# Reframing Stock Assessment As Risk Management; An Management Strategy Evaluation for Atlantic Tuna Risk is an uncertainty that matters.

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# Introduction

The objectives of fish stock assessment are to estimate stock status, to predict the response of a population to management and to validate the predictions to ensure that they are consistent with reality (**?**). While a definition of risk is an uncertainty that matters (**?**). What matters depends on management objectives, and whether objectives are achieved depends on the management framework. For this reason management strategy evaluation (MSE **?**Punt et al., 2014; **?**) is increasingly being used to develop robust control mechanisms (e.g. **?**). Where a robust system is one that still functions correctly in the presence of uncertainty or stressful environmental conditions (Radatz et al., 1990). A definition of uncertainty is the difference between models and reality (**?**) and a good model should be simple enough to facilitate the design of a control system, yet complex enough to give confidence that designs based on it will work on the true system (Zhou et al., 1996).

We are uncertain, to varying degrees, as much of the past is hidden from us, we have only limited information about the present and no knowledge of the future **?**. This is particularly true in fisheries science and management where uncertainties and the risks they create are pervasive owing to natural variability in components of aquatic ecosystems, imperfect information about those components, and lack of perfect control over fisheries **?**. An important sources of uncertainty related to stock assessment modelling is *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 **?**.

In this study we show how to reframe stock assessment as risk management using Management Strategy Evaluation (MSE) and an example based on tuna stocks managed by the International Convention for the Conservation of Atlantic Tuna (ICCAT).

When managing fisheries decisions have to be made with incomplete knowledge, i.e. uncertainty about many processes . Therefore many fisheries organisations have adopted the Precautionary Approach (PA, Garcia, 1996) which requires that undesirable outcomes be anticipated and measures taken to reduce the probability of them occurring. Risk is defined as *an uncertainty that, if it occurs, will have an effect on objectives* (Hillson, 2011) and requires a proactive approach since to reduce risk requires managing the causes of uncertainty rather than just the consequences. In traditional stock assessment uncertainty may result in a lack of action (e.g. Fromentin et al., 2014). Reframing uncertainty as risk is therefore consistent with the PA.

MSE is used to determine how well management measures achieve their objectives given uncertainty, intrinsic variability and the occurrence of environmental events inherent to the system (Kirkwood and Smith, 1995). Therefore MSE can help in reframing stock assessment as risk management by evaluating what combinations of data, knowledge and algorithms to estimate stock status and set control measures best meet management objectives.

A consequence of the adoption of the PA is that stocks are assessed regularly with respect to limit reference points (LRPs). These indicate the state of a fishery or a stock considered undesirable and when fishing effort should be reduced so that are not reached (Gabriel and Mace, 1999). Target reference points (TRPs) may also be used to guide management and allow objectives such as achieving Maximum Sustainable Yield (MSY) to be met. The conventions of some Regional Fisheries Management Organisations (RFMOs) such as the ICCAT, however, were signed before the PA was drafted and so do not explicitly address the PA (De Bruyn et al., 2012). The advice framework of ICCAT was originally based on achieving MSY; although limit reference points are now also being defined. This is in contrast to other scientific frameworks such as that of the International Commission for the Exploration of the Sea (ICES), which was originally based on LRPs and TRP are only now being incorporated. Scientific advice advice of the tuna RFMOs like ICCAT, who are responsible for the management of tuna and tuna like species in areas beyond national jurisdiction, is based on a common scientific advice framework (Kell et al., 2015). An exception is the Commission for the Conservation of Southern Bluefin Tuna CCSBT) which used MSE to develop an empirical harvest control rule (Hillary et al., 2015).

We define stock assessment as the description of the characteristics of a 'stock' so that its biological reaction to being exploited can be rationally predicted and the predictions tested. Under this definition MSE is an important tool to test predictive and management capability. The 'characteristics' of a stock are represented by the Operating Model (OM), a mathematicalstatistical model used to simulate the resource dynamics and to generate monitoring data when projecting forward. MSE may be used to simulation test a Management Procedure (MP), which is the combination of pre-defined data, together with an algorithm to provide a value for a TAC or effort control measure. The MP may include a HCR and a stock assessment estimator, but does not have to for example CCSBT used MSE to develop a model free MP based on year to year changes and trends in empirical indicators.

An objective of MSE is to develop a robust control or management system rather than to identify a "best fit" to the available data, since stock assessment datasets typically do not contain information on key processes e.g. those that determine productivity (**?**). A robust system is one that still functions correctly in the presence of uncertainty or stressful environmental conditions (Radatz et al., 1990).

In traditional stock assessment is assumed that system dynamics are known and expressed in the form of a mathematical model and that a management control, such as a total allowable catch (TAC) can be adjusted based on that knowledge. MSE in contrast involves the simulation testing of closed-loop feedback systems, based on a management procedure (MP), i.e. the combinations of data, knowledge and algorithms used to estimate stock status and set control measures. The algorithms used to estimate stock status are generally simpler than traditional stock assessments; (Geromont and Butterworth, 2014) showed that simple MPs can perform as least as well as conventional stock assessments. The specification of the OM is a key task, there are various ways to do this (Kell et al., 2006) but all require consideration of a range of hypotheses about resource dynamics (e.g. Leach et al., 2014).

Risk depends on the definition of uncertainty. Stock assessment working groups often focus on technical aspects related to modelling e.g. the defintions of Rosenberg and Restrepo (1994) mainly focus on aspects that can be quantified in mathematical models. The characterisation of uncertainty is ultimately a pragmatic choice depending on the purpose of a particular application. There are other classifications of uncertainty, for example chapter 2, defines ‘statistical uncertainty‘ which includes the structural, process and observation uncertainties, and combines model error, structural uncertainty and value uncertainty into structural uncertainty; then summarises the different sources based on those that can be reduced and those that are inherent to the system i.e.

**Irreducible** aleatoric

- Process
- Implementation

**Reducible** epistemic

- Statistical
- Structural

## Material and Methods

### Case Study

### Management Strategy Evaluation

When running an MSE control actions from the HCR are fed back into an Operating Model (OM) that represents the system being managed so that its influence on the simulated stock and hence on future fisheries data is propagated through the stock and fishery dynamics. In engineering this is known as closed loop feedback control (Zhou et al., 1996). Feedback relaxes the requirement of having to have an exact model of the system being managed since the effect of the control actions on the system are monitored and adjusted accordingly.

However, traditional stock assessment advice mainly considers uncertainty about sampling and processes (e.g. recruitment) when uncertainty about the actual dynamics has a larger impact on achieving management objectives (Punt, 2008). For this reason, Management Strategy Evaluation (MSE Butterworth and Punt, 1999; Kell et al., 2003, 2006; Punt and Donovan, 2007; Punt et al., 2014; Hillary et al., 2013) and simulation modelling is increasingly been used to evaluate the robustness of advice frameworks to the main sources of uncertainty.

(Kell et al., 2015; Edwards and Dankel, 2015)

## Management Strategy Evaluation

All acronyms are tablulated in Table .

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

1. Identification of management objectives and mapping these to performance measures in order to quantify how well they have been achieved;
2. Selection of hypotheses for the OMs;
3. Conditioning of the OMs using data and knowledge and possible rejection and weighting of hypotheses;
4. Identifying candidate management strategies and coding these as MPs, i.e.the combination of pre-defined data, together with an algorithm to which such data are input to set control measures;
5. Projecting the OMs forward using the MPs as a feedback controller, i.e.where information about the gap between the actual and reference levels is used to alter the gap in some way (**?**); and
6. Agreeing the MP that best meets management objectives.

### *Management Objectives*

a) Management objectives, such as maximizing average catch, minimizing inter-annual fluctuations in TAC levels, returning or maintaining the stock in the green quadrant of the Kobe plot, etc., taking into account the requirements of Rec.[11-13];

b) Acceptable quantitative level(s) of probability of achieving and/or maintaining stocks in the green zone of the Kobe plot and avoiding limit reference points; and

c) Timeframes for halting overfishing on a stock and/or rebuilding an overfished stock.

***Operating Model***

The Operating Model scenarios are summarised in Table 1 and those for the Observation Error Model in 1.

The management objectives and performance statistics are summarised in Tables 1 and 1 respectively.

*Observation Error Model*

The Management Procedure (MP) is based on a biomass dynamic model uses total catch biomass and catch per unit effort (CPUE) data. These data are sampled from the OM by the Observation Error Model (OEM), the component of the OM that generates fishery-dependent and/or fishery-independent resource monitoring data.

In the past the SCRS of ICCAT stock assessment working groups have tended to run stock assessment including all the available CPUE series. CPUE indices tend to be conflicting and this practice result is parameter estimates intermediate to what would be obtained from the data sets individually, and Schnute and Hilborn (1993) showed the most likely parameter values are not intermediary but occur at one of the apparent extremes. Therefore a new procedure is being used by the SCRS; i.e. groups of indices that show similar trends are identified and these are these groups of CPUEs are run as separate assessment scenarios; then a hindcast is run (Kell et al. submitted) to distinguish signal from noise. Only those CPUEs which past the hindcast test are then used in the actual assessment.

A 30% CV was chosen based on the Multifan-CL fits to the CPUE; no bias was found in the main longline CPUE or evidence of hyper-stability. In most tuna stock assessments, due to the lack of fisheries independent data, commercial catch per unit effort (CPUE) is used as a proxy for relative abundance. CPUE standardisation is intended to allow for changes in operational procedures, which may result in increases in efficiency and catchability. However, it has long been recognised that such time series may not accurately reflect trends in population abundance (e.g. Beverton and Holt, 1993; Harley et al., 2001; Maunder et al., 2006; McKechnie et al., 2013; Polacheck, 2006). Particularly since factors that affect changes in the spatial distribution of populations and the allocation of effort in response to management and economic drivers can affect catch and effort independent of stock abundance (e.g. Paloheimo and Dickie, 1964; Tidd et al., 2011). While interactions between changes in oceanographic conditions and exploitation can drive spatial and temporal dynamics (see Fromentin et al., 2013; Arrizabalaga, 2014).

We therefore adopt the MSE approach used by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) where robustness trials are conducted (Hillary et al., 2015) based on hypotheses about the relationship between CPUE and stock abundance (Table 1). These are i) positive bias in future longline CPUE due to a trend in catchability; and ii) hyper-stability where there is nonlinear relationship between longline CPUE and abundance so that proportional changes in actual abundance are greater than those observed in the CPUE (Harley et al., 2001).

### *Management Procedure*

The approach taken by ICCAT is that of the IOTC. Where in the determination of appropriate reference points and harvest control rules, consideration must be given to major uncertainties, including the uncertainty about the status of the stocks relative to reference points. IOTC will also assess through management strategy evaluation the performance of reference points, including any interim reference points, and of potential harvest control rules to be applied as the status of the stocks approaches the reference points. The scientific committee of the IOTC is therefore setting interim limit and target reference points for current use in defining limits and targets. MSE will then be used to evaluate the LRPs these as part of a HCR. The approach taken by the albacore working group allowed advice to be provided in the Kobe framework consistent with the Commissions decision making policy for development and application of conservation and management measures (Rec. 11-13). In order to advance the Commission-SCRS dialogue, the Albacore WG provided information to the Commission on the basis of a range of interim HCR parameters, i.e. target fishing mortalities and biomass threshold (or buffer which if the stock fell below would result in fishing mortality being reduced). The HCR meets the Commissions policy objectives based on the assessment outcomes, e.g. 1) For 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 in the upper right yellow quadrant of the Kobe plot (overfishing), the Commission shall immediately adopt management measures designed to result in a high probability of ending overfishing in as short a period as possible. 3) For stocks in the red quadrant of the Kobe plot (overfishing and overfished), the Commission shall immediately adopt management measures, designed to result in a high probability of ending overfishing in as short a period as possible and the Commission shall adopt a plan to rebuild these stocks, and 4) For stocks in the lower left yellow quadrant of the Kobe plot (overfished but no overfishing), the Commission shall adopt management measures designed to rebuild these stocks in as short a period as possible.

The harvest control rule (HCR) used is shown in Figure 1; the brown line sets the harvest rate (y-axis) depending on the estimated stock biomass (x-axis). The black line is the replacement line, i.e. for a given stock biomass a harvest rate above the black line will cause the stock to decline and a harvest rate below the line will cause the stock to increase. The light blue line shows the simulated stock. For a given target harvest rate (i.e. the horizontal part 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 or threshold biomass reference point) the harvest rate is reduced progressively to a minimum level of harvest rate at a biomass level equal to the LRP.

Biomass dynamic models combine recruitment, growth and natural mortality into a three parameters population model i.e. the intrinsic growth rate ($r$), carrying capacity ($K$) and shape of the surplus production curve ($p$). It is assumed that recruitment is a linear function of stock and all individuals spawn at age 1, have the same body mass, and that M is constant. We use the term biomass dynamic rather than surplus production since surplus production can also be considered when using an age structured model (**?**).

### *Simulation*

## Results

The impact of OM assumption on reference points and population parameters are summarised in Figure 2. In all cases the production function was skewed to the left, this means that the Schaefer (Logistic) production model is probably not appropriate and that a Pella-Tomlinson form with BMSY¡0.5B0 is probably more realistic. An asymmetric yield curve will also allow lower levels of current depletion to be possible as productivity will be less impaired at low biomass. Of all the life history parameters steepness had the biggest impact (e.g. on $r$ and $F_{MSY}$).

To understand the impact of misspecification of the production function a logistic production function was fitted to the OM scenarios for 1000 Monte Carlo replicates and the estimates of reference points and population compared with the OM values (red vertical line) in (Figures 3 for p=1 and 4 for p known). Rows correspond to the quantity that was penalised, columns show the quantity being estimated; red indicates where the estimated quantity was also penalised.

## Discussion

## Conclusions

## 1. Acknowledgement

This study does not necessarily reflect the views of ICCAT and in no way anticipates the Commission's future policy in this area.

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**Table 1.** Operating Model Scenarios; Base Case values in bold.

| | Levels (N) | $\prod$ N | Values |
|---|---|---|---|
| stock recruitment relationship | 2 | 2 | **Beverton and Holt**; Cushing |
| Steepness | 2 | 4 | **.9**; .75 |
| $M$ | 2 | 8 | **Lorezen**; Chen & Watanabe |
| $Growth$ | 2 | 16 | **N. Atl. Life History**; Slower growth |
| $Maturity$ | 2 | 32 | **N. Atl.**; Life History |
| Selectivity I | 2 | 64 | **as Mat**, domed |
| Selectivity II | 2 | 128 | **as Mat**, juvenile |
| Autocorrelation | 2 | 256 | **0**; 0.3 |

**Table 2.** Observation Error Model Scenarios; Base Case values in bold.

| | Levels (N) | $\prod$ N | Values |
|---|---|---|---|
| Trend in catchability | 2 | 2 | **None**; 50% |
| Hyperstability | 2 | 4 | **1**; 0.75 |

308 ## Tables

**Table 3.** Management Objectives

| Rule | Definition |
|---|---|
| O1 | Maintain the stock in the *green kobe quadrant* |
| O2 | Achieve the maximum continuing catch |
| O3 | Maintain high employment |
| O4 | Stability of yield |
| O5 | Stability of effort |

**Table 4.** Performance Statistics

| Statistic | Definition |
|---|---|
| P1 | Probability of SSB $\geq B_{MSY}$ and F $\leq F_{MSY}$ |
| P2 | Catch |
| P3 | Effort |
| P4 | AAV Catch |
| P5 | AAV Effort |

**Table 5.** Acronyms

| | Definition |
|---|---|

## Figures

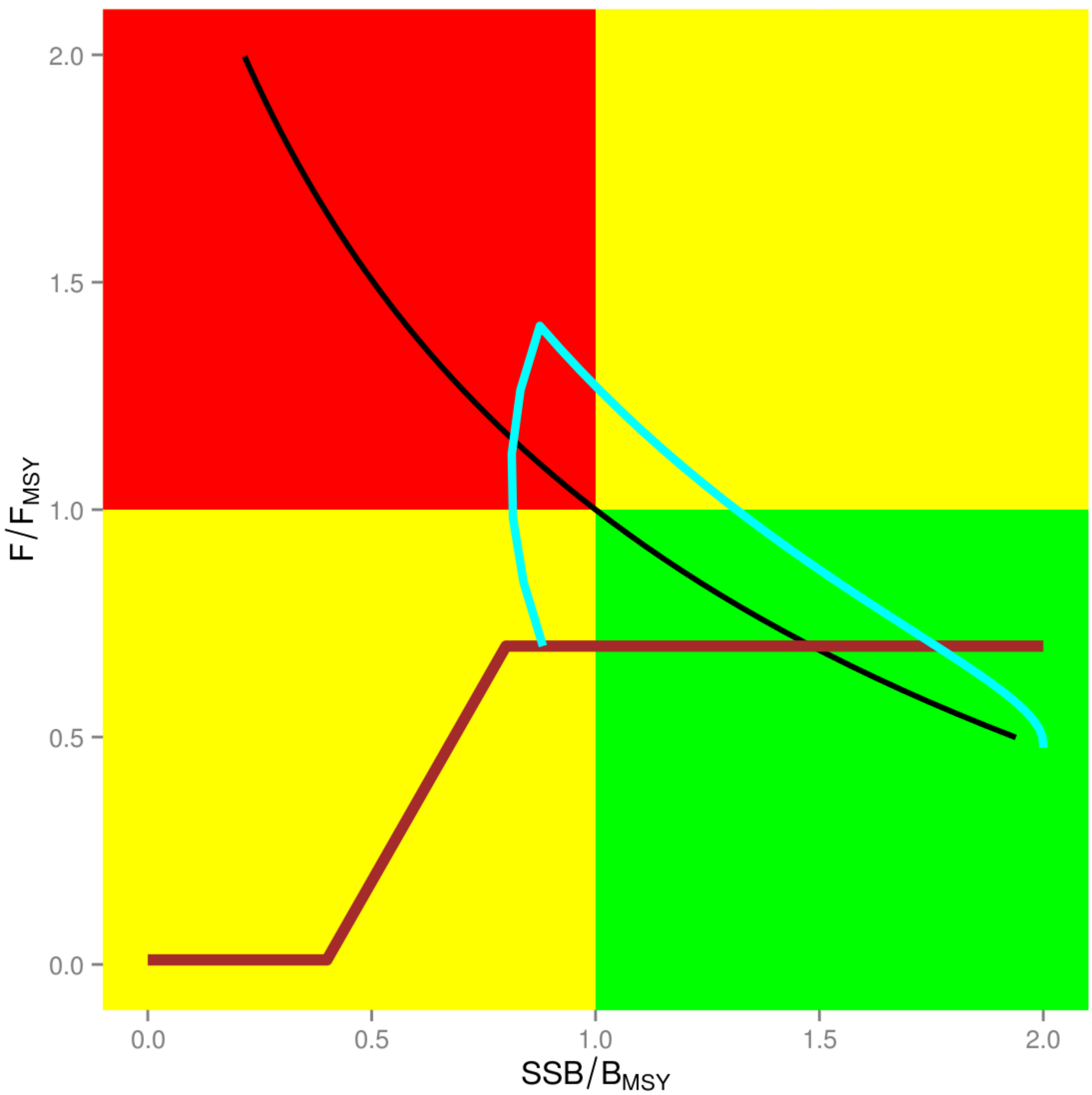


**Fig. 1.** Harvest Control Rule (brown) plotted on a phase plot of harvest rate relative to $F_{MSY}$ and stock biomass relative to $B_{MSY}$; the light line is the simulated stock and the black line is the replacement line.

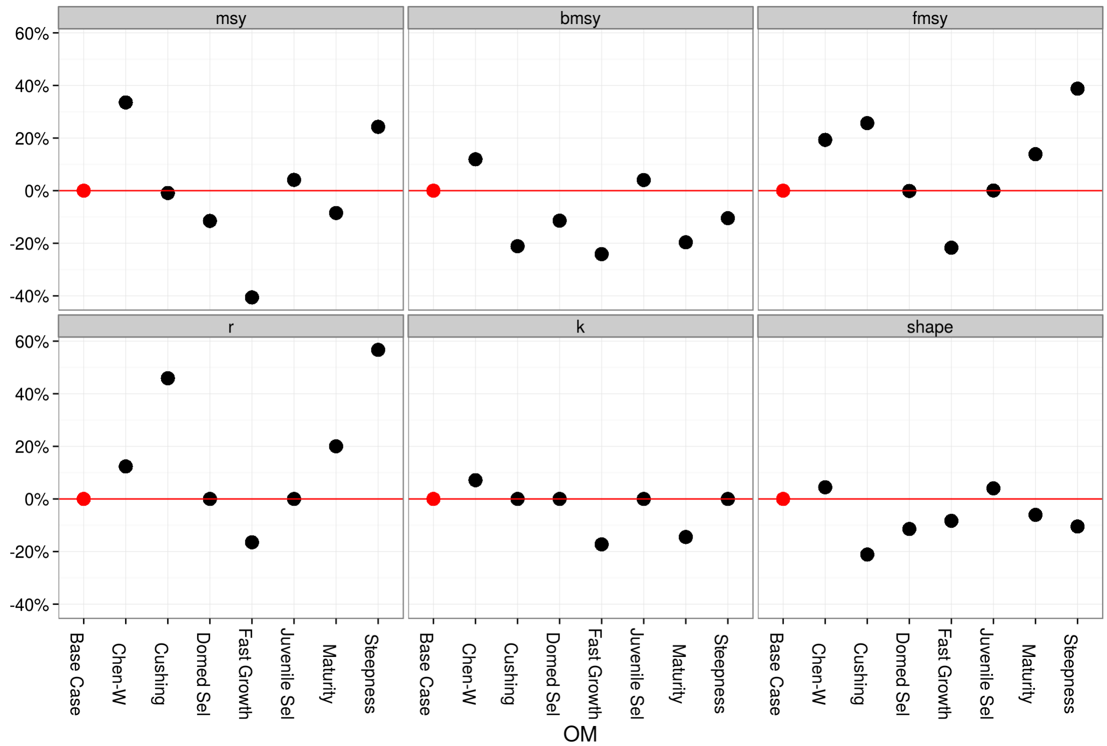


**Fig. 2.** Population parameters and reference points by OM scenarios, values are relative to the Base Case (red).

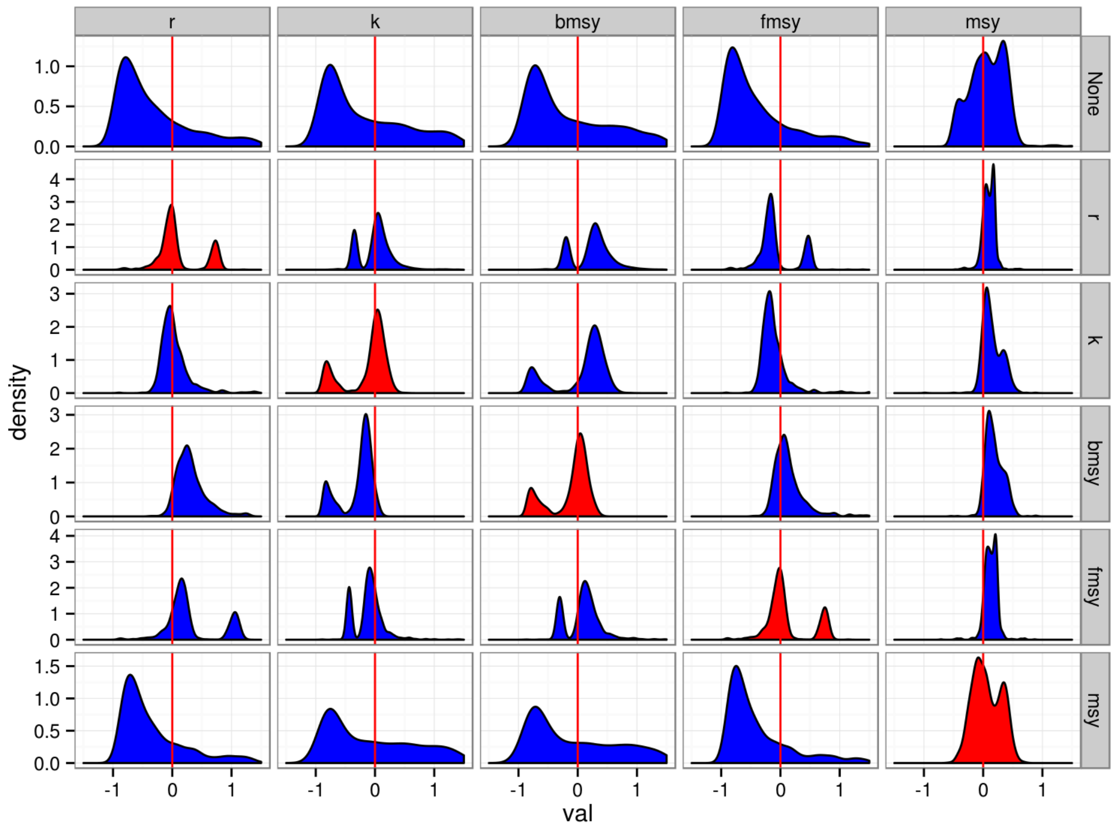


**Fig. 3.** A comparison of reference points and population parameters estimated by the Stock Assessment in the MP for the Base Case OM, where the production function is assumed to be symmetric (p=1). Columns give the quantity and rows indicate the value was penalised in the likelihood based on the OM value.

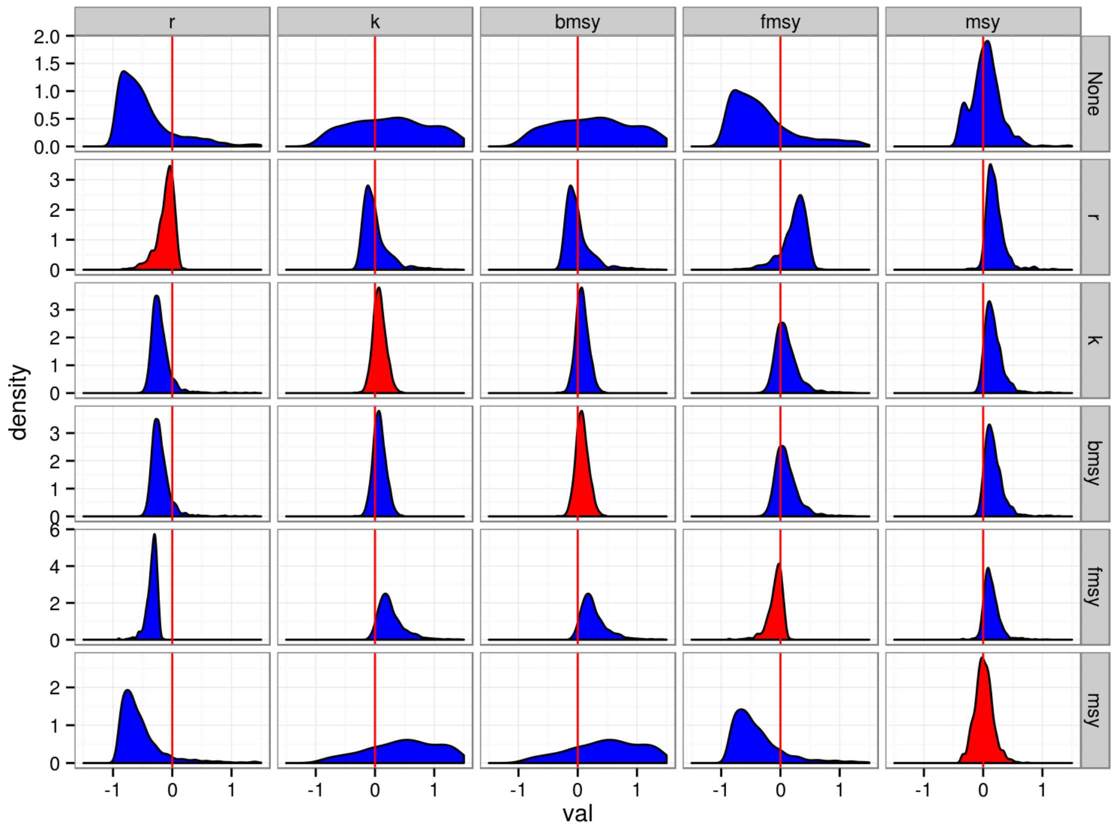


**Fig. 4.** A comparison of reference points and population parameters estimated by the Stock Assessment in the MP for the Base Case OM, where the production function has the same shape as in the OM. Columns give the quantity and rows indicate the value was penalised in the likelihood based on the OM value.

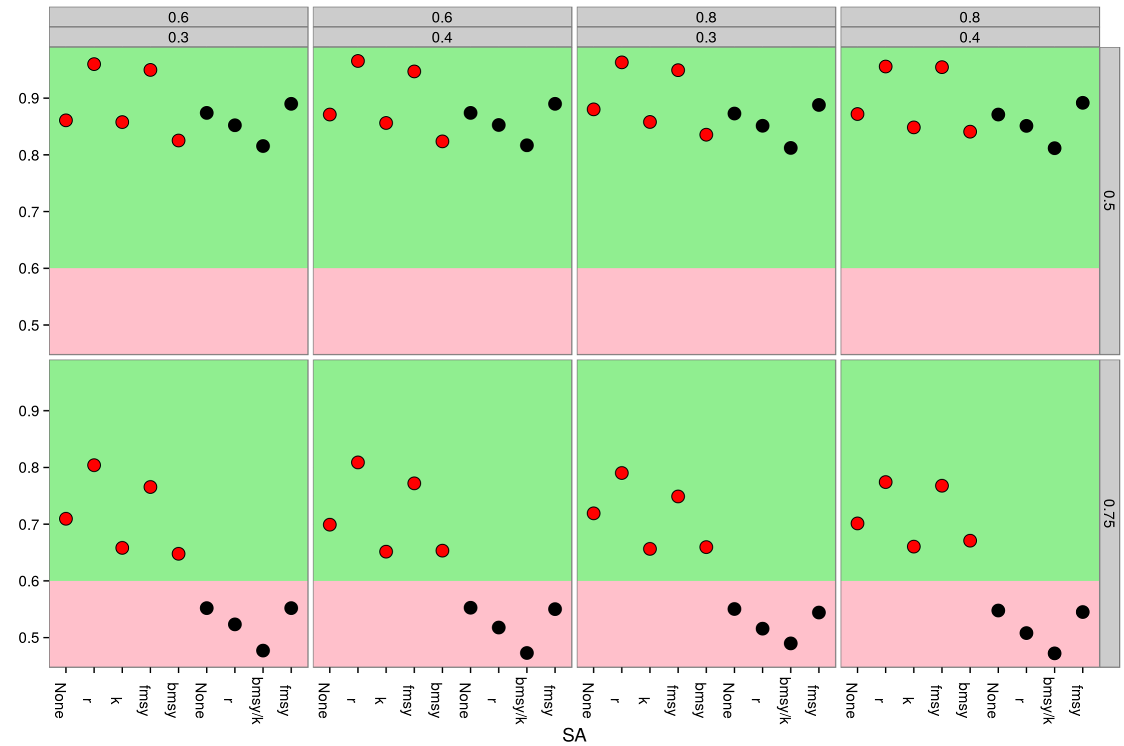


**Fig. 5.** Probability of being in the green quadrant of the Kobe phase plot, by biomass thresholds and limits as a proportion of $B_{MSY}$ (columns) and fishing mortality targets as a proportion of $F_{MSY}$ (rows)

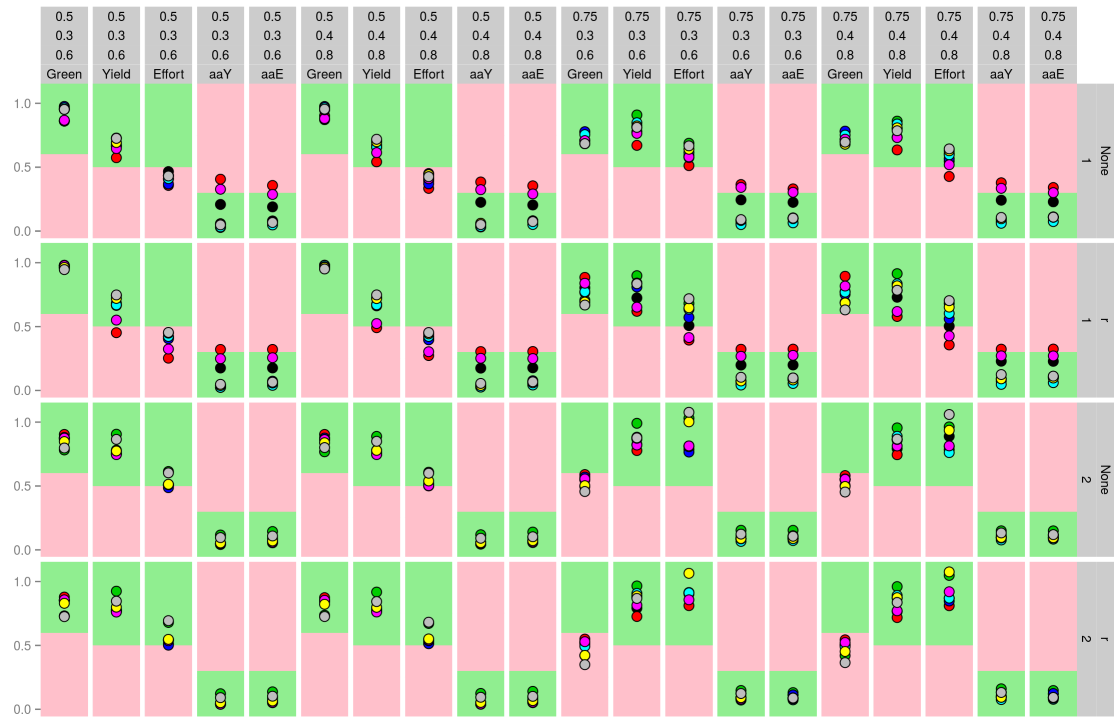


**Fig. 6.** Summary.

## 2. Appendix

# Equations

## Operating Model

Growth was modelled by the Von Bertalanffy (1957) growth equation i.e.

$$L_t = L_\infty(1 - e^{-kt-t_0}) \tag{1}$$

where $L_\infty$ is the asymptotic length attainable, $k$ the rate at which the rate of growth in length declines as length approaches $L_\infty$, and $t_0$ is the time at which an individual is of zero length.

Mass-at-age is then derived from length using a scaling exponent ($a$) and the condition factor ($b$)

$$W_t = a \times W_t^b \tag{2}$$

Maturity ($Q$) was either based on Santiago (2004) or derived as in Williams and Shertzer (2003) from the theoretical relationship between $M$, $K$, and age at maturity ($a_Q$) based on the dimensionless ratio of length at maturity to asymptotic length (Beverton, 1992). It was then modelled by the logistic equation with 2 parameters: age at 50% ($a_{50}$) and 95% ($a_{95}$) mature.

$$f(x) = \begin{cases} 0 & \text{if } (a_{50} - x)/a_{95} > 5 \\ a_\infty & \text{if } (a_{50} - x)/a_{95} < -5 \\ \frac{m_\infty}{1.0+19.0^{(a50-x)/a95)}} & \text{otherwise} \end{cases} \tag{3}$$

Natural mortality ($M$) at-age was derived from Lorenzen and Enberg (2002) and Chen and Watanabe (1989), i.e.

for Lorenzen

$$M_t = 3.00 * W_t - 0.288 \tag{4}$$

and Chen-Watanabe

$$M_t = \begin{cases} \frac{k}{1-e^{-k(t-t_0}} & \text{for } t < t_m \\ \frac{k}{a_0} + a_1(t-t_m) + a_2(t-t_m)^2 & \text{for } t < t_m \end{cases} \tag{5}$$

where

$a_0 = 1 - e^{-k(t-t_0)}$

$a_1 = ke^{-k(t-t_0)}$

$a_2 = -0.5k^{2e^{(-k(t-t_0))}}$

$t_m = \frac{1}{k}log(1 - e^{-kt_0}) + t_0$

Selectivity was modelled using a double normal (see Hilborn et al., 2000) with three parameters that describe the age at maximum selection ($a1$), the rate at which the left hand limb increases ($sl$) and the right hand limb decreases ($sr$) which allows flat topped or domed shaped selection patterns to be chosen.

$$f(x) = \begin{cases} 2^{-[(x-a_1)/s_L]^2} & \text{if } x < a_1 \\ 2^{-[(x-a_1)/s_R]^2} & \text{otherwise} \end{cases} \tag{7}$$

Stock recruitment relationships were either (Cushing, 1973)

$$R = aS^b \tag{8}$$

or Beverton and Holt (**?**)

$$R = \frac{S}{a+bS} \tag{9}$$

## Observation Error Model

## Management Procedure

The biomass of a stock next year ($B_{t+1}$) is equal to the biomass this year $B_t$, less the catch ($C_t$) plus the surplus production ($P_t$) i.e.

$$B_{t+1} = B_t - C_t + P_t \tag{10}$$

$P$ is given by the Pella-Tomlinson surplus production function (Pella and Tomlinson, 1969)

$$\frac{r}{p} \cdot \; B(1 - (\frac{B}{K})^p) \tag{11}$$