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Demonstration Management Strategy Evaluation for Chub Mackerel Using Open-Source Tools

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Summary

The purpose of this paper was to provide a complete technical MSE exercise to demonstrate MSE accessibility in the light of new open-source software. A single structural form of MP was developed that sets TACs to a fixed multiple of observed relative abundance indices. Twelve derivatives of this MP were tested that included varying index multipliers and numbers of years for smoothing the observed index. These MPs were tested over a two-dimensional grid of operating models including three scenarios for natural mortality rate and two for index hyperstability. These operating models were conditioned using existing VPA assessment tools for chub mackerel. When tested by MSE closed-loop simulation, the performance of the MPs spanned a wide trade-off between biomass and yield outcomes. In general performance was encouraging but a wider range of operating models that include future recruitment scenarios would provide a substantially tougher test of such MPs. Priorities for development of an MSE framework include the specification of management performance metrics and the identification of core uncertainties in system dynamics for the conditioning of operating models.

Introduction

Management Strategy Evaluation

Management Strategy Evaluation (MSE) is increasingly adopted in fisheries to identify management procedures (MPs, a.k.a. harvest strategies: algorithms that calculate management recommendations from data) that are robust to uncertainty in system dynamics and observation processes (Butterworth and Punt 1999; Cochrane et al. 1998). MSE relies on operating models that simulate the fishery system including fishing dynamics, population dynamics, observation processes and the implementation of management recommendations. MPs are simulation tested in 'closed-loop' where by the fishery system is projected and the MP iteratively applied in future years accounting for feedback between the MP, the simulated system and the data. By using a simulated system, the expected performance of MPs can be quantified over a wide range of uncertainties.

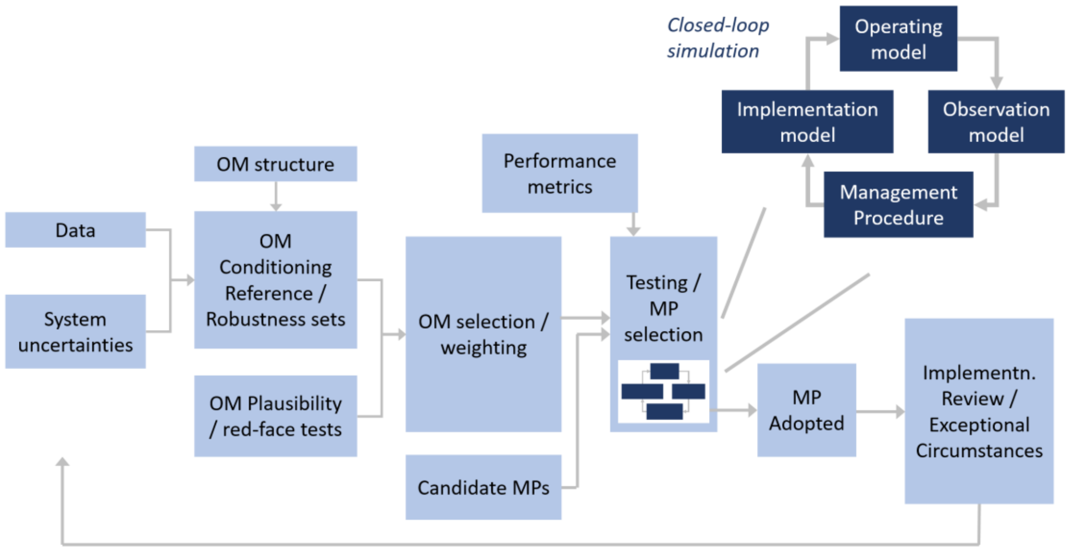

Fig. 1. Steps in a typical MSE process. Data are organized and system uncertainties summarized to specify operating models by conditioning. After evaluating the plausibility of the conditioned operating models these are selected or weighted and used to comparatively test candidate MPs against established management performance metrics. After an MP is adopted and in use, its ongoing performance can be evaluated empirically by comparing the data observed with those expected from the MSE (Implementation Review).

The MSE approach allows managers to quantify performance trade-offs, identify robust MPs that can achieve desirable management outcomes and establish the value of various data-collection programs. By adopting an MP, stakeholders agree to a shared set of rules for future management, alleviating uncertainties in the interpretation of stock assessment advice in terms of management advice.

Appropriateness of MSE for Chub Mackerel

Chub Mackerel is a relatively short-lived species that has undergone large historical changes in stock size (recruitment strength). A number of management procedures can provide highly responsive TAC advice that is robust to large changes in vulnerable stock size. For example, index-based MPs that set TACs at a fixed multiple of the index (or mean of indices, or temporally smoothed indices) can respond much faster to natural fluctuations in stock size than stock assessments. Such MPs are very simple, easy to apply and can have high robustness to a wide range of operating model scenarios (e.g. large changes in carrying capacity, moderate changes in sustainable fishing rate).

Open-source MSE software

MSE has many important advantages over conventional stock assessment-based management. However where they have been previously applied, MSE processes have tended to be relatively expensive, technically complex and time consuming. This demonstration makes use of two open-source R packages for MSE that were designed to alleviate this technical bottleneck: the Data Limited Methods toolkit, (DLMtool, Carruthers and Hordyk 2018a, b) and the Management Strategy Evaluation toolkit (MSEtool, Huynh et al. 2019). These are amongst the fastest, most flexible and extensible open-source software packages for conducting MSE for fisheries in the full spectrum from data-poor (e.g., prescriptive management such as size limits and time-area closures) to data-rich (e.g., statistical catch-at-age models linked with harvest control rules).

The operating model of MSEtool is highly flexible, for example allowing for complex spatial dynamics, age-based movement, multi-stock dynamics and multi-fleet control rules. As such, it can be used to investigate the robustness of candidate MPs to a wide range of uncertainties that may be relevant to the Chub Mackerel fishery. It is straightforward to convert conventional stock assessments to MSEtool operating models. In the course of this demonstration, a function VPA2OM() was coded and released in the MSEtool R package that allows the bootstrapped VPA assessments of Chub Mackerel to be easily converted into operating models (equivalents already exist for Stock Synthesis, Casal and iSCAM stock assessment models).

DLMtool and MSEtool are currently used by Canadian DFO, the California Department of Fish and Wildlife (Hordyk et al. 2017), the Marine Stewardship Council, the International Commission for the Conservation of Atlantic Tunas, and the US National Oceanic and Atmospheric Administration (NOAA) as MSE frameworks for the testing of management procedures, identifying data collection priorities and quantifying management reference points. Through these collaborations, MSEtool and DLMtool have been subject to independent review and peer review in the primary literature (Carruthers and Hordyk 2018a).

These packages were used by NOAA to establish operating models for six tropical reef fish in the Caribbean (SEDAR 2016a) and eight stocks in the Gulf of Mexico (SEDAR 2016b), the MP for lane snapper was used to set the catch limit currently implemented in that fishery. The U.S. Mid-Atlantic Fisheries Management Council also used DLMtool to identify acceptable biological catch limits (McNamee et al. 2016) and develop operating models to test MPs for black sea bass, Atlantic mackerel, and blueline tilefish (Miller 2016, Wiedenmann 2019).

MSEtool was used recently as the MSE framework for San Francisco Bay Herring (CDFW 2019, Appendix A) from which an MP has now been adopted. Additionally, the California Department of Fish and Wildlife are in the process of establishing MPs for 9 other in-shore fisheries in California. Ongoing MSEtool applications include Atlantic swordfish, West Atlantic skipjack tuna (International Commission for the Conservation of Atlantic Tunas) and B.C. yelloweye and quillback rockfishes (DFO).

Methods

All code for conducting the analyses and figures of this paper are available by request from the GitHub repository 'tcarruth/PCM-MSE'

Demonstration Operating Models

A TMB VPA stock assessment (Yukami et al. 2019) was used as the basis for specifying demonstration operating models for Chub Mackerel. The VPA is of the domestic stock assessment of Japan in fiscal year 2018. The VPA used age-specific data (catch-, weight-, and maturity-at-age) from 1970 to 2018 and four abundance indices (two for recruitment and two for spawning stock biomass).

A total of six operating models were specified that were a cross of three levels of natural mortality rate (0.4, 0.3, 0.5) and two assumptions about linearity in the relationship between indices and biomass (beta is estimated allowing for hyperstability/hyperdepletion, beta is fixed to 1 assuming indices are proportional to biomass) (Table 1). In each case a VPA stock assessment was conditioned to data and 96 bootstrapped simulations were generated.

A set of dedicated functions were programmed to extract the bootstrapped VPA estimates and then convert them to an MSEtool operating model. The latter function 'VPA2OM', is now available in the MSEtool R package.

Tab. 1. The demonstration grid of operating models. A factorial cross of three levels of natural mortality rate and two assumptions about the linearity of the relationship between indices and biomass (estimation of the beta parameter allows for indices that are hyperstable or hyperdeplete).

Operating model		**Natural mortality rate**	**Beta parameter estimated or fixed at 1 (proportional)**
#1	M4_Est	0.4	Estimated
#2	M3_Est	0.3	Estimated
#3	M5_Est	0.5	Estimated
#4	M4_Fix	0.4	Fixed
#5	M3_Fix	0.3	Fixed
#6	M5_Fix	0.5	Fixed

The VPA2OM function contains a check that the VPA stock assessment is recreated exactly in the historical reconstruction of the operating model (these are the same calculations used in MSE projections) (Figure 2).

For the purposes of this demonstration, perfect management implementation (perfect adherence to TACs) was assumed. The two spawning stock biomass indices were projected for use in MPs (Figure 3). The statistical properties of these indices (precision and lag-1 autocorrelation) was generated according to the historical fit of these data to SSB.

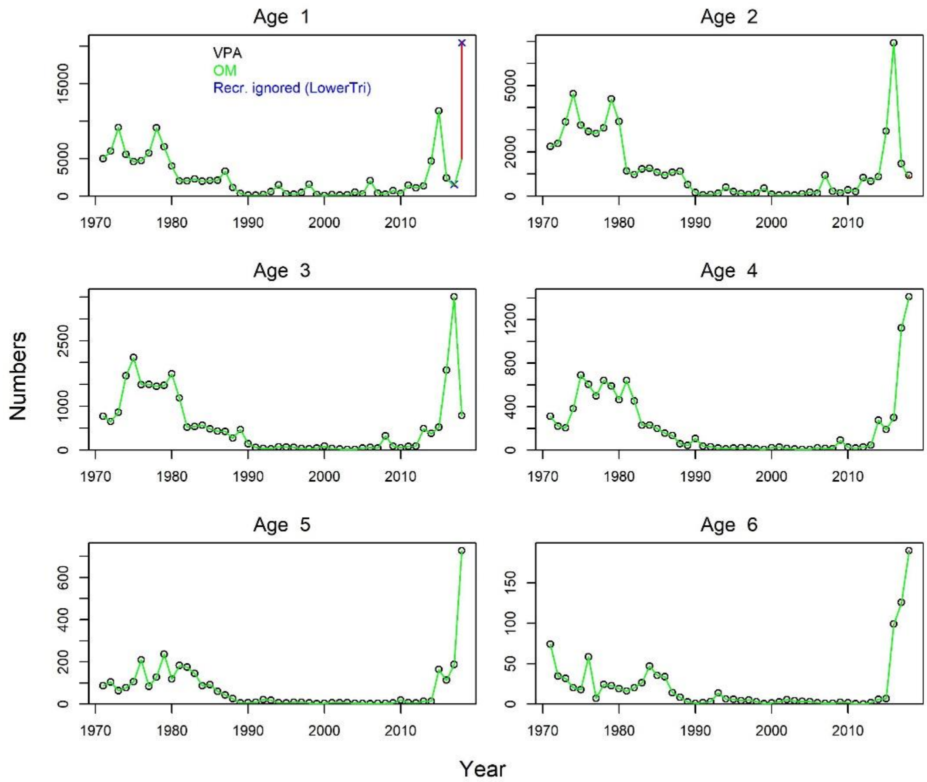

Fig. 2. Confirmation that historical VPA estimates of numbers at age (black points) are exactly recreated in the MSEtool operating model (green line). Blue crosses indicate those recruitments (age 1 numbers) that were considered not reliably estimated and were ignored (the recent lower-triangle of numbers). Vertical lines show discrepancies between VPA estimates and the MSEtool reconstructed numbers, here showing an essentially perfect match.

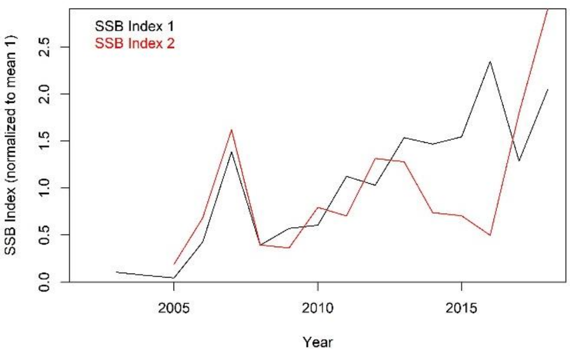

Fig. 3. The historical spawning stock biomass (SSB) indices used in VPA conditioning and simulated in future MSE projection years for use by the index-based MPs.

Example Management Procedures

A total of 15 management procedures were tested in MSE closed-loop simulation (Table 2). Of these 15, nine were index based MPs. These 9 index based MPs averaged SSB index data over 3 varying time periods and had 3 varying index calibrations (low, moderate and high). The remaining 6 were theoretical reference MPs used to frame index MP performance. These included zero catches, fractions of FMSY (perfectly known) and current fishing effort (current fishing mortality rate at age).

The 9 index based MPs were derivatives of a simple calibrated (fixed F) index-based MP that sets the TAC in year *y* equal to a calibrated average of two spawning stock biomass indices *I*:

$$TAC_{y+1} = \frac{\sum_{i=1}^{2}\sum_{y-n}^{y-1} q_i I_{i,y}}{2n} \qquad (1)$$

where *q* is the calibration by index and *n* is the number of years prior to the current year over which index values are averaged.

Tab. 2. Management procedures tested in this demonstration

MP	Description
L_1	Low index calibration (q_1=0.0023, q_2=0.005), data averaged over last year (*n*=1).
M_1	Moderate index calibration (q_1=0.0075, q_2=0.023), data averaged over last year (*n*=3).

H_1	High index calibration (q_1=0.035, q_2=0.01), data averaged over last year (n=6).
L_3	Low index calibration (q_1=0.0023, q_2=0.005), data averaged over last 3 years (n=1).
M_3	Moderate index calibration (q_1=0.0075, q_2=0.023), data averaged over last 3 years (n=3).
H_3	High index calibration (q_1=0.035, q_2=0.01), data averaged over last 3 years (n=6).
L_6	Low index calibration (q_1=0.0023, q_2=0.005), data averaged over last 6 years (n=1).
M_6	Moderate index calibration (q_1=0.0075, q_2=0.023), data averaged over last 6 years (n=3).
H_6	High index calibration (q_1=0.035, q_2=0.01), data averaged over last 6 years (n=6).
NFref	Zero fishing
FMSYref25	Fishing at 25% of FMSY levels (perfect knowledge of FMSY and vulnerable biomass)
FMSYref50	Fishing at 50% of FMSY levels (perfect knowledge of FMSY and vulnerable biomass)
FMSYref75	Fishing at 75% of FMSY levels (perfect knowledge of FMSY and vulnerable biomass)
FMSYref	Fishing at FMSY levels (perfect knowledge of FMSY and vulnerable biomass)
curE	Current fishing effort and selectivity (perfect knowledge)

Identification of generic management performance metrics

Since the VPA assumes no stock-recruitment relationship, the OMs are reconstructed assuming very high steepness (Beverton-Holt stock-recruitment relationship) of 0.99. At values greater than 0.95, conventional MSY-related quantities such as FMSY become problematic particularly in short-lived species where predominantly mature fish are caught. In such cases FMSY can tend to infinity. An alternative is to use yield-per-recruit type reference points (e.g. F0.1). A detailed exploration of performance metrics may be required for Chub mackerel, but for purposes of this demonstration we use biomass relative to BMSY as a principal measure of biomass performance, acknowledging that this may not be appropriate.

Five metrics were used to summarize the performance of MPs including two relating to biomass (SB, LB), two relating to magnitude of yields (SY, LY) and one relating to inter-annual variability in yield (AAVY) (Table 3).

Tab. 3. The five performance metrics used to characterize MP performance among operating models.

Perf. Metric	**Description**
SB	Short-term biomass. Average biomass in the first 10 years of the projection (2019-2028)

LB	Long term biomass. Average biomass in the last 10 years of the projection (2039-2048)
SY	Short-term yield. Average catches in the first 10 years of the projection (2019-2028)
LY	Long term yield. Average catches in the last 10 years of the projection (2039-2048)
VY	The average annual variability in yield. The mean of: absolute difference in catches between years *y* and *y*+1 divided by the catches in year *y*.

Results

Operating models #2 M3_Est and #6 M5_Fix provide the most disparate performance outcomes among the various MPs. Overall however, comparable patterns in the performance outcomes among the MPs (Figs 4 and 5). The most aggressive MPs (type 'H_' that set TACs to the highest multiplier of the indices) achieved the highest short-term (SY) and long term yields (LY) indicating that they were not leading to chronic overfishing over the 30 year projection.

The number of years used for averaging the index (*n*) did not appear to meaningfully impact MP performance compared to the index multiplier *q* (grouping by colors in Figs 4 and 5).The aggressive index based MP using a single year of index data (H_1) was closest to idealized FMSY performance. However it has a substantial cost in term of long-term biomass. The reference MPs could achieve high yields without affecting long term yield indicating that factors unrelated to fishing affect yield performance. The probability of staying above 50% BMSY was low for the high and moderate ('H_' and 'M_') MPs and substantially higher for the more conservative low ('L_') MPs.

The future projections all included a reduction back to historical mean recruitment levels leading to reductions in both biomass and catch using the index-based MPs (Fig. 6). In general, the projected yield and biomass outcomes were very similar among the operating models (Fig. 6.) indicative of a narrow range of future stock size and productivity scenarios.

Comparing management procedures across all operating models shows an overlap in long-term biomass and yield performance among the high and moderate index-based MPs ('H_' and 'M_', Fig. 7.) The more conservative low MPs ('L_') had distinctly higher biomass outcomes and overlapping yield outcomes.

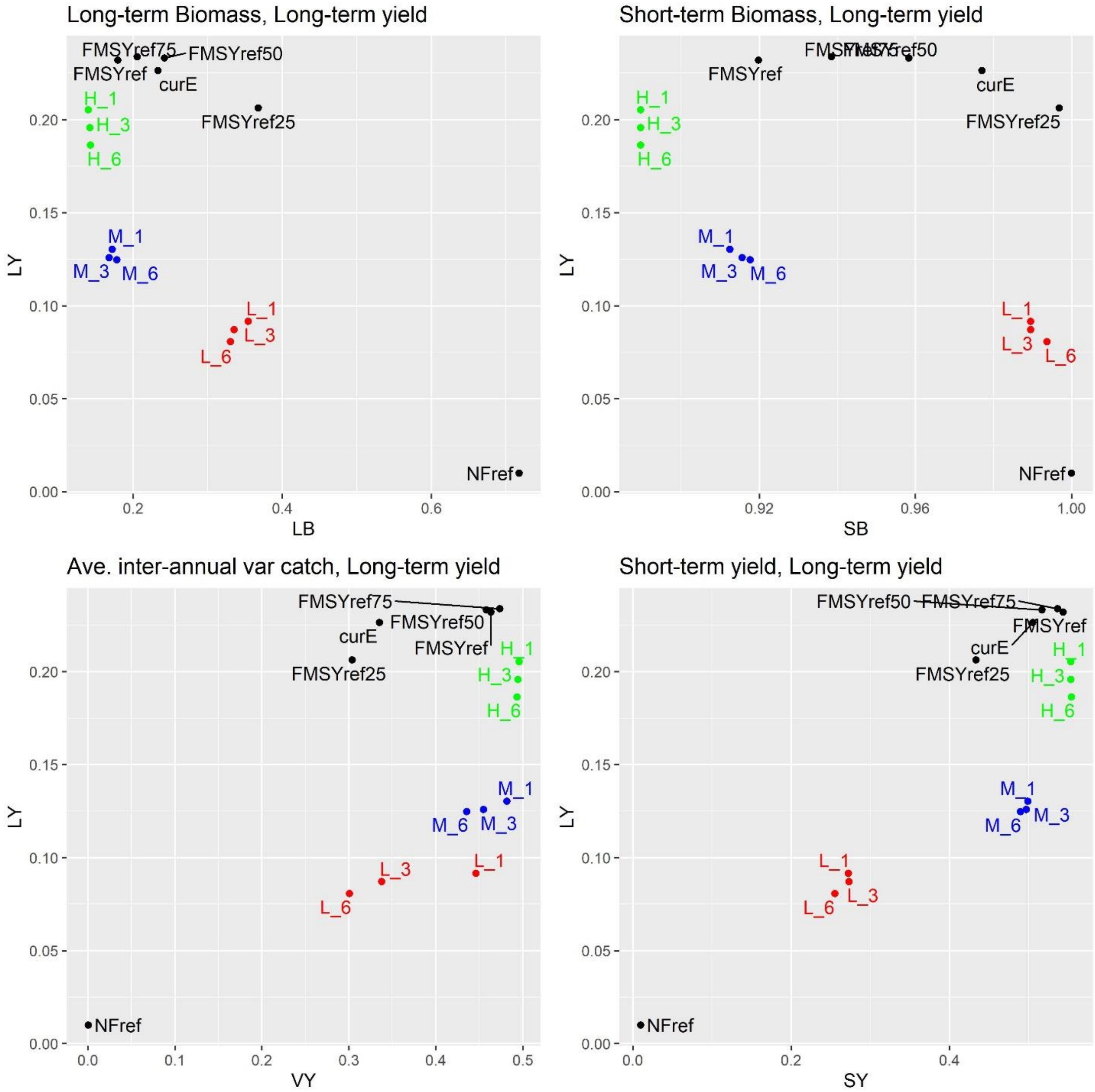

Fig. 4. Performance trade-offs among MPs for operating model #2 M3_Est

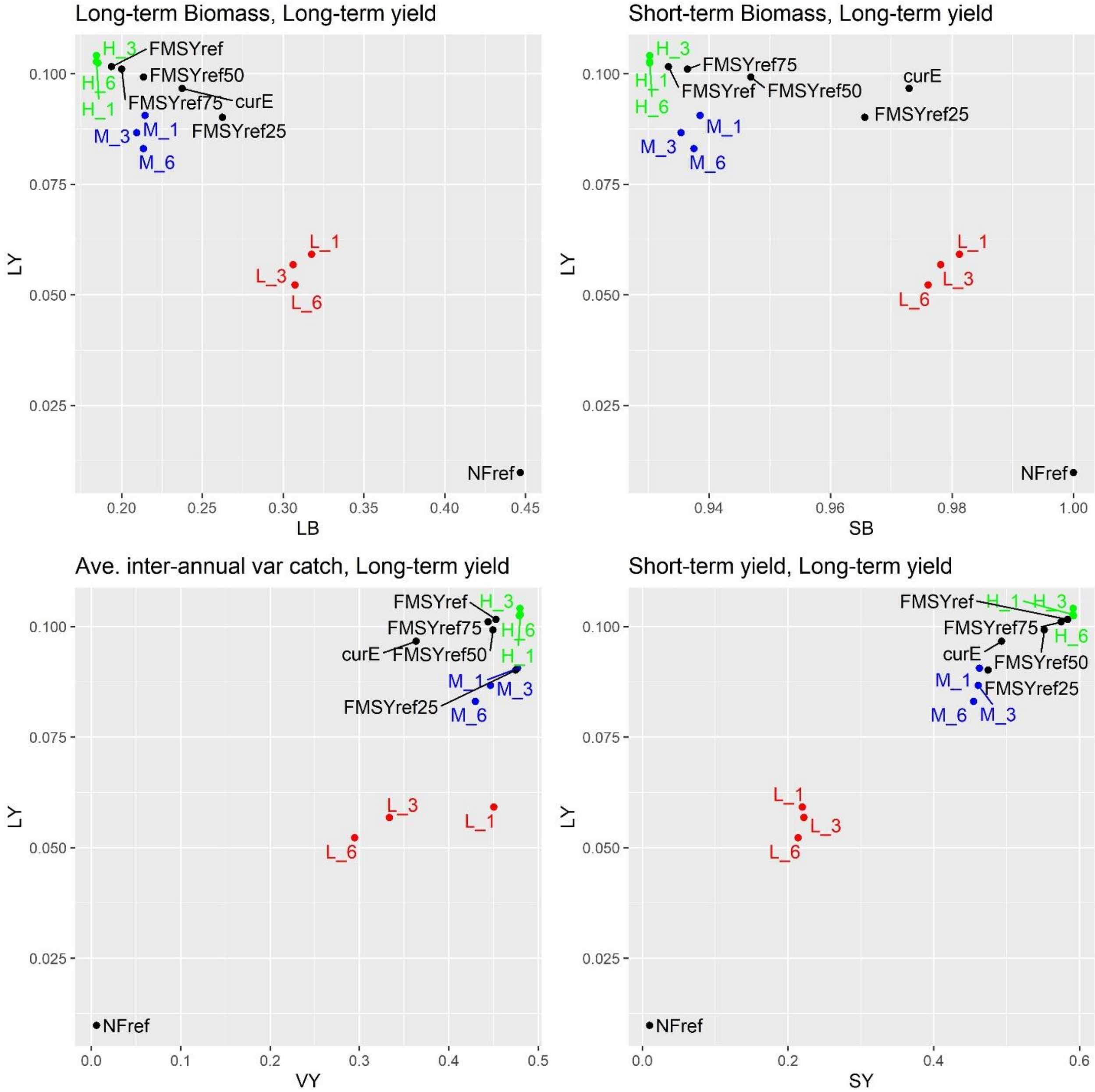

Fig. 5. Performance trade-offs among MPs for operating model #6 M5_Fix

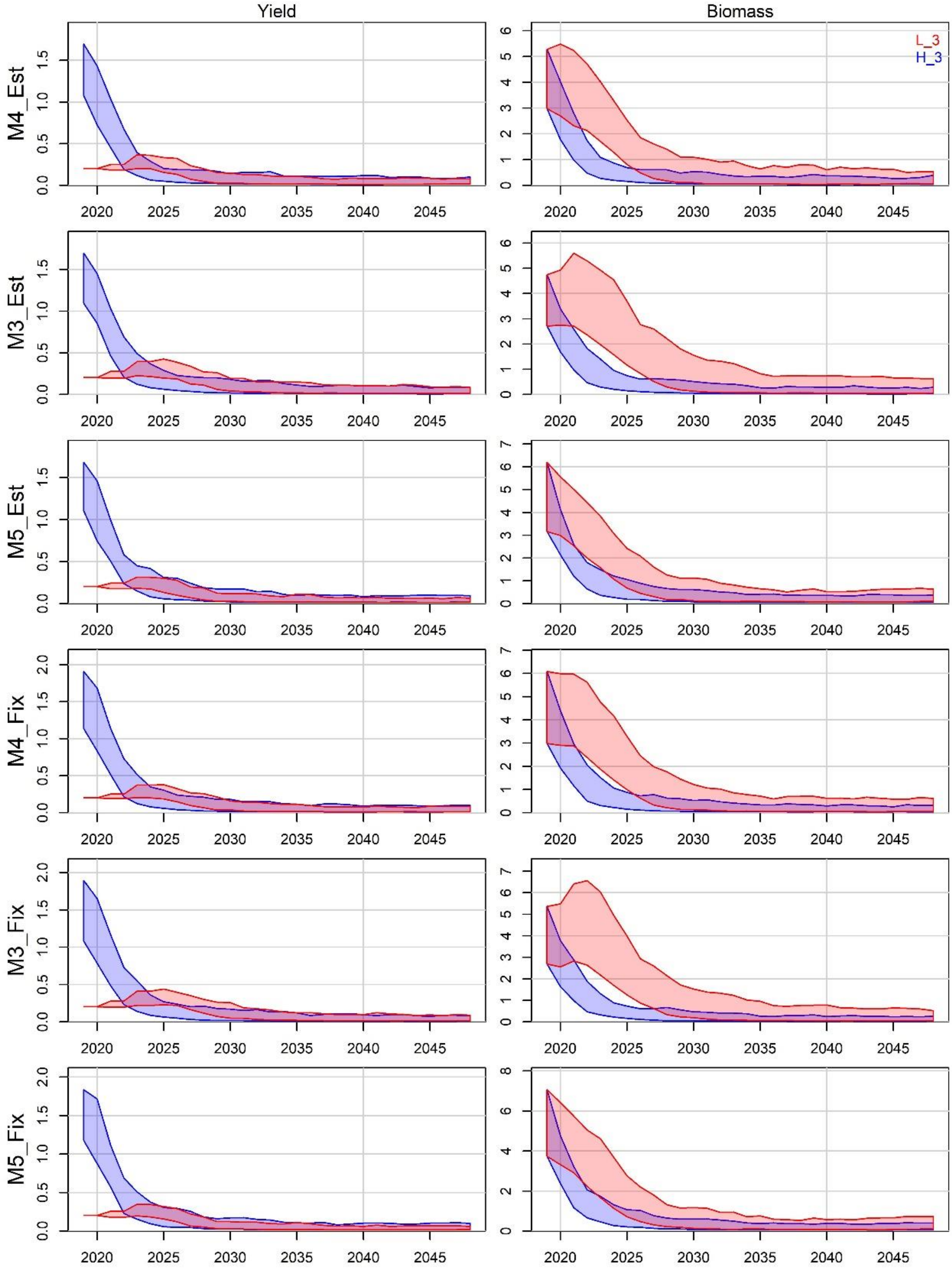

Fig. 6. Yield and biomass projections for two management procedures 'L_3' and 'H_3'.

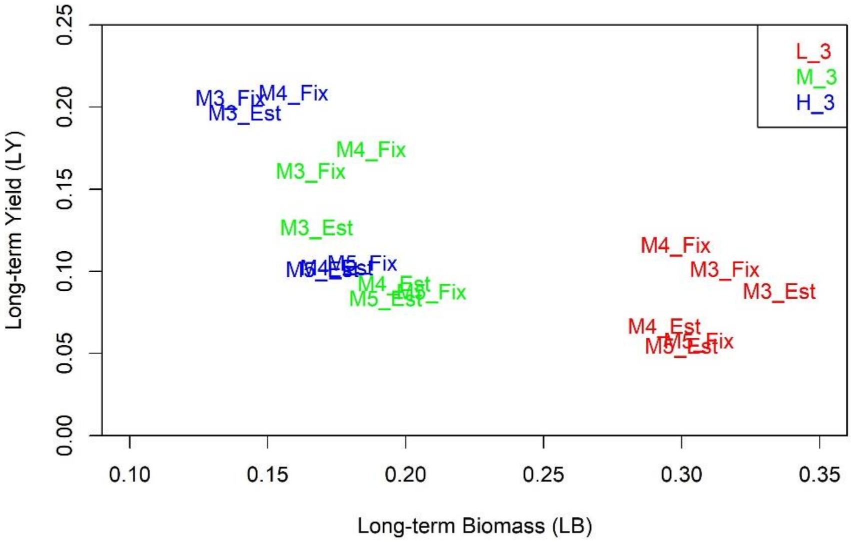

Fig. 7. Comparative MP performance among all operating models.

Discussion

The purpose of this paper was to provide a complete technical MSE exercise to demonstrate MSE accessibility in the light of new open-source software. Consequently, only a single structural form of MP was investigated that aimed to set catch limits at a constant multiplier of the indices (essentially a fixed harvest rate MP). Nonetheless, some of the derivatives of this simple MP obtained reasonably good biological and yield performance over the set of six operating models. Although these operating model included only two types of uncertainty (natural mortality rate and index hyperstability) these have been found to be amongst the most influential other MSE settings. These encouraging results may be improved upon by alternative structural forms of MP using more sophisticated statistical techniques.

One area in which the operating models were arguably too alike was their simulated future recruitment strength. All operating models assumed a resumption of mean recruitment levels after a recent spike, leading to very similar long-term biomass outcomes in MSE projections. Given the large recruitment strength changes that have occurred historically, a fully specified set of operating models for Chub Mackerel may include future recruitment shifts as a more comprehensive test of candidate MPs.

The relative ease with which technical aspects of MSE can now be completed does not lessen the critical requirement for a carefully designed and implemented MSE *process* that establishes appropriate objectives, working groups and timelines. At least three groups can be envisaged, each representing distinct roles and responsibilities in an MSE process. At the highest level is project oversight whose group members steer the MSE process, set objectives and timelines, allocate resources and communicate with commissioners. The second group are MSE users: these include any stakeholder who wishes to investigate the MSE framework and test candidate MPs. This group only requires the technical skills required to interact with the MSE software. The third group is focused on technical aspects of MSE framework development: the mathematical and statistical aspects of MSE development including the fitting of models and the simulation of plausible future data. Technical group members may also assist in the development of candidate MPs.

The MSEtool software alleviates much of the work load for the technical group as these modelling aspects have already been developed. Rather than developing a costly MSE framework from the ground up, substantially fewer resources can be spent on a technical review of the existing software. Additionally, any technical resources can be spent on the development of more sophisticated MPs that could substantially improve real management outcomes should an MP be adopted.

An impediment to MSE exploration by working groups in other settings has been the excessive time taken to conduct OM conditioning and MSE calculations (in some cases a number of weeks). In total, it took less than 5 minutes to condition the six operating models and run the MSEs for 96 simulations, all 15 MPs (2 year management advice update interval) and 30 projection years. This computation efficiency can greatly speed advances in an MSE process by increasing the number of iterations that can be completed within and between meetings.

A fully specified MSE framework for Chub Mackerel has a number of components not considered in this demonstration. For the sake of brevity, two important technical components were omitted: assigning plausibility to OMs and MP Implementation Review (establishing exceptional circumstances protocols that decide when to reevaluate the use of an MP). The former requires expert judgement from a working group (which is not easily anticipated) and a demonstration of the latter requires an MP to be adopted and in use. These technical exercises occur after OM conditioning and prior to MP adoption and are therefore occur during the development of the MSE framework.

There are however two aspects where progress can be made in the near-term: the identification of management performance metrics (e.g. probability of yield exceeding some level over a set of projected years) and the identification of the core axes of uncertainty over which to specify operating models. Other MSE processes have considered uncertainties such as natural mortality rate, somatic growth, maturity schedule, data weighting, index hyperstability, future recruitment strength, and the parametrization and form of the stock recruitment relationship. Where possible, the number of operating models should be sufficiently wide ranging to have confidence over MP performance but include as few OMs as possible so that MSE results are more easily interpreted.

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