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# AN EXAMPLE MANAGEMENT STRATEGY EVALUATION OF A HARVEST CONTROL RULE

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*SUMMARY*

*We show for North Atlantic Albacore how Management Strategy Evaluation (MSE) can be used to evaluate the performance of a limit reference point (LRP) as part of a harvest control rule (HCR).*

*RÉSUMÉ*

*Nous montrons pour le germon de l'Atlantique Nord comment l'évaluation de la stratégie de gestion (MSE) peut être utilisée pour évaluer la performance d'un point de référence limite (PRL) dans le cadre d'une norme de contrôle de la ponction (HCR).*

*RESUMEN*

*Se muestra, para el atún blanco del norte, cómo se puede utilizar la Evaluación de la estrategia de ordenación (MSE) para evaluar el rendimiento de un punto de referencia límite (LRP) como parte de una norma de control de la captura (HCR).*

*KEYWORDS*

*Albacore, FLR, Harvest Control Rule, Management Procedure, Management Strategy Evaluation, OperatingModel, R.*

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## 1. Introduction

In this paper we show how Management Strategy Evaluation (MSE) can be used to evaluate the performance of a limit reference point (LRP) as part of a harvest control rule (HCR). The Precautionary Approach Garcia [1996] requires stock status to be assessed relative to limits and targets, to predict outcomes of management alternatives for reaching the targets and avoiding the limits, and to characterize the uncertainty in both of these. These requirements impose specific needs for research, stock assessments, monitoring and management. Under the Precautionary Approach (PA) the use of a harvest control rule (HCR) is recommended to specify in advance what actions should be taken when limits are reached. However, although harvest control rules may include several precautionary elements, it does not necessarily follow that they will be precautionary in practice (Kirkwood and Smith, 1995). Since many harvest control rules are not evaluated formally to determine the extent to which they achieve the goals for which they were designed, given the uncertainty inherent in the system being managed (Punt 2008). For this reason Management Strategy Evaluation (MSE) using simulation modelling has increasingly been used to evaluate the impact of the main sources of uncertainty inherent in the system being managed (Cooke 1999, McAllister *et al*. 1999, Kell *et al.* 1999).

## 2. Material and Methods

MSE is the process of testing generic harvest strategies or Management Procedures (MPs) using an Operating Model (OM). An OM is a mathematical statistical model that describes the resource dynamics in simulation trials and for generating resource monitoring data when projecting forward Rademeyer *et al.* (2007). A MP is the combination of pre-defined data, together with an algorithm to which such data are input to provide a value for a TAC or effort control measure. The intention is to demonstrate, through simulation trials, that the MP provides robust performance in the presence of uncertainties. In some cases the MP is ran as an auto-pilot, i.e. once the data are given to the MP and a TAC is then generated which is then implemented without negotiation. However, MSE has also been used to develop elements of management plans, e.g. to set inter-annual bounds on TACs (Kell *et al.*, 2006).

MSE involves a number of steps (Punt and Donovan, 2007) i.e.

1. Identification of management goals (and performance measures to quantify the extent to which those goals have been achieved).
2. Selection of hypotheses which impact on the risk of not achieving those goals, and development of Operating Models which represent those hypotheses.
3. Conditioning of the Operating Models on the available data and knowledge (and possible rejection of hypotheses [or combinations of hypotheses] which are not compatible with those data and knowledge).
4. Identification of candidate management strategies.
5. Simulation of the performance of the management strategies by projecting the Operating Model forward in which management is set using the management strategy.
6. The evaluation of the management strategies based on the performance measured.

### *2.1 Management Objectives*

To quantify how well management objectives are met by a particular management strategy is done using performance statistics.

The precautionary approach (PA) recommends that $F_{MSY}$ be considered as an upper limit on harvest rate. However, the ICCAT convention was signed prior to the development of the PA and so there is no implicit mention of limit reference points in the convention. The original management objective of ICCAT is to provide the maximum continuing catch, interpreted as using maximum sustainable yield (MSY) as a target. Recently the tuna Regional Fisheries Management Organisations (tRFMOs) have developed a common framework for the provision of management advice, i.e. the Kobe Framework de Bruyn *et al*. (2012).

Amongst other things this requires advice to be provided relative to $F_{MSY}$ and $B_{MSY}$ and for management options to be reported with respect to the resulting probability over time of B < $B_{MSY}$ and F > $F_{MSY}$. This requires stock assessment advice to be presented as phase plot (**Figure 1**) where the x-axis corresponds to biomass relative to $B_{MSY}$ and the y-axis corresponds to harvest relative to $F_{MSY}$. Quadrants are defined for the stock and fishing mortality relative to $B_{MSY}$ and $F_{MSY}$; i.e. red when B < $B_{MSY}$ and F > $F_{MSY}$, green if B > $B_{MSY}$ and F < $F_{MSY}$, and yellow otherwise. I.e. the red quadrant refers to an overfished stock subject to overfishing, green to a stock which is neither overfished or subject to overfishing and the yellow to a stock which is either overfished stock or subject to overfishing.

Management advice from the ICCAT Commission is based on recommendation [Rec-11-13] i.e.

1. For stocks that are not overfished and not subject to overfishing (i.e., stocks in the green quadrant of the Kobe plot), management measures shall be designed to result in a high probability of maintaining the stock within this quadrant.
2. For stocks that are not overfished, but are subject to overfishing, (i.e., stocks in the upper right yellow quadrant of the Kobe plot), the Commission shall immediately adopt management measures, taking into account, inter alia, the biology of the stock and SCRS advice, designed to result in a high probability of ending overfishing in as short a period as possible.
3. For stocks that are overfished and subject to overfishing (i.e., stocks in the red quadrant of the Kobe plot), the Commission shall immediately adopt management measures, taking into account, inter alia, the biology of the stock and SCRS advice, designed to result in a high probability of ending overfishing in as short a period as possible. In addition, the Commission shall adopt a plan to rebuild these stocks taking into account, inter alia, the biology of the stock and SCRS advice.
4. For stocks that are overfished and not subject to overfishing (i.e. stocks in the lower left yellow quadrant of the Kobe plot), the Commission shall adopt management measures designed to rebuild these stocks in as short a period as possible, taking into account, inter alia, the biology of the stock and SCRS advice.

This translates into the objectives summarized in **Table 1**. However, important elements are missing, e.g. probability and associated risk levels, time scales and the power of the scientific advice framework to actually predict the performance of management. There is also the original objective (O0) of achieving the maximum continuing catch and other objectives of keeping stakeholders happy. Within a body managing Areas Beyond National Jurisdiction (ABNJ) translates into potentially conflicting and not always explicitly expressed objectives. Particularly since there are implicit economic and human welfare objectives as well. For such objectives we look at discounted yield (O4) and effort (O5) as proxies for revenue or food supply and employment.

*2.1.1 Performance Measures*

Performance measures are summarized in **Table 2**. We also ran two additional OM trials, where we assume perfect implementation of F based management, i.e. for $F_{min}$ and $F_{MSY}$. The former provides a base line for stock recovery given the biology of the stocks and the later provides estimates of MSY and $B_{MSY}$ the variability to be expected when F equals $F_{MSY}$. Any MP will perform below the base lines levels allowing relative as well as absolute comparisons to be made.

***2.2 System Dynamics***

The major part of conducting an MSE is the selection of hypotheses which impact on the risk of not achieving management objectives, these relate to hypotheses about population dynamics and the behaviour of fleet including their response to management. Operating Models have to be developed which represent those hypotheses, there will always be alternative aims when evaluating MPs and different ways to condition OMs.

***2.3 Conditioning of the Operating Model***

Conditioning of the Operating Models on the available data and knowledge (and possible rejection of hypotheses [or combinations of hypotheses] which are not compatible with those data and knowledge). There are four main ways to construct operating models Kell *et al.,* (2006). Many evaluations of may use all four to some extent. The amount of knowledge, data requirements, and complexity of implementation differs quite markedly among these four types. Considerations below are expressed mostly in a Bayesian context, but there are other valid philosophies when constructing operating models.

1. The operating model is the currently-used stock assessment model. Although use of the assessment model as the operating model seems to imply that assessment models describe nature almost perfectly, if a OMP cannot perform well when reality is as simple as implied by an assessment model, it is unlikely to perform adequately for more realistic representations of uncertainty. Basing an operating model on the current assessment model has arguably the lowest demands for knowledge and data.
2. The operating model is a model that can represent all of the available (and valid) data. The values for the parameters of the operating model are based only on the data for the fishery under consideration (i.e. in Bayesian models, priors would be non-informative, so that only data would speak). This approach is based on the idea that all relevant data sets are available and that only data matter when considering future events. The operating model need not be identical to the models underlying the assessments used as part of the OMPs. This approach assumes that, with no information to the contrary, the future will be similar to the past, which is a strong assumption.
3. As for (2) except that, in Bayesian models, priors would describe in a formal way the knowledge of scientists related to the validity of information sources. Probabilities, other than those available from data, may come from, for example, meta-analyses. This is still a data-orientated approach, but other data sources than those for the fishery under consideration have an impact when conditioning the operating model.
4. As for (3) except that the emphasis is on expert beliefs and other a priori information about the processes that may aspect the behaviour of management systems in the future (i.e. the focus is on the future, not on putting historical data). This is a less data-, and more hypothesis-orientated approach. For example, climatic change studies may show that a regime shift is possible (even though one has never been seen in the historical data sets) and should be taken into account when selecting ways to provide management advice. It is important therefore that operating models are flexible so that they can deal with such factors.

In this example we use (1) to ensure continuity of advice and transparency to working group members, i.e. the OM was based on Multifan-CL. However simulation test using Multifan-CL as part of an MP would be computationally intensive we use a simpler stock assessment model for the MP *i.e* a biomass dynamic model. For conditioning of the OM we posed three hypotheses about the biological parameters and then ran Multifan-CL to convergence (see SCRS/2013/34 for full details).

### *2.4 Management Strategies*

Modelling a management strategy requires identification of candidate strategies. A generic MP based on a biomass dynamic model is described in SCRS/2103/33. This includes an estimator of stock parameters based on time series of catch and indices of abundance, calculation of reference points with associated uncertainty and an algorithm for projection based on a hockey stick harvest control rule (HCR). The HCR also includes constraints on changes in F (and hence implicitly on capacity and effort) and catches (hence revenue).

A HCR is also shown as part of the phase plot in **Figure 1**, the orange line is the HCR and where a harvest rate (y-axis) is set for a given stock biomass (x-axis). The black line is the replacement line, i.e. for a given stock biomass any harvest rate above the black line will cause the stock to decline and any harvest rate below the line will cause the stock to increase. Therefore for the target harvest rate (i.e. the horizontal segment of the HCR) the target biomass is given by the intersection of the two lines. If the stock declines below the break point (i.e. a trigger biomass) then harvest rate is reduced progressively to a minimum level of harvest rate at a biomass level referred to as $B_{lim}$.

### *2.5 Simulations*

Simulation are used to evaluate the performance of the MP by projecting the OM forward and setting quotas using the management strategy implicitly coded in the MP, i.e. using feedback between the MP and the OM. We only considered 3 OMs based on biology. Other hypotheses could have been considered for example some fleets are assumed to have the same selectivity as there was insufficient information in the data to estimate these independently selectivity was also assumed not to change over time. Both assumptions are unlikely to be true. The catch and size data are also not true observations have been generated in a variety of ways. There is therefore considerable uncertainty in the fleet data and assumptions.

*2.5.1 Uncertainty*

It is important to consider appropriate sources of uncertainty; traditional stock assessments mainly consider only uncertainty in observations and process (e.g. recruitment). However, uncertainty about the actual dynamics (i.e. model uncertainty) has a larger impact on achieving management objectives (Punt 2008). Therefore when providing management advice it is important to consider appropriate sources of uncertainty. Rosenberg and Restrepo (1994) catagorised uncertainties in fish stock assessment and management as being related to: fi Processes; caused by disregarding variability, temporal and spatial, in dynamic population and fisheries processes;

- Observations; sampling error and measurement error;
- Estimation; arising when estimating parameters of the models used in the assessment procedure;
- Models; related to the ability of the model structure to capture the core of the system dynamics;
- Implementation; where the effects of management actions may differ from those intended.

Uncertainty due to implementation is often ignored but it is recognised to be an important aspect related to the success of management plans (Peterman 2004). However, little actual work has been done on including implementation error in MSE, to do so requires a better understanding of fishers response to management (e.g. Tidd, Palmer *et al*. in prep.). Particularly since the effects of a HCR can be quite different from those intended because of the response of fishers to economic incentives and HCRs are generally poorly equipped to represent human welfare and MSEs tend not to represent implementation error well Milner-Gulland and Rowclifie [2011]. Sources of uncertainty related to Models include:

- structural uncertainty; due to inadequate models, incomplete or competing conceptual frameworks,
- or where significant processes or relationships are wrongly specified or not considered. Such situations tend to be underestimated by experts (Morgan and Henrion, 1990) and,
- value uncertainty; due to missing or inaccurate data or poorly known parameters
- Here we consider uncertainty due to
- Process error in future recruitment
- Measurement error in historic catches
- Estimates of stock status and reference points obtained from a biomass dynamic model
- Structural uncertainty, i.e. about the true biological processes.

### *2.6 Evaluation*

Is based on comparing the performance measures and hence management objectives and the trade-ofis between them.

### *2.7 Software*

Software used was a biomass production model implemented as a package in R, this allows it to be used with a variety of other packages for plotting, summarising results and to be simulation tested, e.g. as part of the FLR tools for management strategy evaluation (Kell *et al.*, 2007).

## 3. Examples

**Figures 10, 11 and 12** plot a number of possible realisations of the simulated projections from the OM (coloured lines) along with the medians and inter-quartiles (black lines), for F : $F_{MSY}$, B : $B_{MSY}$ and catch. Rows are HCR options and columns the scenario. The first HCR is for reference, i.e. what would the performance be if we could actually fish at $F_{MSY}$? Within the Monte Carlo trials (i.e. each choice of scenario and HCR) random numbers were used reused, e.g. so that realisation (i.e. iteration) n is comparable across trials. These plots show that basing judgment on the expected outcomes (e.g. the medians) is very misleading since yield and F (and hence effort) will be very different. I.e. it will show a large amount of variability and 50% of the time the actual outcomes will be outside the confidence range. Therefore evaluation of the HCRs should be based on appropriate performance measures see **Figures 14 and 15**.

However, first we look at the recovery rate in **Figure 14**, this shows the probability of the stock recovering to be greater than $B_{MSY}$ while F is maintained below $F_{MSY}$, i.e. the stock is in the green Kobe quadrant. Within a OM scenario the choice of $B_{Trigger}$ (i.e. 0.6 or 0.8) has no effect, it is the choice of the $F_{Target}$ that matters. The stock recovers quickest if the dynamics correspond to OM1 and slowest if they correspond to OM2, i.e. the mortality in the plusgroup determines recovery rate.

Performance measures related to sustainability are presented in **Figure 16**, these show the probability after recovery of

- staying in the Green Quadrant after recovery.
- F being less than $F_{MSY}$
- SSB being greater than > $B_{MSY}$
- SSB being greater than $B_{Loss}$, i.e. the smallest spawning biomass observed in the series of annual values of the spawning biomass.

In this case $B_{Loss}$, is the same as the Minimum Biological Acceptable Level (MBAL). A spawning biomass level below which, observed spawning biomasses over a period of years, are considered unsatisfactory and the associated recruitments are smaller than the mean or median recruitment (Serchuk and Grainger, 1992).

Performance measures related to economics are presented in **Figure 15**, these show the inter-quartiles (bars) and medians (dots) for

- median yield after recovery.
- Total Yield
- Discounted (at 5%) Total Yield
- median Effort after recovery.
- Total Effort
- Discounted (at 5%) Total Effort

Values have been scaled by the maximum value of that measure across all trials (i.e. so all values lie between 0 and 1).

If the main objective is sustainability then any HCR that fails to meet the evaluation criteria in **Figure 14** should not be selected for implementation. I.e. an $FT_{arget}$ of 0.7 times $F_{MSY}$ has a less than 0.5 probability of the stock staying in the Green Quadrant after recovery. There is also a high probability of SSB falling to a lower level than has been seen in the entire historical time series. Therefore it appears that the target F level is more important than the $B_{Triggers}$ considered. The choice of HCR can be refined by considering the Economic objectives, i.e. it may be possible to select a preferred option that satisfies the sustainability criteria.

## 4. Discussion

The study presented in this paper is not intended to be used for management advice, rather it is intended to demonstrate how MSE can be used to develop a LRP that meets management objectives given uncertainty consistent with the Precautionary Approach. I.e. to provide an example of a framework that can be used to perform an actual MSE. As noted above the stages of conducting an MSE include Identification of management goals was done for sustainability objectives based on recovery of a stock to the Green Kobe Quadrant, ensuring it then stays there. For economic objectives differences in long-term yield and effort (e.g. capacity) levels were compared. However, to do a full economic impact assessment analyses should be done by fleet. These objectives were mapped to Performance Measures that can allow the benefits and tradeoffs of the different Management Strategies to be compared. However, important issues such as probability and risk levels and time scales have not been explicitly stated by the Commission these need to be agreed before any evaluation.

Hypotheses about the stock dynamics were based on the biological assumptions, then Multifan-CL was used to estimate stock parameters using the WG data. However, there is considerable uncertainty about the catch data, fishing behaviour and stock structure for example (Fonteneau 2007). All of which may have a major impact on the risk of not achieving the management goals. It doesn't mean that it is necessary to create Operating Models to represent all possible hypotheses but ways of ensuring that advice is robust to what is known should include in the MSE. For example by using stock assessment models in the MP that do not require catch-at-age data to be produced before and assessment is conducted.

Conditioning of the Operating Models is an important step and more thought needs to be conducted in order to determine what hypotheses to consider and how to weight them (SCRS2103-34). How to include appropriate data and knowledge and possible rejection of hypotheses (or combinations of hypotheses) which are not compatible with those data and knowledge. For efficiency robustness test may help, i.e. to allow hypotheses to be discounted as they have little effect on the Performance Measures. This will require uncertainty to be considered in a systematic way, i.e. for selecting scenarios agreed a priori.

Management Strategies considered were based on a biomass dynamic model, with a hockey stock harvest control rule, which set a TAC each year. There are a wide range of options that could have been considered e.g. limiting inter-annual variability in TACs or effort or setting TACs for three years. This is relatively easy to do in the framework presented but requires a dialogue with managers. However, as there has been no agreed ASPIC/Biomass Dynamic stock assessment and it will be necessary for the Albacore WG to agree on this before any LRP can be developed. Uncertainty A major impact on the OM are the assumptions about the catch data, the CV of the residuals to the catch-at-age is >130%, as well as noise there will be considerable bias. i.e. if the basic data were bootstrapped then very differences outcomes may be generated. Stock recruitment assumptions may have a big effect on outcomes and could be explored further, i.e. as robustness trials.

## 5. Conclusion

A full MSE requires appropriate uncertainty to be considered, particularly in the choice of OM scenarios. One way of doing this is base the choice of scenarios are based on a factorial design. A full factorial experiment is one whose design consists of two or more factors, each with discrete possible values or levels, and where experimental units take on all possible combinations of these levels across all factors. Such a design is better able to represents the complexity of the real world and allows an evaluation of whether the effect of one factor depends on the level of another factor. The potentially large number of combinations in a full factorial design may mean that it is not possible to run them all in the time available in a stock assessment working group. Therefore a fractional factorial design in which some of the possible combinations are omitted may be preferred.

However, when conducting a Management Strategy Evaluation a large number of scenarios need to be considered to evaluate the main sources of uncertainties, i.e. the Operating Models (OM) will need to be conditioned on a wider range of data and knowledge that routinely considered within a stock assessment. In other words while only a few scenarios are routinely be considered within an ICCAT stock assessment, many more scenarios will need to be run as part of an MSE. This presents a potential problem if the Scenarios from an MSE result in different conclusions from those ran in a stock assessment. It is proposed that a base case be proposed and then factors with levels that represent the main uncertainties. In the stock assessment WG the main effects can be evaluated by varying 1 factor at a time. Hopefully this will allow the stock assessment to bracket the main uncertainty and act as a simple screening experiment, to determine the factors have the greatest influence on the perception of stock dynamics. Based on the identification of the most important factors, a multi-level designed experiment can then be developed for the MSE that includes interactions between factors.

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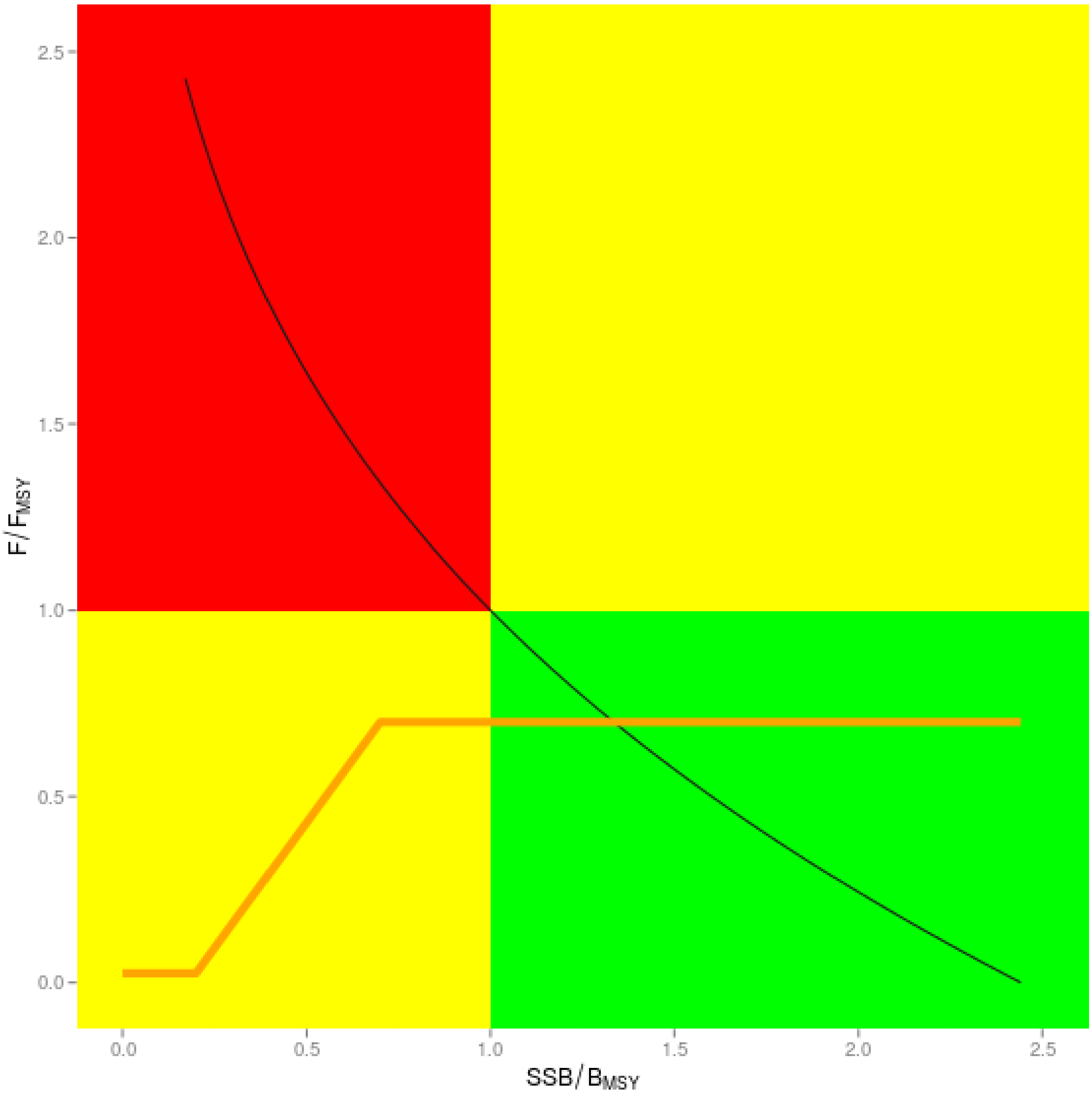


**Figure 1.** A phase plot of harvest rate relative to $F_{MSY}$ and stock biomass relative to $B_{MSY}$, with an example of a Harvest Control Rule (orange) and replacement line (black).

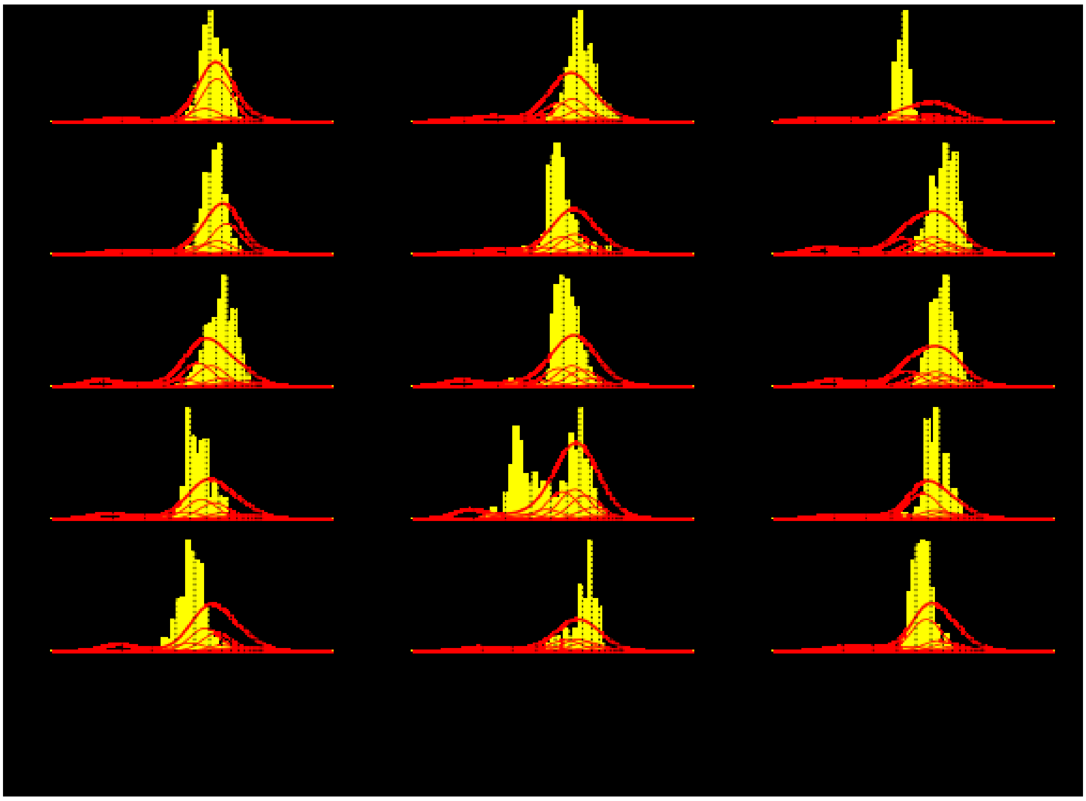

**Figure 2.** Observed size measurements (histograms) and fitted size distributions (lines).

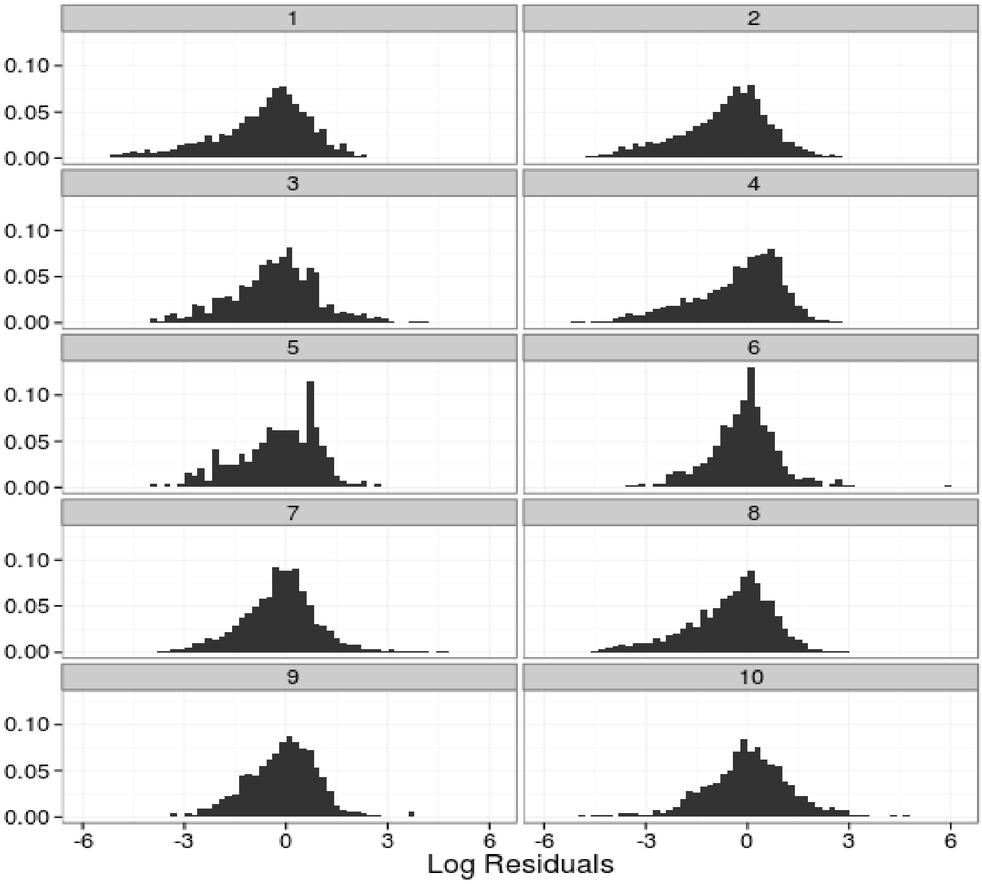


**Figure 3.** Catch-at-age residuals from Multifan-CL fits.

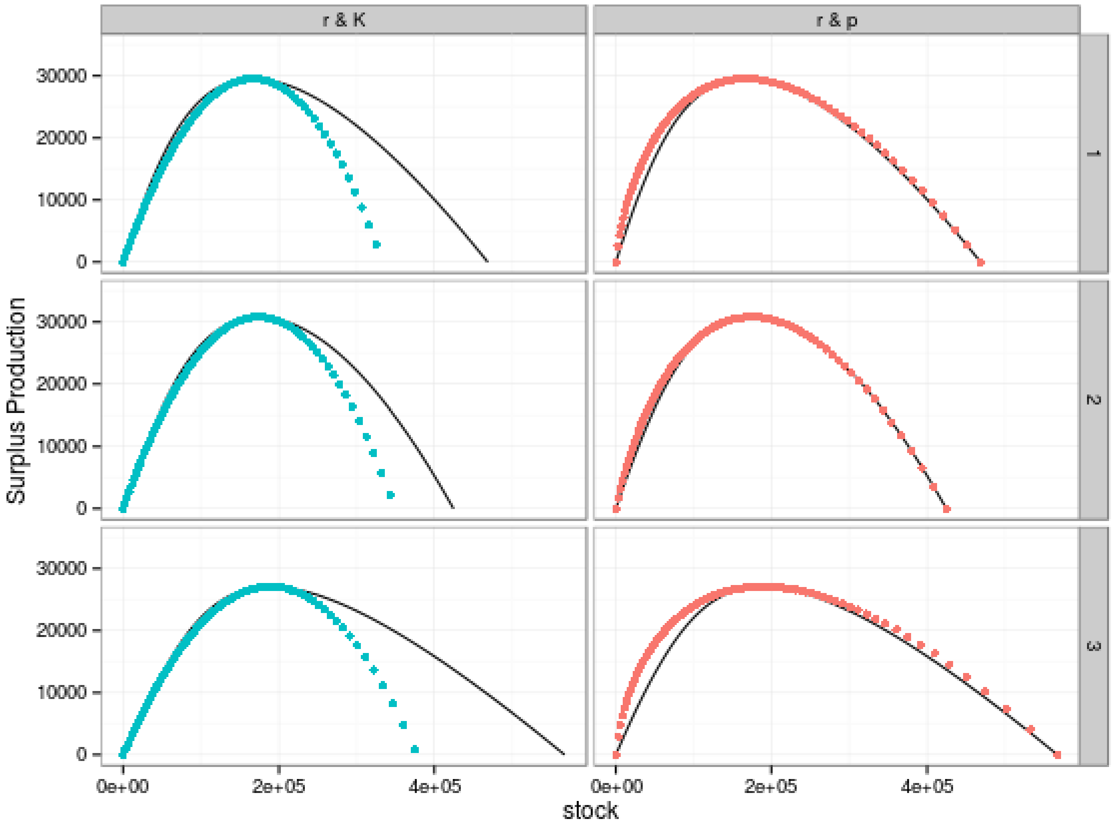


**Figure 4.** Comparison of surplus production functions (dots) with OM age based production curves (lines).

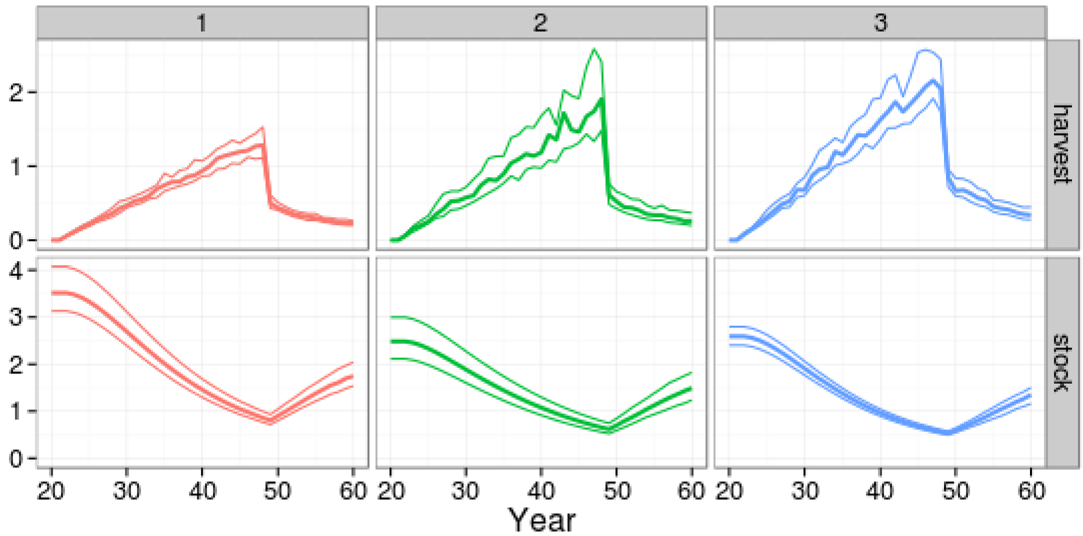


**Figure 5.** Comparison of time series of harvest rate and stock biomass derived from a Monte Carlo simulation based on the variance covariance matrix.

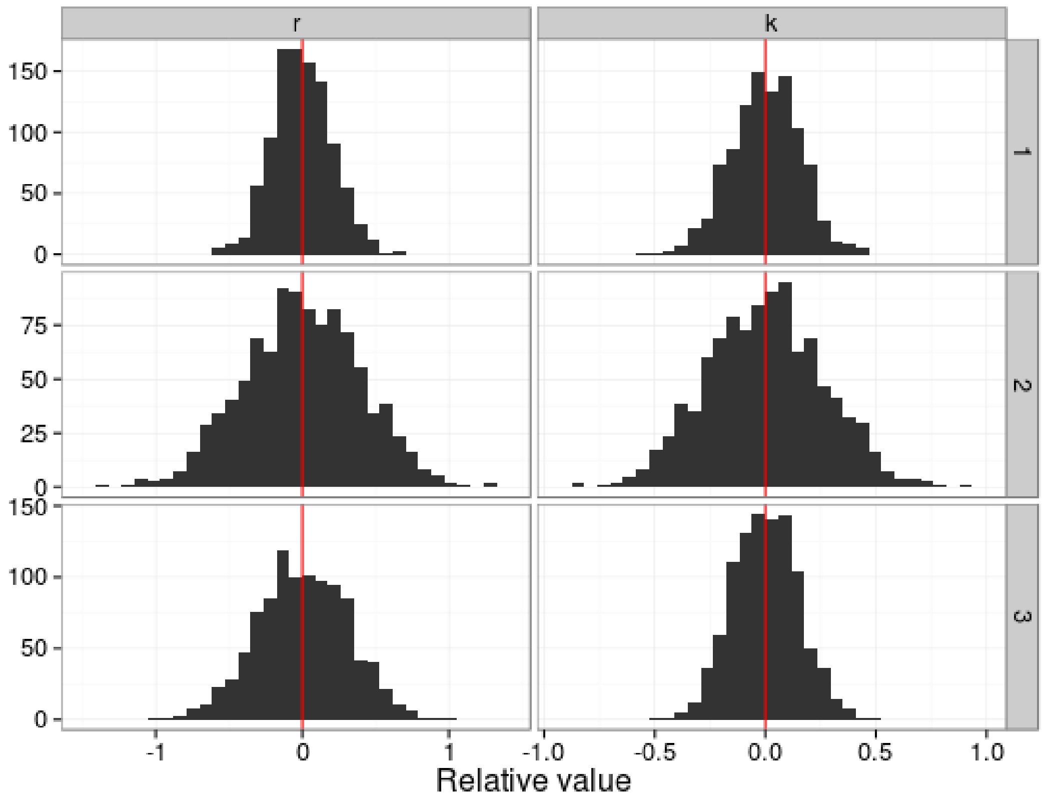


**Figure 6.** Comparison of biomass dynamic parameters derived from a Monte Carlo simulation based on the variance covariance matrix.

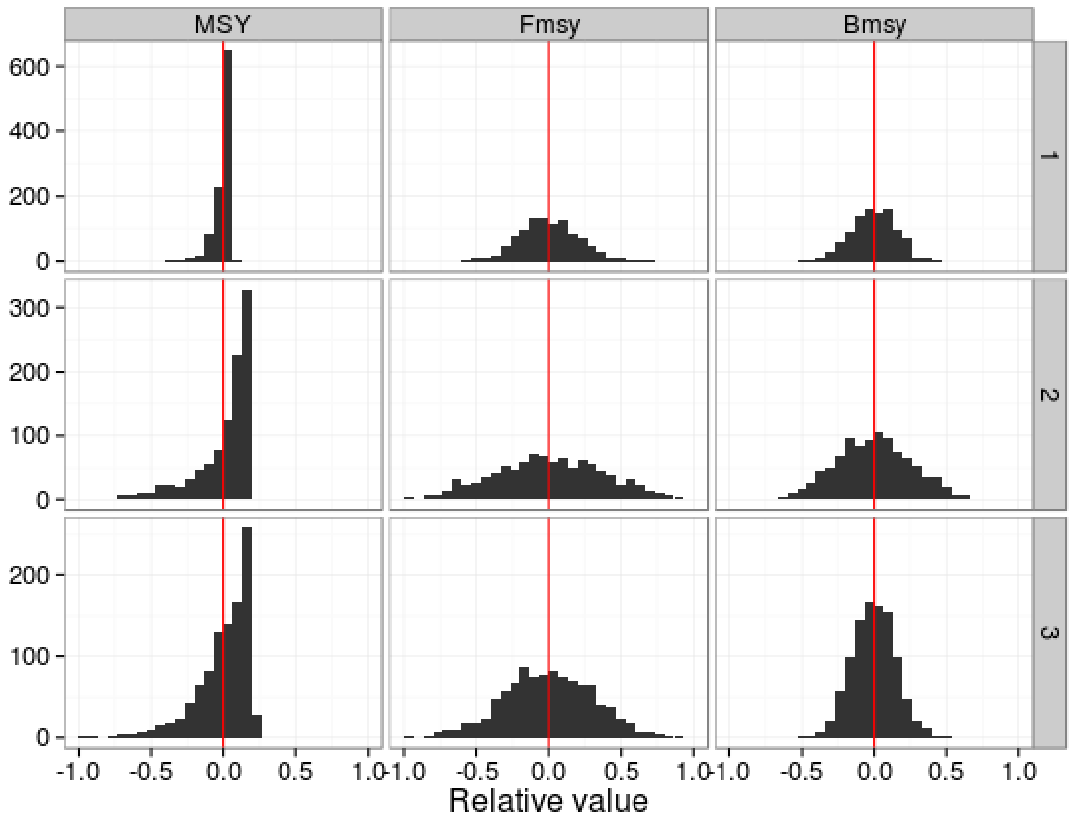


**Figure 7.** Comparison of reference points derived from a Monte Carlo simulation based on the variance covariance matrix.

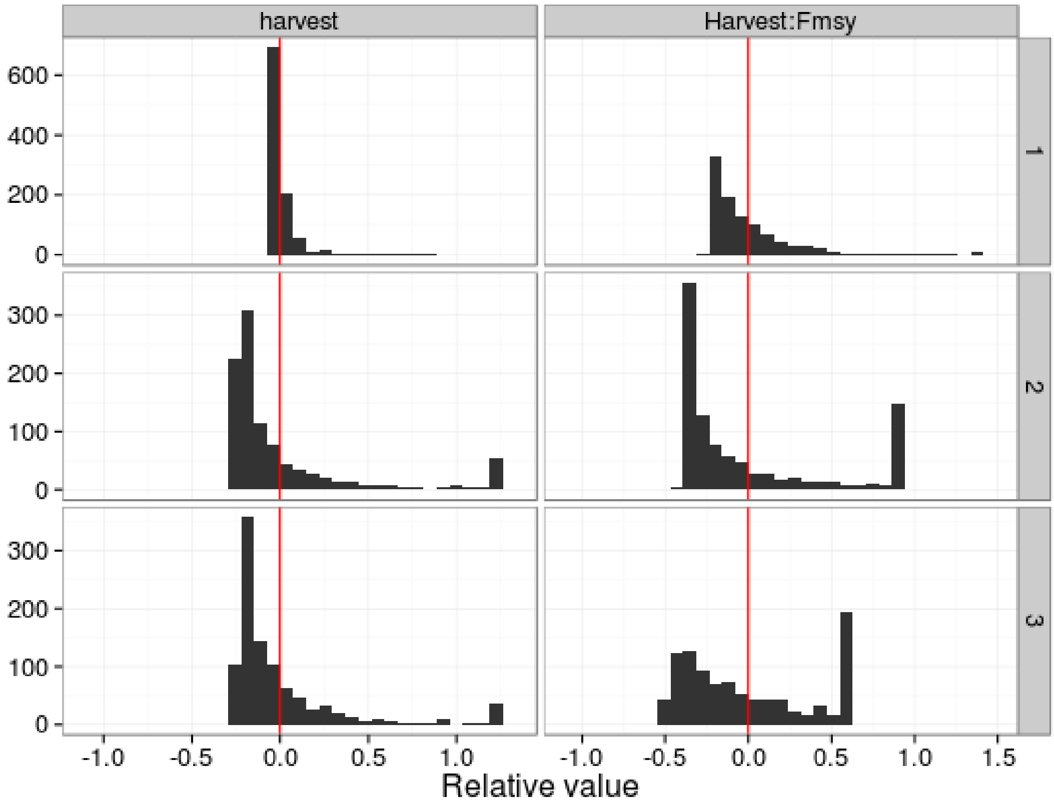


**Figure 8.** Comparison of harvest rate and harvest rate relative to $F_{MSY}$ derived from a Monte Carlo simulation based on the variance covariance matrix.

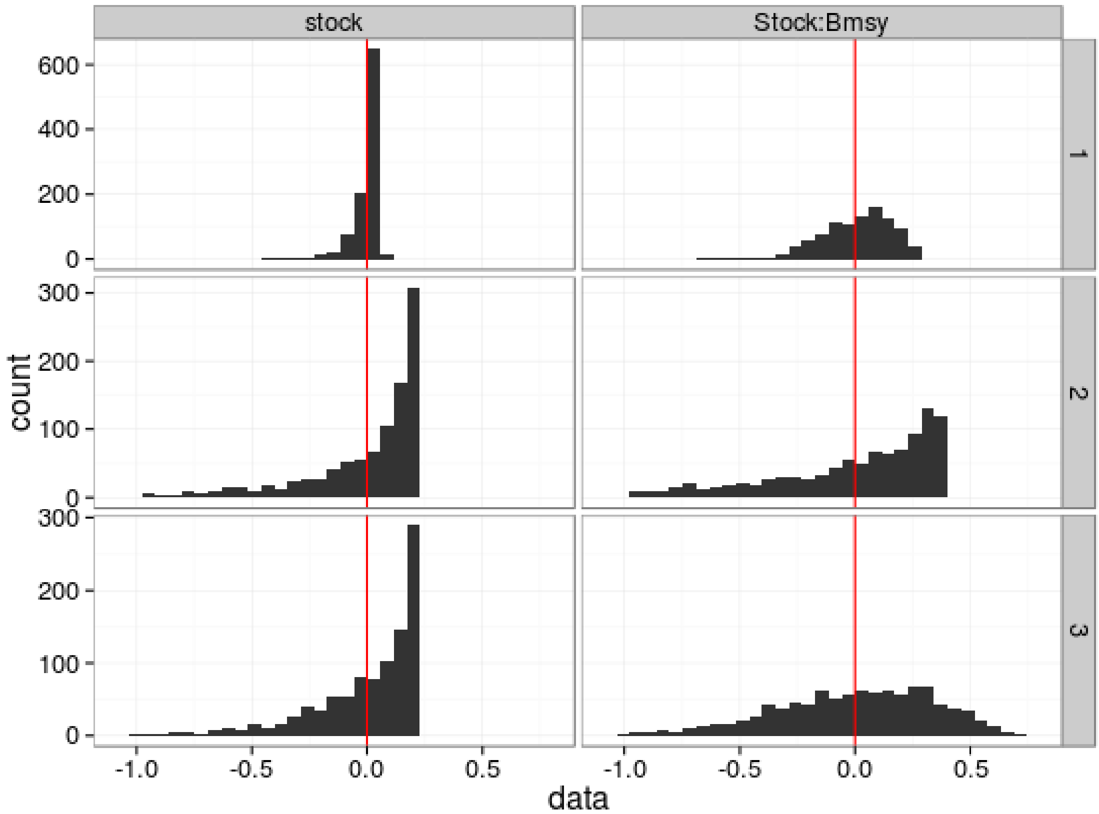


**Figure 9.** Comparison of stock biomass and stock relative to $B_{MSY}$ derived from a Monte Carlo simulation based on the variance covariance matrix.

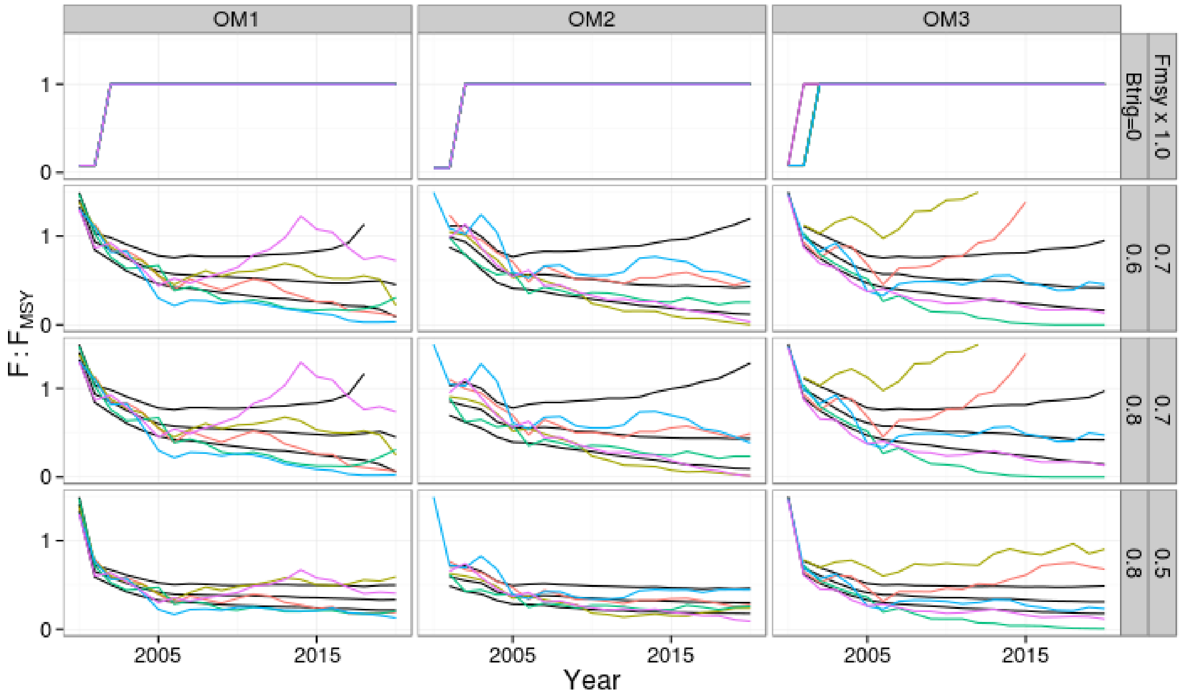


**Figure 10.** Harvest rate relative to $F_{MSY}$ worm plots (colour) with inter quartiles and medians (black).

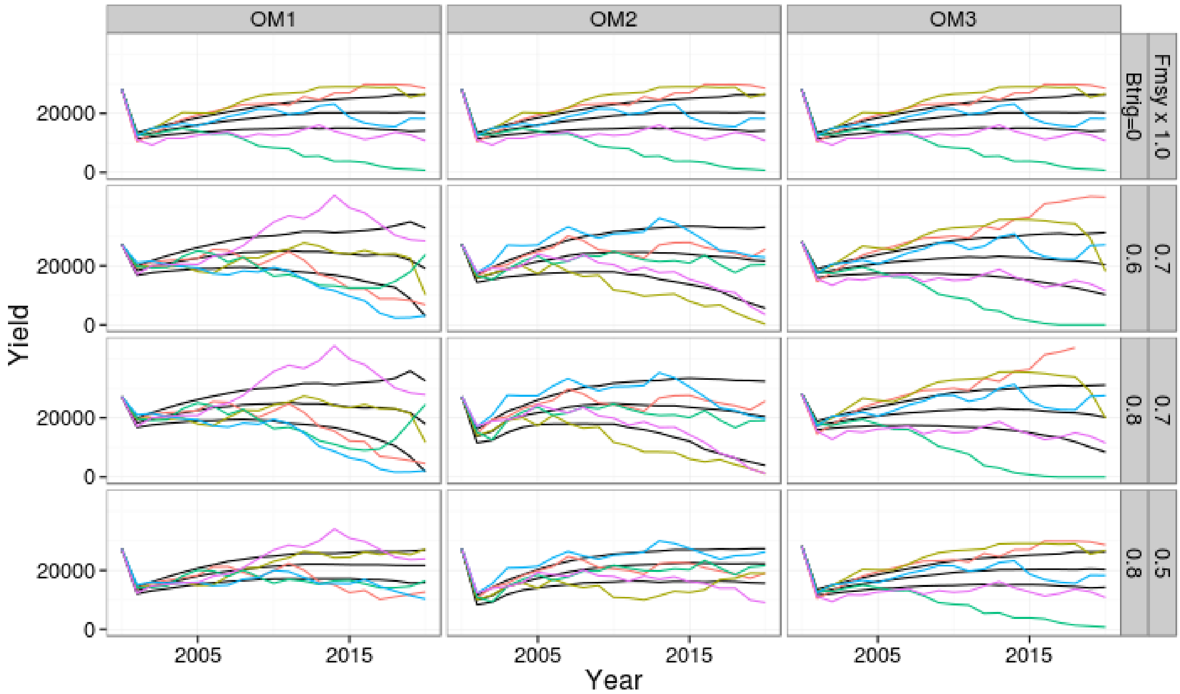


**Figure 11.** Stock biomass relative to $B_{MSY}$ worm plots (colour) with inter quartiles and medians (black).

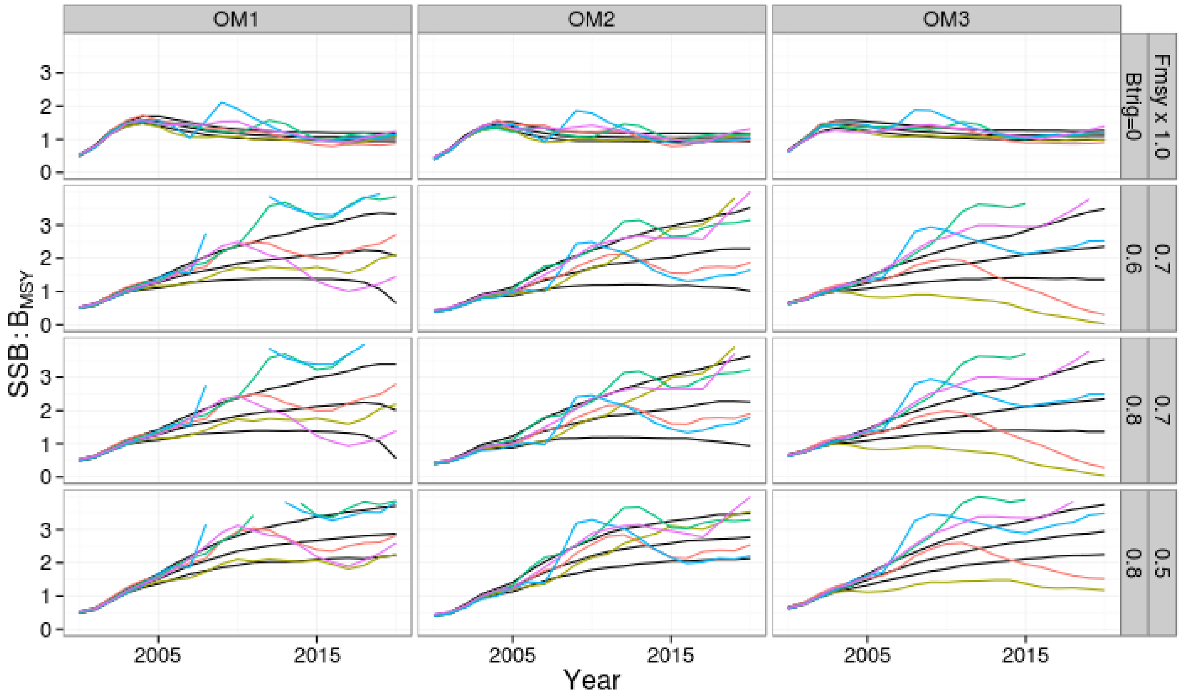


**Figure 12.** Yield worm plots (colour) with inter quartiles and medians (black).

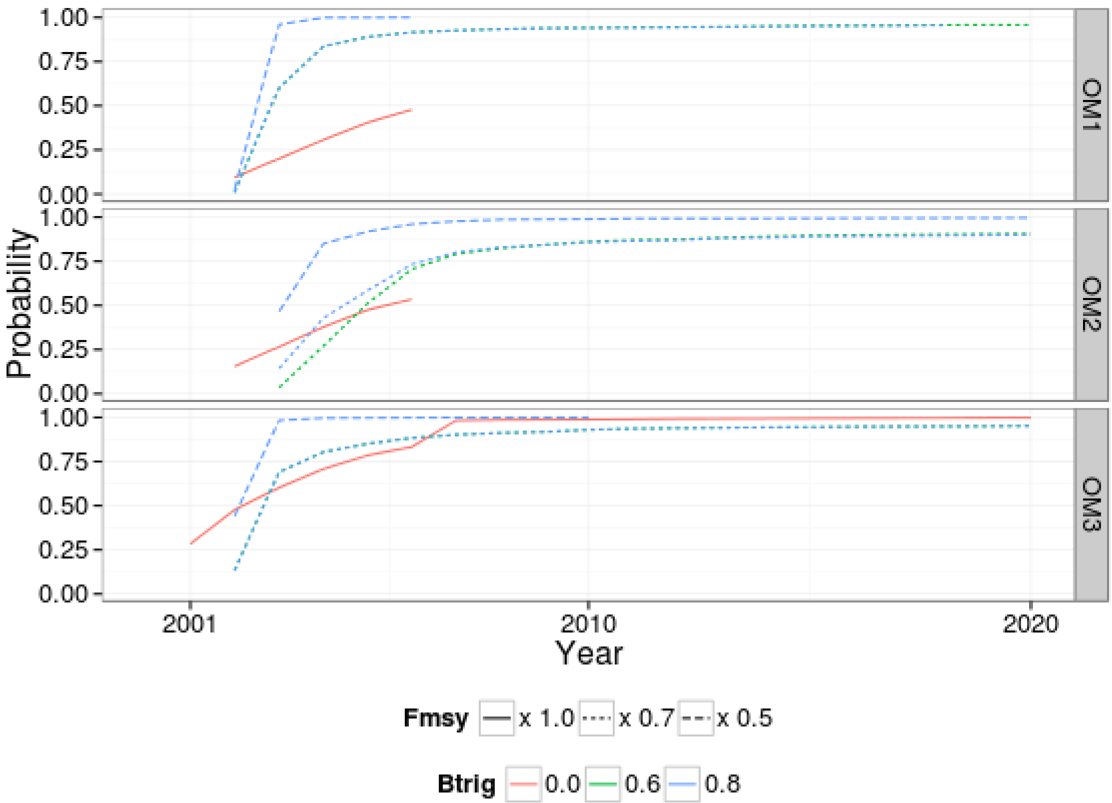


**Figure 13.** Probability of stock recovery, i.e. being in the green quadrant of the Kobe Phase plot.

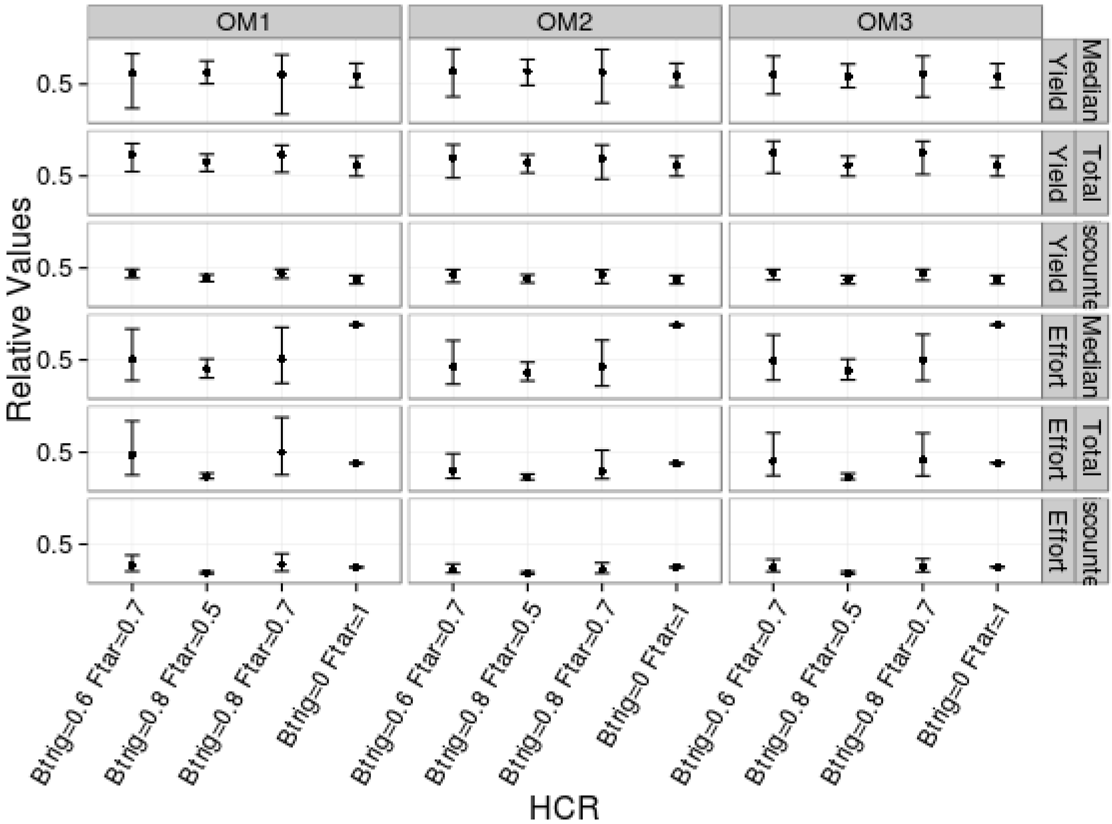


**Figure 14.** Summary of sustainability performance measures.

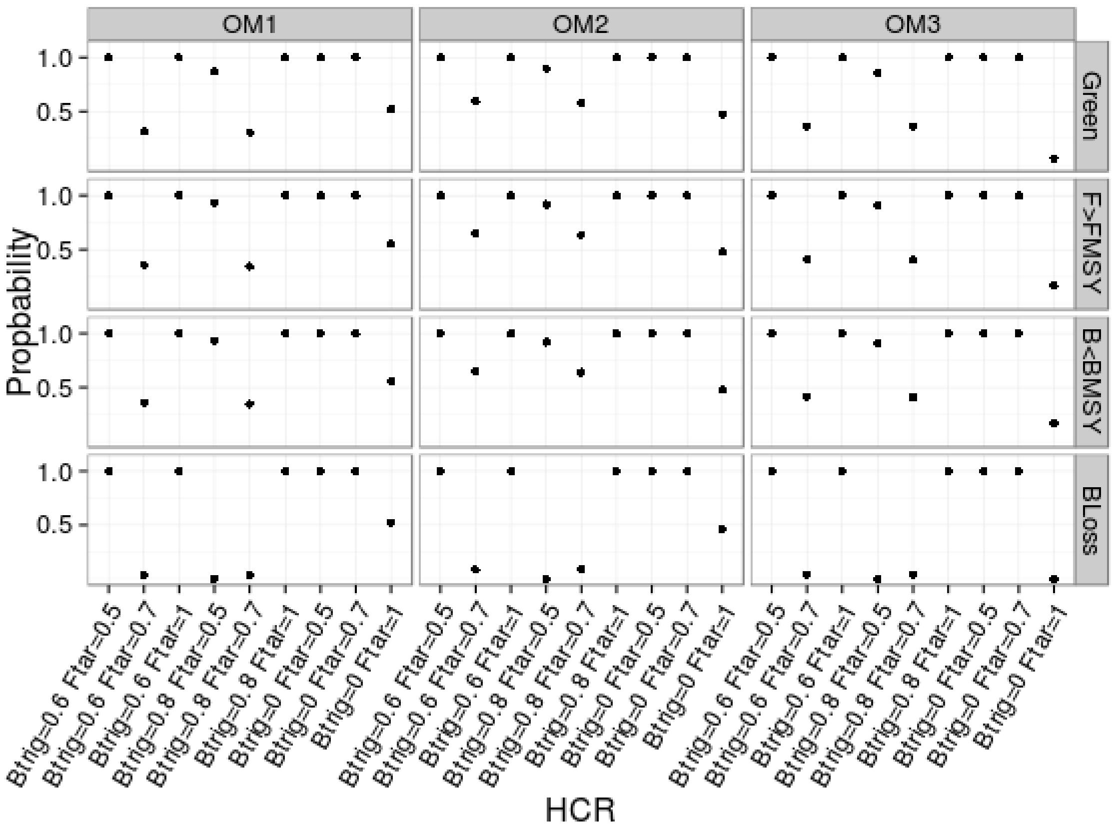


**Figure 15.** Summary of economic performance measures.