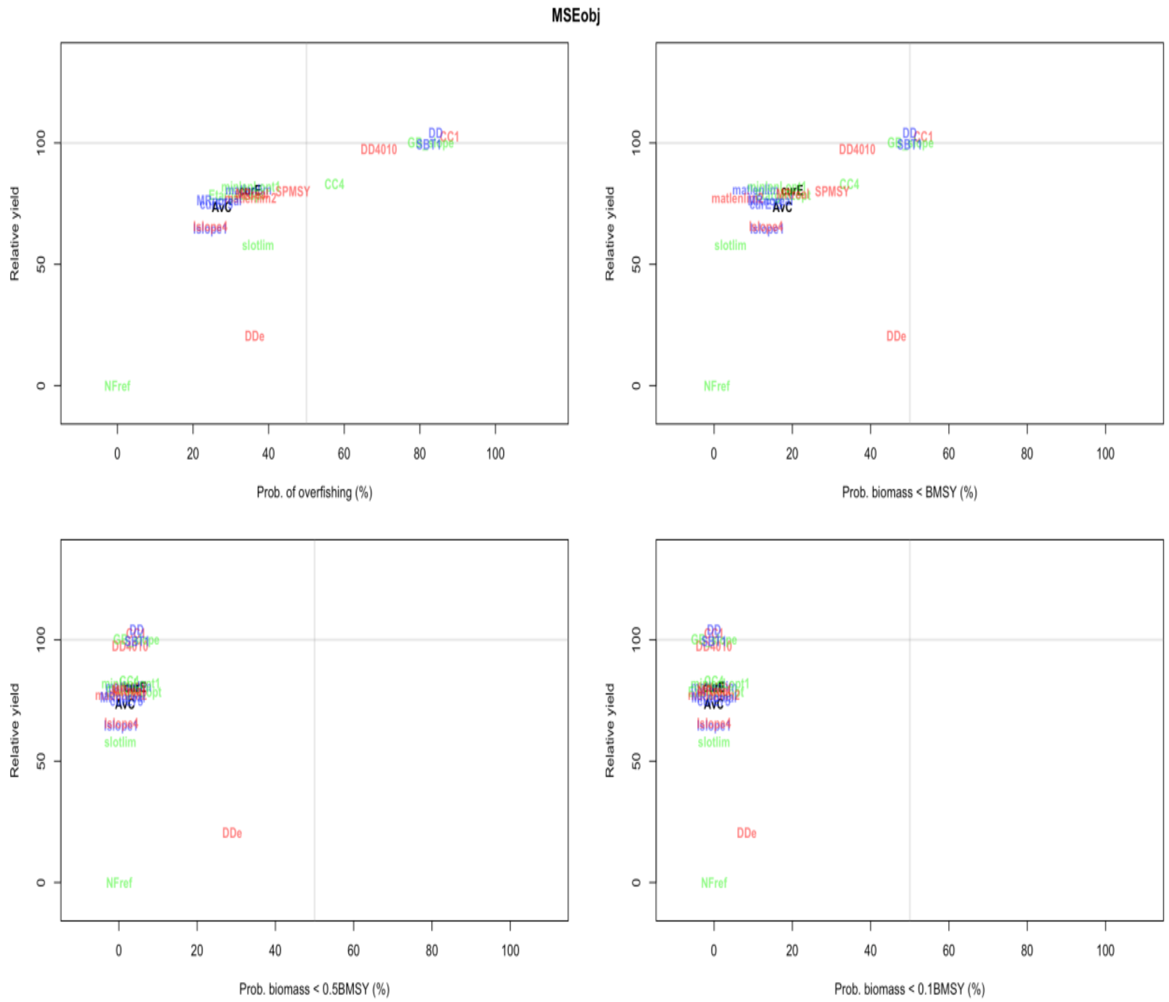

Figure 13 Trade-off plots. Fifteen of the twenty-one MPs have a possibility of 20% to 50% for overfishing while more than 75% of MPs have a possibility of less than 40% for B/BMSY<1.

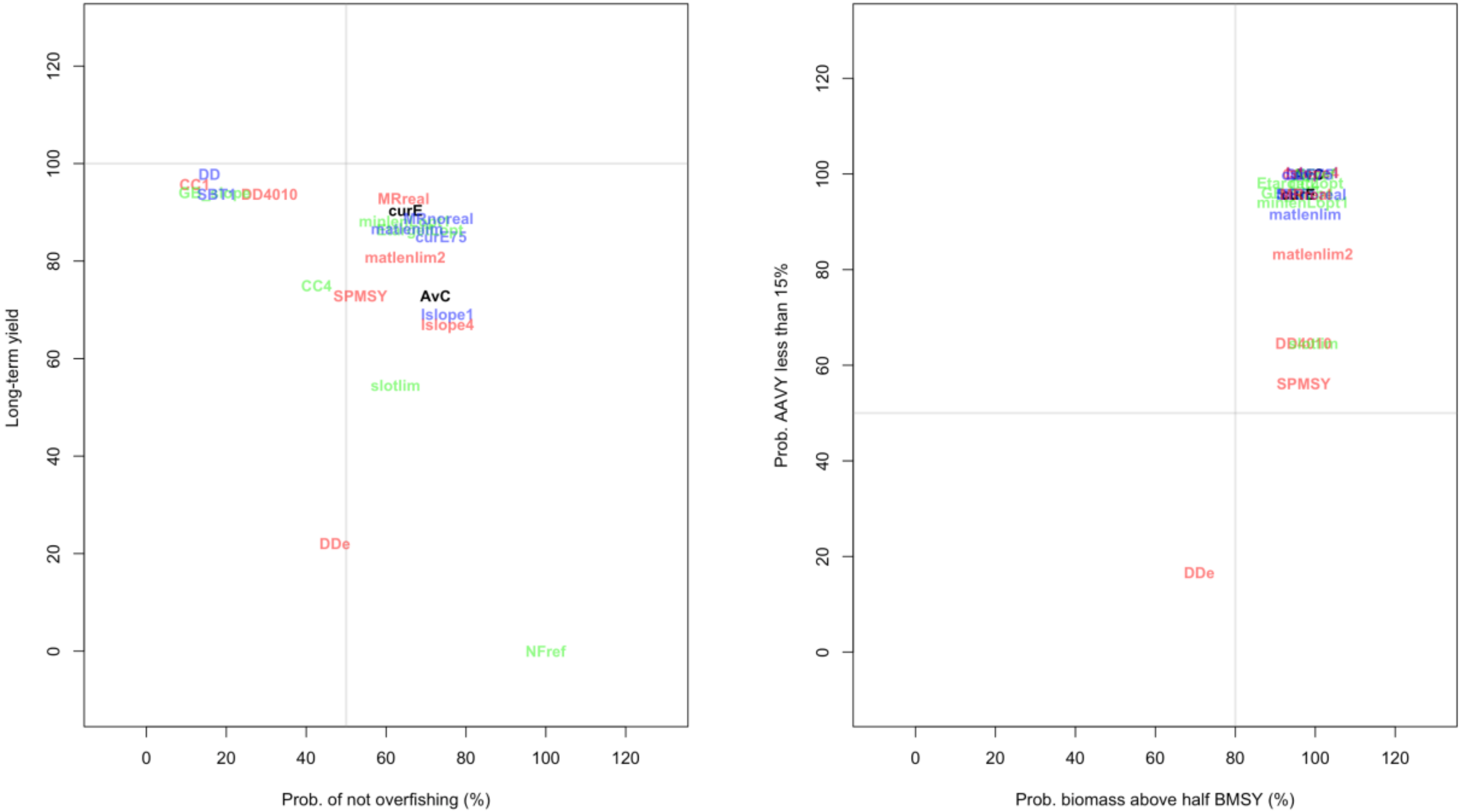

Figure 14 Initiatory trade-off plots . MPs in range of 50% to 80% of overfishing with long-term yield in range of 60 to 100 show the best performance in trade-off. Meanwhile, whatever average annual yield is, probability of biomass above half BMSY is 100%.

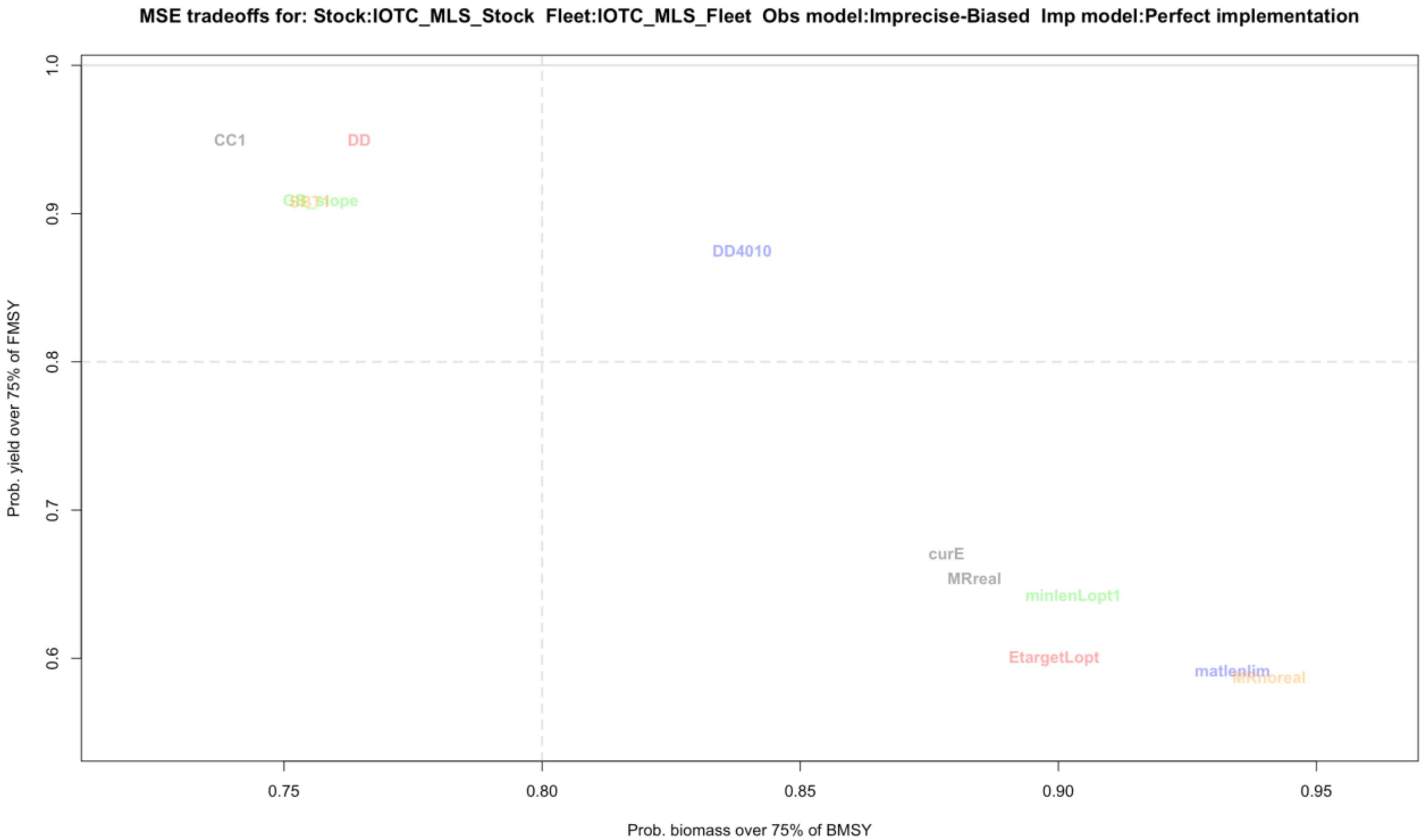

Figure 15 Final trade-off results under selecting condition. DD4010 shows the best performance of all the MPs.

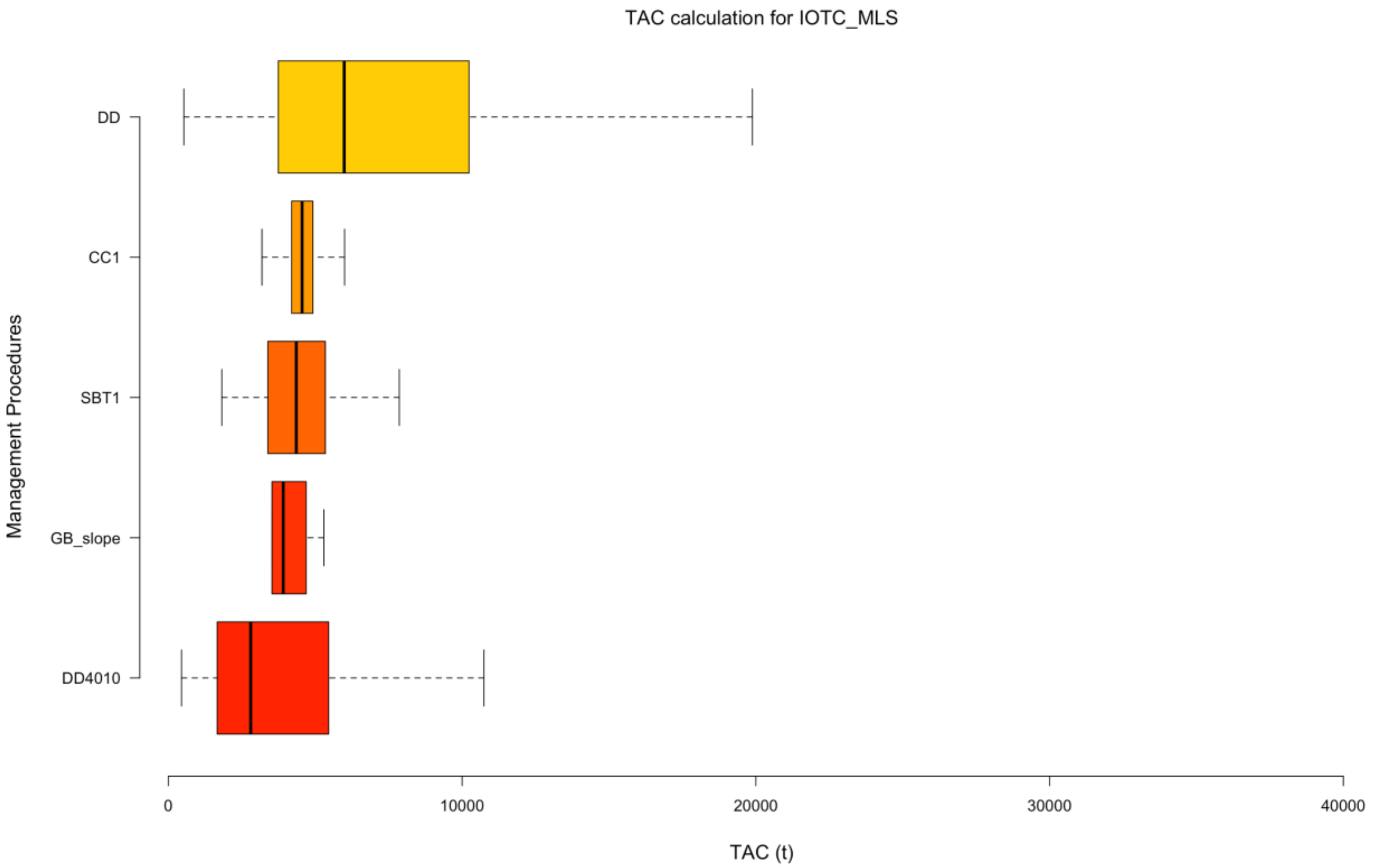

Figure 16 TAC calculation using Japan CPUE (50% CI marked boxes in simulate range).

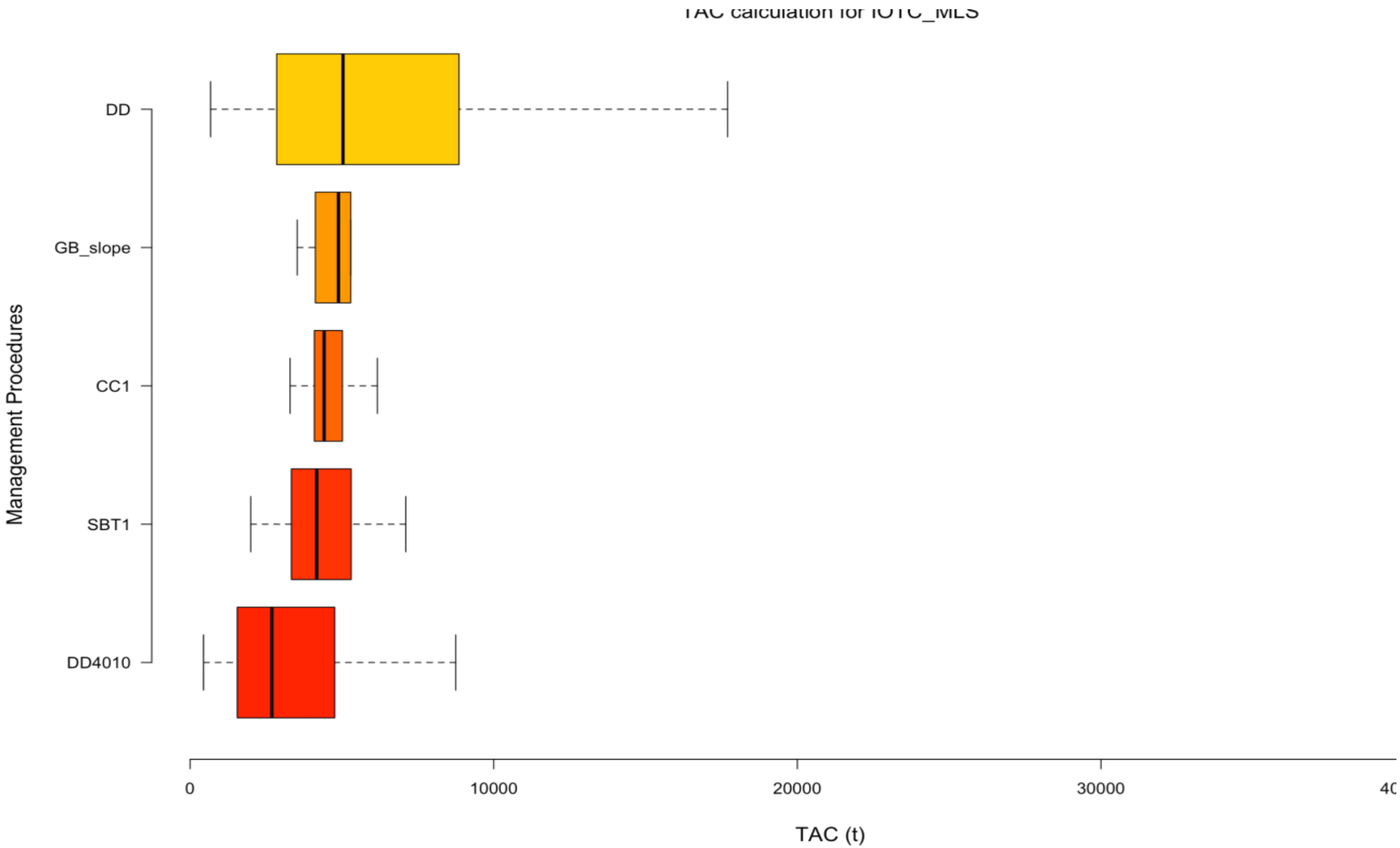

Figure 17 TAC calculation using Taiwan, China CPUE (50% CI marked boxes in simulate range).

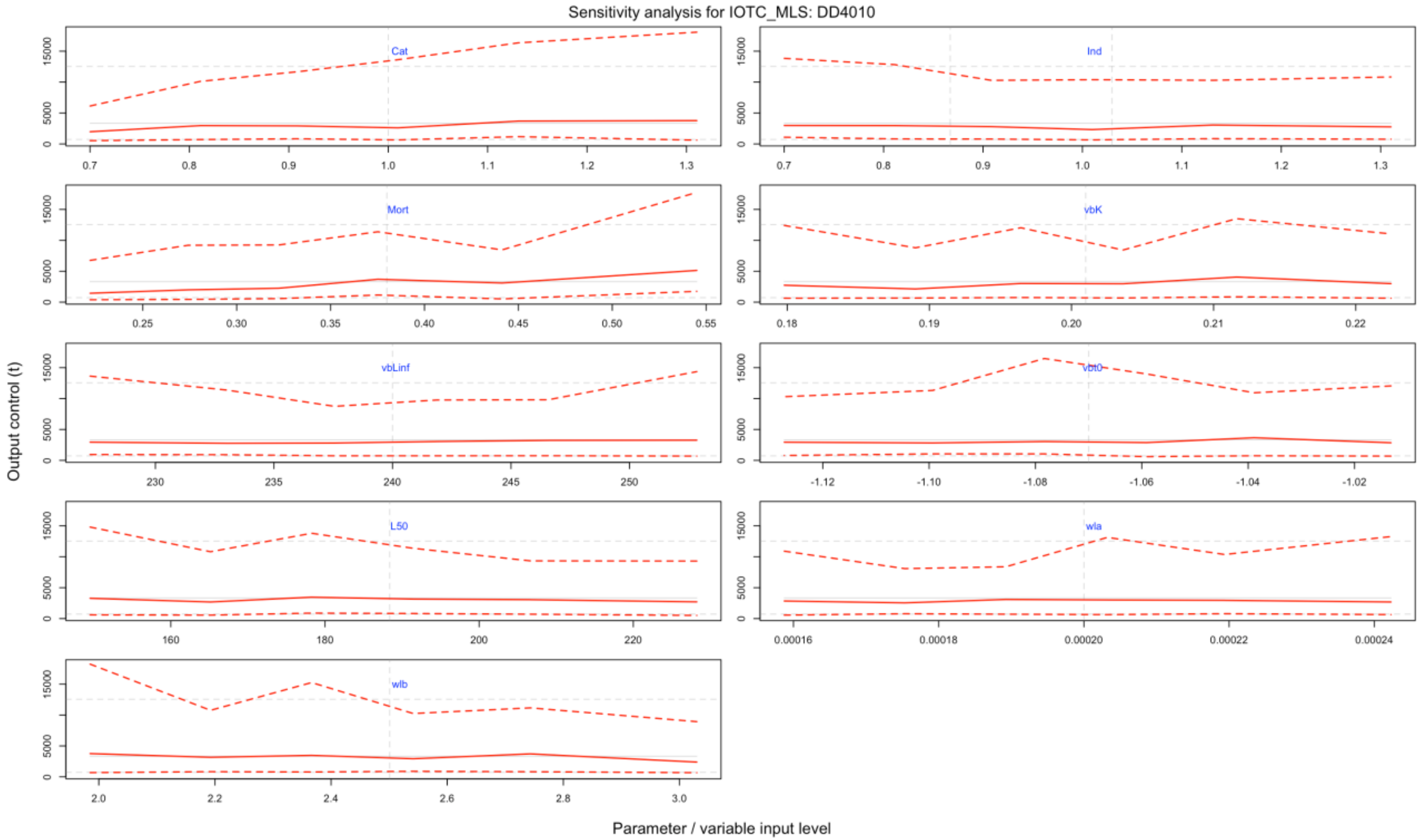

Figure 18 Sensitivity analysis (DD4010). DD4010 is sensitive to parameter Cat and Mort.

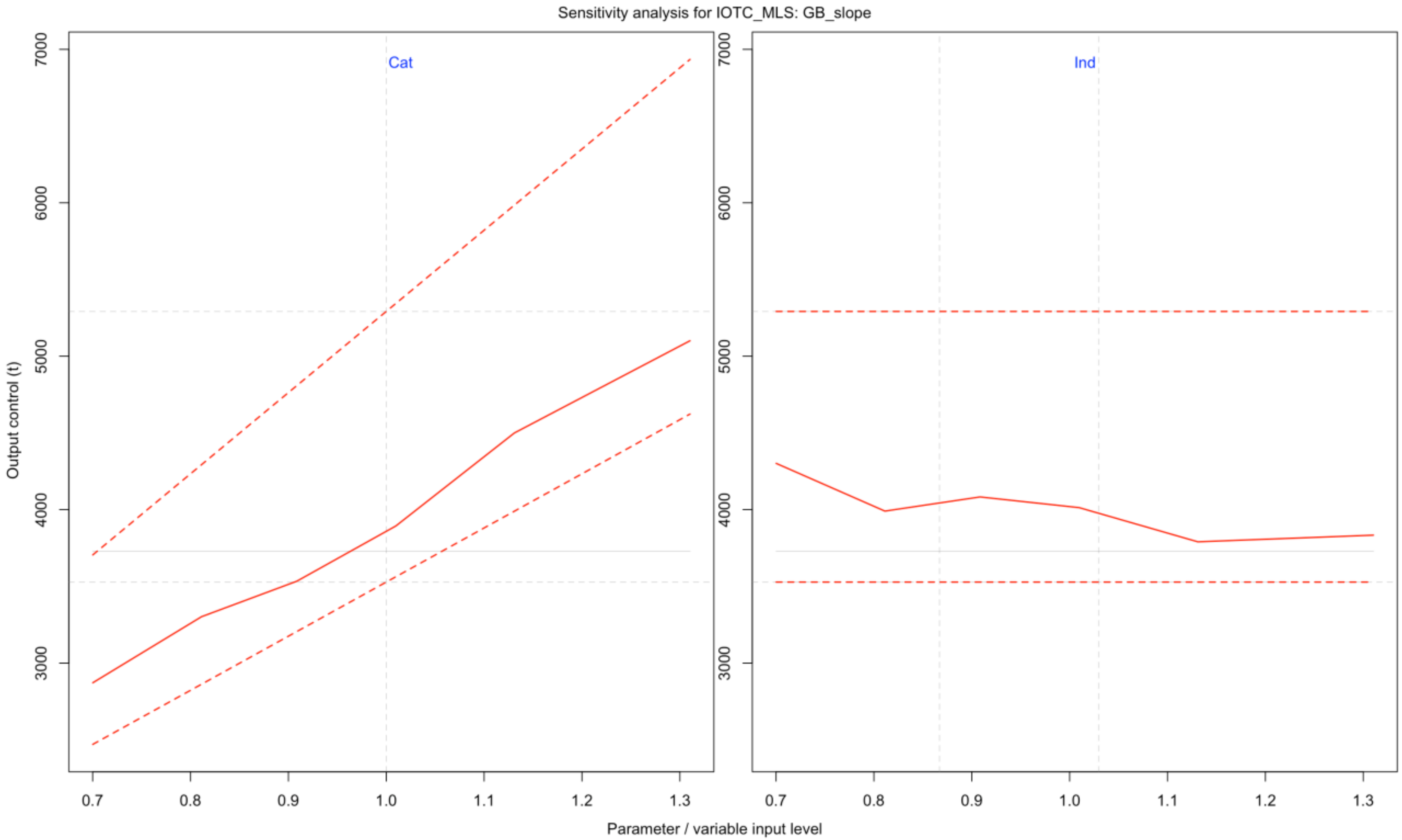

Figure 19 Sensitivity analysis (GB_slope). GB_slope is sensitive to parameter Cat.

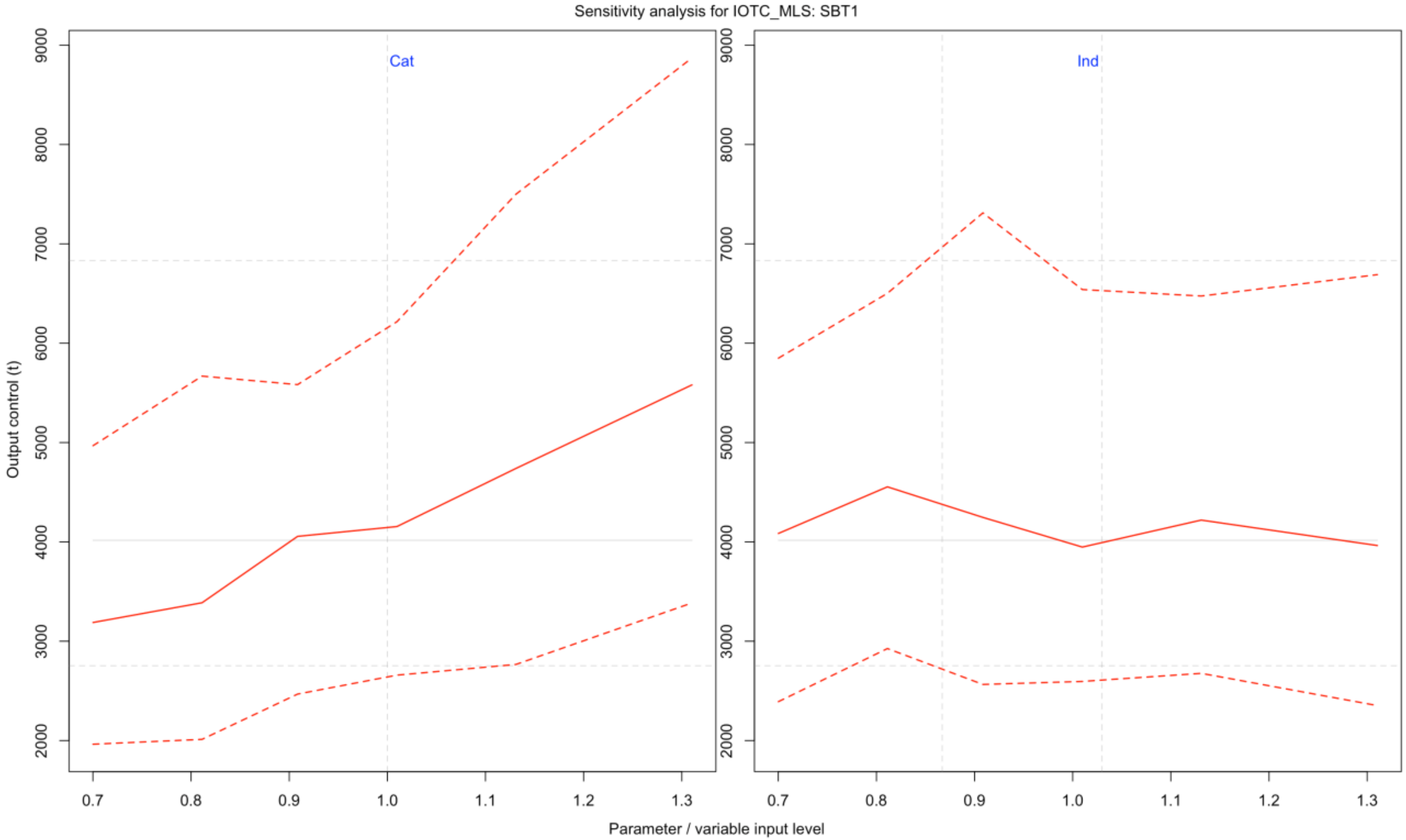

Figure 20 Sensitivity analysis (SBT1). SBT1 is sensitive to parameter Cat.

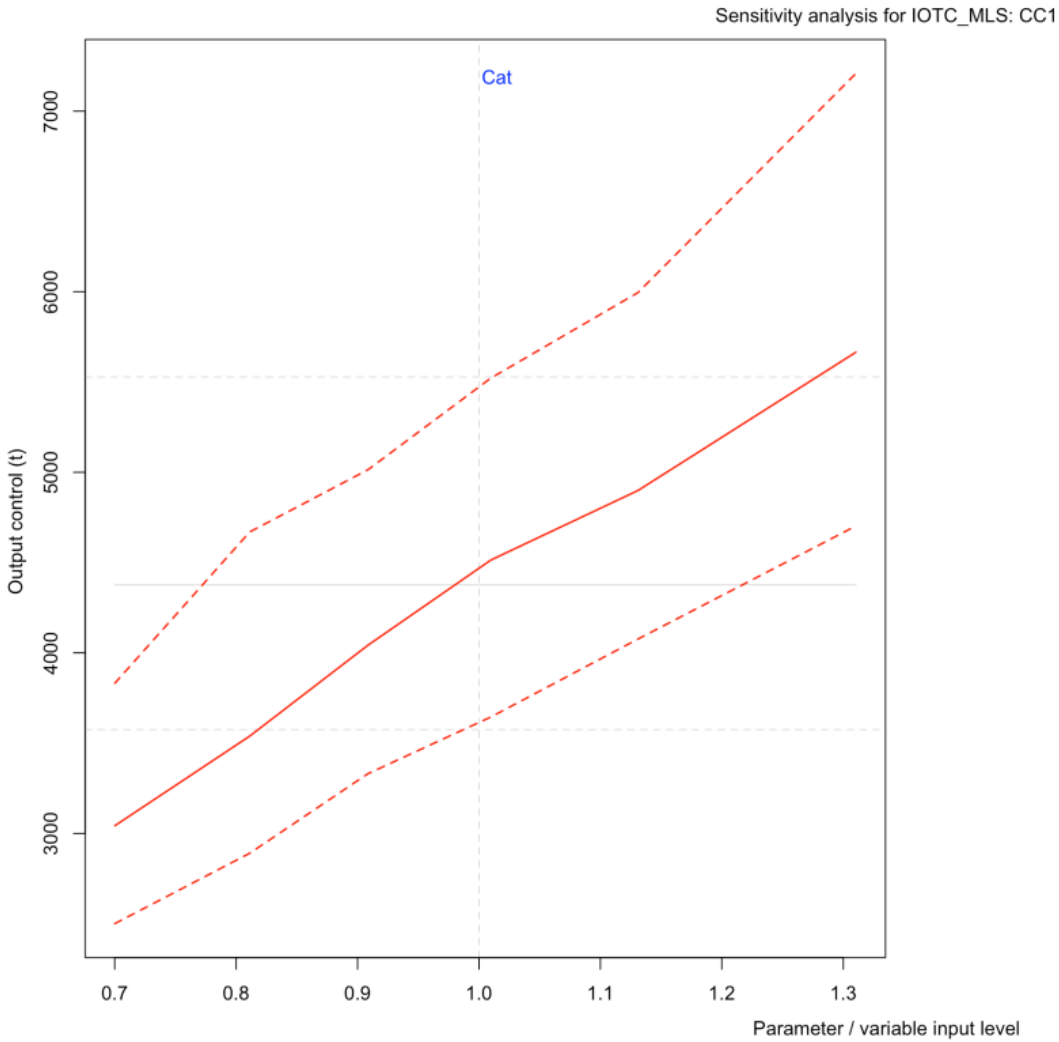

Figure 21 Sensitivity analysis (CC1). CC1 is sensitive to parameter Cat.

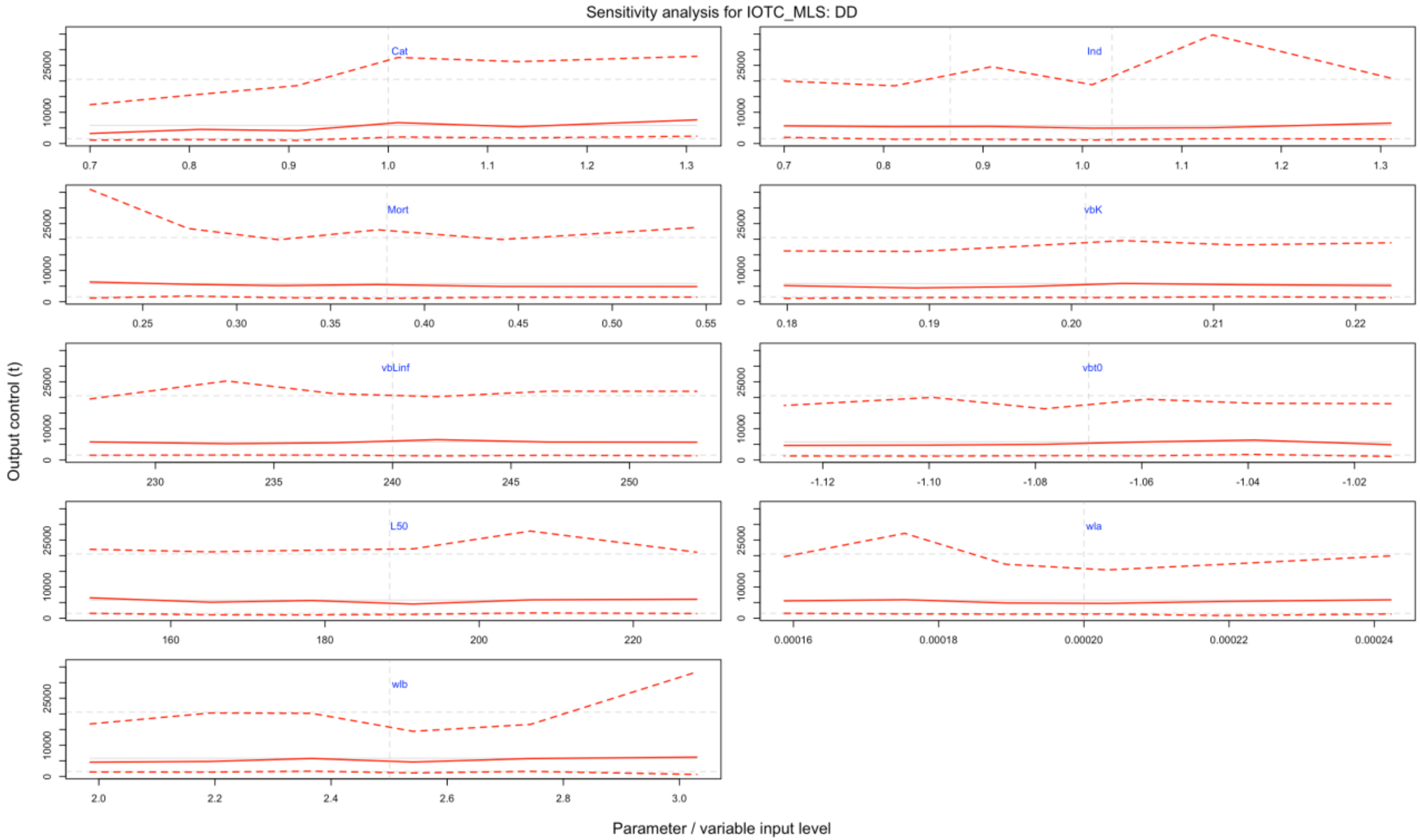

Figure 22 Sensitivity analysis (DD). DD is sensitive to parameter Cat.

Appendix A: Slots of class ‘Stock’.

Slot name	Description
Name	Name of the Stock object
maxage	The maximum age of individuals that is simulated
R0	The magnitude of unfished recruitment
M	Natural mortality rate
Msd	Inner-annual variability in natural mortality rate expressed as a coefficient of variation
Mgrad	Mean temporal trend in annual mortality rate, expressed as a percentage change in M per year
h	Steepness of the stock recruit relationship
SRrel	Type of the stock recruit relationship (Beverton-Holt/Ricker)
Linf	Maximum length
K	The vulnerability of the longest (oldest) fish
t0	Vector of verticies, index for years at which historical selectivity pattern changed. If left empty, historical selectivity is constant
a	Length-weight parameter alpha
b	Length -weight parameter beta
L50	Length at 50% maturity
L50_95	Length increment
D	Current level of stock depletion
Perr	Process error, the CV of lognormal recruitment deviations
period	Period for cyclical recruitment pattern in years

Appendix B: Slots of class 'Fleet'.

Slot name	Description
Name	Name of the Fleet object
nyears	The number of years for the historical simulation
Spat_targ	Description of fishing in relation spatial biomass
Esd	Inner-annual variability in fishing mortality rate
EffYears	Vector of verticies, years at which to simulate varying relative effort
EffLower	Lower bound on relative effort corresponding to EffYears
EffUpper	Upper bound on relative effort corresponding to EffYears
LFS	Shortest length that is fully vulnerable to fishing
L5	Shortest length corresponding to 5 percent vulnerability
Vmaxlen	The vulnerability of the longest (oldest) fish
SelYears	Vector of verticies, index for years at which historical selectivity pattern changed. If left empty, historical selectivity is constant
AbsSelYears	Optional values for SelYears , used for plotting only and must be of same length as SelYears
L5Lower	Optional vector of values of length SelYears, specifying lower limits of L5
L5Upper	Optional vector of values of length SelYears, specifying upper limits of L5
LFSLower	Optional vector of values of length SelYears, specifying lower limits of LFS
LFSUpper	Optional vector of values of length SelYears, specifying upper limits of LFS
VmaxLower	Optional vector of values of length SelYears, specifying lower limits of Vmaxlen
VmaxUpper	Optional vector of values of length SelYears, specifying upper limits of Vmaxlen
qinc	Average percentage change in fishing efficiency
qvc	Inter-annual variability in fishing efficiency
IsRel	Are the selectivity parameters relative to size-of-maturity? TRUE or FALSE
CurrentYr	The current calendar year (final year) of the historical simulations

Appendix C: Slots of class ‘Data’.

Slot name	Description
Name	The name of the case study
Year	A vector of years that correspond to catch and relative abundance data
Cat	Total annual catches
Ind	Relative abundance index
t	The number of years corresponding to AvC and Dt
AvC	Average catch over time t
Dt	Depletion over time t
ML	Mean length time series
Mort	Natural mortality rate
FMSY_M	An assumed ratio of FMSY to M
BMSY_B0	The most productive stock size relative to unfished
L50	Length at 50 percent maturity
L95	Length at 95 percent maturity
Lbar	Mean length of catch over Lc
Lc	Modal length
LFC	Length at first capture
CAA	Catch at age
Dep	Stock depletion Bnow/Bunfished
Abun	An estimate of absolute current vulnerable abundance
SpAbun	An estimate of absolute current spawning stock abundance
vbK	The von Bertalanffy growth coefficient
vbLinf	Maximum length
vbt0	Theoretical age at length zero
wla	Weight-length parameter alpha
wlb	Weight-length parameter beta
steep	Steepness of the Beverton Holt stock-recruitment relationship
Maxage	Maximum age
Units	Units of the catch/absolute abundance estimates

Appendix D: Slots of class ‘Imp’.

Slot name	Description
Name	The name of the implementation error object
TACSD	Lognormal standard deviation in fraction of TAC taken
TACFrac	Mean fraction of TAC taken
ESD	lognormal standard deviation in fraction of TAE taken
EFrac	Mean fraction of recommended effort taken
SizeLimSD	lognormal error in size limited implementation
SizeLimFrac	Mean fraction of the size limit
DiscMort	Discard mortality rate