PRELIMINARY MANAGEMENT STRATEGY EVALUATION FOR BLUE SHARK IN THE INDIAN OCEAN USING A DATA-LIMITED APPROACH

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SUMMARY

In tuna-RFMOs there has been an effort to move to quantitative stock assessments for pelagic sharks, especially for the main species such as blue shark Prionace glauca. In IOTC, blue shark was last assessed in 2017 with the use of an integrated length-based age-structured model (SS3). This paper now presents a preliminary exercise with data-limited Management Strategy Evaluation (MSE) to test options for different potential management procedures (MPs), using the data-limited methods toolkit (DLMtool). Reference points have not yet been adopted for sharks in IOTC, so for this exercise we set some tentative reference points noting that those can be updated in the future as needed. Eighty-nine MPs were evaluated with 9 considered potentially acceptable. Options and trade-offs between those MPs are shown and described in the paper. We have focused mainly on trade-offs between biomass and yield, but according to the management objectives agreed other performance metrics can be applied. Even thought this is a preliminary exercise at this point, we hope that it provides initial thoughts and opens the discussion for the advancement of the blue shark management and conservation in the Indian Ocean.

KEYWORDS: Blue shark, data-limited methods toolkit (DLMTool), Indian Ocean, management strategy evaluation (MSE), pelagic fisheries.

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1. Introduction

Blue shark (*Prionace glauca*) is one of the pelagic shark species most frequently caught as bycatch of pelagic fisheries all over the world, sometimes as targeted species. It is considered one of the main shark species in tuna-RFMOs worldwide. In the Atlantic and Indian Oceans, from the previously conducted ERAs, blue shark received a high vulnerability ranking as it was estimated as one of the most productive shark species, but was also characterized by a high susceptibility to longline gear (Cortés et al., 2015; Murua et al., 2012), while in the Pacific it was found to be one of the most vulnerable species to pelagic longliners.

Blue shark is most likely the pelagic elasmobranch species for which more data is currently available, including biological data, recent reported catch, discard data and length composition data. Particularly, an extensive review of the Atlantic and Indian Ocean size composition was performed using detailed observer data (Coelho et al., 2018). However, there are still considerable uncertainties in the reported historical catch data and discard rates for this species.

In tuna-RFMOs there has been an effort to move to quantitative stock assessments for pelagic sharks, especially in the most recent years and for the main shark species. *P. glauca* is the only species with a quantitative stock assessment in the three oceans. Specifically, in the Pacific Ocean, the North stock was last assessed using a production model and an integrated age-structured model (using SS3, the Stock Synthesis model platform) which was used for management advice: For that stock it was estimated that spawning biomass is above biomass at Maximum Sustainable Yield (MSY) and relative fishing mortality is below fishing mortality at MSY (ISC, 2017). In the Atlantic Ocean, for the South stock Bayesian production models were applied for which some models and/or model runs predicted that the stock was not overfished and that overfishing was not occurring while others predicted that the stock was overfished and that overfishing was occurring (Anon., 2015). For the North Atlantic stock, all scenarios considered with the Bayesian surplus production model and also an integrated model (Stock Synthesis) indicated that the stock was not overfished and that overfishing was not occurring, however it was acknowledged that there still remained a high level of uncertainty in data inputs and model structural assumptions, by virtue of which the possibility of the stock being overfished and overfishing occurring could not be ruled out (Anon., 2015). ICCAT is the only tuna-RFMO that has adopted a regulation measure regarding blue shark, which aims to maintain the catches of blue shark to levels not higher than during the period 2011-2015.

Specifically for the Indian Ocean, a first stock assessment was attempted in 2015; however due to uncertainties in the input data it was not possible to provide stock status. A new assessment was performed in 2017 by the IOTC Working Party on Ecosystems and Bycatch (WPEB) with improved data. Four stock assessment models were applied in 2017, specifically a data-limited catch only model (SRA), two Bayesian biomass dynamic models (JABBA with process error and a Pella-Tomlinson production model without process error) and an integrated age-structured model (SS3). All models produced similar results suggesting the stock is currently not overfished nor subject to overfishing, but with the trajectories showing consistent trends towards the overfished and subject to overfishing quadrant of the Kobe plot. The major sources of uncertainties identified were catches and CPUE indices of abundance (IOTC, 2017).

As noted above, blue shark has recently been assessed using quantitative methods on all oceans, using mostly integrated age-structure models. However some models remain highly uncertain due to uncertainties and conflicts in the input parameters. Therefore, since a considerable number of the required pieces of information is already available (mainly catch series, relative indices of abundance and size distributions), one possible next step in the short/medium term for the assessment of the species could rely on the improvement in information that could lead to more robust implementation of the models currently used in assessment and a reduction of the uncertainty of the results. Therefore, the objectives of this working document is to provide a draft option of that possible next step, in this case with the development of a preliminary exercise with data-limited Management Strategy Evaluation (MSE) to test options for different management procedures (MPs).

2. Material and methods

2.1. Operating model

Using the R package 'DLMtool' (Carruthers and Hordyk, 2018a;b; R Core Team, 2018) an age-structured spatial operating model (e.g. Carruthers et al., 2014) was constructed based on the last IOTC 2017 Stock Synthesis base case assessment (Rice, 2017). In DLMtool, an OM contains four separate components, each containing a set of parameter values for different aspects of the simulation:

- Stock - parameters describing the stock dynamics
- Fleet - parameters describing the fishing fleet dynamics
- Obs (Observation) - parameters describing the observation processes (how the observed fishery data is generated from the simulated data)
- Imp (Implementation) - parameters describing the management implementation (how well the management regulations are implemented)

The Indian Ocean blue shark OM is extensively documented in the DLMtool Fishery Library of operating models (Anon, 2018).

2.2. Management procedure evaluation

Eighty-nine MPs were evaluated in the Indian Ocean blue shark MSE, including four reference methods (FMSYref , FMSYref50 , FMSYref75 , and NFref), which relate to fishing under conditions of perfect knowledge. At this stage, no additional custom management procedures (complementary to the existing ones in DLMtool) were developed to be tested by this preliminary MSE.

A check for MSE convergence was performed, based on if the relative position of the tested management procedures was stable with respect to the following performance metrics (Figure 4.3.1):

- AAVY: Average Annual Variability in Yield.
- LTY: Average Long-Term Yield relative to Reference Yield (yield at FMSY).
- P10: Probability Spawning Biomass above 10% BMSY.
- P100: Probability Spawning Biomass > BMSY.
- P50: Probability Spawning Biomass above 50% BMSY.
- POF: Probability F < FMSY.
- STY: Average Short-Term Yield relative to Reference Yield (yield at FMSY).
- Yield: Yield relative to Reference Yield (yield at FMSY).

The number of simulations (300) was sufficient and it is assumed that the MSE model has converged (**Figure 1**).

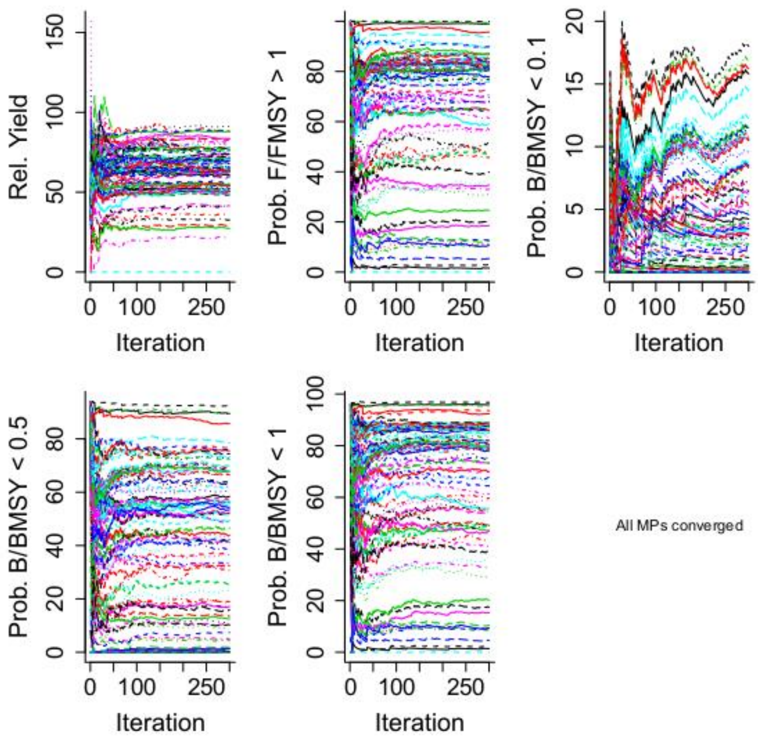

Figure 1. Convergence diagnostic plot (continuous change in relative position of a particular management procedure is an indication that more iterations are required for the model to converge. All tested management procedures converged).

After checking for MSE convergence, acceptable management procedures (from all that were tested) were identified on the basis of compliance with previously agreed minimum performance limits and management performance targets. Management procedures that fulfill both the minimum performance limits and the management targets are considered to be acceptable options for managing the fishery concerned. As a first step, the minimum performance limits and management performance targets considered were aimed at selecting acceptable methods with a low likelihood of the stock being depleted to low levels and a high probability that the stock biomass is maintained close to the management target.

The defined minimum performance limits and management performance targets were:

1. Minimum performance limits used to eliminate management procedures considered too risky for management:

80% probability biomass in years 11-50 (last 40 years of projection time) and years 41-50 (last 10 years of projection time) of the projected years (50) above 0.2 B0. The underlying reason for using both time periods was to warrant that management procedures had a high probability of not falling below the biomass limit for the entire period of the projection, while accounting for simulations where biomass may start below the limit and need a reasonable time to rebuild. The second argument for assessing biomass levels over the last 10 years of the fifty-year projection was to avoid an instance where the biomass is well above the minimum limit for most the projection period, but declining and eventually crashing during the end of the projection period.

2. Removing management procedures that are unlikely to accomplish the management targets for the stock:

50% probability that the biomass in the last 10 years of the projection period (years 41-50) is above 0.25 B0 (assumed target level).

The acceptable management procedures were then inspected in relation to current conditions, trends in B/BMSY and F/FMSY and analysis of trade-offs of several performance metrics (e.g. yield vs probability of overfishing and/or being overfished). The value of information was analyzed through the sensitivity of the performance of the MPs with respect to the assumed parameters in the OM and the observation error model (OEM). This analysis was performed for the four management procedures with the greatest sensitivity.

3. Results

Fourteen management procedures overtook the performance limit of at least 80% probability that biomass is above 0.20 B0 in the last 40 years of the projection (**Figure 2**). Twelve management procedures met the requisites for the performance metric of at least an 80% probability that biomass is above 0.20 B0 in the last 10 years of the projection period (**Figure 3**).

All management procedures that passed the performance limit of at least 80% probability that biomass is above 0.20B0 in the last 40 years of the projection also passed the limit of at least an 80% probability that biomass is above 0.20 B0 in the last 10 years of the projection period.

Two management procedures, DAAC and AvC , met the requirements for the first performance limit (at least 80% probability that biomass is above 0.20B0 in last 40 years), but did not pass the second performance limit (at least an 80% probability that biomass is above 0.20B0 in last 10 years of the projection period).

Nine management procedures passed the requirements for the management objective of at least 50% probability that biomass is above 0.25B0 in the last 10 years of the fifty-year projection period (**Figure 4**). Three of the management procedures that passed both performance limits did not passed the requirements for the management target.

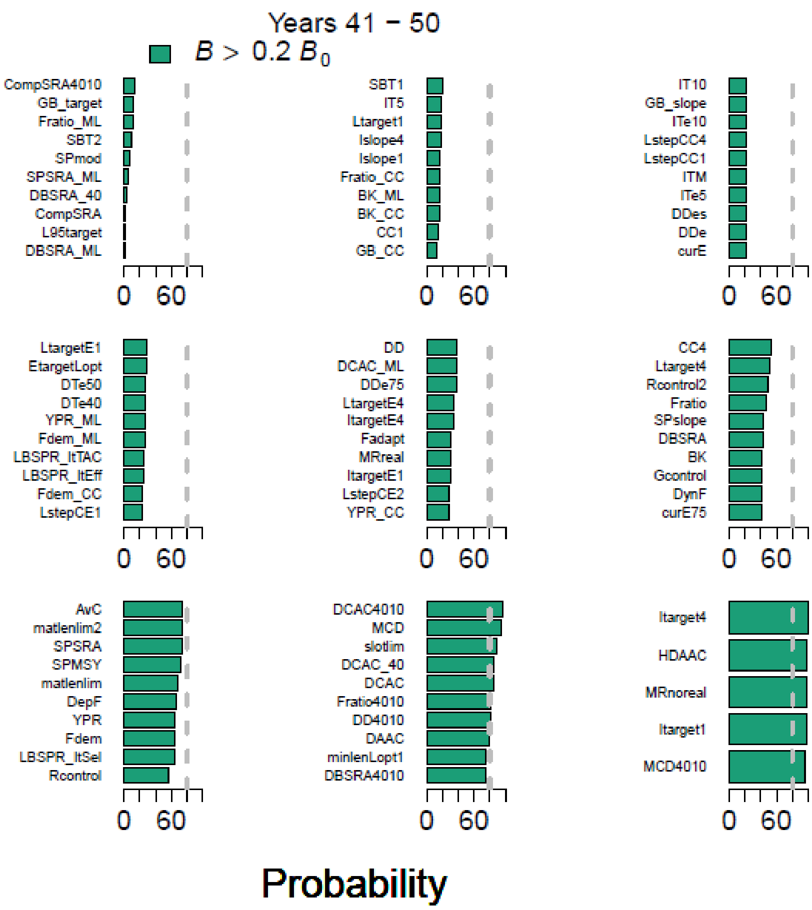

Figure 2. Probability of each management procedure meeting the performance limit of at least 80% probability that biomass is above 0.20B0 in the last 40 years of projection.

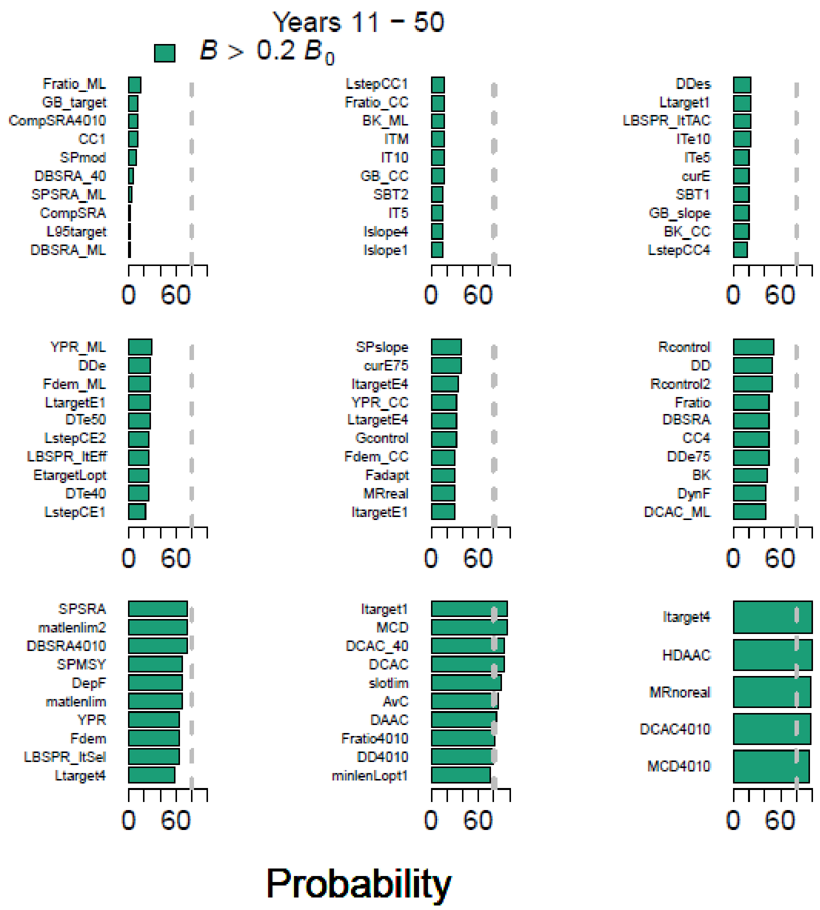

Figure 3. Probability of each management procedure meeting the performance metric of at least an 80% probability that biomass is above 0.20B0 in last 10 years of the projection period.

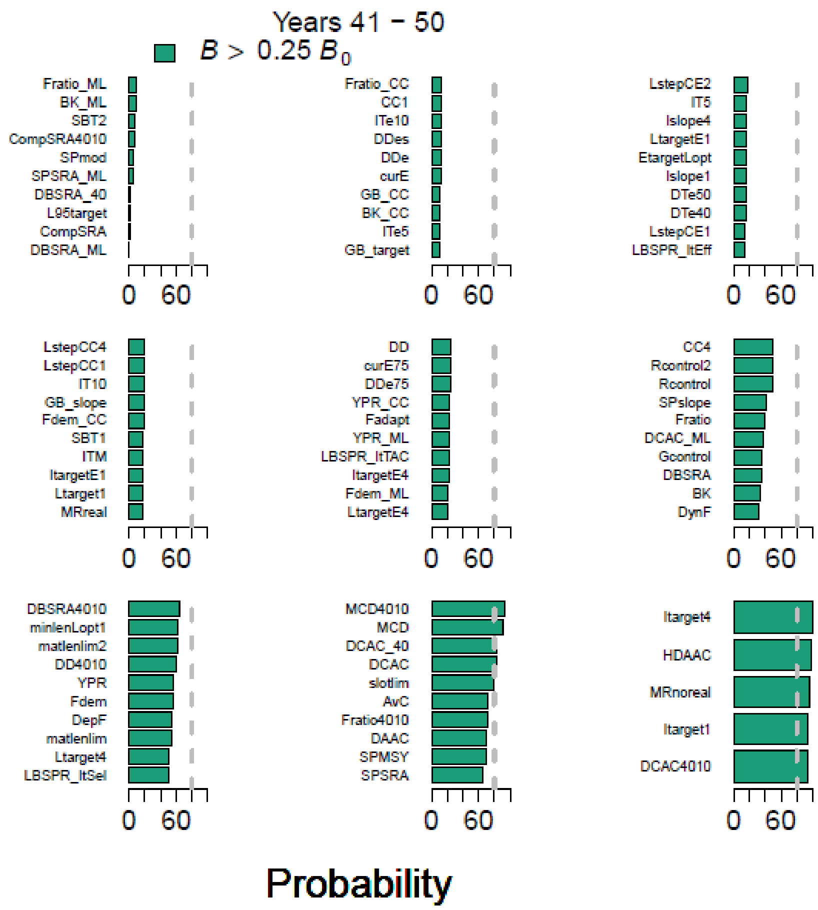

Figure 4. Probability of each management procedure meeting the management objective of at least 50% probability that biomass is above 0.25B0 in the last 10 years of the fifty-year projection period.

From the tested MPs, 9 were considered potentially acceptable management procedures for the Indian Ocean blue shark, specifically:

• DCAC: Depletion-Corrected Average Catch. An MSY proxy that accounts for catches occurring whilst dropping to productive stock sizes. *Output Control Method*.

• DCAC_40: DCAC assuming depletion is 40%. DCAC where stock depletion is fixed at 40%. *Output Control Method*.

• DCAC4010: Delay-Difference assessment linked to a 40-10 rule . A 40-10 harvest control rule is added to the Delay-Difference management procedure. *Output Control Method*.

• MCD: Mean Catch Depletion management procedure. Management procedure to demonstrate high information content of depletion TAC = mean catches*2*depletion. *Output Control Method*.

• MCD4010: MCD linked to a 40-10 rule. A 40-10 harvest control rule is added to the MCD management procedure. *Output Control Method*.

• HDAAC: Hybrid Depletion Adjusted Average Catch. Essentially DCAC multiplied by 2*depletion and divided by BMSY/B0 (Bpeak) when below BMSY, and DCAC above BMSY. *Output Control Method*.

• Itarget1: CPUE target management procedure. TAC is adjusted to achieve a target CPUE. *Output Control Method*.

• Itarget4. CPUE target management procedure (more biologically precautionary). TAC is adjusted to achieve a target CPUE. *Output Control Method*.

• MRnoreal. Area 1 Marine Reserve with no reallocation. Sets a marine reserve in Area 1 with no reallocation of fishing effort to area 2. *Input control methods-Spatial*.

These MPs include eight output control methods (methods that return a TAC) and one input control method (MRnoreal, a spatial control that prevents fishing in area 1 and does not reallocate this fishing effort to area 2).

A comparison of the median biomass and median yield over the last 5 years of the projection relative to the last year in the historical period is showed in **Figure 5**. All the acceptable management procedures imply a reduction in yield in the long term (five last years of the projection) with respect to current yield (last year of the historical period). Yield decrease in the range of 0.31 to 0.57. There is an obvious trade-off with respect to the expected long-term yield relative to current yield and the expected long-term biomass relative to current biomass.

Itarget1 and MRnoreal are the management procedures that represent a smaller loss in yield. HDAAC shows the higher value in expected long-term biomass at the expense of decreased long-term yield. A lower reduction in long term yield comes at the expense of being less precautionary (lower expected long-term biomass).

The other acceptable management procedures have similar performance in terms of expected long term yield relative to current yield and expected long-term biomass relative to current biomass.

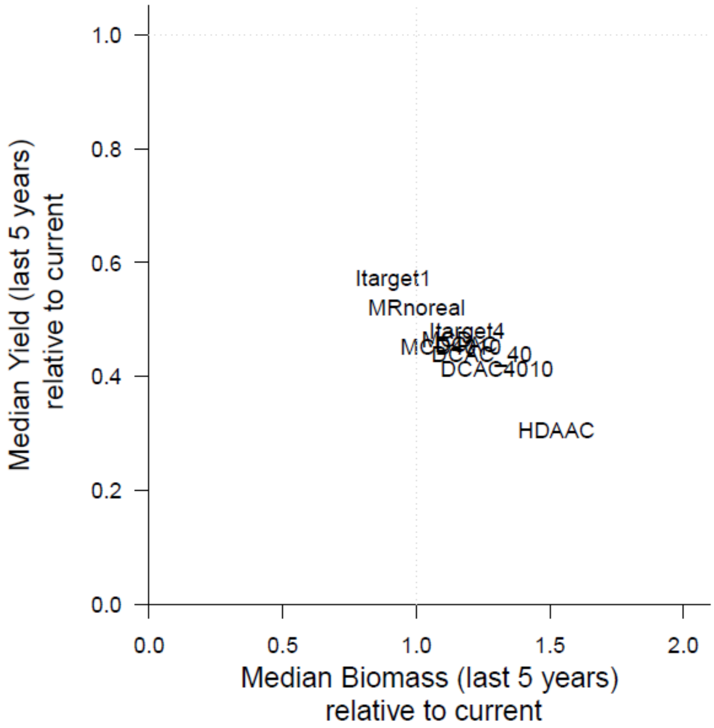

Figure 5. Median biomass and median yield over the last five years of the projection relative to the last year in the historical period.

Trends in biomass relative to biomass at maximum sustainable (B/BMSY), and fishing mortality relative to the rate corresponding to maximum sustainable yield (F/FMSY) for each simulation, management procedure and projection year are presented in **Figure 6**. In general, the relative biomass for the stock increases through the projection period for all the acceptable management procedures, with the median relative biomass increasing from the first year to the final year of the projection. Nevertheless, the distributions show quite notable variability, suggesting that although the methods work well on average, the final biomass was very low in some simulations.

The distribution of fishing effort for each management procedure in the final year of the projection period is shown in **Figure 7**; trends appear to be fairly flat for the projected years, and less variable than the biomass trends.

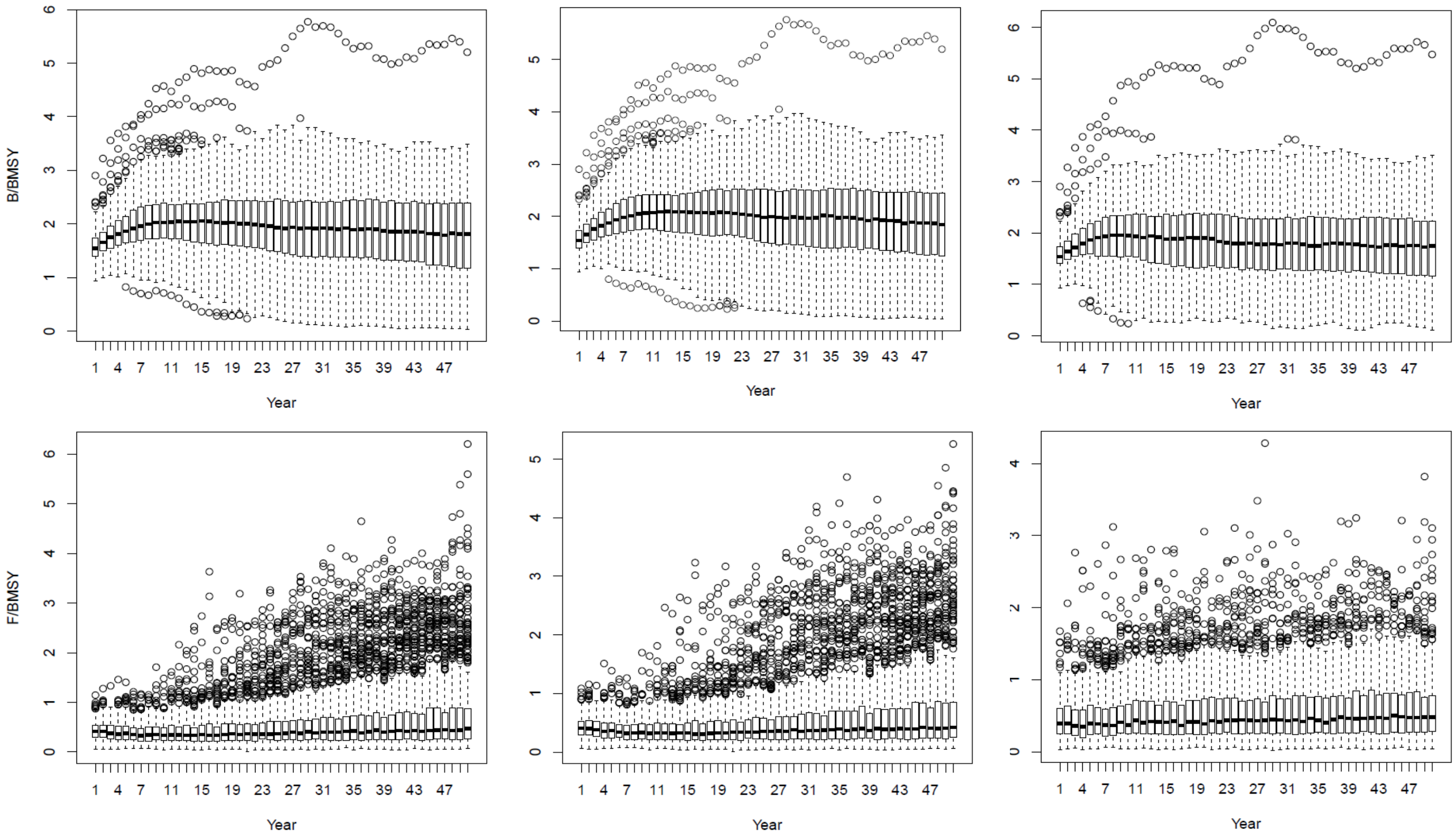

Figure 6. Distribution of B/BMSY (top) and F/FMSY (bottom) for the projection years for DCAC (left panels); DCAC_40 (middle panels) and MCD (right panels).

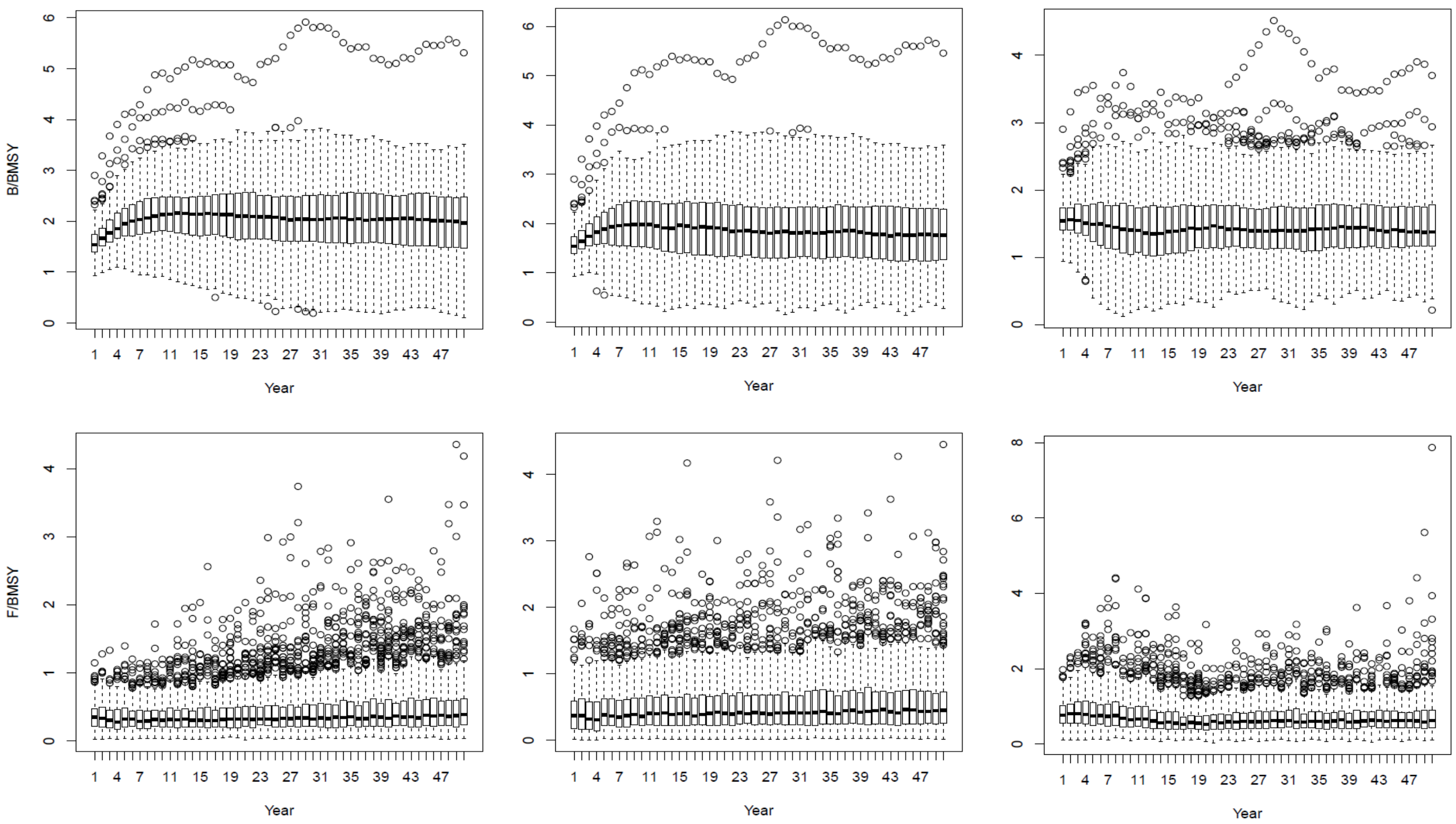

Figure 6 (*continued*). Distribution of B/BMSY (top) and F/FMSY (bottom) for the projection years for DCAC4010 (left panels); MCD4010 (middle panels) and Itarget1 (right panels).

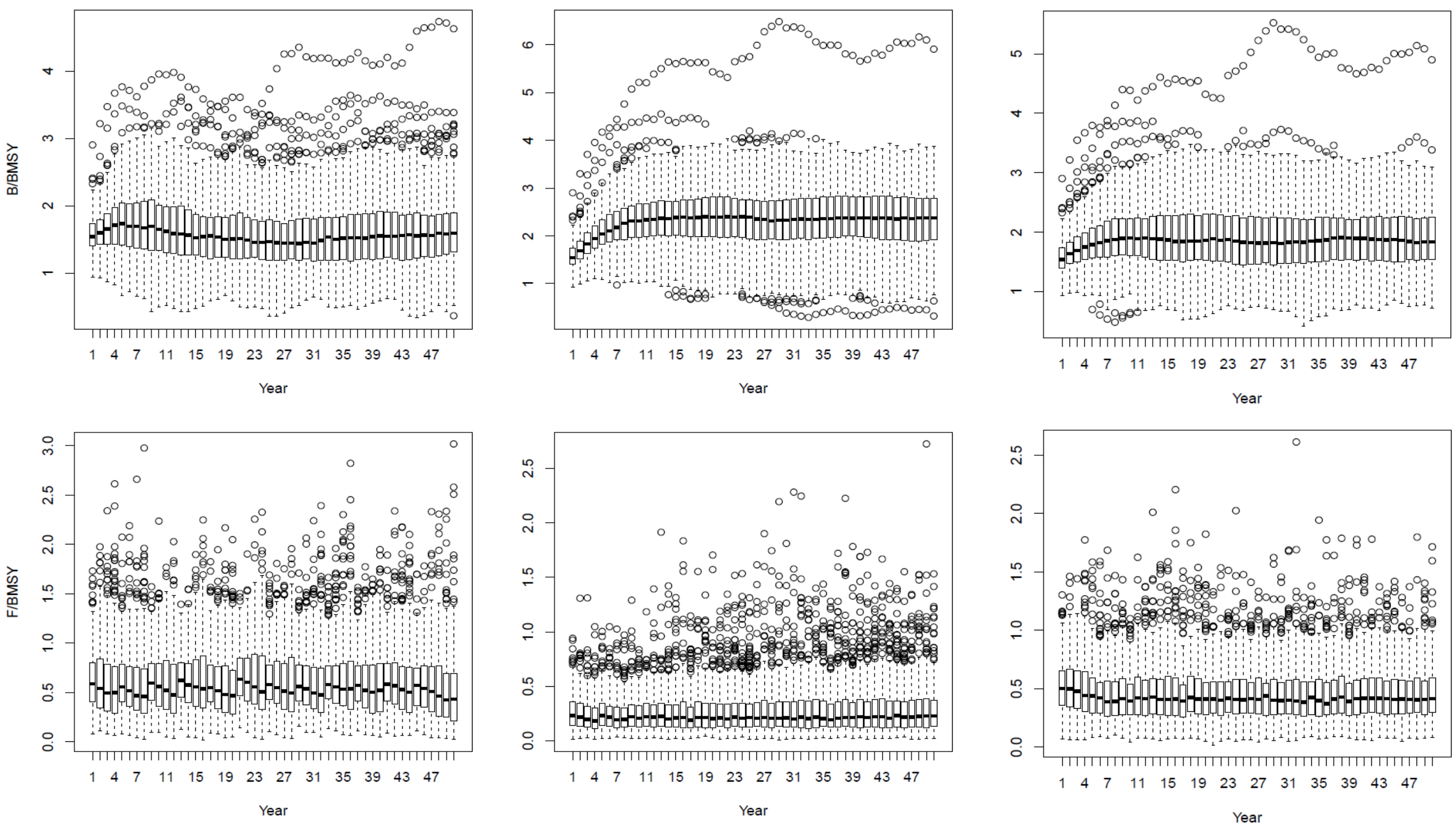

Figure 6 (*continued*). Distribution of B/BMSY (top) and F/FMSY (bottom) for the projection years for MRnoreal (left panels); HDAAC (middle panels) and Itarget4 (right panels).

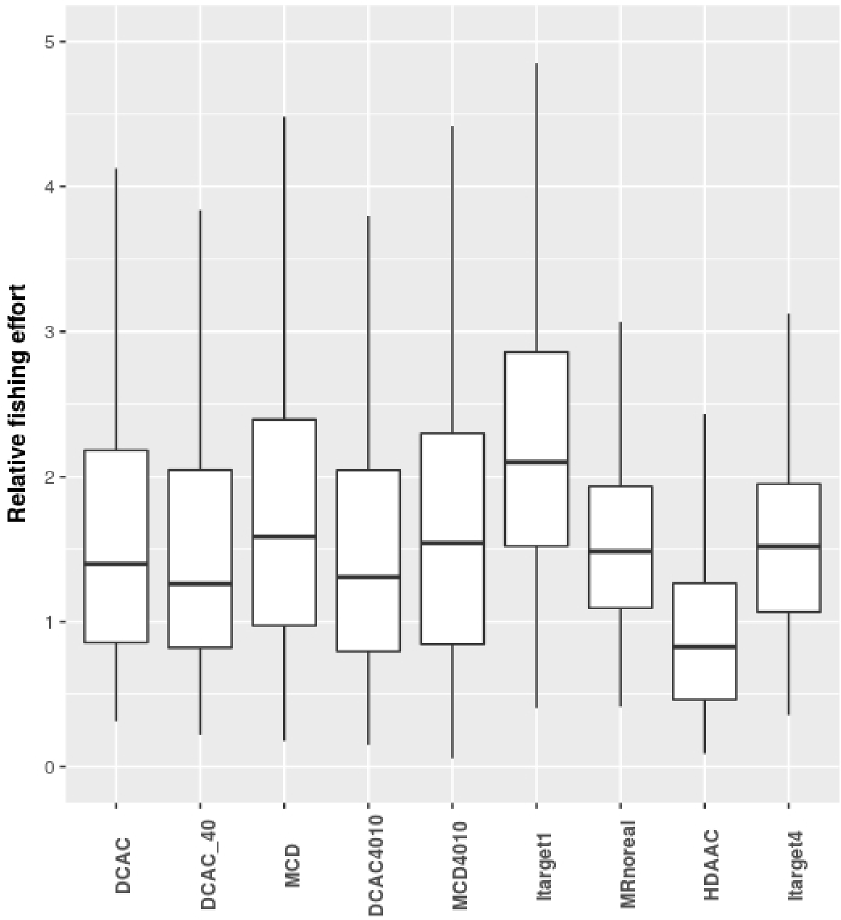

Figure 7. Relative fishing effort in the final year of the projection by management procedure

Trade-off between the expected relative yield and the probability of overfishing (F>FMSY), and the probability of the biomass being below three different reference points (B<BMSY, B<0.5BMSY, B<0.1BMSY) is presented in **Figure 8**. The Itarget1 management procedure results in the highest long-term yield with remarkably low probability of overfishing and biomass being below the different reference points (B<BMSY, B<0.5BMSY, B<0.1BMSY). The HDAAC management procedure shows the lowest probabilities that the biomass will fall below the different reference points.

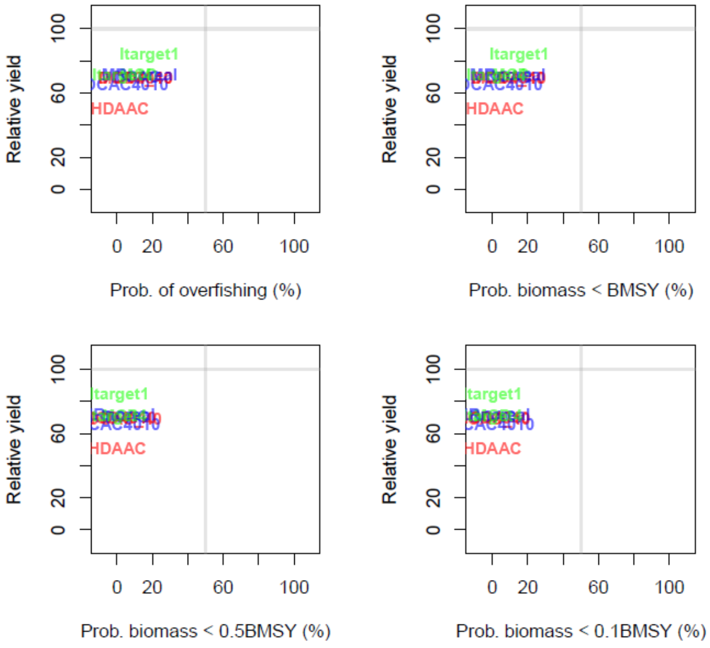

Figure 8. Trade-off between the expected relative yield and the probability of overfishing (F>FMSY) and the probability of the biomass being below three different reference points: B<BMSY, B<0.5BMSY, B<0.1BMSY.

Comparison of long-term yield (LTY: fraction of simulations getting over half FMSY yield in the last ten years of the projection) vs short-term yield (STY: fraction of simulations getting over half FMSY yield in the first ten years of the projection) and variability in yield (VY: fraction of simulations where average annual variability in yield is less than 10 percent) vs biomass level (B10: the fraction of simulations in which biomass stays above 10 percent of BMSY) is shown in **Figure 9**.

Only one MP (HDAAC) presents a probability lower than 50% of short term and long term yield getting over half FMSY yield. The remaining MPs have similar probabilities, except for Itarge1 which presents more than 80% probability of short term and long term yield getting over half FMSY yield. All MPs have a very high probability (close to 100%) of the biomass being above 0.1BMSY but a very low probability (close to zero) that the VY in yield is less than 10%.

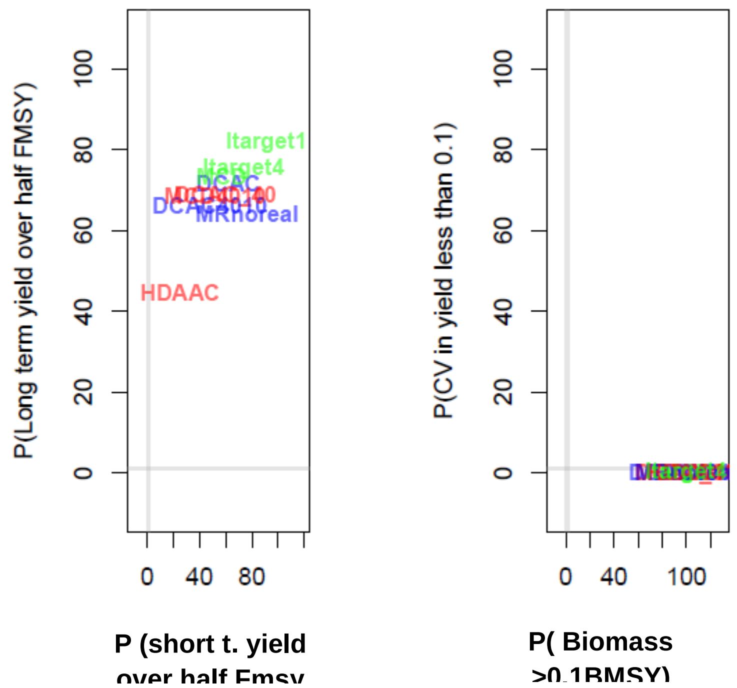

Figure 9. Trade-off between long-term and short-term yield, and the trade-off between biomass being above 0.1 BMSY and the expected variability in the yield.

The distribution of various statistics (performance metrics) can be examined for the acceptable (or all tested) management procedures using boxplots. In **Figure 10** the distributions of the performance metrics B/B0, B/BMSY, F/FMSY, average annual variation in yield (AAVY), average annual variation in effort (AAVE), and relative long-term yield in the last 10 years of the projection.

Regarding these performance metrics, all MPs have a high probability of biomass in the last 10 years of projection being above 0.2B0. Only DCAC and DCAC10 present less than 90 percent probability that the biomass is above 0.2B0. From the acceptable MPs, three have more than 90 percent probability of the biomass in the last 10 years of projection being above BMSY, the remaining MPs have a probability of being above BMSY between 81 and 89 percent.

All acceptable MPs present a similar probability of AAVY being less than 30% in the last 10 years of the projected time, varying between 49 and 58 percent for the different MPs. Similarly, for the AAVE MPs presented similar probabilities of being below 30% variation in the last 10 years. Regarding the relative long-term yield most MPs presented similar relative long term yield, except HDAAC which had lower relative long-term yield and Itarget1 which presented a slightly higher relative long-term yield.

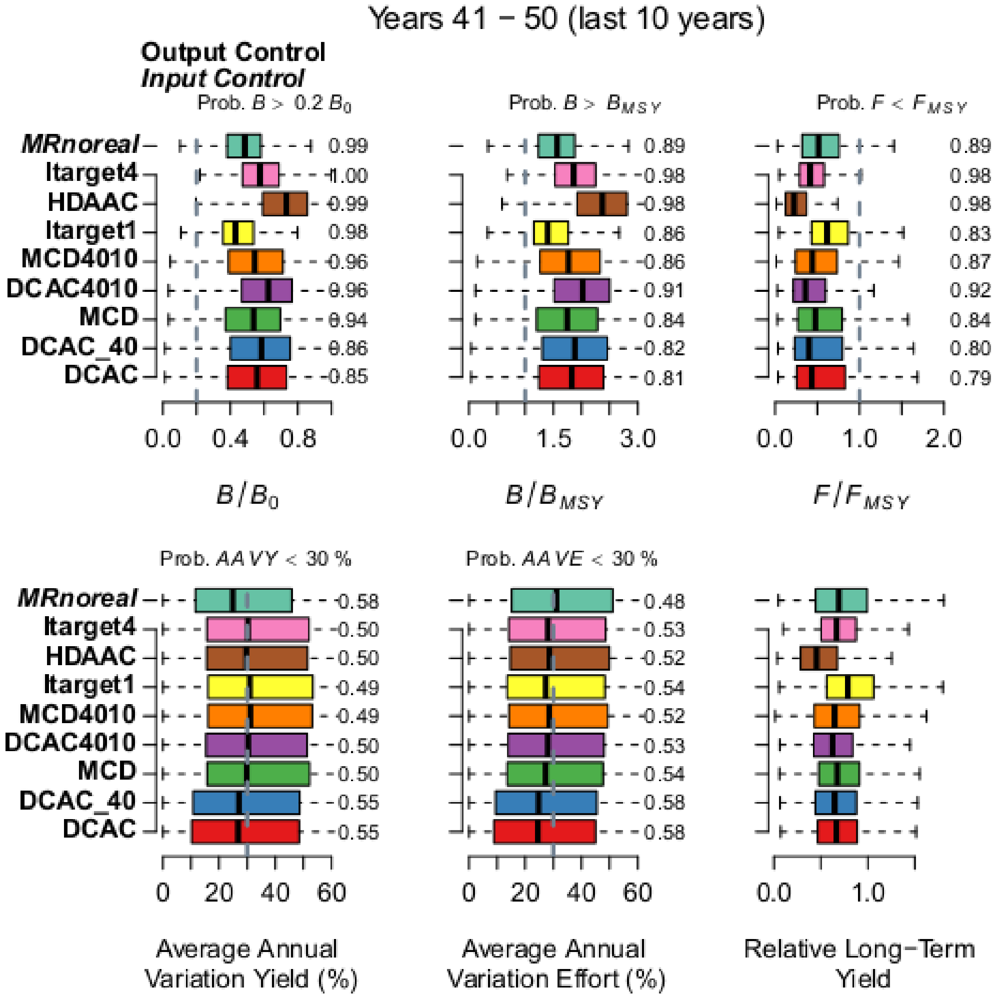

Figure 10. Performance metrics B/B0, B/BMSY, F/FMSY, average annual variation in yield (AAVY), average annual variation in effort (AAVE), and relative long-term yield in the last 10 years of the projection for the acceptable management procedures.

The proportion (%) of simulations ending up in each of the four quadrants - F>FMSY & B<BMSY; F<FMSY & B<BMSY; F<FMSY & B>BMSY; F>FMSY & B>BMSY - of the Kobe phase plot by acceptable management procedure is presented in **Figures 11**.

Of the acceptable MPs, MRnoreal has the lowest probability of the stock being in the F<FMSY & B>BMSY quadrant of the Kobe phase plot. HDAAC and Itarget4 had the highest probability (97%) of the simulations ending up in the F<FMSY & B>BMSY quadrant of the Kobe phase plot. Except for DCAC and DCAC_40, which had a probability of being in the F<FMSY & B>BMSY quadrant of the Kobe phase plot of around 80 percent, but had the highest probabilities of the simulations ending up in the F>FMSY & B<BMSY quadrant of the Kobe phase plot, all remaining MPs had relatively

high probability of being in the F<FMSY & B>BMSY quadrant and relatively low probability of being in the F>FMSY & B<BMSY quadrant of the Kobe phase plot.

Trade-off plot showing the probability of exceeding a biomass reference level (biomass over 75% of BMSY) and a yield reference level (yield over 75% FMSY) is shown in **Figure 12**. All MPs have a probability above 90 percent of the biomass being over 75% of BMSY. Regarding yield, HDAAC had the lowest probability of yield being over 75% FMSY, and Itarget1 the highest, while the remaining MPs had similar probabilities of yield being over 75% FMSY (around 34 to 40 percent).

Trade-offs between the probability of not overfishing and long-term yield, and the probability of not being in an overfished state versus the probability of the annual variation in yield being less than 15% is presented in **Figure 13**.

Regarding the trade-off between the probability of not overfishing and long-term yield, HDAAC had a higher probability of not overfishing, but a lower long term yield compared with other MPs, while Itarget1 presents the reverse situation, with higher long-term yield but lower probability of not overfishing.

In relation to the probability of not being in an overfished state versus the probability of the annual variation in yield being less than 15%, all MPs have a very high probability of not being in an overfished state but all present an extremely low probability of the annual variation in yield being less than 15%.

Sensitivity of relative long-term yield and biomass with respect to the observation model parameters are presented in **Figure 14**. Relative long term-yield is mostly sensitive to bias in observed catches (Cbias) and bias in observed stock depletion (Dbias), especially for MP MCD, which shows that bias in depletion will have an effect on the relative long term-yield. Likewise, final biomass for MPs DCAC, DCAC_40 and DCAC4010 are highly sensitive to Cbias while MCD is mostly sensitive to Dbias.

Sensitivity of relative long-term yield and biomass with respect to the operating model parameters is shown in **Figure 15**. For both relative long-term yield and biomass all Mps are mostly sensitive to the mean fraction of TAC taken (FracTAC).

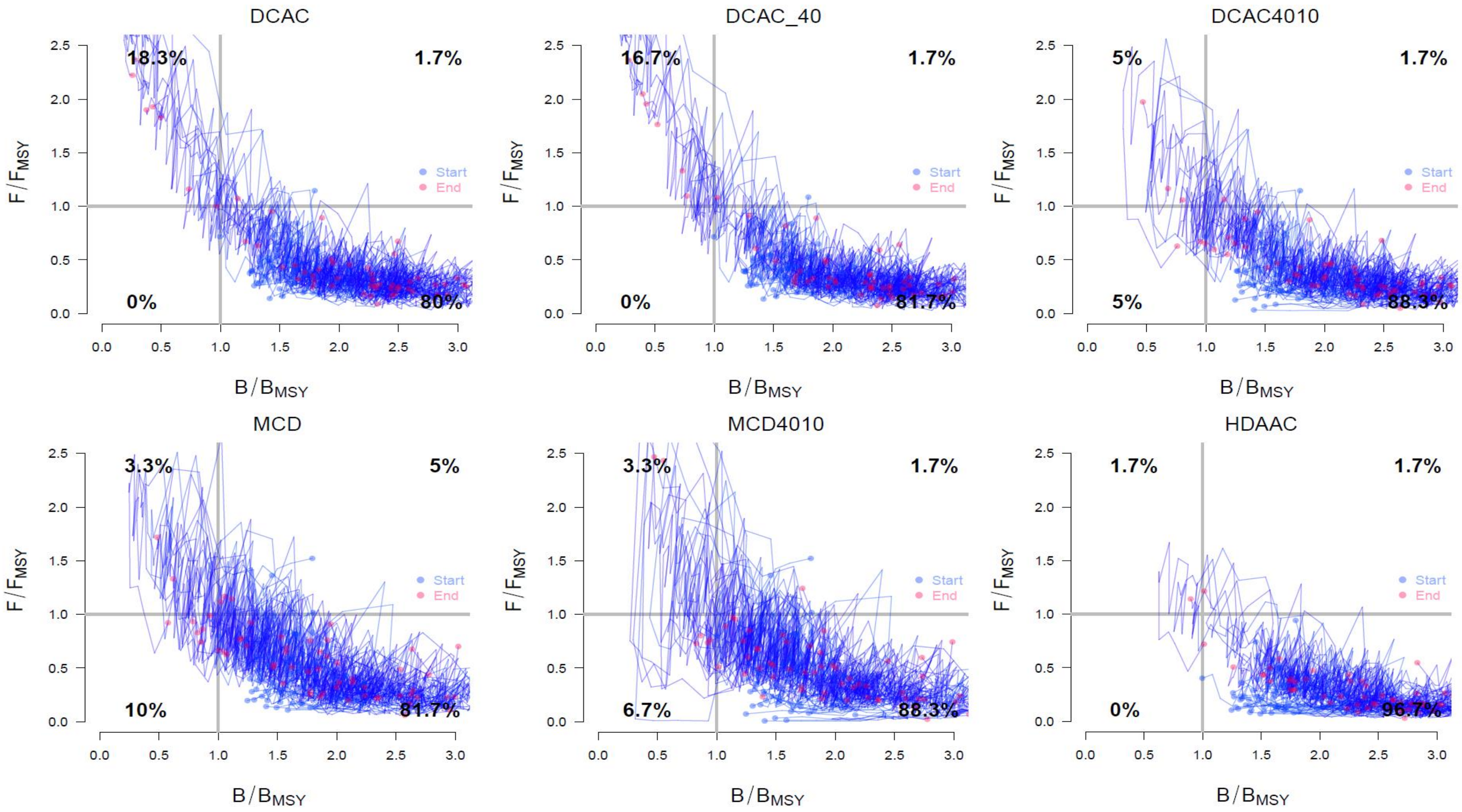

Figure 11. Proportion (%) of simulations ending up in each of the four quadrants of the Kobe phase plot for each acceptable management procedure.

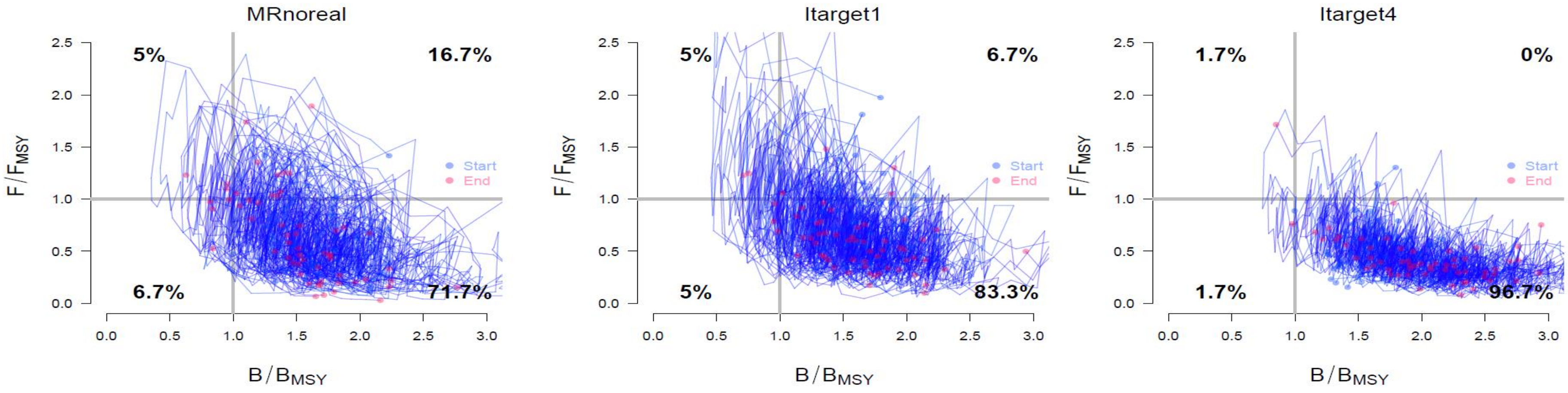

Figure 11 (*continued*). Proportion (%) of simulations ending up in each of the four quadrants of the Kobe phase plot for each acceptable management procedure.

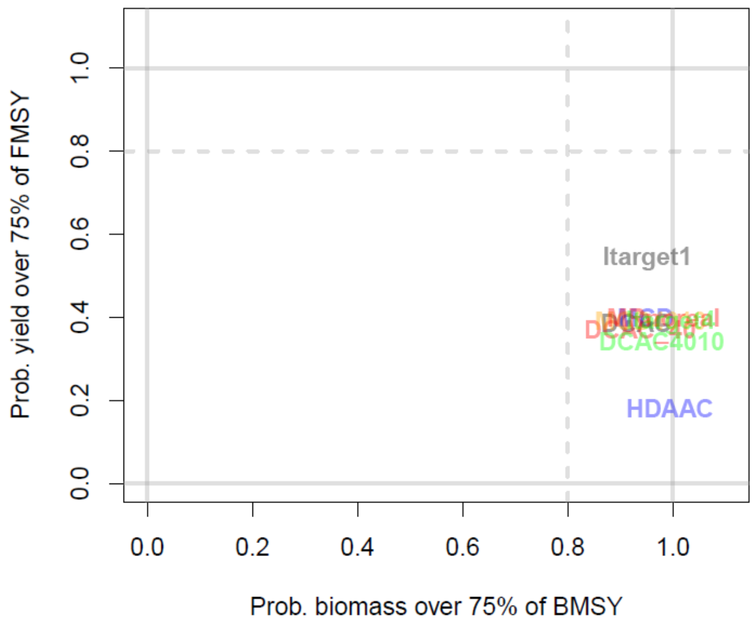

Figure 12. IOTC trade-off plot: probability of biomass being above 75% of BMSY versus probability of yield being above 75% of FMSY.

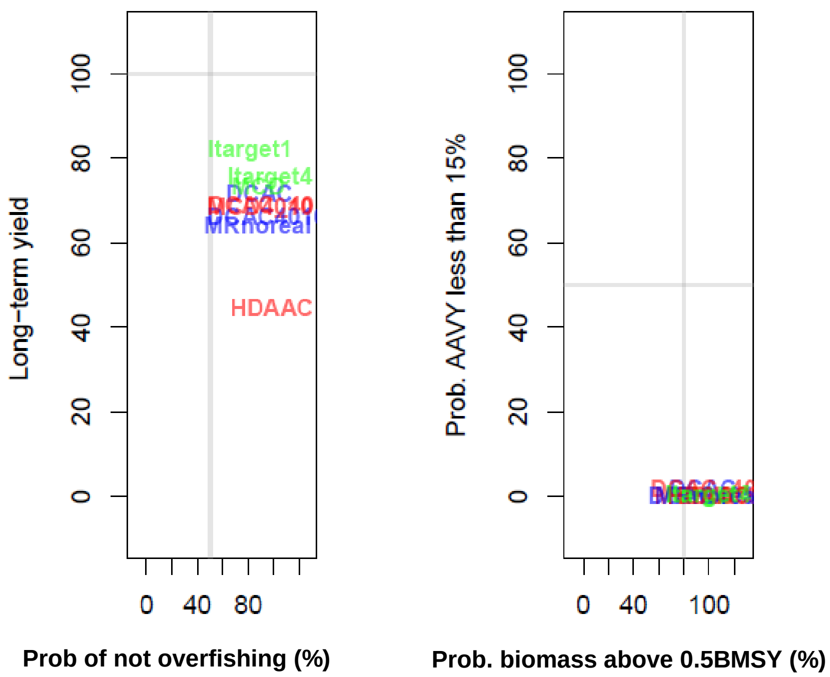

Figure 13. NOAA trade-off plot: probability of not overfishing and long-term yield (left), and the probability of not being in an overfished state versus the probability of the annual variation in yield being less than 15% (right).

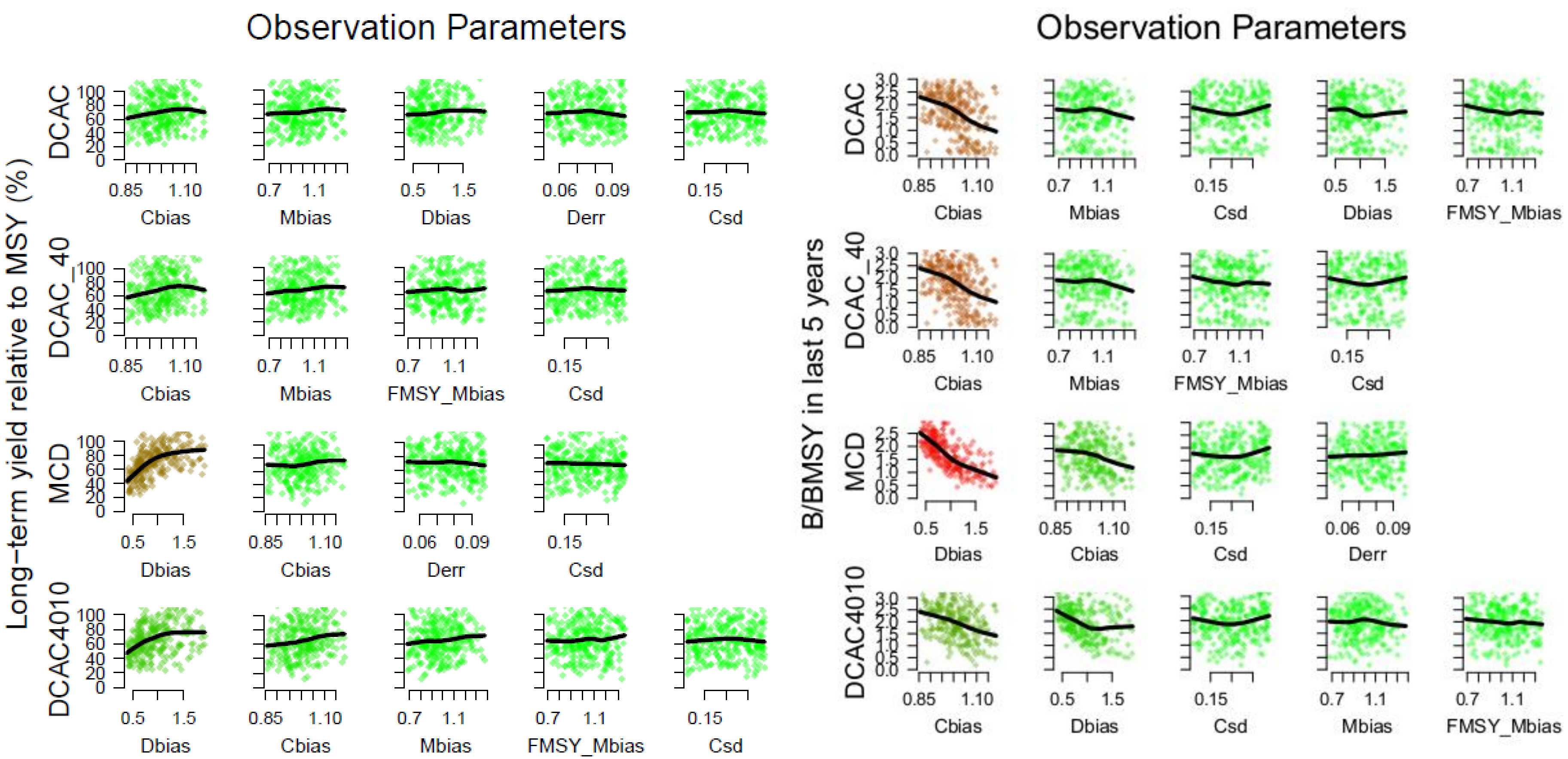

Figure 14. Relative long-term yield changes with respect to the observation error model (OEM) parameters (left panel) and final biomass (B/BMSY) with respect to the OEM parameters (right panel).

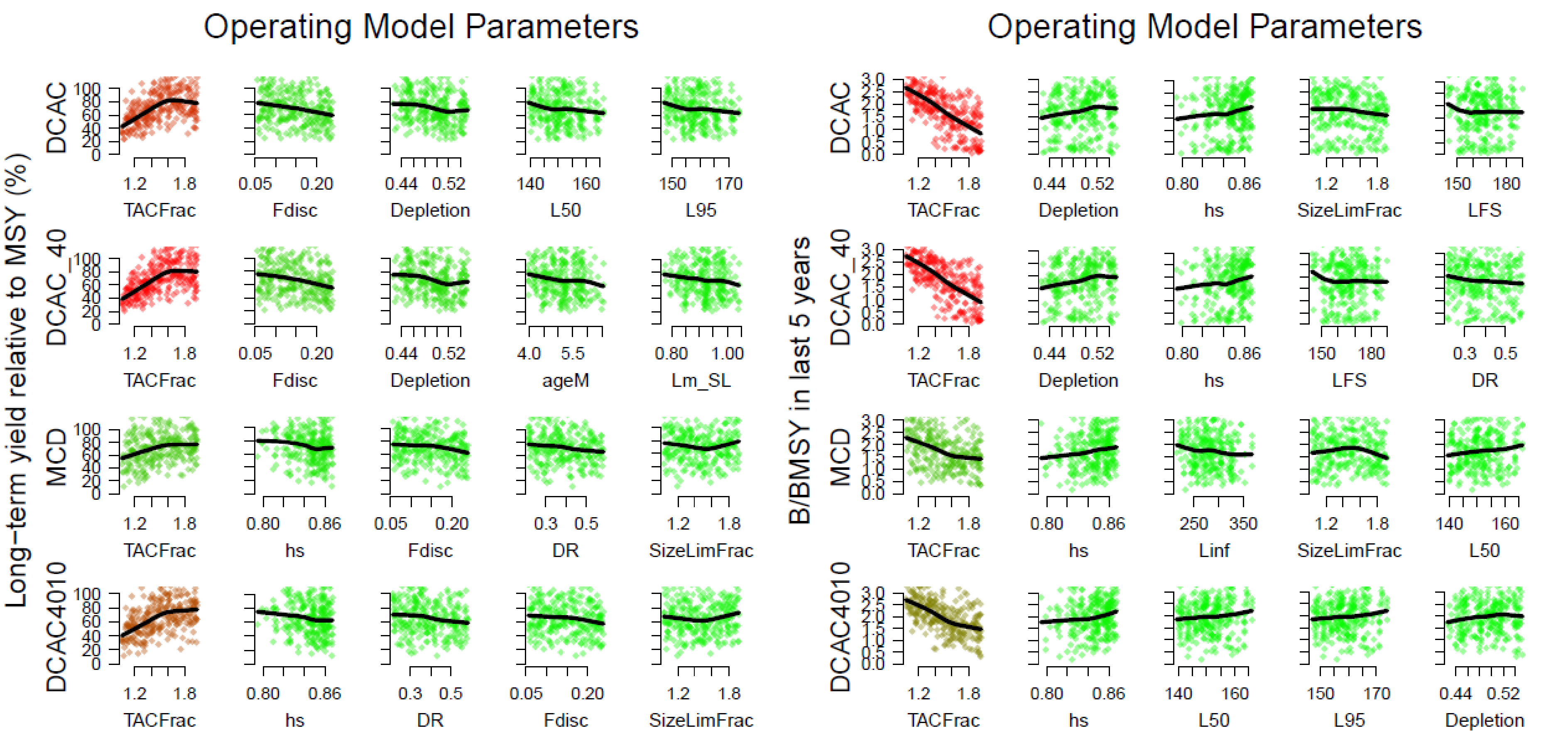

Figure 15. Relative long-term yield changes with respect to the operating model (OM) parameters (left panel) and final biomass (B/BMSY) with respect to the OM parameters (right panel).

4. Discussion

Management Strategy Evaluation (MSE) allows uncertainty and error to be explicitly incorporated and to identify and select which Management Procedures (MP) among a set of candidate strategies are more robust to uncertainty (Punt et al., 2016). Furthermore, it enables fisheries scientists to advise managers on the trade-offs involved for each MP (Bunnfeld et al., 2011). Managers can then balance trade-offs and decide which MP is more suited for each management objective (Punt et al., 2016; Bunnfeld et al., 2011). MSE should allow the involvement of stakeholders, managers and fishery scientists since its inception. For the implementation of a MSE framework it is essential that management objectives and the associated performance metrics, as well as, decision on the minimum performance limits and targets, be decided in an integrated manner between all involved parties.

Since no reference points have yet been adopted for sharks in IOTC, for this preliminary work on Indian Ocean blue shark MSE we have tentatively used a 80% probability of biomass in years 11-50 and years 41-50 of the projected years (50) above 0.2B0 and a 50% probability that the biomass in the last ten years of the projection period (years 41-50) is above 0.25B0, but there are many options for performance metrics (e.g., probability of staying above 50% of SSBMSY, spawning stock biomass at maximum sustainable yield, probability of achieving greater than 50% MSY yield). Management procedures that fulfilled both the minimum performance limits and the management targets were considered to be acceptable options for managing this fishery. The application of the limits and target detailed above led to nine out of 89 MPs being considered acceptable.

Regarding the performance of the acceptable MPs, overall, there was a high probability of the final biomass being above BMSY. Trade-offs between MPs were evident for biomass *vs* relative long-term yield, e.g. HDAAC being more conservative with a higher probability of the final biomass being above MSY at the expense of a lower relative long-term yield, while Itarget1 has a higher relative long-term yield but a lower probability of the biomass being above MSY. For this preliminary work we have focused mainly in trade-offs between biomass and yield, but according to the management objectives agreed for the fishery, other performance metrics can be applied (e.g., time to rebuild the stock).

Regarding the sensitivity analysis, this analysis does not identify specific data to be collected or improved but simply highlights where operating model uncertainty may lead to selection of MPs that are not performing as well as other MPs due to the risks associated with parameter uncertainty (Carruthers & Kell, 2017). For example, biomass and final yield were mostly sensitive to TacFrac, in this case, because no information on this was available and a high degree of variability in adherence to the TAC among years was set in the OM. Improved estimates of the adherence to the TAC would help improve the performance of the MPs.

The operating model standard 'OMx' used by DLMtool is also compatible with a data-rich sister package MSEtool (Carruthers et al., 2018c) that is currently being released. MSEtool has over 20 data-rich assessment MPs (e.g. statistical catch at age models) coded in Template Model Builder that can be easily combined with a range of harvest control rules (e.g. a 40-10 rule). MSEtool also includes additional functions for specifying complex spatial operating models and detecting 'exceptional circumstances' for detecting when MPs are not performing as expected. It follows that the current preliminary MSE presented here may be extended to consider the cost-benefit of moving to more data-rich management procedures that rely on alternative assumptions and require additional data.

4. Acknowledgments

The research conducted for this paper was funded by the EU Commission through the Specific Contract "*EASME/EMFF/2015/1.3.2.3/SC01-Improving scientific advice for the conservation and management of oceanic sharks and rays*" under the Framework Contract EASME/EMFF/2016/008 "*Provision of Scientific Advice for Fisheries Beyond EU Waters*".

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