Management strategy evaluation for the Indian Ocean skipjack tuna fishery

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1. Summary

This report describes work towards Management Strategy Evaluation (MSE) for the Indian Ocean skipjack tuna (*Katsumwonus pelamis*) fishery. MSE is the simulation-based evaluation of alternative fisheries management policies. This research was initiated by the Maldives pole-and-line fishery in partial fulfillment of the conditions of its Marine Stewardship Council (MSC) certification (Adam et al 2013) and developed as part of the work programme of the Working Party on Methods (WPM) of the Indian Ocean Tuna Commission (IOTC).

A simulation model of the skipjack fishery in the Indian Ocean was developed to use as the basis for MSE. The model attempts to capture the complexities of the fishery whilst remaining simple enough too be both understandable and computationally tractable. The model is spatially explicit with an age-structured fish population and four fishing gears in each of three regions (West, East and Maldives).

Several classes of management procedure were developed and preliminary evaluations done. These classes were intended to be illustrative of the diversity of potential MPs and their relative performance. These classes included MPs based on regular estimates of total mortality (e.g. from tagging), relative catch-per-unit-effort (CPUE) and estimates of stock status from stock assessments.

The development of both the simulation model and management procedures (MP) as well as preliminary evaluations were presented to IOTC Working Parties, feedback obtained and revisions made. In February 2016, a workshop of Indian Ocean coastal states was held to focus on a particular class of MP to form the basis of proposal to the Commission. That workshop concluded that, in the short term, a management procedure based on the existing triannual stock assessments was most appropriate. The "Mald2016" management procedure, which sets a annual catch limit based on the estimate of stock status from each stock assessment was subsequently developed and refined based on further feedback. Evaluations of this MP are presented.

Alongside, the IOTC's other MSE work programmes for albacore, yellowfin and bigeye tuna, this work has contributed to the establishment of fisheries management procedures within the Indian Ocean. However, this work is only the first step. We conclude with a discussion of the inadequacies of this study and highlight where more work is required.

2. Model

Management strategy evaluation, as a simulation based exercise, requires a simulation model of the fishery. In the MSE context, the term "operating model" is often used to describe such a model (to distinguish it from an "assessment model" which may be part of the MP itself). In this section we provide a general overview of the structure of the simulation model developed for the Indian Ocean tuna fishery.

2.1. Structure and assumptions

The following convention is used for assigning symbols in the following model equations: Greek lower case letters for model parameters (e.g. α for the intercept of the length-weight relationship), Roman capital letters for model variables (e.g. N for numbers), and Roman lower case letters for variable or parameter array subscripts (e.g. $N_{r,a,s}$, ϕ_r). Using this convention means that in some instances model parameters are given different symbols than are usually used. However, it has the advantage of clearly distinguishing model parameters (i.e. values which are independent of other values in the model and are usually estimated) from model variables (i.e. values which are dependent upon parameters and the model dynamics). The subscript for time, t, is usually omitted from the model equations below except where it is necessary to be explicit regarding the time step involved.

As well as documenting the current structure of the model, this section also notes where potential changes could be made. Usually, these potential changes would make the model more complex. Our approach has been to start simple and add complexity where necessary, in particular, in response to comments and suggestions from IOTC Working Parties.

2.1.1. Dimensions

Several dimensions are used to partition aspects of the model (e.g. fish numbers, catches). Table 1 provides the symbols associated with each of these dimensions.

2.1.1.1. Time

The model uses a quarterly, i.e. three month, time step (t). Each time step, t, has an associated calendar year (y) and calendar quarter ($q \in 0, 1, 2, 3$).

2.1.1.2. Regions

Three regions (r) are defined, West (we), Maldives (ma) and East (ea) (Figure 1). The term "region" is used in preference to "area" because using the latter would confound the a subscript which is also used for age.

Initially three regions were defined mostly on the basis of differences in the main fishing gears used in each: purse-seine in the west, pole-and-line in the Maldives, and gill-net in the east. Although the Maldives is a small region spatially, it accounts for a large proportion of the total catch (see later sections). A three region structure also provided alignment between the model structure and the two available abundance indices, CPUE from the western purse seine fleet and CPUE from the Maldive pole-and-line fleet.

There is little information available on biological stock definitions for Indian Ocean skipjack tuna. However, based on what information is available, Fonteneau (2014), suggested four regions be used, with the western region divided into northern and southern regions at the equator. Following this suggestion, in 2015, the western region was divided into separate south-west (SW) and north-west (NW) regions. The spatial distribution of catches by the EU purse seine fleet shows a strong discontinuity of the catch distribution at -10 degrees south (Figure 1) so the western region was divided on this basis rather than at the equator.

However, after this change was made, and further analyses were done the WPM concluded that there was little basis for separating the SW region (dominated by highly seasonal catches in the Mozambique channel) and no reliable information for estimating movement between SW and NW. Thus, in ealry 2016, the model was reverted to three regions.

2.1.1.3. Fish age and size

Fish recruit to the model in each quarter and the model keeps track of their numbers by their age (a), in quarters up to six years i.e. $0, 1, 2, \ldots, 23$. Fish size (s) is represented in forty, 2cm bins, $0-2, 2-4, \ldots, 78-80cm$.

2.1.1.4. Fishing methods

Four fishing methods (i.e. gears) (m) are defined : purse seine (ps), pole and line (pl), gill net (gn) and other (ot). There are differences in the size distribution of free-school and associated-school purse seine sets. However, given the low proportion of free-school sets, particularly in recent years, it was considered unnecessary to model these subcomponents separately.

Table 1: Summary of model dimensions and symbols used for each.

Symbol	Description
Time	
t	Time step
y	Calendar year
q	Calendar quarter; 1 = Jan-Mar
Regions	
r	Region subscript
we	West region
ma	Maldives region
ea	East region
Fish age and size	
a	Fish age group
$\vec{a}$	Maximum age in the model
s	Fish size group
$\vec{s}$	Largest size group in the model
Fishing methods	
m	Fishing method subscript
ps	Purse seine
pl	Pole and line
gn	Gill net
ot	Other

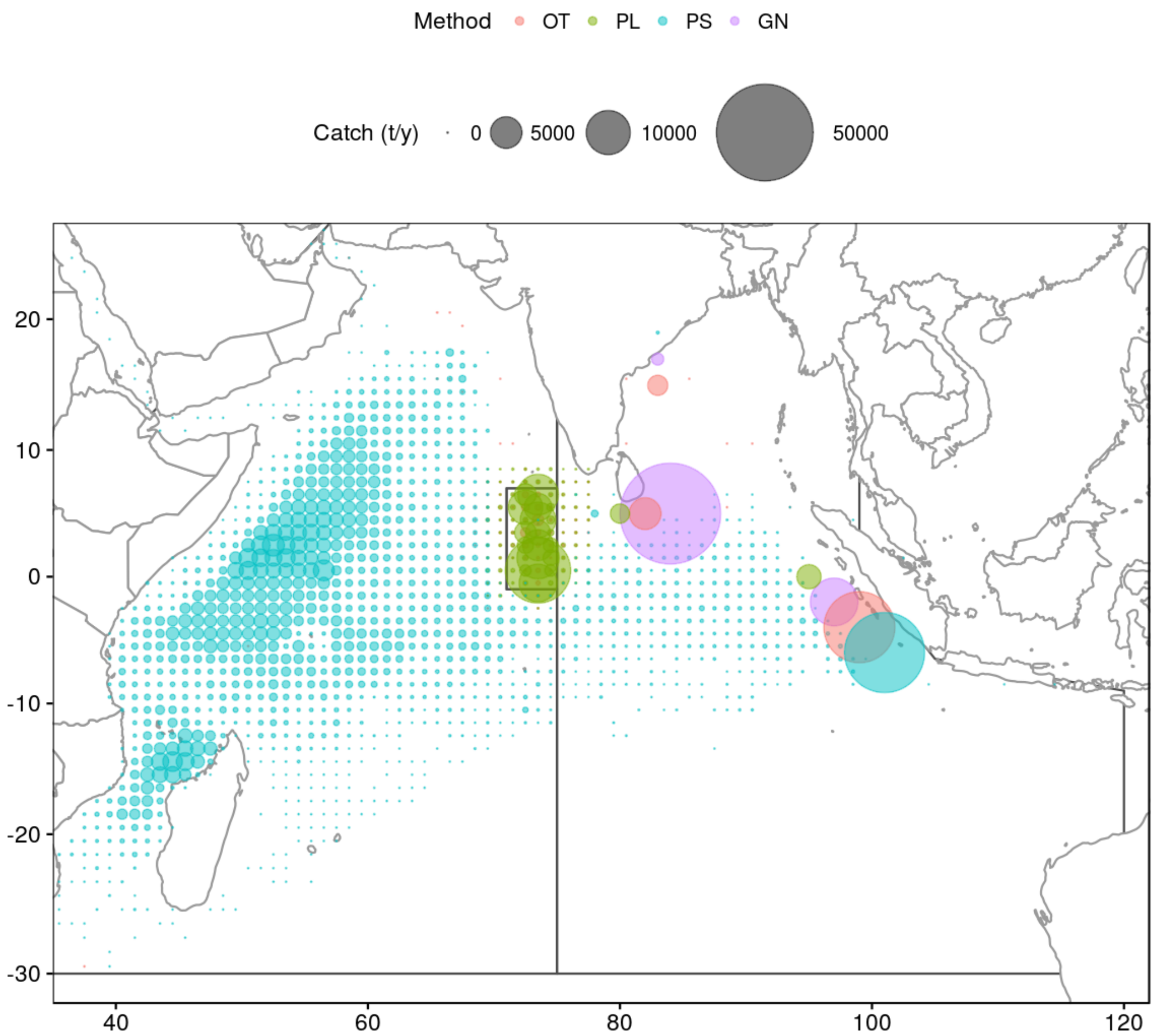


Figure 1: Map of the three regions defined for the model and the spatial distribution of average annual catch by method, 2005-2014. The position of catches from the western purse-seine and the Maldive pole-and-line fisheries is based on reported latitude and longitudes. The position of other catches is indicative only and only shown for the main coastal nations catching skipjack - Indonesia, Sri Lanka, India, Pakistan and Iran.

2.1.2. Population dynamics

2.1.2.1. Numbers

Fish numbers are partitioned by region and age $N_{r,a}$. In each quarter, recruitment to the model and ageing occur as follows.

The maximum age group, $\vec{a}$, accumulates fish from the previous age, $\vec{a} - 1$,

$$N_{r,\vec{a}} = N_{r,\vec{a}} + N_{r,\vec{a}-1}$$

For ages 1 to $\vec{a} - 1$, simple ageing occurs,

$$N_{r,a} = N_{r,a-1}$$

For age 0, recruitment occurs,

$$N_{r,0} = R_r$$

where R_r is the number of fish recruiting to age 0 in region r.

Numbers are updated in each quarter by applying natural mortality, movement, and fishing mortality as described in the following subsections.

2.1.2.2. Growth

The distribution of lengths at age is modelled as a normal distribution with a mean and standard deviation,

$$L_a \sim N(\mu, \sigma)$$

Mean length at age is determined from the two-stanza growth model and parameter estimates of Everson et al (2012, 2014).

$$\mu = \lambda \left(1 - e^{-\kappa_2 (a - a0)} \left(1 + \frac{e^{-\phi \cdot (a - a0 - \delta)}}{1 + e^{\delta \cdot \phi}} \right)^{-\frac{\kappa_2 - \kappa_1}{\phi}} \right)$$

where $a0$ age 0, ϕ is the steepness, δ is the inflection.

At present, it is assumed that growth is the same in all three regions. It is likely that in fact growth differs between regions in which case some, or all, of the growth parameters could vary by region e.g λ_r.

2.1.2.3. Weight and maturity

The weight of fish of size s is modelled as an exponential curve,

$$W_s = \alpha (L_s)^\beta$$

Currently, the model assumes that the parameters of the length-weight relationship are the same in the three regions. It is possible that condition factors consistently vary among regions, in which case these parameters could be made to vary by region i.e. α_r, β_r

The proportion of fish of size s that are mature is modelled as a logistic curve,

$$O_s = \frac{1}{1 + \frac{19^{\tau - L_s}}{\upsilon}}$$

Currently, the model assumes that the parameters of the maturity curve are the same in all three regions but could be made to vary by region i.e τ_r, υ_r. In addition, maturity could be modelled as a function of age, rather than size, i.e. O_a.

2.1.2.4. Spawning and recruitment

The proportion of mature fish that spawn in each quarter is allowed to vary according to a quarterly parameter, ρ_q. Currently, this parameter is the same for all regions. Evidence of regional differences in spawning seasonality would suggest making these parameters vary by region.

The biomass of mature fish is a function of the number of fish by age and size and the maturity and weight ogives by size,

$$B_r = \sum_{a=0...\vec{a},s=0...\vec{s}} N_{r,a,s} O_s W_s$$

where O_s is the proportion of fish that are mature at size s, W_s is the weight of fish at size s. We refer to this variable as the "biomass of spawners" and it is used as the basis for determining stock status, i.e B/B_0. It differs from the "spawning biomass" it that it is independent of the seasonal spawning fraction.

The total number of eggs produced is based on the total spawning biomass,

$$E = \sum_{r \in \{we,ma,ea\}} B_r \rho_q$$

where ρ_q is the proportion of fish that spawn in quarter q.

The total number of eggs determines the total number of recruits over all three regions, $\overline{R}$ according to the Beverton-Holt stock recruitment function,

$$\overline{R} = 4\eta\theta \frac{E}{(5\eta - 1)E + \dot{E}(1 - \eta)} D_t$$

where η is steepness, θ and $\dot{E}$ are the respectively the number of recruit and eggs in the absence of fishing, and D_t is the recruitment deviation at time t which is lognormally distributed with mean of 1 and standard deviation of σ.

This total recruitment is distributed across the three regions,

$$R_{r,s} = \overline{R} \cdot \chi_r \cdot A_s$$

where χ_r is the proportion of recruits which recruit into region r and A_s is the proportion of recruits that are at size s which is based on a normal distribution with mean, μ and standard deviation ζ,

$$A_s = \frac{1}{\sqrt{2\pi\zeta^2}} e^{-((L_s-\mu)^2)/2\zeta^2}$$

2.1.2.5. Natural mortality

The instantaneous rate of natural mortality at size s is modelled as a function of weight at size s using the form of Lorenzen,

$$M_s = \nu W_s^\gamma$$

To prevent M_s going to very high levels at low s, M_s is restricted to be a maximum of M_{10} (i.e. the mortality at size bin 10, i.e. length of 21cm).

The rate of survival from natural mortality in one quarter of a fish of size s, is,

$$D_s = e^{-0.25M_s}$$

2.1.2.6. Movement

[This section has not been edited to account for the reversion to a three region model (see above)]

The movement of fish among the four regions can be described using a matrix of the proportion of fish moving from region $\dot{r}$ to region r in one quarter. This matrix potentially has twelve parameters (since the parameters are proportions the diagonal elements are determined from the other elements in the row). To reduce the number of parameters, we make some simplifying assumptions:

- that movement between two adjacent areas is non-directional (i.e. that the proportion of fish in the MA region that move to the NW region is the same as the proportion of fish in the MA region that move to the NW region),
- that there is no direct movement within one quarter between SW and MA, and between SW and EA (i.e. that the movement parameters for these pairs are zero)

The movement parameter matrix thus becomes:

$$M_{\dot{r},r} = \begin{bmatrix} 1 - \omega_{sw,nw} & \omega_{sw,nw} & 0 & 0 \\ \omega_{sw,nw} & 1 - \omega_{sw,nw} - \omega_{nw,ma} - \omega_{nw,ea} & \omega_{nw,ma} & \omega_{nw,ea} \\ 0 & \omega_{nw,ma} & 1 - \omega_{nw,ma} - \omega_{ma,ea} & \omega_{ma,ea} \\ 0 & \omega_{nw,ea} & \omega_{ma,ea} & 1 - \omega_{nw,ea} - \omega_{ma,ea} \end{bmatrix}$$

defined by the parameters $\omega_{sw,nw}, \omega_{nw,ma}, \omega_{nw,ea}, \omega_{ma,ea}$.

Currently, movement is uniform across all ages and sizes. An alternative would be to have separate movement parameters for each age or size e.g. $\omega_{nw,ma,a}$, or more simply, to model the relative proportion of fish moving as varying by age or size. Also, currently there is no seasonal movement.

In summary, at present, whilst the model keeps account of fish numbers by region, only two of the biological characteristics of the stock vary by region: the proportion of recruitment going to each and the movement between each. As noted above, many of the model's parameters could be made to vary by region but this is likely to be of little value without information with which to inform how much those parameters should vary by region.

2.1.3. Harvest dynamics

The biomass that is vulnerable to each method, m in each region r, is calculated by summing over ages and sizes,

$$V_{r,m} = \sum_{a=0,\ldots,\vec{a},s=0,\ldots,\vec{s}} N_{r,a,s} W_s P_{m,s}$$

where $P_{m,s}$ is the relative selectivity of method m for fish of size, s.

Selectivity is modelled as a function of length using a piecewise spline with knots at every ten centimeters from 20cm to 80cm.

Catches are compiled by region and method, $C_{r,m}$ from IOTC data. The exploitation rate in region r of method m is then,

$$E_{r,m} = \frac{C_{r,m}}{V_{r,m}}$$

2.2. Parameters priors and sensitivity ranges

For each model parameter a prior probability distribution and a sensitiveity range is defined. The priors are used in conditioning algorithms and are intended to represent the knowledge and associated uncertainty regarding a parameter based on previous research. For some parameters, such as stock recruitment steepness η, there is unlikely to be any information in the data and so the prior may be influential. The sensitivity range is used in robustness testing of candidate management procedures to assess how sensitive a they are to parameter values which are possible but which are determined, on the basis of either priors or conditioning, to be unlikely.

At present, only some of these prior distributions are used in conditioning because parameter estimates from the latest stock assessment are being used where possible. However, for those parameters which are not estimated or assumed in the assessment (e.g. movement parameters), these priors will be of relevance. The priors described here should not be considered definitive and ideally should be be refined in consultation with a wider group of Indian Ocean tuna scientists.

2.2.1. Spawning and recruitment

In the western Indian Ocean, skipjack spawning appears to occur all year but with periods of greater activity during the North-east monsoon (November to March) and South-west monsoon (June to July) (Grande 2013 and references cited therein). Grande (2013) summarised the percentage of fish in the "spawning capable" phase in the months January to July. This percentage was highest during January and February (85%) decreasing to 51.9% in May and then increasing again to 82.4% in June and 73.3% in July. These percentages were used as the basis for a uniform prior on each ρ_q (Table 2). We assumed that the spawning percentage during the fourth quarter, October to December, was the same as during the second quarter.

Following Mangel et al. (2010) the prior for stock-recruitment steepness is based on a beta probability distribution function for a precursor parameter

$$\dot{\eta} \sim B(10, 2)$$

$$\eta = \frac{\dot{\eta} + 0.25}{1.25}$$

where $B(.)$ is the beta distribution. This formulation allows for η to be constrained between 0.2 and 1. The resulting prior for steepness has a median of 0.84 and 5, 20, 80 and 95th percentiles of 0.67, 0.76, 0.9, 0.93 respectively.

For the standard deviation of stock-recruitment deviations, σ a lognormal prior with a mean of 0.6 and a standard deviation of 0.5 was used based on Myers (2002) Figure 6.5 which has a median of about 0.6 for Scombridae.

2.2.2. Mortality

The instantaneous rate of natural mortality at 1kg, ν, the same normal prior as in Sharma et al (2012) was used which has a mean of 0.8 and a standard deviation of 1.

A prior for the allometric exponent of the weight to natural mortality function, γ was based on Lorenzen (1996) who estimated a value on -0.29.

2.2.3. Growth

The priors for the growth curve parameters were from Hillary (2011). His Table 2 provides estimated posterior distributions for κ, λ and φ from analysis of tagging data. For comparision, Sharma et al(2012) assumed 0.37 and 70 for κ, λ based on Anganuzzi & Million (pers. comm.).

Hillary's estimate of 78.8 for φ seems to be very high given that this is a coefficient of variation an hence needs to be multiplied by the increment to calculate a standard deviation (although note that Hillary's Equation 1 says multiplied by the length).

2.2.4. Weight and maturity

Priors for length-weight parameters, α and β, were based on the fixed values used in Sharma et al (2012) with a coefficient of variation of 5% (Table 2).

Priors for maturity ogive parameters, τ and υ were based on the results of Grande (2013). For the inflection point, τ, based on Grande's estimated a value of 39.9cm, a normal prior with mean of 40cm and a coefficient of variation of 5% was used. Note that Table 4.2 of Grande (2013) indicates that some earlier studies in the Indian Ocean estimated values around 42-43cm for the inflection point. Sharma et al (2012, 2014) assumed 38cm based on Grande et al. (2010).

Figure 7.3 of Grande (2013) shows 5% and 95% maturity at about 35cm and 44cm respectively. Given a 50% maturity of 40cm this corresponds to a steepness parameter, υ, of about 5cm. A normal distribution with a mean of 5cm and a 10% c.v. was used (Table 2).

2.2.5. Movement

There is little quantitative information on movement rates between the three regions. A uniform prior, $U(0.2, 0.8)$ was used for all elements of the movement matrix $M_{\dot{r},r}$

2.2.6. Selectivity

Priors for selectivity parameters were based on estimates from the previous assessment (Figure 1 of Appendix 2 in Sharma et al 2012).

Table 2: Prior probability distributions and sensitivity rages for model parameters. Note that this table may be incomplete. Distributions are indicated as follows: fixed $F(value)$, uniform $U(lower, upper)$, normal $N(mean, sd)$, lognormal $L(mean, sd)$, beta $B(\alpha, \beta)$, mesa $M(\min, lower, upper, \max)$

Symbol	Description	Units	Prior distribution	Sensitivity range
Weight				
α	Coefficient of the length-weight relationship	$t \cdot cm^{-3} \cdot 10^{-6}$	$N(5.32, 0.266)$	4-6
β	Exponent of the length-weight relationship	-	$N(3.35, 0.1675)$	3.0-3.6
Maturity				
τ	Inflection point of the maturity ogive	cm	$N(40, 2)$	35-55
υ	Steepness of the maturity ogive	cm	$N(5, 0.5)$	2-10
Spawning				
ρ_q	Proportion of mature fish spawning in quarter q	-	$\begin{bmatrix} \rho_1 \sim U(0.8, 0.9) \\ \rho_2 \sim U(0.4, 0.6) \\ \rho_3 \sim U(0.8, 0.9) \\ \rho_4 \sim U(0.4, 0.6) \end{bmatrix}$	
Recruitment				
θ	Virgin recruitment	-		
η	Steepness of the stock-recruitment relationship precursor parameter	-	$B(10, 2)$	
σ	Standard deviation of stock-recruitment deviations	-	$L(0.6, 0.5)$	
χ_r	Proportion of total recruits that recruit into region r	-		
μ	Mean length of fish at the end of the first quarter	-		
ζ	Standard deviation of the length of fish at the end of the first quarter	-		
Natural mortality				
ν	Instantaneous rate of natural mortality at a weight of 1kg	yr^{-1}	$N(0.8, 1)$	0.4-1.0
γ	Exponent of weight to natural mortality rate function		$N(-0.29, 0.07)$	[-0.2,-0.4]

Symbol	Description	Units	Prior distribution	Sensitivity range
Growth				
μ	Mean size of fish in their first quarter	cm	$F(20)$	
ϕ	Standard deviation of fish in their first quarter	cm	$F(5)$	
κ	Maximum growth rate	$cm \cdot y^{-1}$	$N(0.28, 0.012)$	0.2-0.4
λ	Assymptotic length	cm	$N(73.7, 1.09)$	70-80
φ	Growth variability	cm	$N(78.8, 2.32)$	
Movement				
$\omega_{\dot{r},r}$	Proportion of fish moving from region $\dot{r}$ to region r		$U(0.2, 0.8)$	0-1

2.3. Implementation

The source code for this project is managed using the Git distributed version control system and is publicly available at https://github.com/iotcwpm/SKJ. The `README.md` file of the repository provides a useful entry point for understanding the organisation of the code.

The model has been implemented using the C++ programming language. C++ was chosen for its high computational speed, considered an important requirement for a model of this complexity, which is to be used to evaluate numerous candidate management procedures, several thousand times. The C++ code is generally well documented and web navigable documentation, generated using the tool Doxygen, is available at http://iotcwpm.github.io/SKJ/doxygen/. As the model is being refined this documentation is updated and as such it should be considered more up-to-date than the above descriptions and equations which may have been superseded.

In addition to the core C++ code, R scripts for the preparation of input data and for the generation of output summaries are available in the repository.

2.4. Outputs

This section presents model outputs generated from the `run` task (i.e. `./ioskj.exe run`) which uses the reference parameter set defined in the `parameters/input` folder. Since those parameter values are user inputs the following may not reflect best parameter estimates. These summaries are primarily intended for illustrating the model structure.

2.4.1. Weight

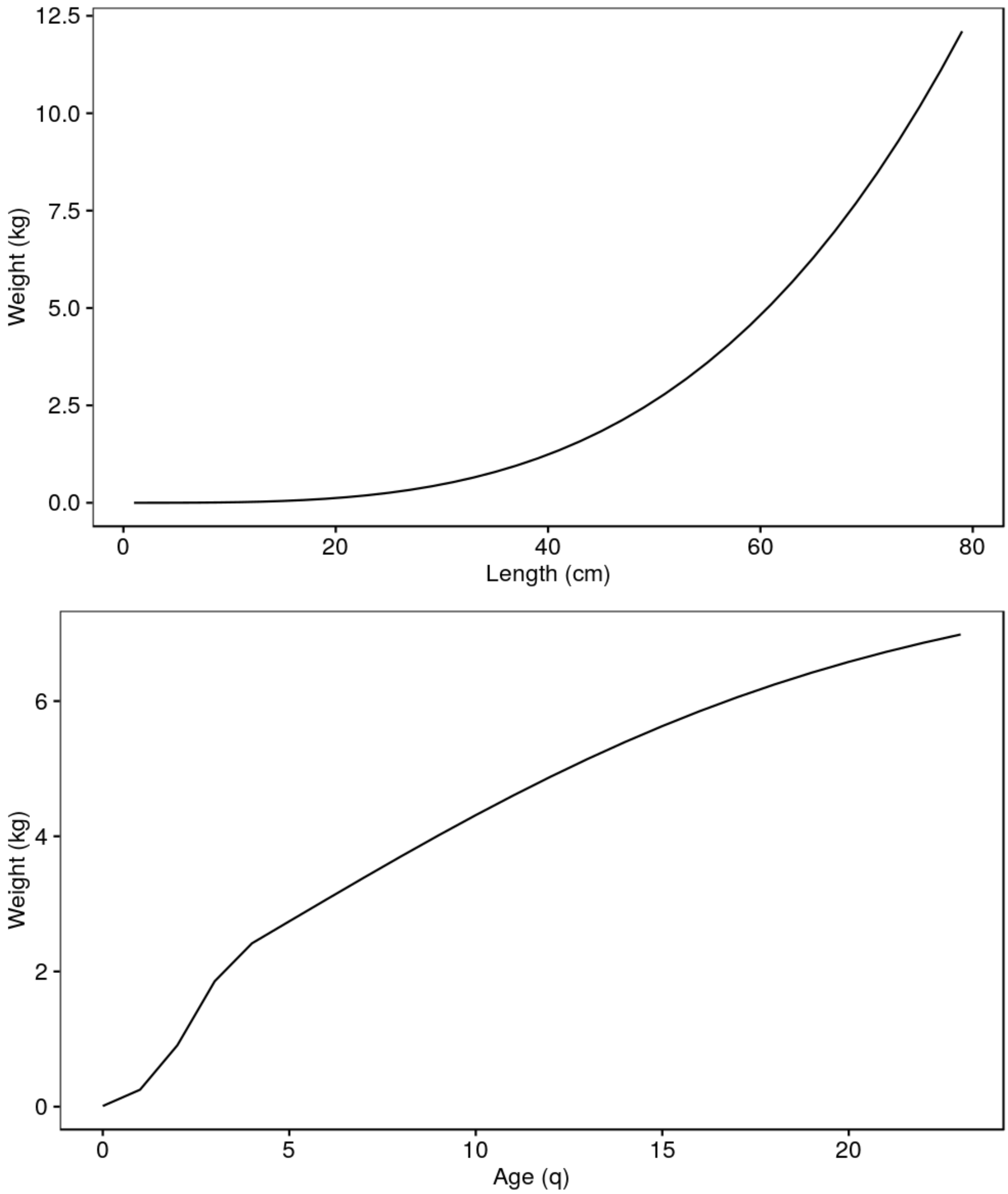


Figure 2: Predicted weight (kg) at length (top) and age (bottom)

2.4.2. Maturity

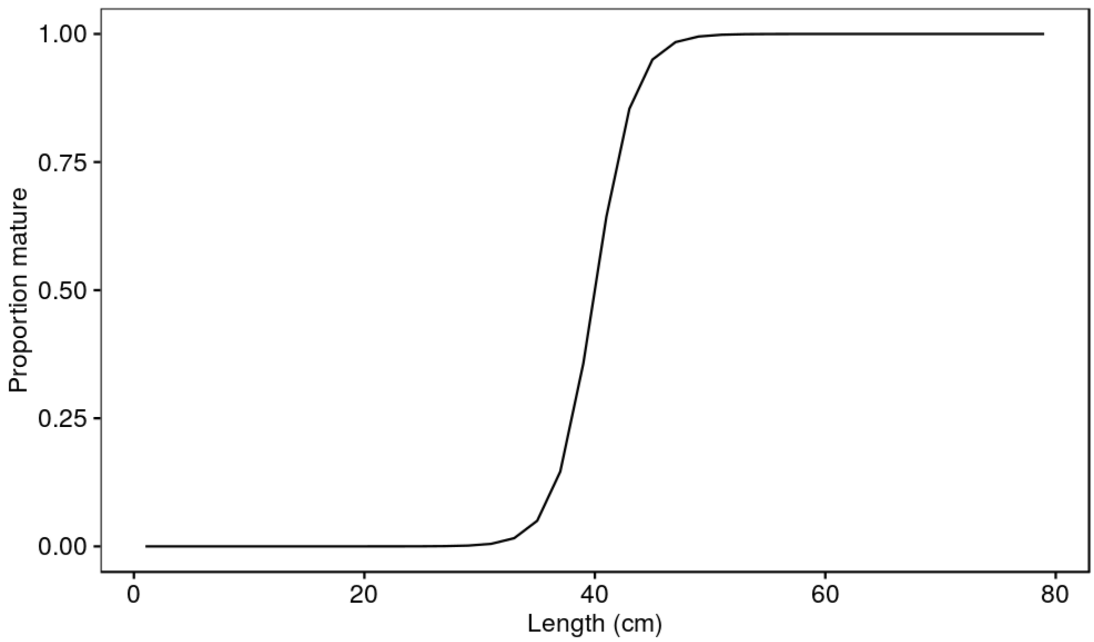


Figure 3: Maturity at length.

2.4.3. Growth

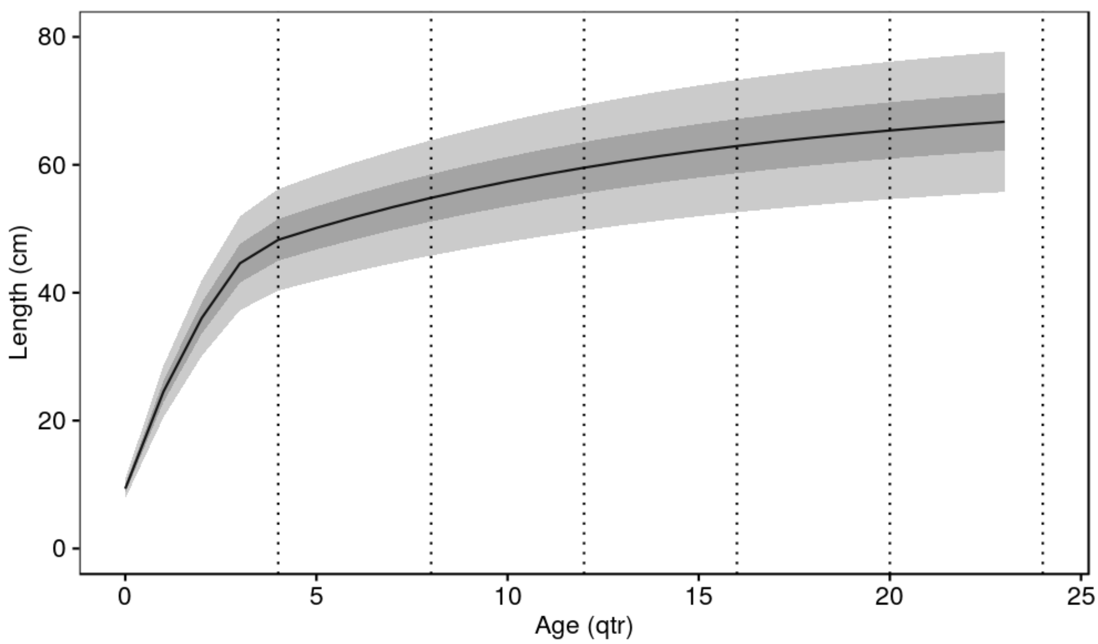


Figure 4: Length at age. Bands represent 50% (inner) and 90% (outer) of lengths for a particular age.

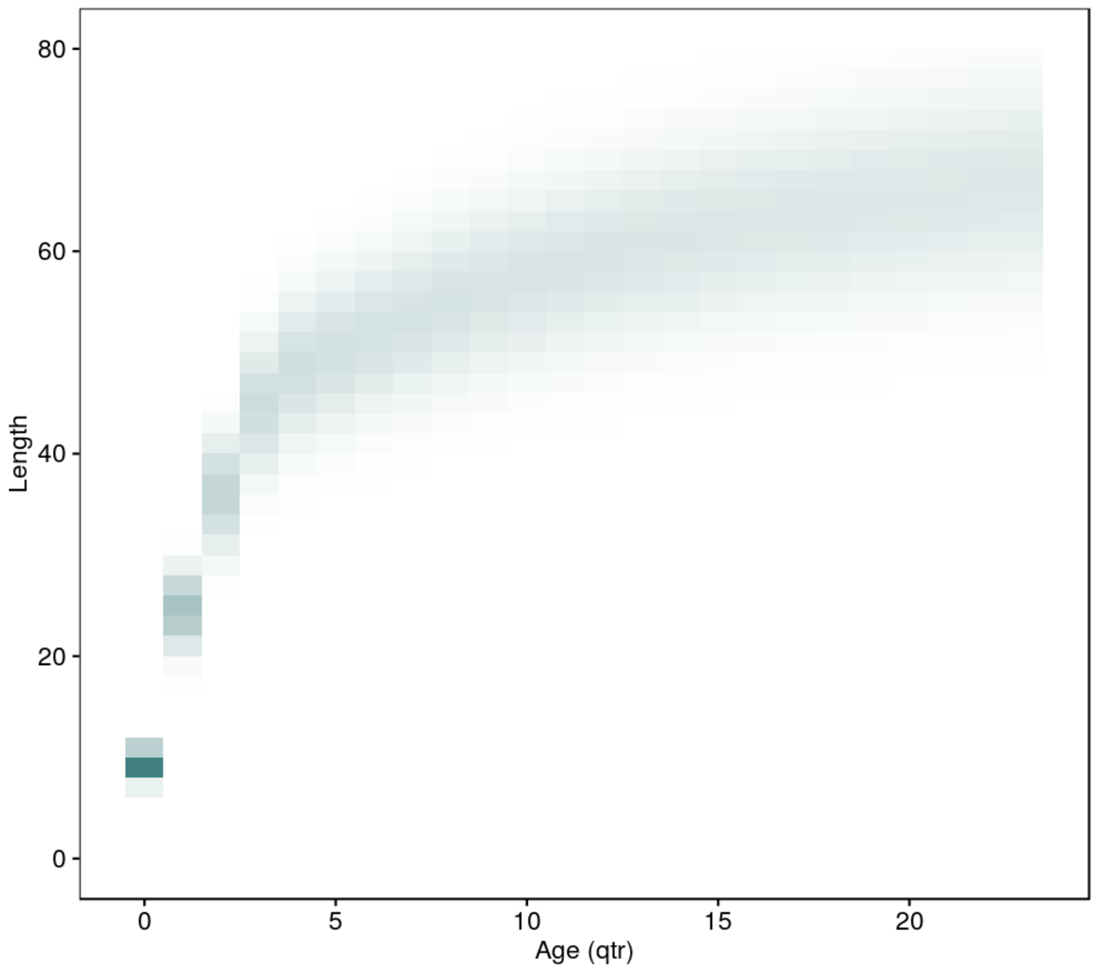


Figure 5: Length distribution at age. Proportion of fish within each size bin by age. Text values are only shown where proportion > 0.01

2.4.4. Mortality

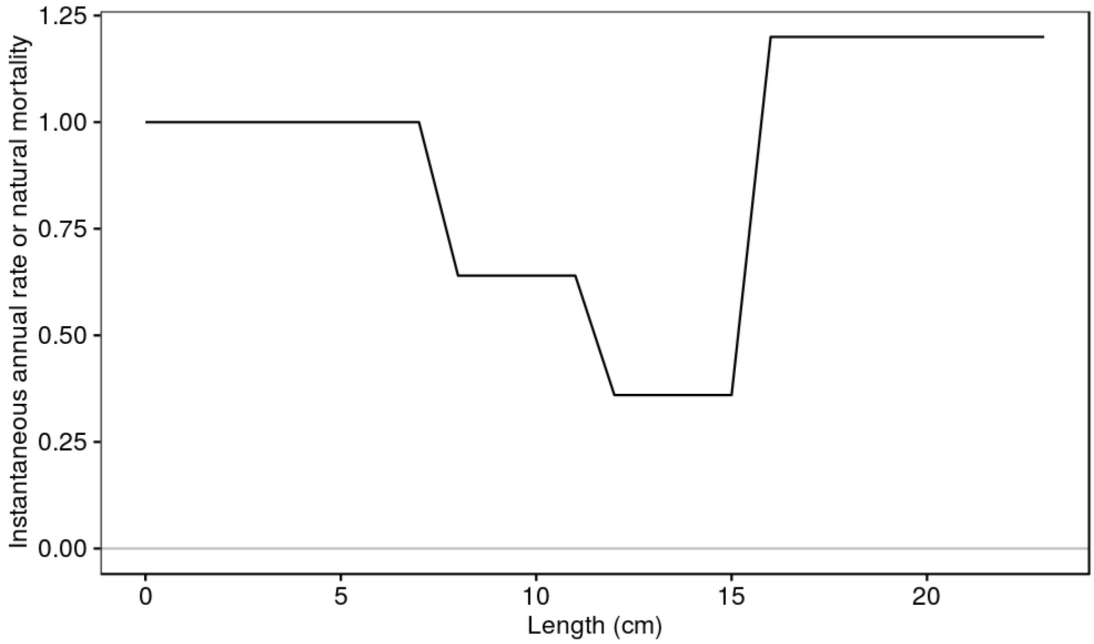


Figure 6: Mortality at length.

2.4.5. Movement

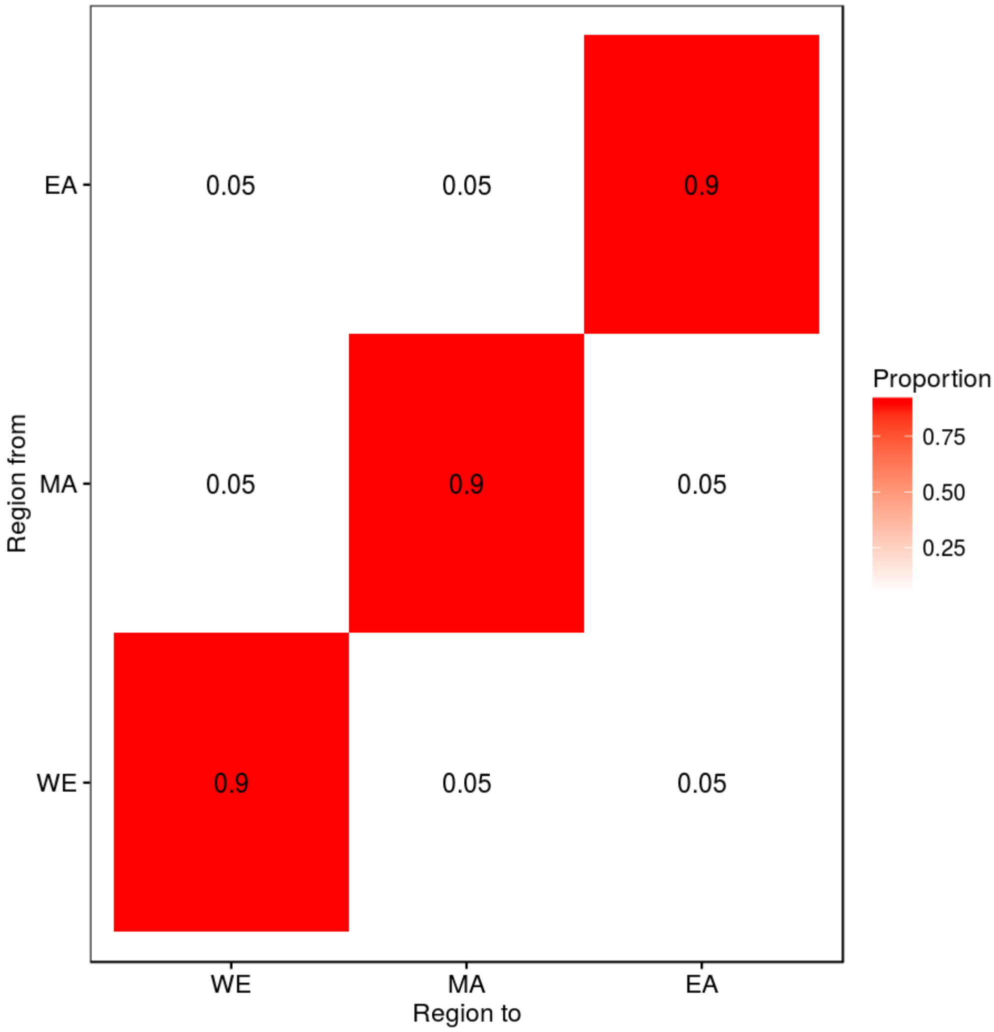


Figure 7: Movement proportion by quarter. Each cell indicates the proportion of fish moving from one region to another in one quarter.

2.4.6. Selectivities

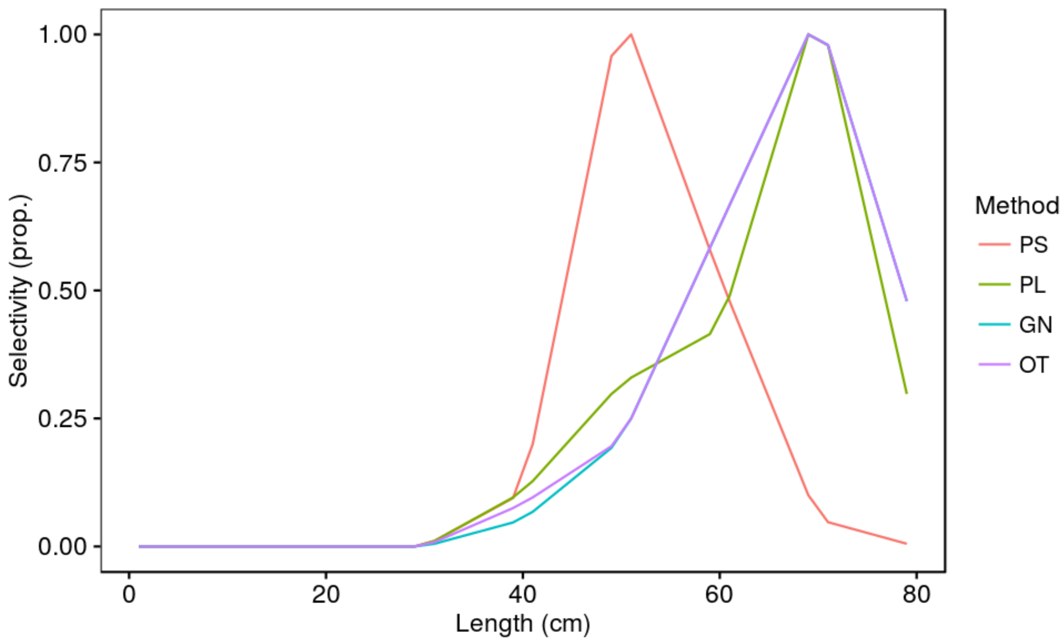


Figure 8: Selectivity at length by fishing method.

2.4.7. Biomass and recruitment trajectories

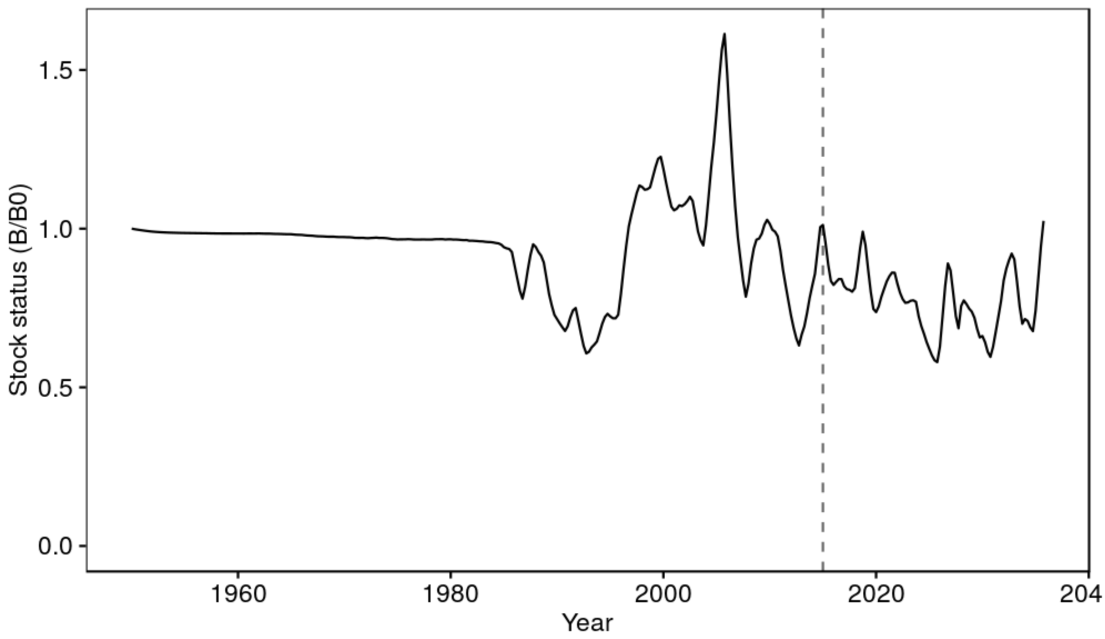


Figure 9: Stock status trajectory.

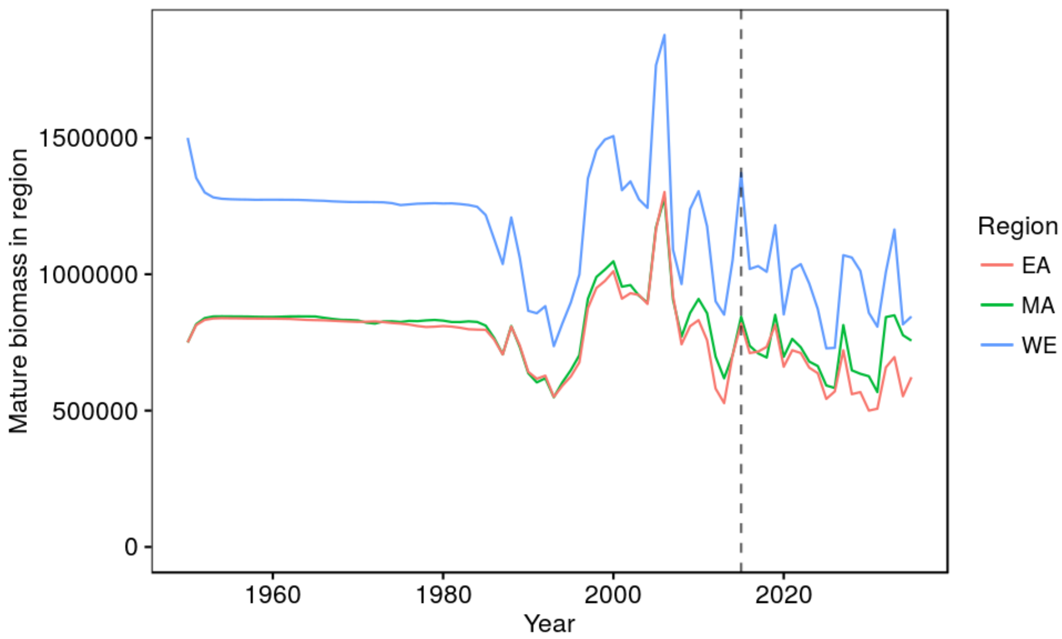


Figure 10: Biomass of spawners by region (first quarter).

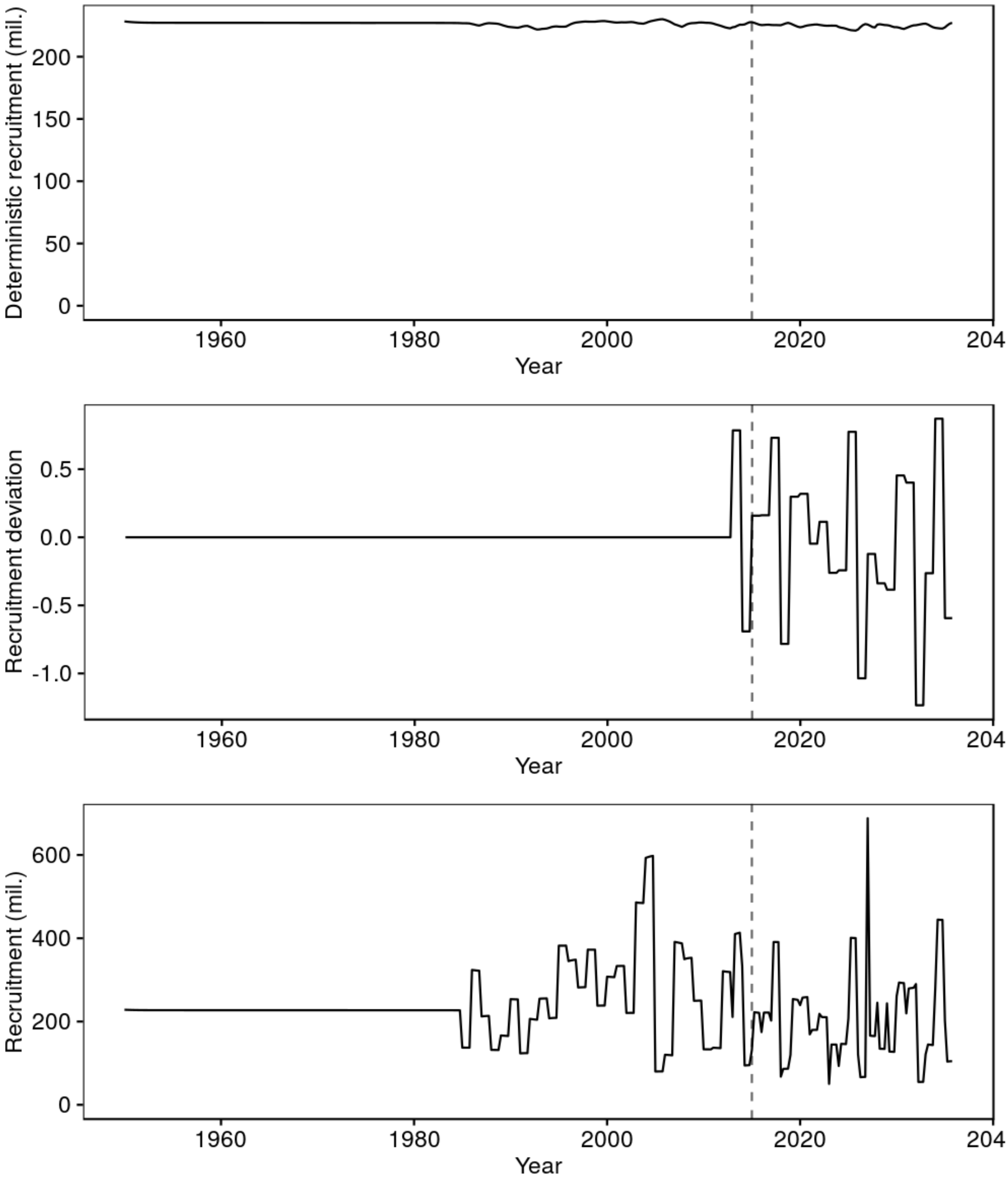


Figure 11: Recruitment trajectories

2.4.8. Fishery related trajectories

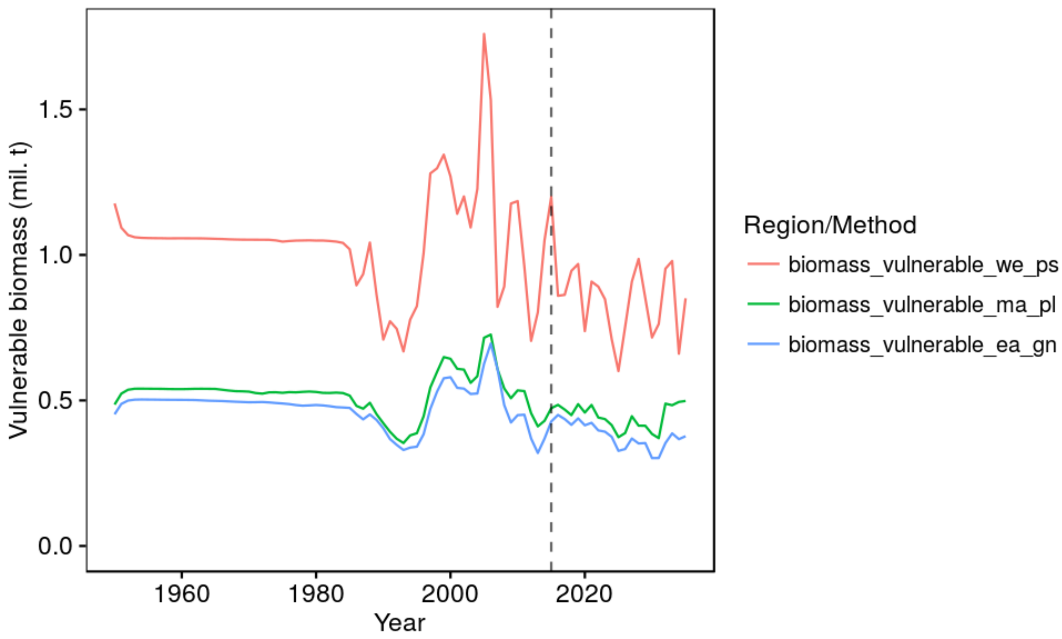


Figure 12: Vulnerable biomass trajectories for the three main fisheries

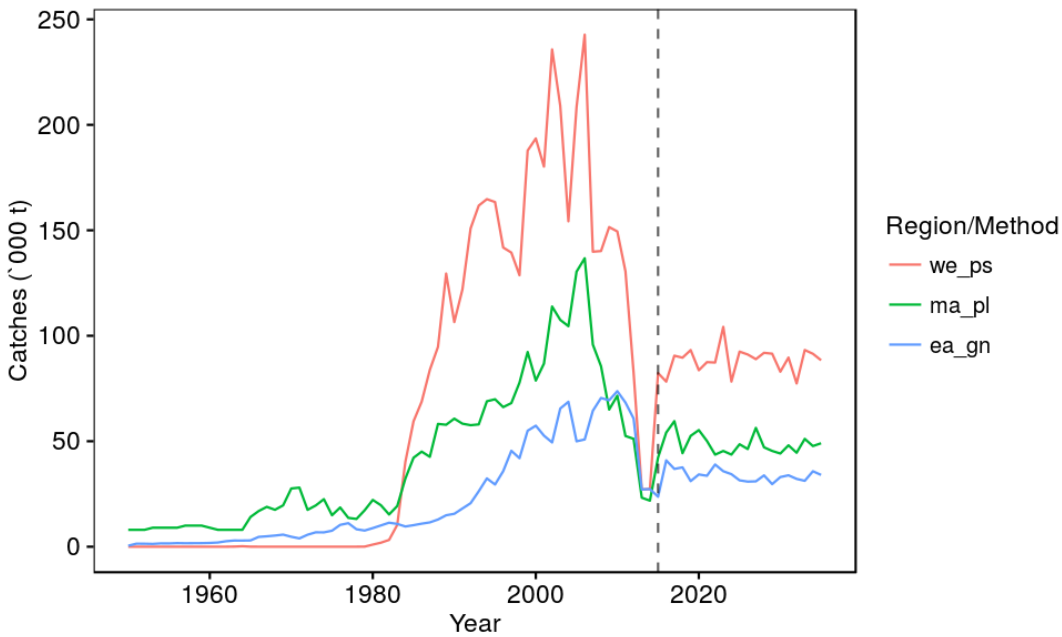


Figure 13: Catch trajectories for the three main fisheries

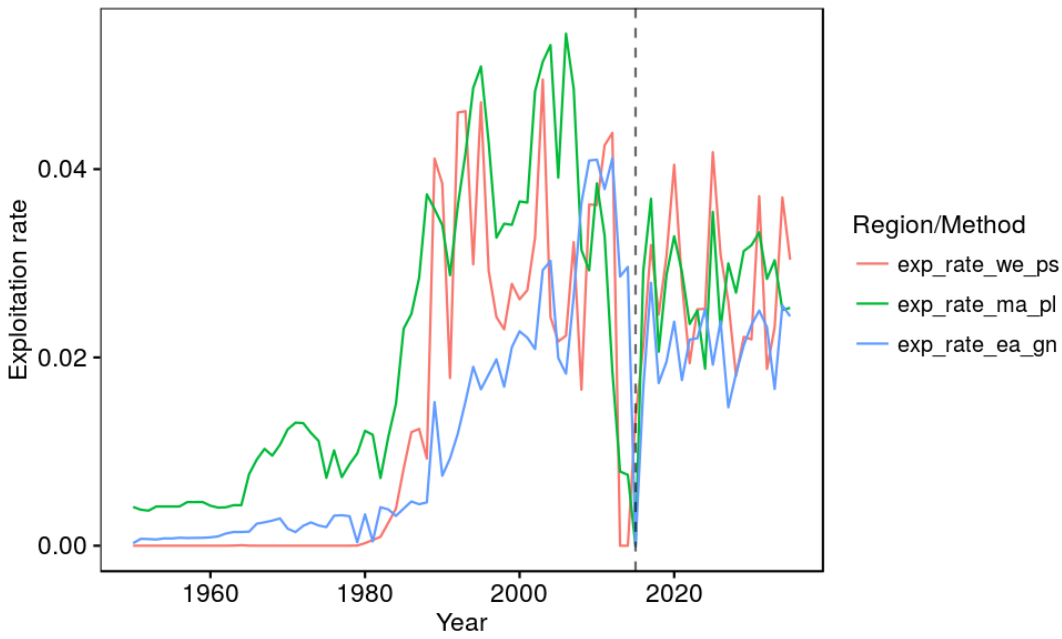


Figure 14: Exploitation rate trajectories for the three main fisheries

2.5. Yield curve and types of reference point

This section describes the overall yield curve and reference points related to maximising sustainable yield. All of these yield related outputs are dependent on the parameters used. The results presented in this section are based on the reference parameter set (read in from files in the `parameters/input` folder) and are **illustrative only**. Ideally their sensitivity to alternative parameter values should be investigated. The main intention of this section is to illustrate the pros and cons of alternative type of reference points (e.g. B_{msy} v B_0 based) for the Indian Ocean skipjack tuna fishery.

The `ioskj.exe` executable has a `yield` task which generates the yield curve and maximum sustainable yield (MSY). The yield curve is the equilibrium catch as a function of exploitation rate. This is generated by the model's `yield_curve` method which takes the model to deterministic equilibrium under a range of exploitation rates from 0 to 1. MSY is determined by the model's `msy_find` method which uses Brent's minimisation algorithm to find the exploitation rate which maximises yield.

In a simple biomass dynamics model the entire fish population is assumed to be selected by the fishery and thus the yield curve and MSY are a function of only the biological parameters. In the current model, yield is a function of the biological parameters, the fishery selectivity parameters and the distribution of fishing effort (i.e. relative exploitation rates) across fisheries (i.e. region/method subsets). If the shape of the selectivity curves or the relative exploitation rates of the fisheries changes then both MSY and the shape of the yield curve will change. Currently, the yield curve and MSY are calculated assuming that the specified exploitation rate applies to the three main fisheries in each region, western purse seine (W-PS), Maldive pole-and-line (M-PL) and eastern gillnet (E-GN). For all other fisheries, the exploitation rate is assumed to be 0. The model's `yield_per_recruit` method calculates the numbers at age, mean length and weight at age from which a yield-per-recruit cureve can be derived.

2.5.1. Overall yield curve

Table 3 presents various quantities associated with alternative biomass levels. Figure 15 presents plots of various variables related to the yield curve against each other. For these simulations, MSY occurs at very high exploitation rates and very low biomass levels (around 25% B0). Also note that the yield associated with lower exploitation rates and higher biomass levels (e.g 40%B0) is only slightly lower than MSY (e.g. at 40%B0 the yield is estimated to be about 87% of MSY). This suggests that, for skipjack, rather than attempting to manage on the basis of MSY, managers may want to consider using a higher biomass target reference point that is based on B0.

Table 3: Exploitation rate, instantaneous fishing mortality rate, and equilibrium yield associated with alternative biomass levels. Note that for $30\ \%\ B_0$ etc, values are approximate because they are taken from the yield curve generated from exploitation rates in increments of 0.05. Also note that these estimates are used in this section for illustration only and no sensitivity to alternative, potentially more accurate, parameter sets has been done.

Biomass level	Exploitation rate (quarterly)	Fishing mortality rate (quarterly)	Yield (quarterly)	Yield/MSY	$B\,/\,B_{msy}$	Effort/Effort at MSY
B_{msy}	0.473	0.641	228685	1	1	1
$30\ \%\ B_0$	0.32	0.231	219831	0.96	1.44	0.677
$40\ \%\ B_0$	0.22	0.151	199196	0.87	1.94	0.465
$50\ \%\ B_0$	0.16	0.107	175606	0.77	2.37	0.338

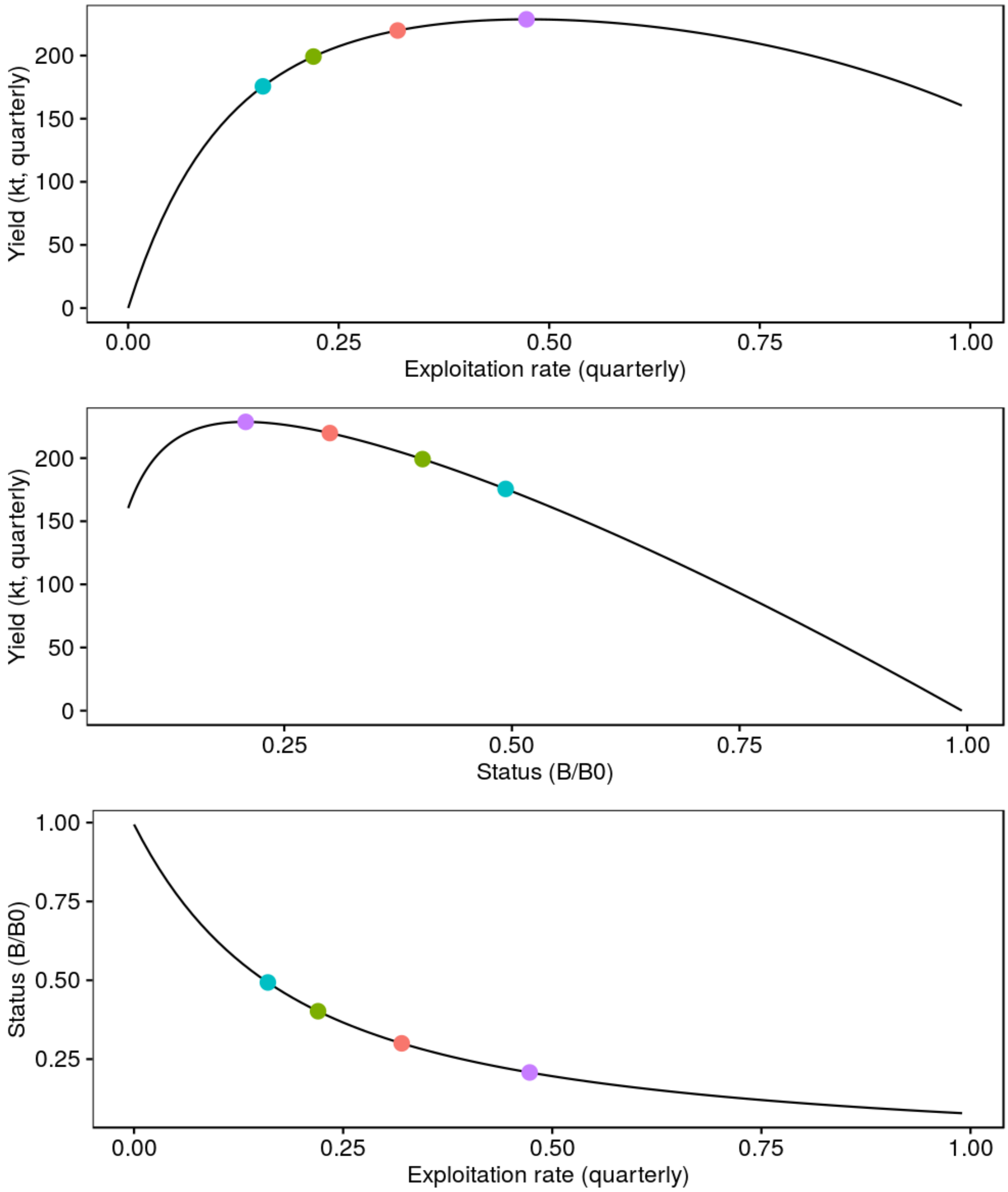


Figure 15: Relations between equilibrium yield, stock status and exploitation rate.(top) Equilibrium yield versus equilibrium exploitation rate. (middle) Equilibrium yield versus equilibrium stock status. (bottom) Equilibrium stock status versus equilibrium exploitation rate.

2.5.2. Fishery-specific yield curves

Each fishing method has a particular size selectivity (Figure 16) and as such, the yield curve for each fishery will differ in shape. In this section we examine the shape of the yield curve for the three main fisheries. Rather than using the biomass of spawners in these fishery-specific yield curves we use the fishery-specific vulnerable (i.e. selected) biomass. Vulnerable biomass is directly proportional to catch rates so is a better measure of how alternative exploitation rates may affect the economic performance of the fishery. At any time, each fishery will have a different vulnerable biomass because of the different selectivity curve.

Note that the vulnerable biomass of all three fisheries is similar at very low exploitation rates. As exploitation rates increase the numbers of older, larger fish decreases, and as such the vulnerable biomass for both M-PL and E-GN decreases (Figure 17 bottom). Given this parameter set, for all fisheries yield is maximized at high exploitation rates (i.e. low biomass) because skipjack mature before they are fully selected (Figure 16).

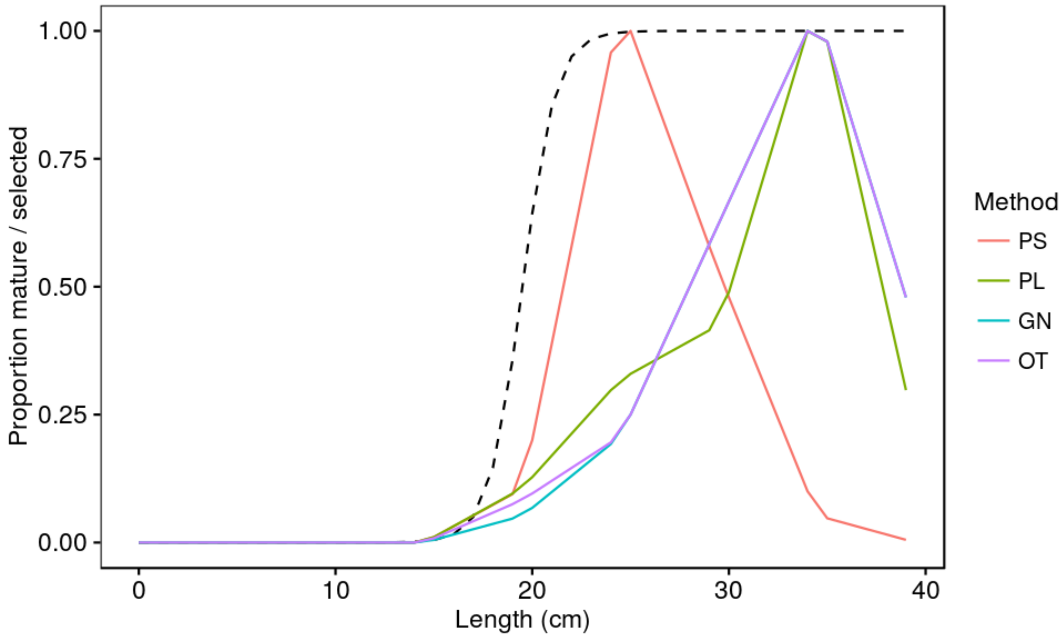


Figure 16: Maturity at length (dotted line) and selectivity at length (by method).

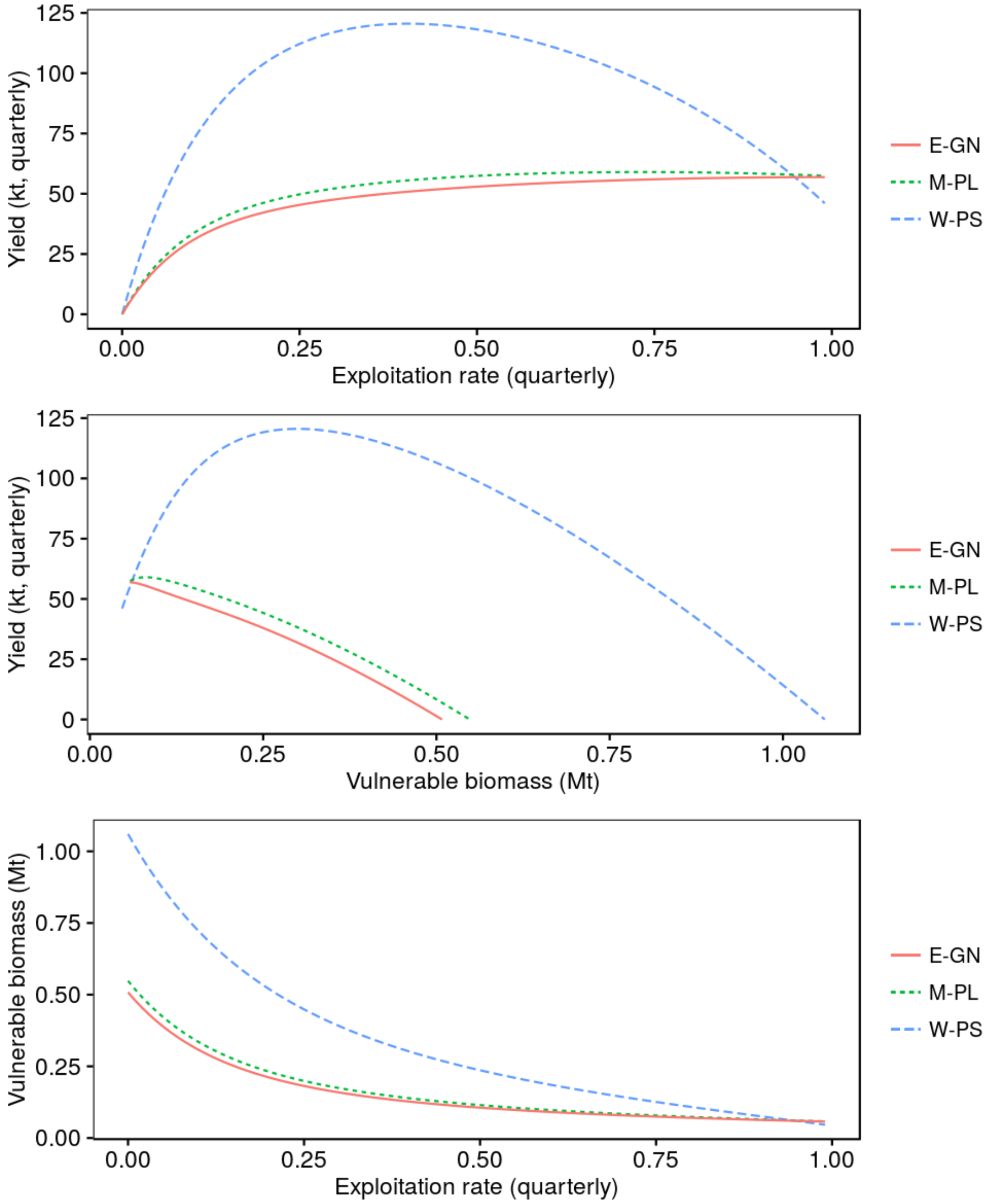


Figure 17: Fishery specific yield curves. Each panel provides a separate line for each fishery (region/method) given that the specified exploitation rate is jointly applied in each fishery.

2.6. Fits

This section displays fits to the data generated from the `run` task (i.e. `./ioskj.exe run`) which uses the reference parameter values defined in `parameters/input` folder. Since those values are user inputs the following may not reflect best parameter estimates. In the following plots the lines indicate values expected from the model while the points represent the observed data.

2.6.1. Maldive pole and line (M-PL) CPUE

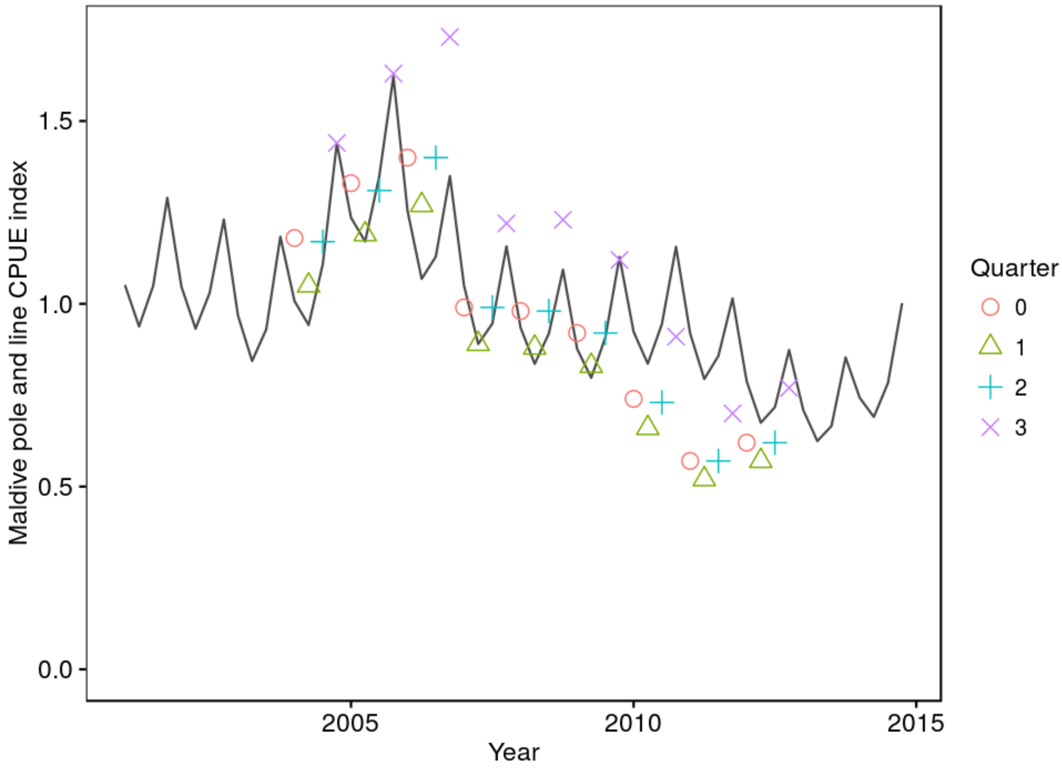


Figure 18: Observed (points) and expected (lines) Maldive (M) pole and line (PL) CPUE.

2.6.2. Western purse seine (W-PS) CPUE

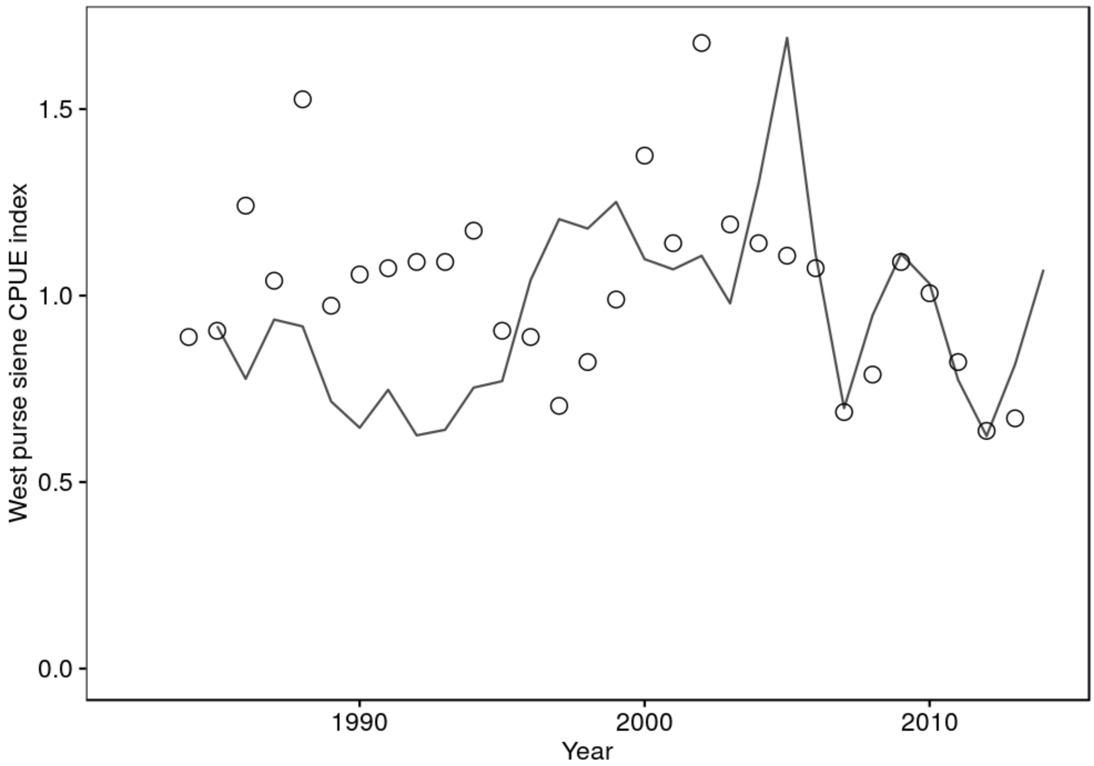


Figure 19: Observed (points) and expected (lines) western (W) purse seine (PS) CPUE.

2.6.3. Western purse seine (W-PS) tagging Z estimates

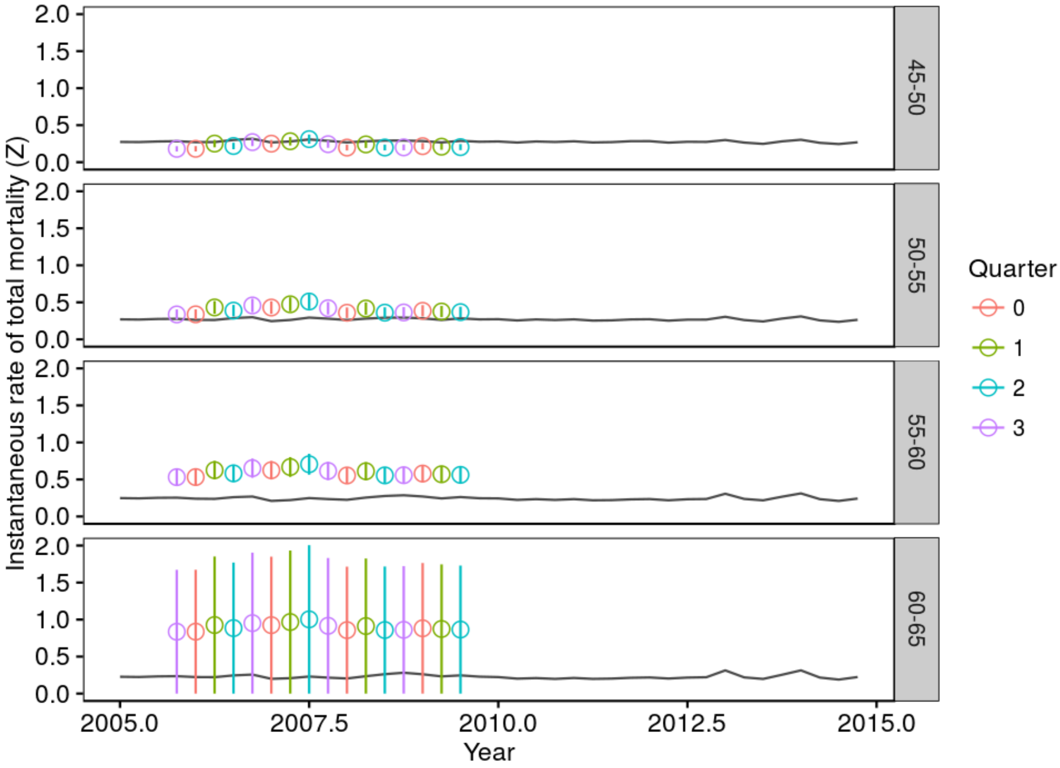


Figure 20: Observed (points) and expected (lines) western (W) purse seine (PS) tagging Z estimates. Error bars indicate +/- one standard error in estimates.

2.6.4. Size frequencies

2.6.4.1. Mean length by region, method, year and quarter

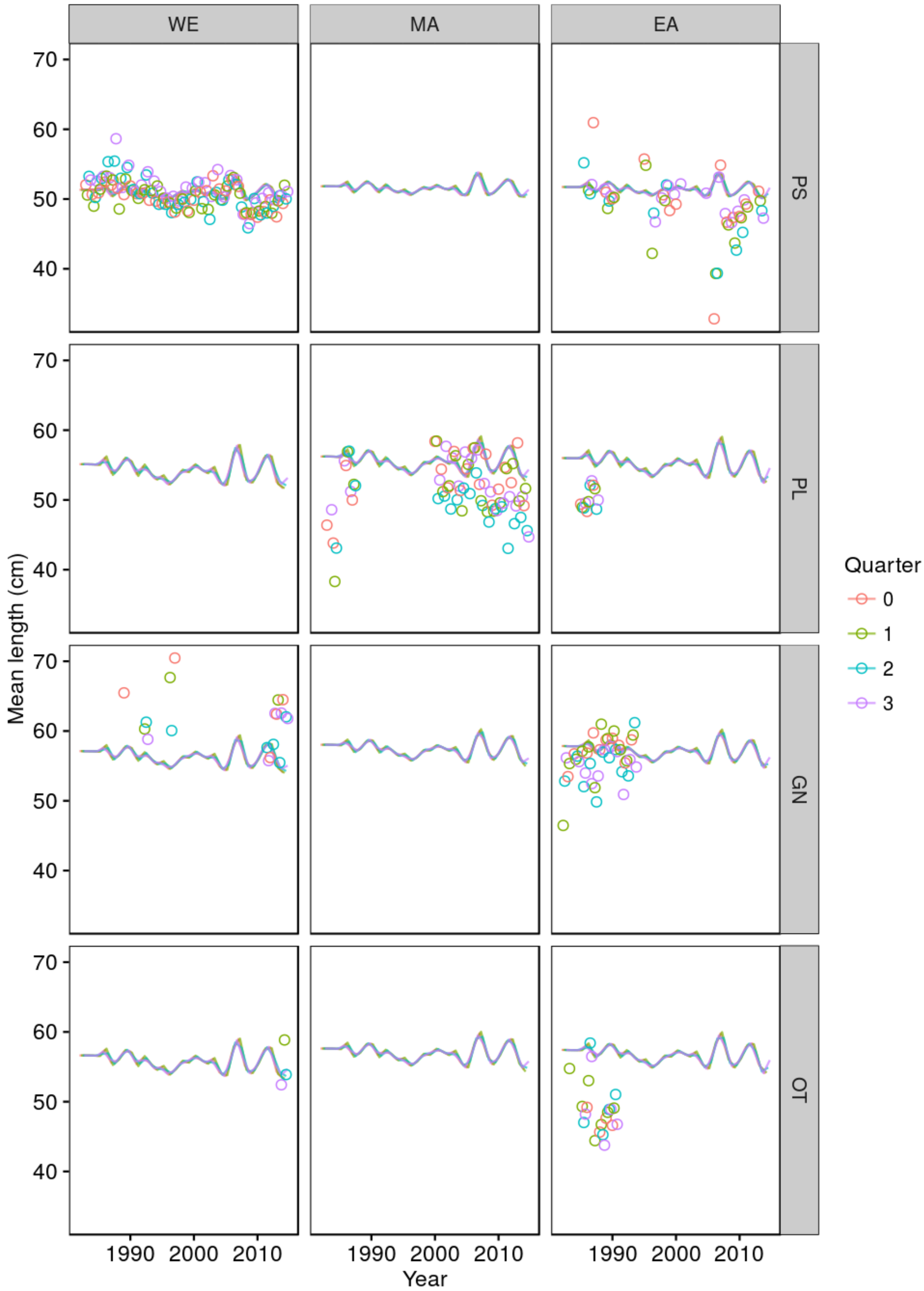


Figure 21: Observed (points) and expected (lines) mean length of catch by region, method, year and quarter.

2.6.4.2. By region, method & quarter (aggregated over years)

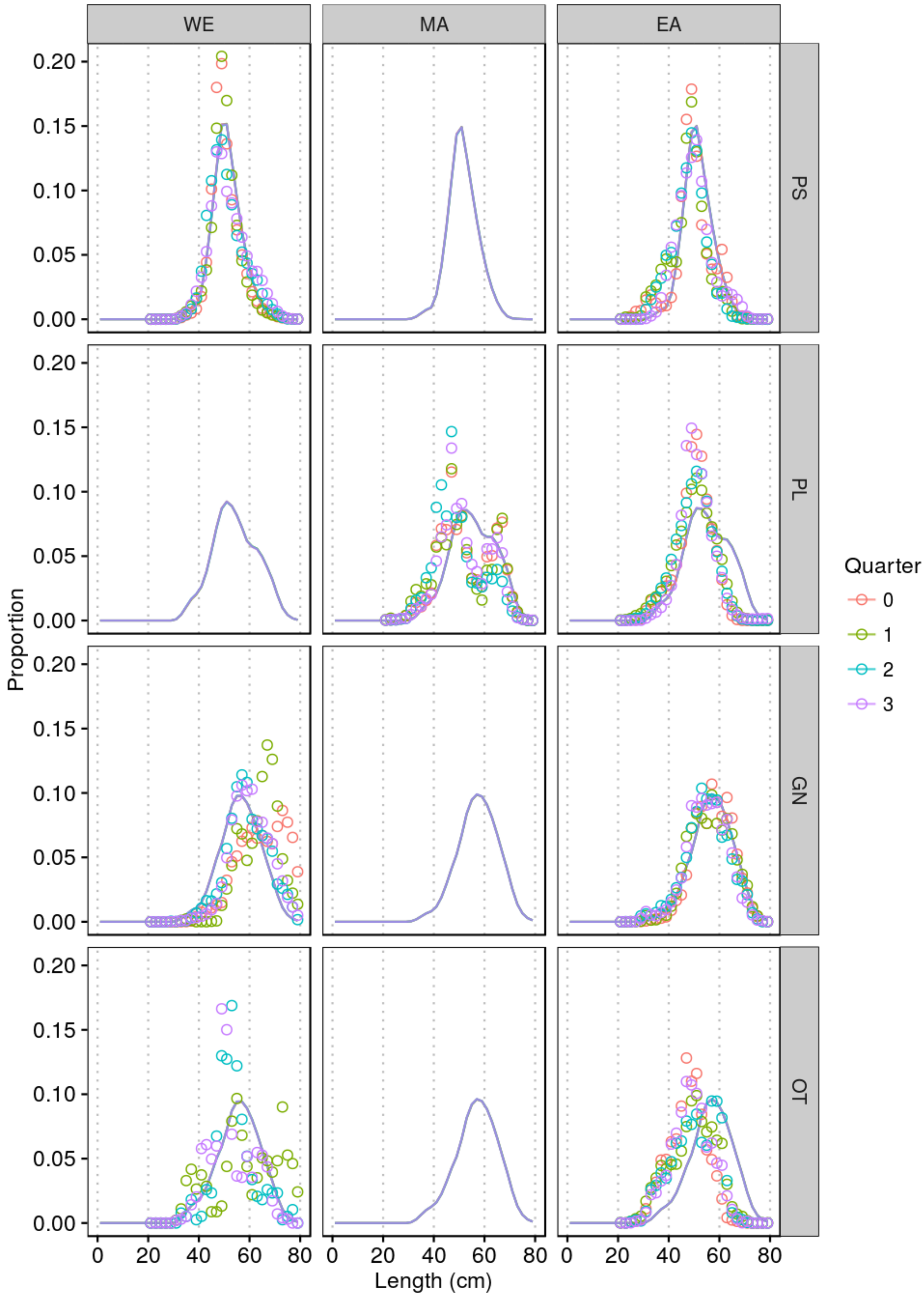


Figure 22: Observed (points) and expected (lines) proportion of catch in each length class by region, method & quarter (aggregated over years).

2.6.4.3. By year for a particular region& method (aggregated over quarters)

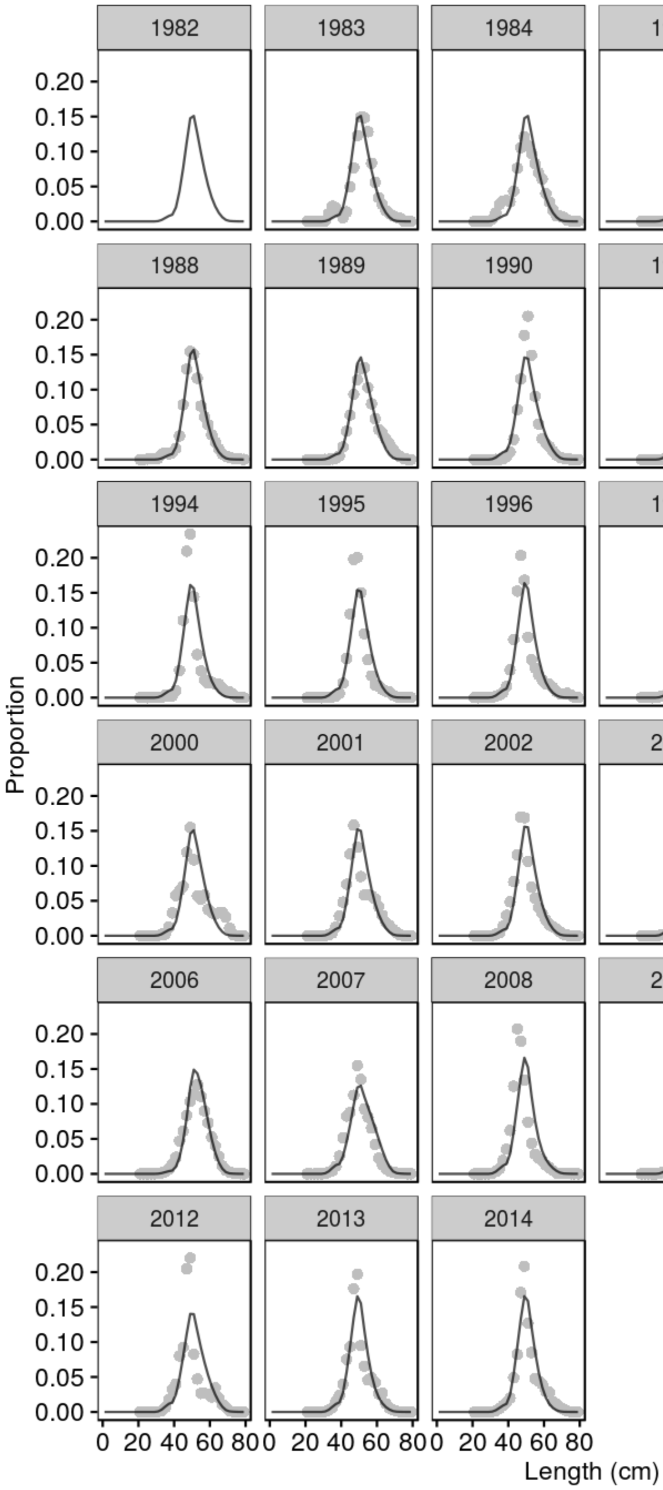


Figure 23: Observed (points) and expected (lines) size frequency distributions for purse seine (PS) in the western region (WE) aggregated over quarters.

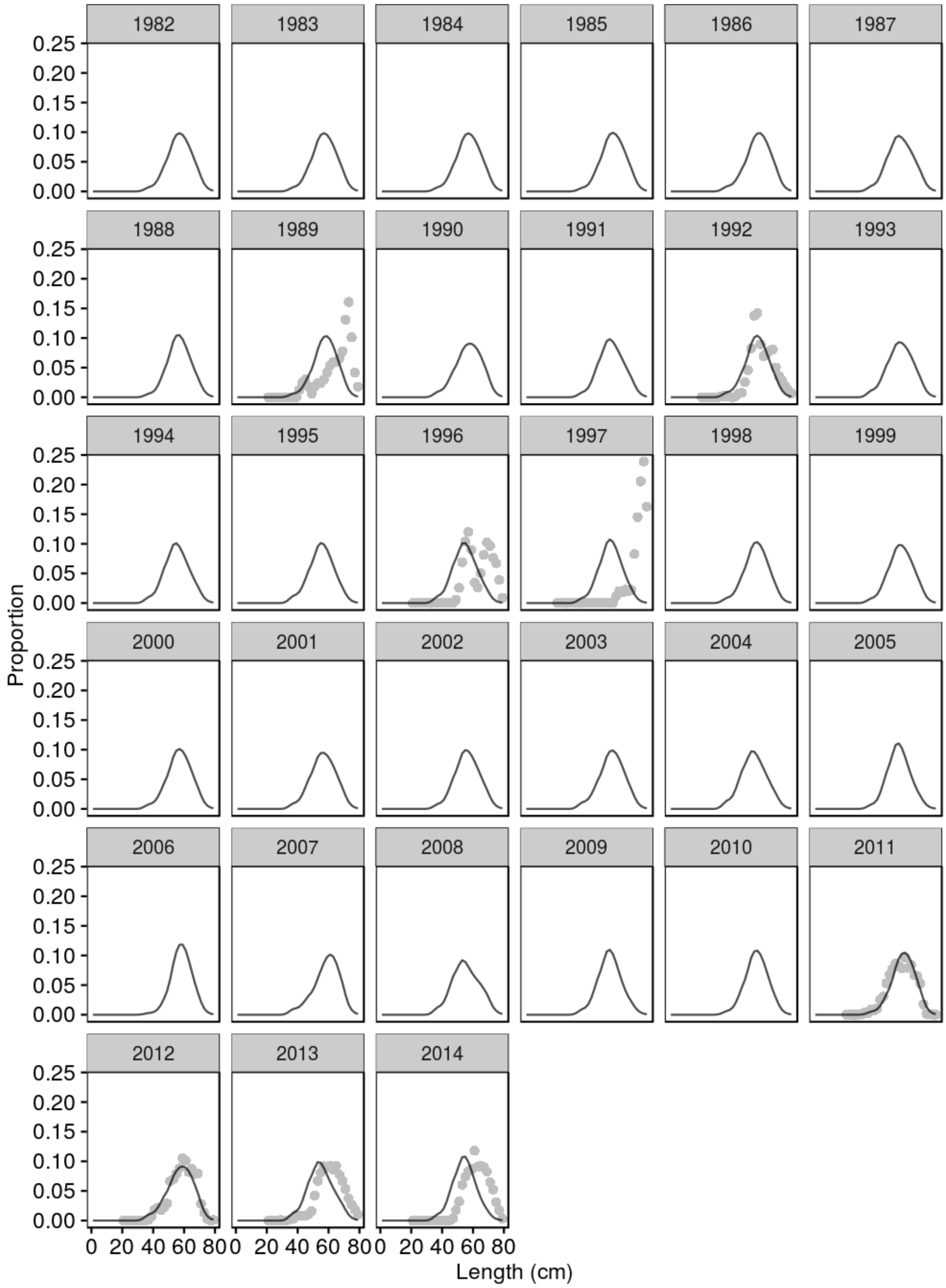


Figure 24: Observed (points) and expected (lines) size frequency distributions for gillnet (GN) in the western region (WE) aggregated over quarters.

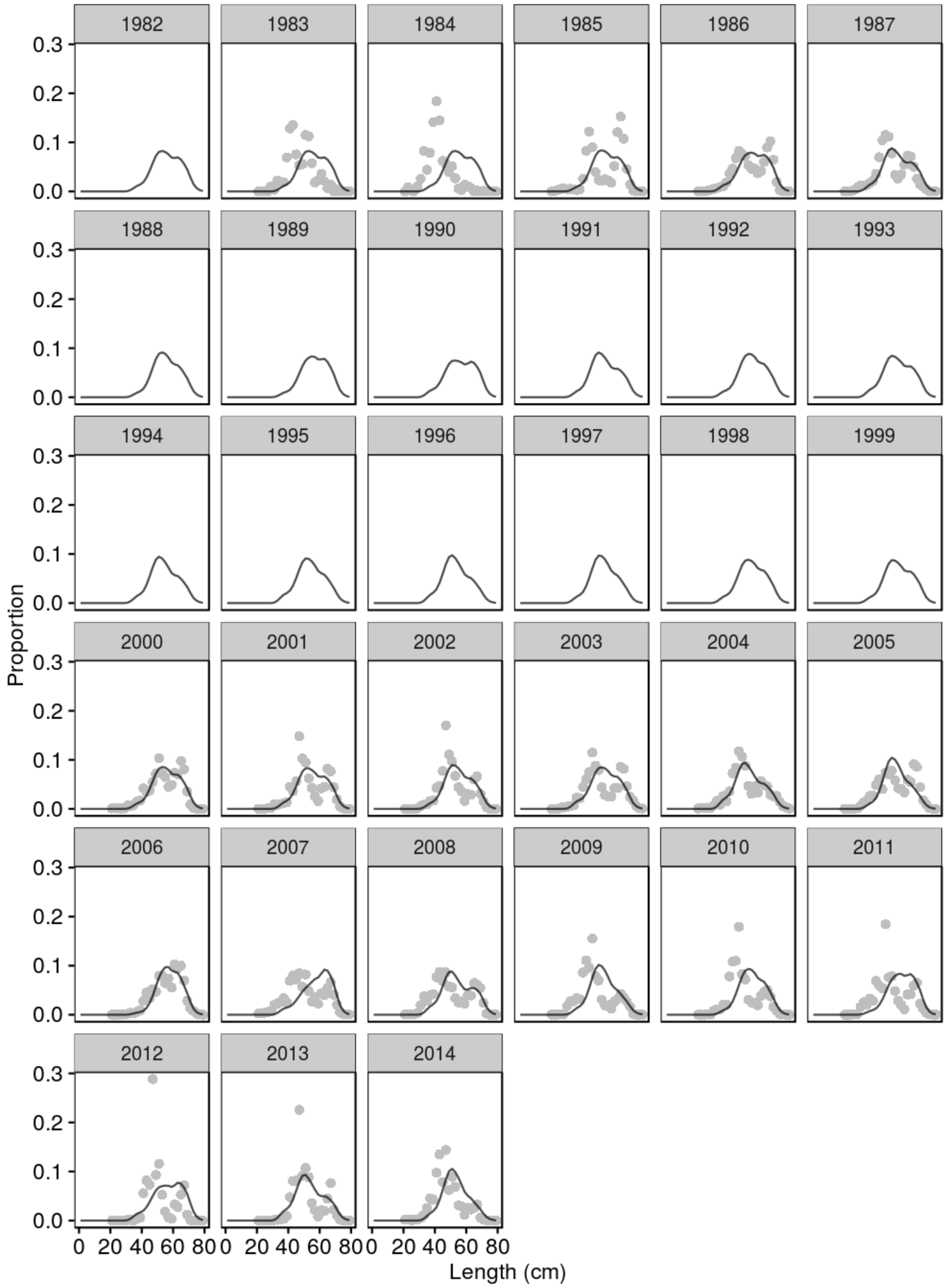


Figure 25: Observed (points) and expected (lines) size frequency distributions for pole and line (PL) in the Maldive region (MA) aggregated over quarters.

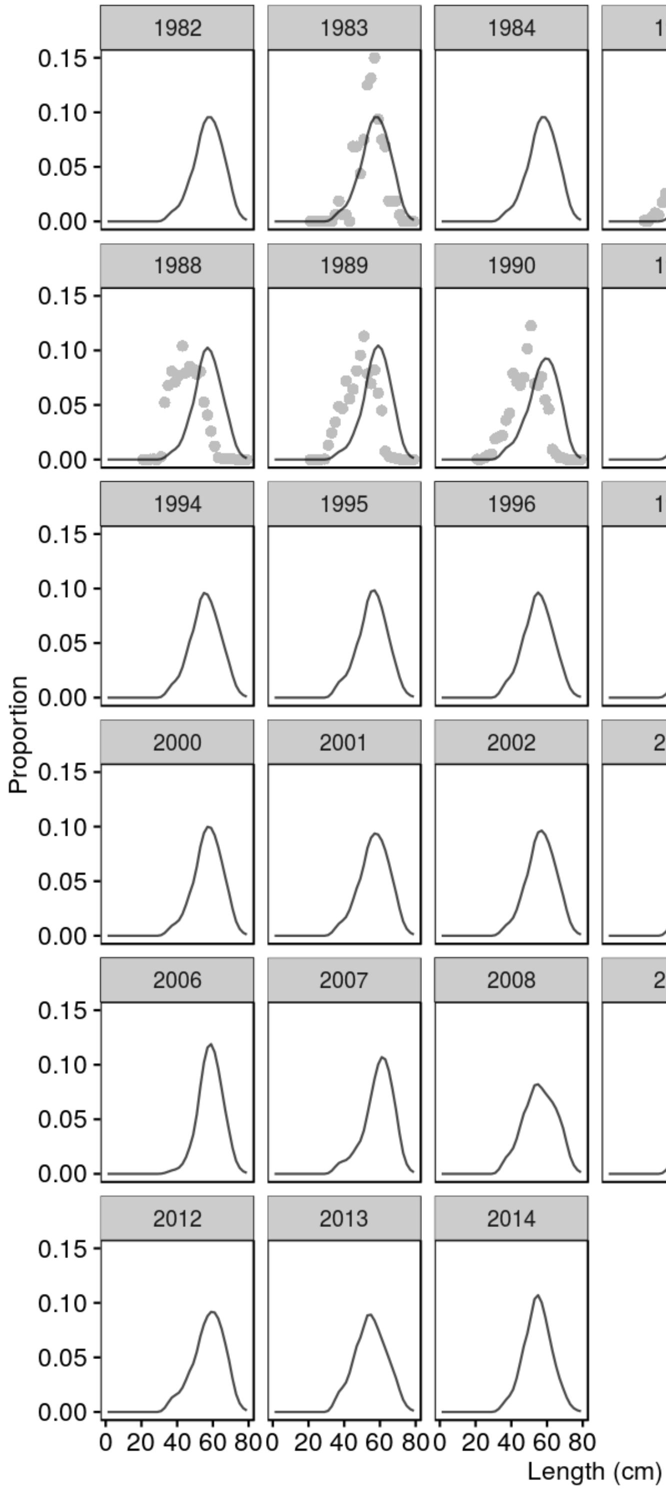


Figure 26: Observed (points) and expected (lines) size frequency distributions for other methods (OT) in the eastern region (EA) aggregated over quarters.

2.6.4.4. By year and quarter for a particular region & method (unaggregated)

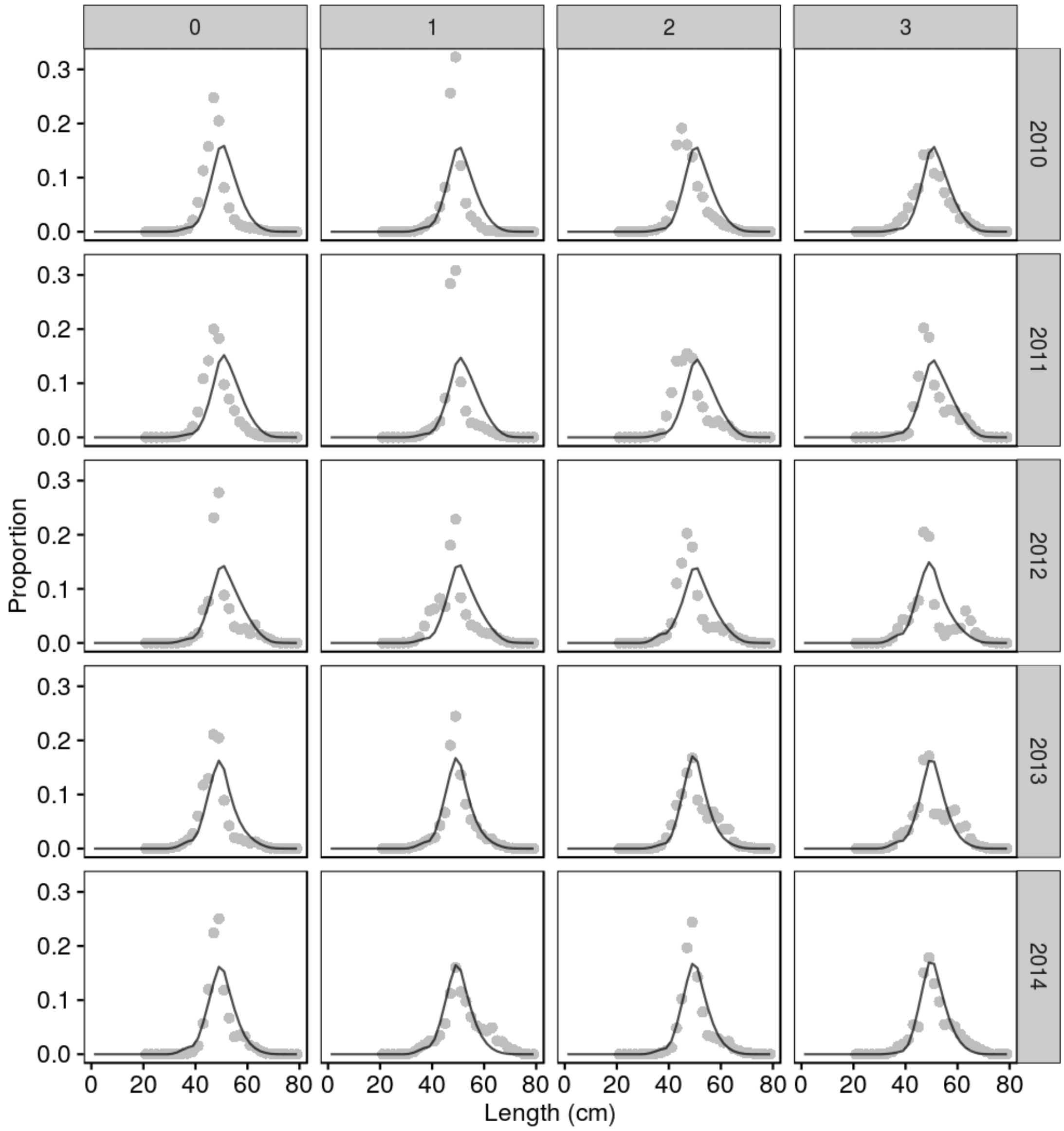


Figure 27: Observed (points) and expected (lines) size frequency distributions for purse seine (PS) in the western region (WE) by year and quarters since 2010.

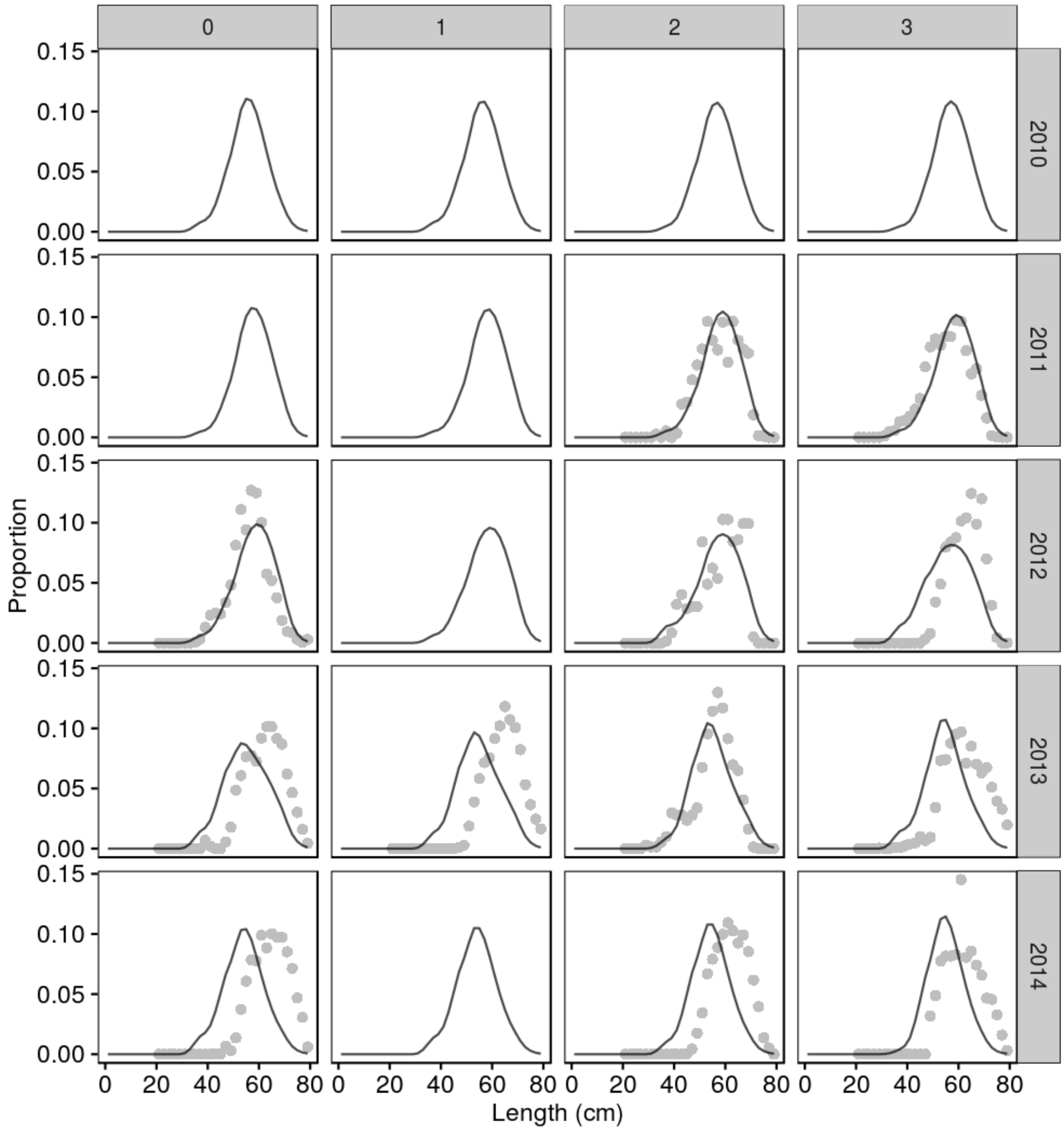


Figure 28: Observed (points) and expected (lines) size frequency distributions for gillnet (GN) in the western region (WE) by year and quarters since 2010.

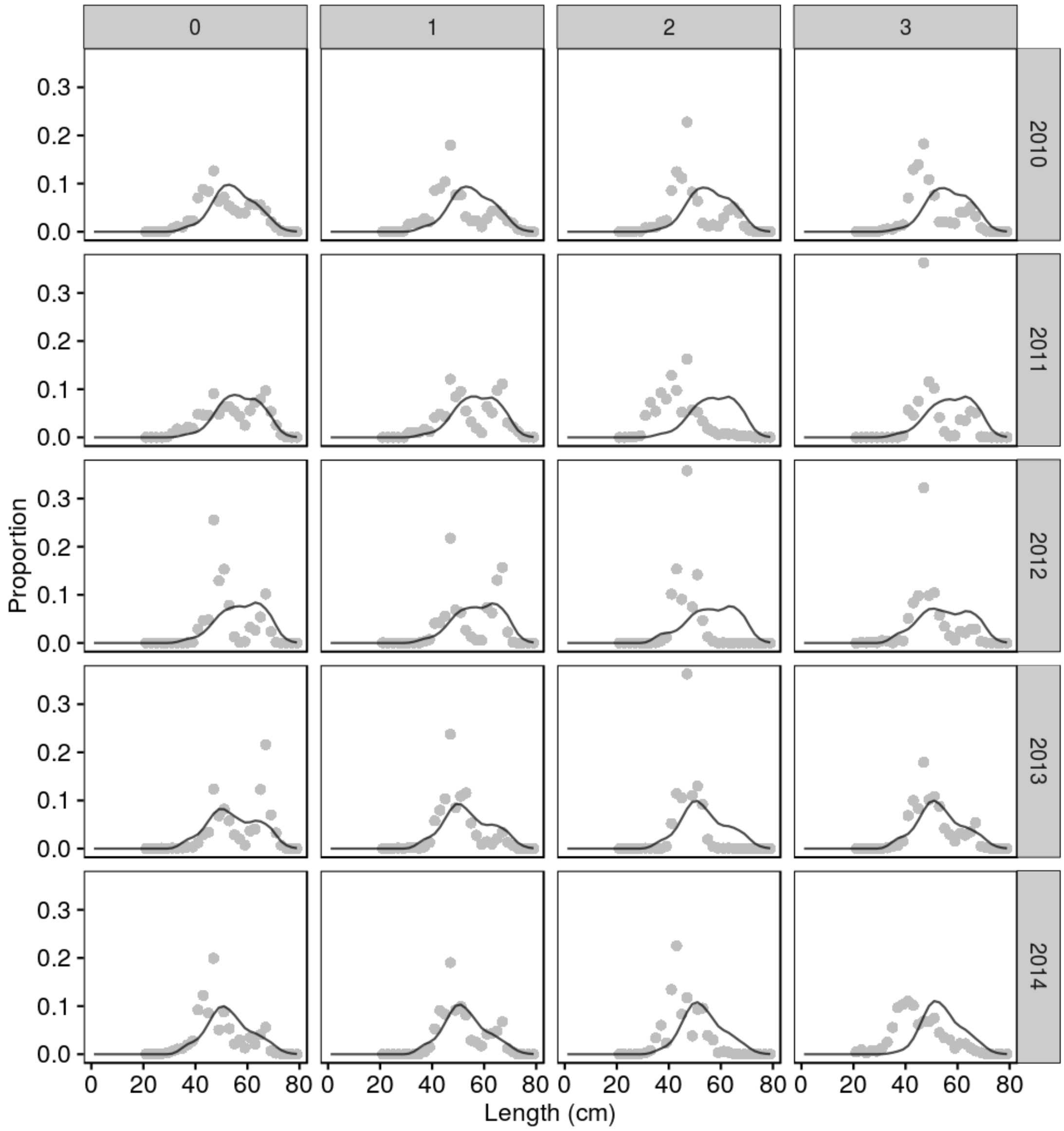


Figure 29: Observed (points) and expected (lines) size frequency distributions for pole and line (PL) in the Maldive region (MA) by year and quarters since 2010.

2.7. Conditioning

This section describes an approach to model conditioning using the Feasible Stock Trajectories (FST) algorithm (Bentley and Langley 2012). Rather than estimating parameters using full likelihoods, FST uses feasibility criterion to accept or reject sets of parameters drawn from their prior distributions. Feasibility criteria can be based on a priori beliefs about the stock or on "features" of the observed data. Although unsophisticated, this approach can provide a pragmatic means for conditioning an operating model.

Table 4: Feasibility criteria used in the FST algorithm

Code	Criterion	Percentage of trials failing this criterion
1	Overall stock status must always be >=10% B0	1.06
2	Overall stock status must be between 40% and 80% B0 in 2013 (to provide consistency with the last stock assessment which estimated stock status to be 0.58%)	12.99
3	Exploitation rate in the three main fisheries (WE-PS, MA-PL, EA-GN) must always be <=0.5	15.72
4	MA-PL CPUE must decrease from 2004 to 2011	28.5
5	WE-PS CPUE must decrease from 2000 to 2011	8.58
6	Total mortality (Z) for 45-50cm fish between 2006 and 2009 must be between 0.1 and 0.4	23.3
7	Cumulative 10, 50 & 90 percentiles for length frequencies by method similar to those in data (see text for details)	2.33

The following figures show the effect of conditioning on a selection of model parameters (for many parameters, for example those concerning movement, there is litle difference betweent he prior and the posterior). They compare the prior probability densities with the posterior densities obtained from the feasibility conditioning. The distributions of rejections by each of the feasibility criteria is also shown.

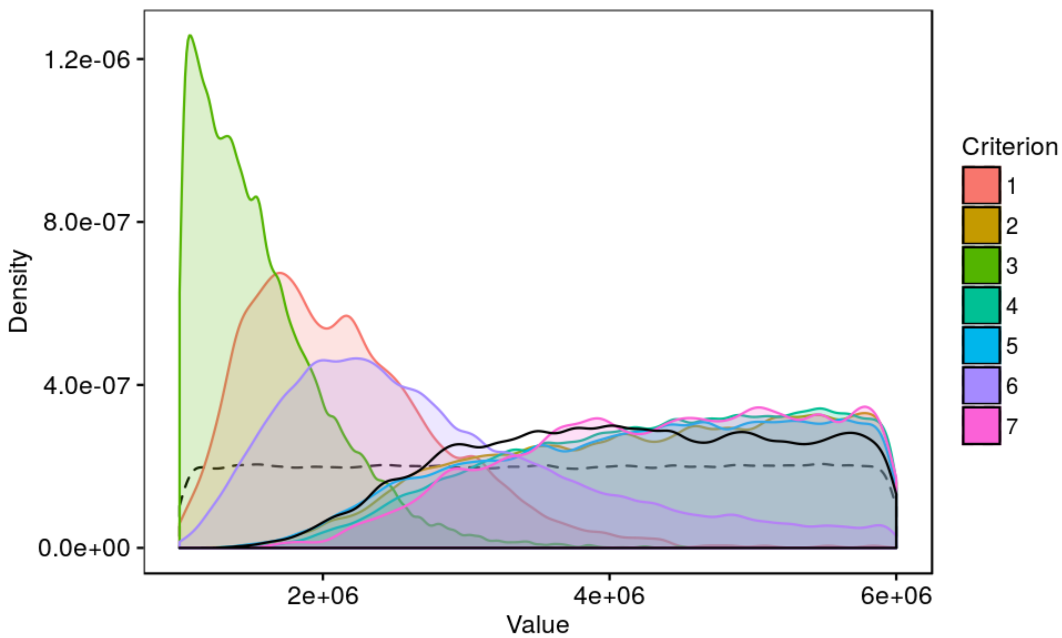


Figure 0: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawners_unfished`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

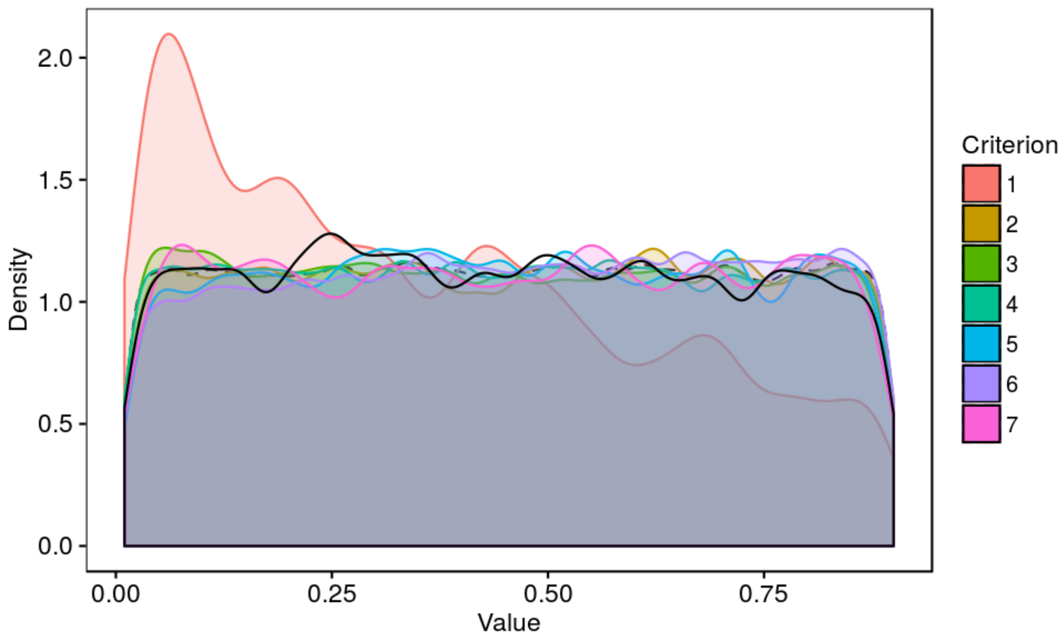


Figure 1: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawners_ma`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

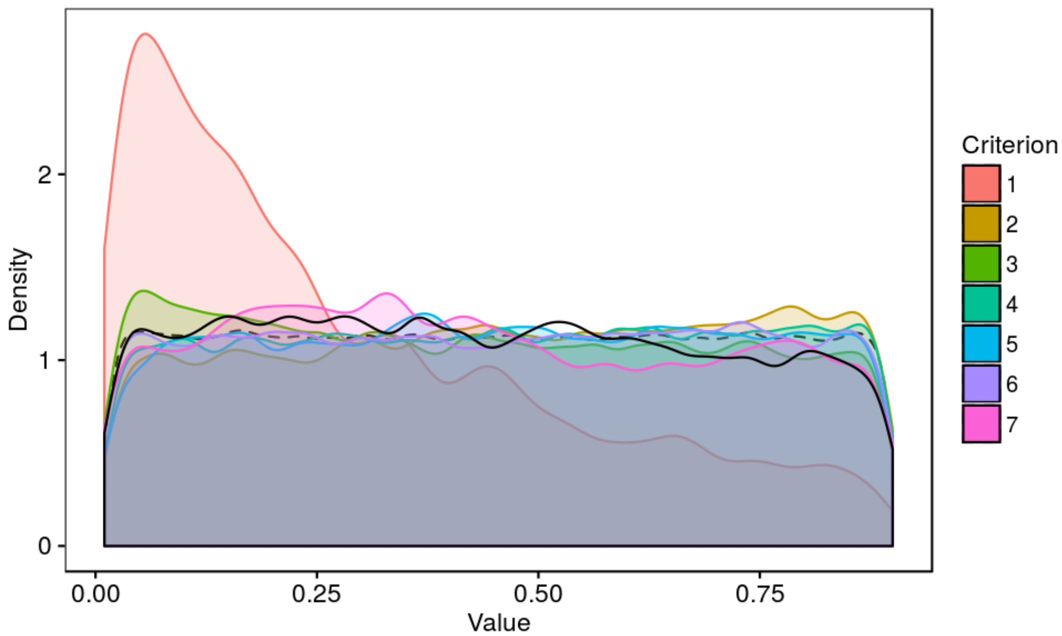


Figure 2: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawners_ea`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

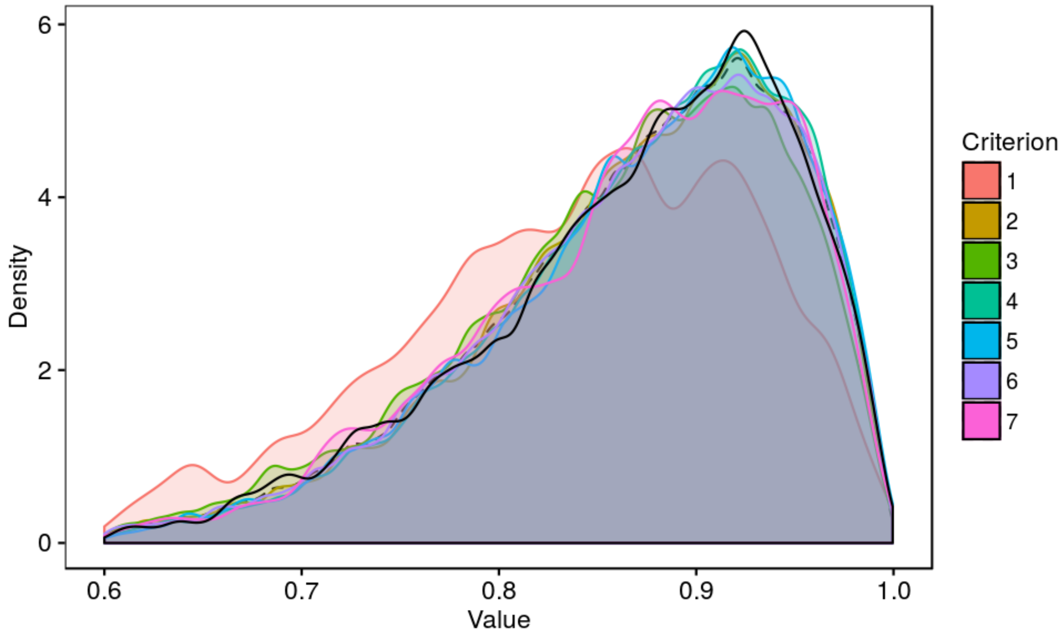


Figure 3: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `recruits_steepness`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

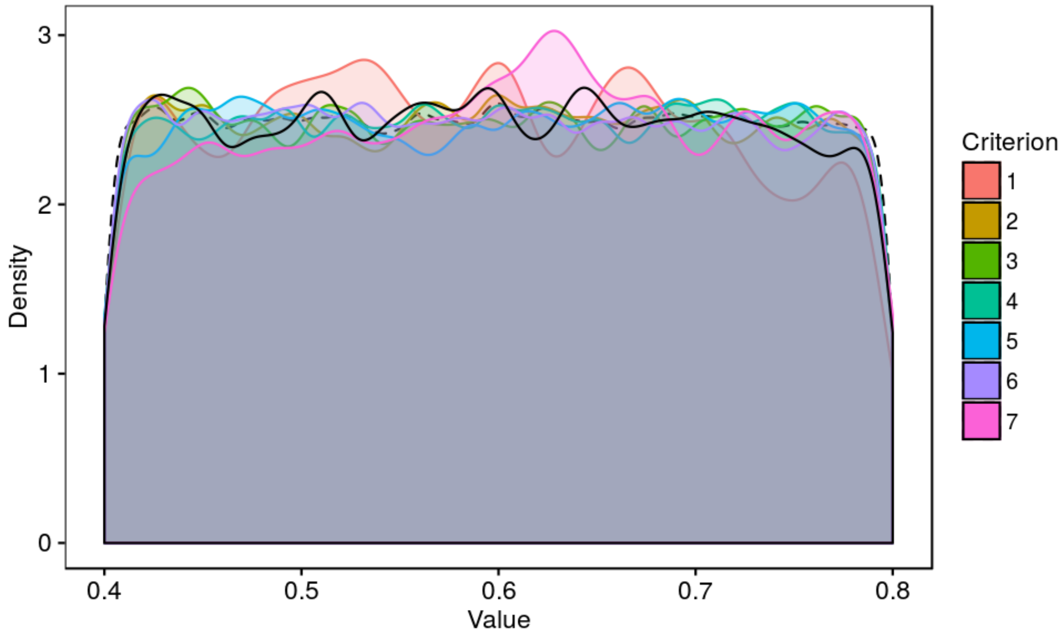


Figure 4: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `recruits_sd`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

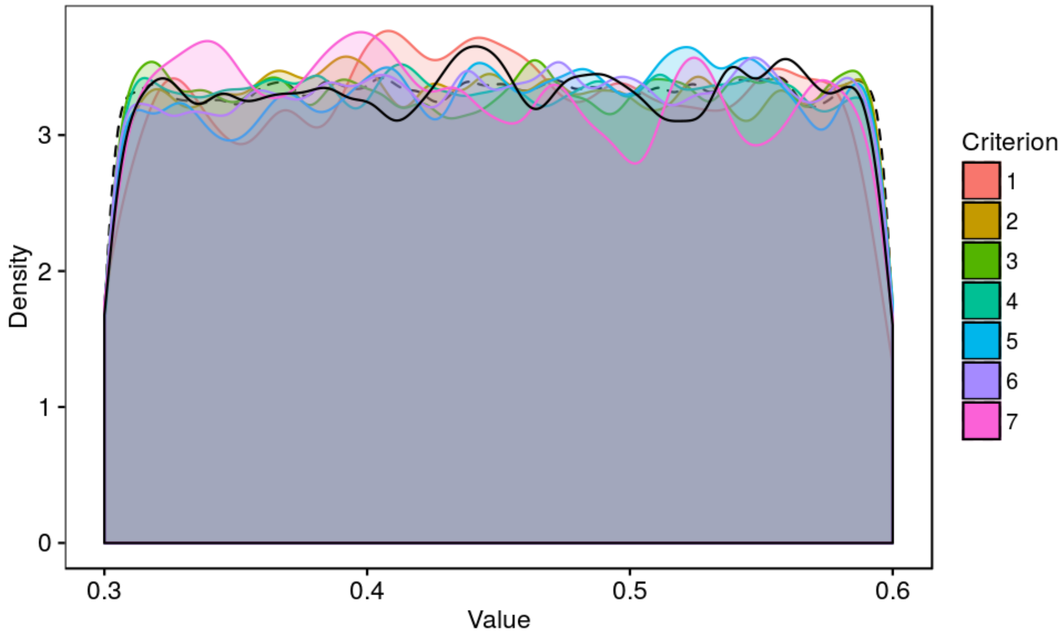


Figure 5: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `recruits_autocorr`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

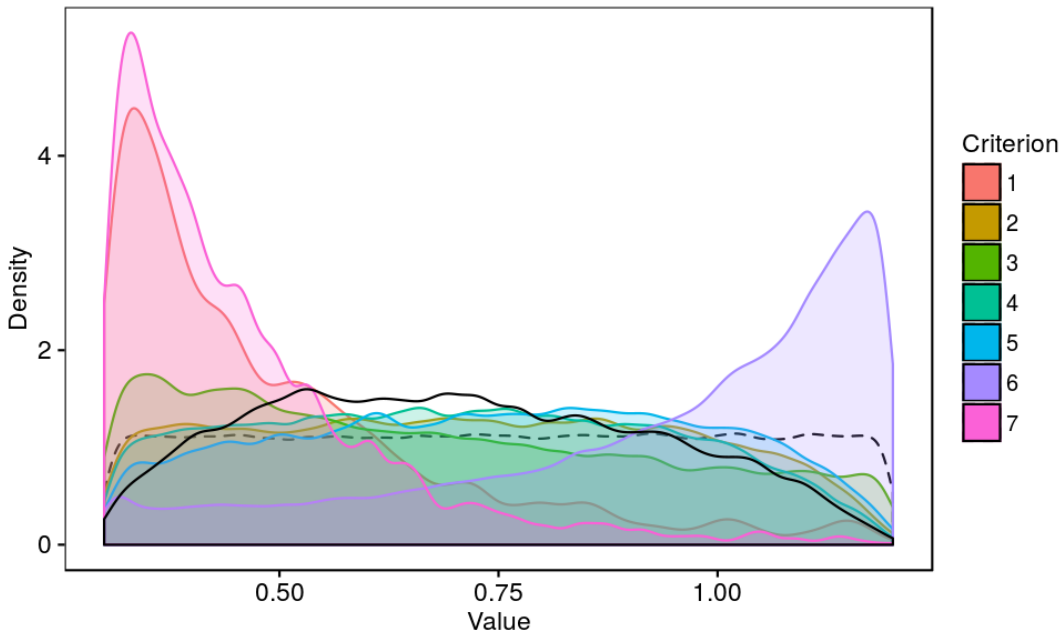


Figure 6: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `mortality_mean`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

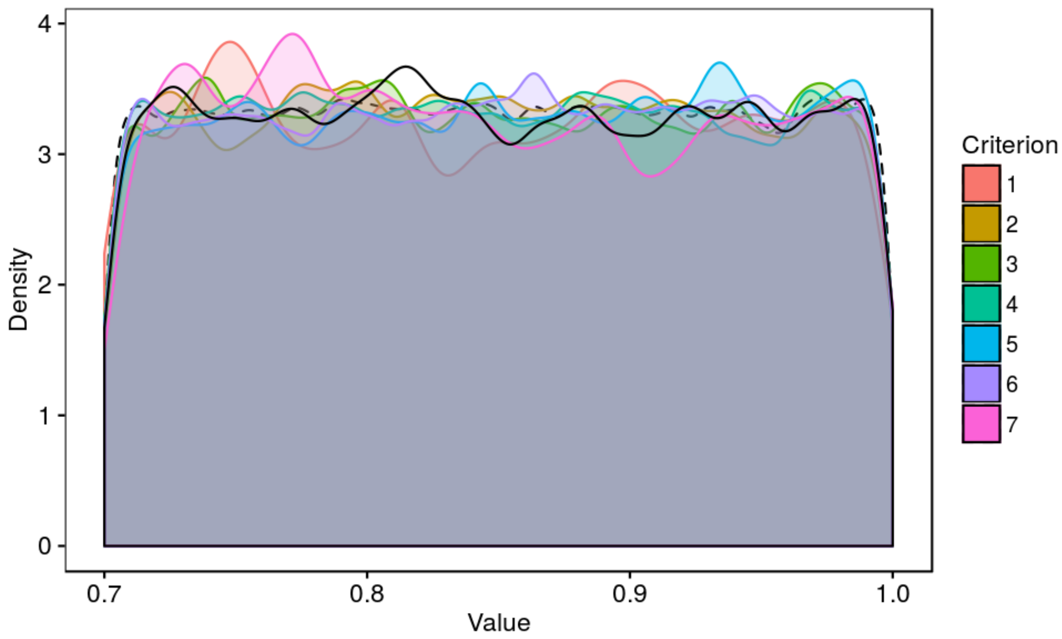


Figure 7: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawning_0`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

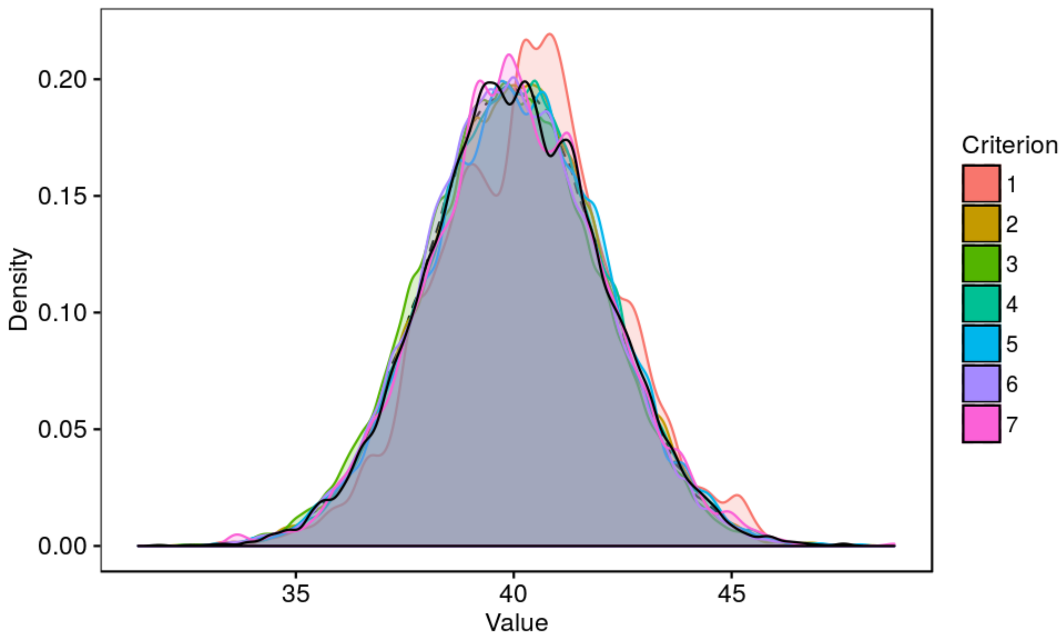


Figure 8: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `maturity_inflection`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

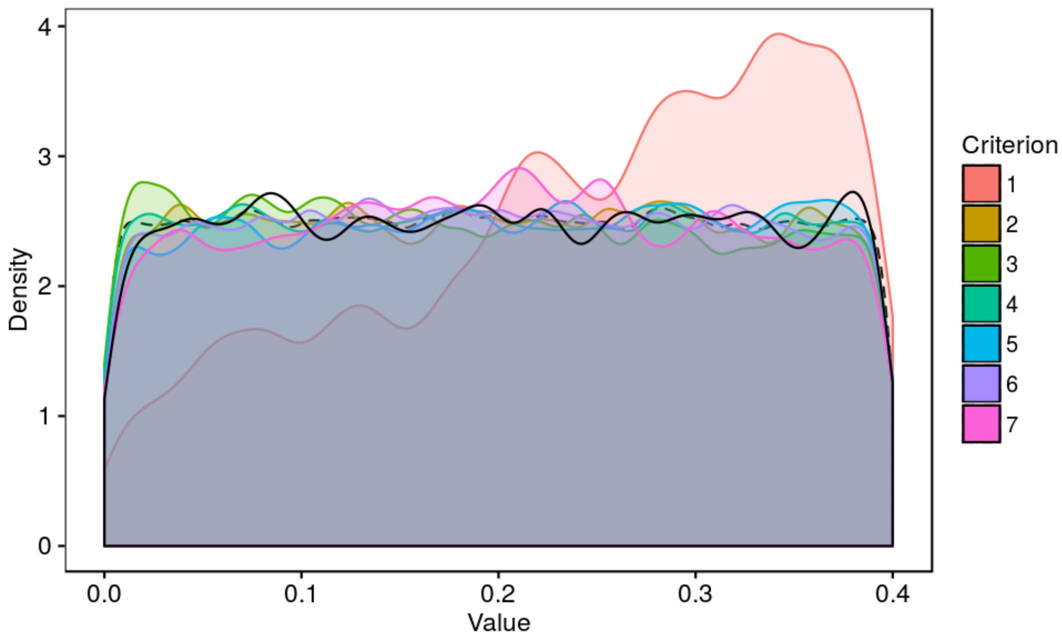


Figure 9: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `movement_we_ma`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

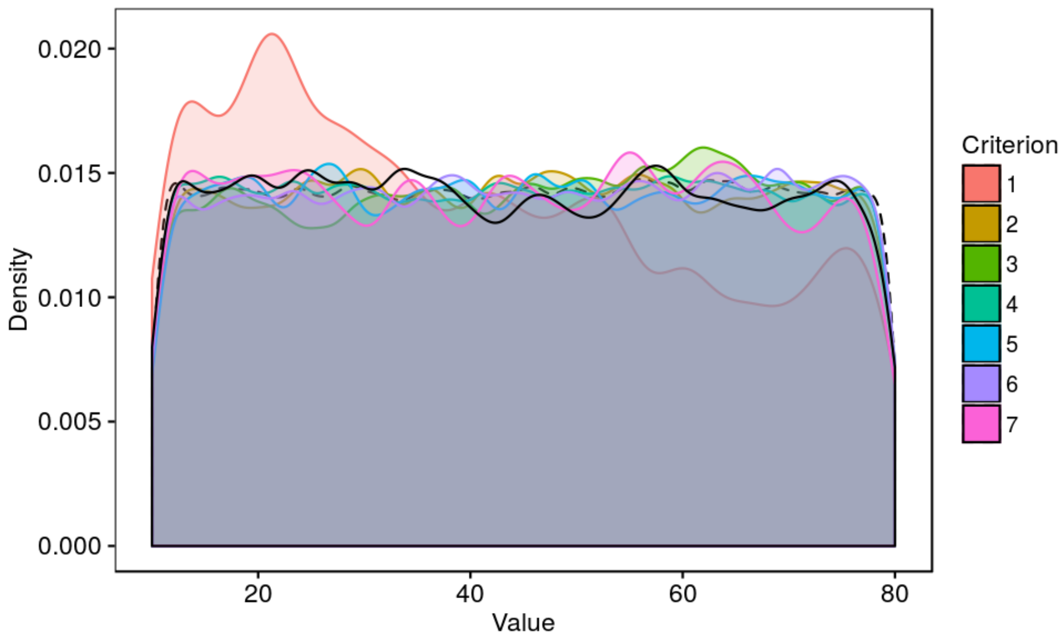


Figure 10: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `movement_length_inflection`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

2.8. Management procedures

This section presents several classes of management procedure (MP). These are examples only, intended to illustrate the wide variety of possible MPs: the data inputs they use, their algorithmic form and the management controls which they alter (e.g. effort versus catch). The final set candidate mangement procedures will be determined in close consultation with the Commission and other stakeholders.

Several classes of management procedure (MP) are presented with each *class* having several *control parameters* which can be varied to alter it's behaviour. We refer to a particular combination of control parameters for a class as an *instance* of that class.

2.8.1. BRule class

The `BRule` class of MP is similar to generic harvest control rules that have been suggested in other tuna fisheries (e.g. SCRS 2011, Scott et al 2013). It assumes that an estimate of stock status is available from an assessment conducted on a regular basis and uses a simple relation between stock status and fishing intensity. Here we define relative stock status as ratio of current spawner biomass as a proportion of the prinstine spawner biomass, B_t/B_0, and relative fishing intensity as the instantaneous rate of fishing mortality F_t. For this study we have investigated the impact of alternative levels of stock assessment precision and implementation error on performance statistics.

In each year the relative biomass is estimated through a stock assessment,

$$\hat{S} = B_t/B_0\varepsilon$$

where ε is a lognormally distributed multiplicative error with mean of 1 and standard deviation of p,

$$\varepsilon \sim LN(1, p)$$

Using $\hat{S}$ the recommended fishing intensity ($\overline{F}$) is calculated. If $\hat{S} < s_l$ then,

$$\overline{F} = 0$$

If $\hat{S} > s_t$ then,

$$\overline{F} = f$$

Otherwise,

$$\overline{F} = \frac{f}{s_t - s_l}\left(\hat{S} - s_l\right)$$

The recommended fishing intensity is applied to the fishery in the following year,

$$F_{t+1} = \overline{F}$$

Table 1 provides a summary of each of the control parameters of `BRule` and their respective values evaluated in this study. Note that IOTC Resolution 13/10 set an interim limit target biomass of B_{msy} (i.e. $b_t = 1$) and an interim limit biomass of $0.4B_{msy}$ (i.e. b_l = 0.4). IOTC Resolution 13/10 also includes a limit reference point of $1.5F_{msy}$.

Table 5: Control parameters of the BRule management procedure class: descriptions and values evaluated.

Parameter	Symbol	Description	Values evaluated
Frequency	i	Frequency of assessments of stock status	2
Estimation precision	p	Precision with which relative stock status is estimated	0.2
Threshold stock status	s_t	Relative stock status below which recommended fishing intensity is reduced	0.2, 0.3, 0.4
Limit stock status	s_l	Relative stock status below which recommended fishing intensity is zero	0.025, 0.05, 0.1
Target fishing intensity	f	Relative fishing intensity	0.2, 0.25, 0.3

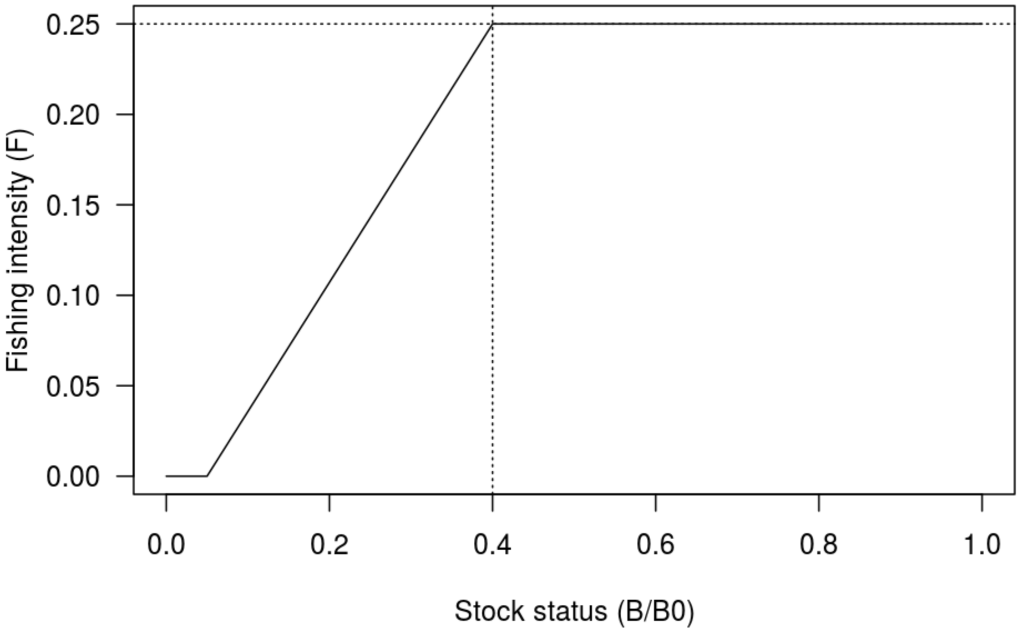


Figure 41: An example instance of the BRule management procedure with $s_l = 0.05, s_t = 0.4$, $f = 0.25$ showing the relation between $\widehat{S}$ and $\overline{F}$.

2.8.2. FRange class

`FRange` seeks to maintain the fishing mortality rate within a defined range. At periodic intervals, defined by the control parameter i, F is estimated (e.g. from a stock assessment or a tagging study) with a defined level of precision, p,

$$\widehat{F} = F\varepsilon$$

where ε is a lognormally distributed multiplicative error with mean of 1 and standard deviation of p,

$$\varepsilon \sim LN(1, p)$$

The estimated fishing mortality is compared to a range defined by two control parameters, f the centre of the range and b the buffer, or width, of the range.

Table 6: Control parameters of the FRange management procedure class: descriptions and values evaluated.

Parameter	Symbol	Description	Values evaluated
Frequency	i	Frequency of estimation of F	2, 5, 7
Estimation precision	p	Precision with which F is estimated	0.2
Target fishing intensity	f		0.2, 0.25, 0.3
Buffer around target fishing intensity	b		0.01,0.02,0.05
Maximum change	f	Maximum allowable percenatge change in effort	0.4

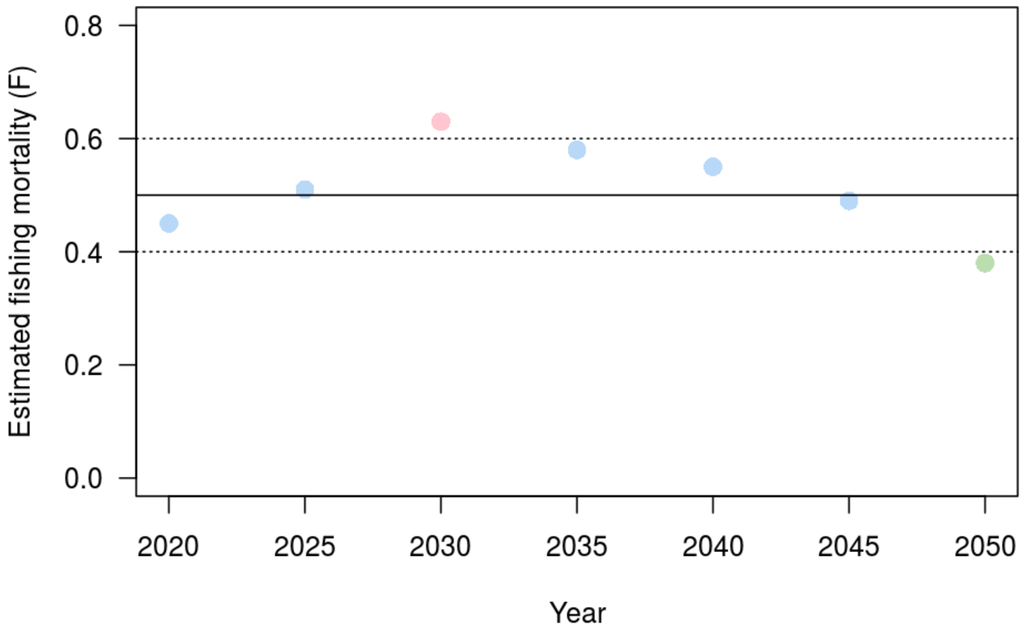


Figure 42: An example instance of the BRule management procedure with $i = 5, f = 0.5, b = 0.1$ illustrating how total allowable catches are increased (green circles) or decreased (red circles) when the estimated fishing mortality is below or above the target range.

2.8.3. IRate class

This management procedure uses CPUE as an index of biomass and sets a total allowable catch (TAC) that, over most of the range of CPUE, is proportional to that index.

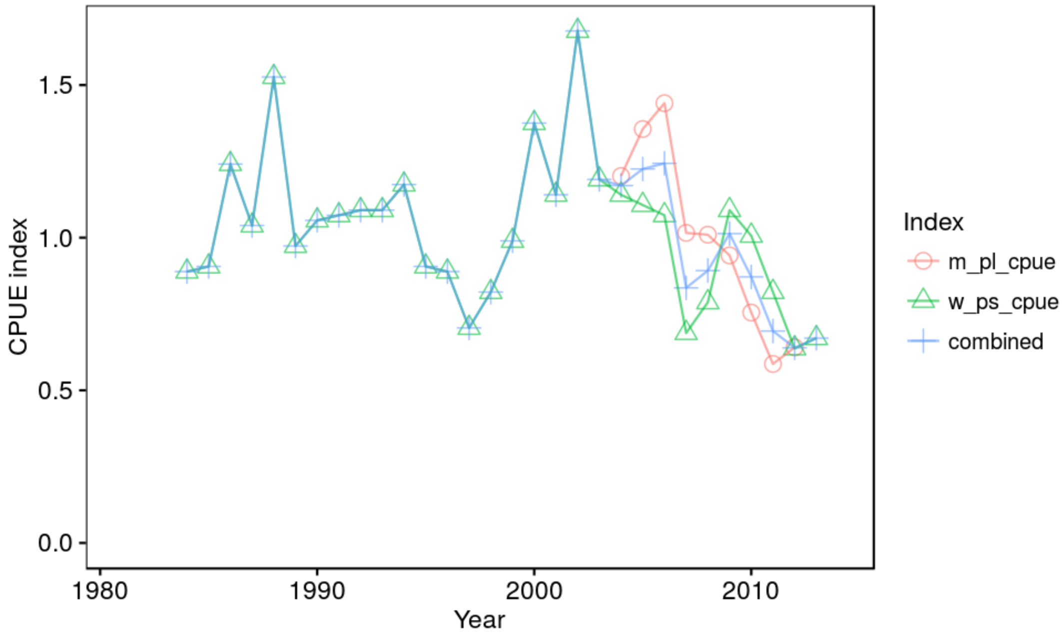


Figure 43: Western purse seine, Maldive pole and line and combined CPUE series.

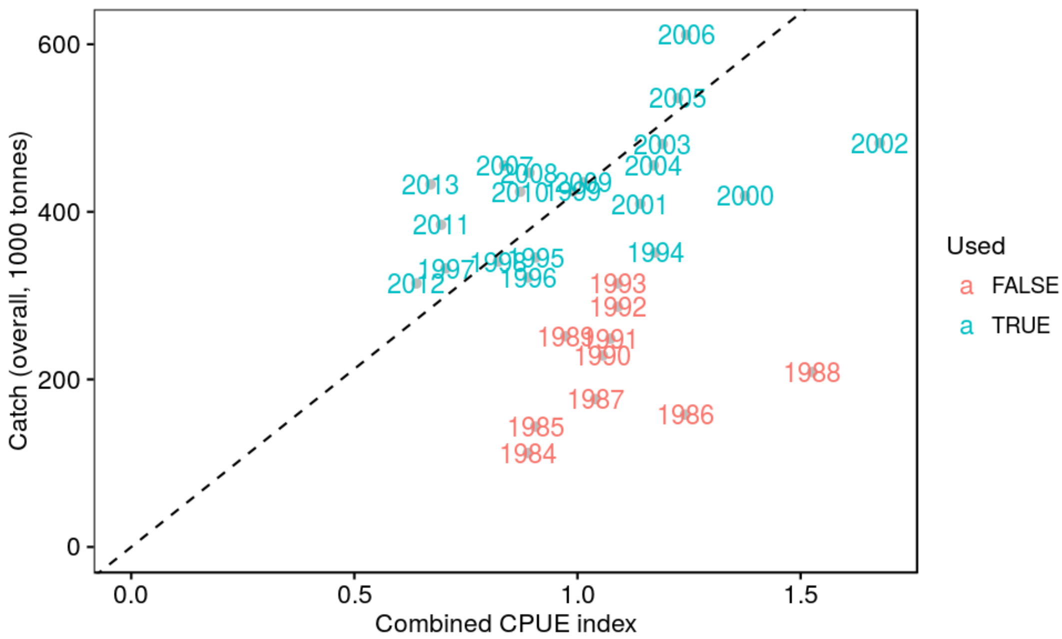


Figure 44: Historical relation between combined CPUE and overall catch. The dashed line has a slope of the catch scalar = 424.93 (geometric mean of the ratio of catches over CPUE).

In each year, a smoothed CPUE, $\bar{I}$ is calculated using an exponential moving average with the responsivesness control parameter, r:

$$\bar{I}_t = rI_t + (1 - r)\bar{I}_{t-1}$$

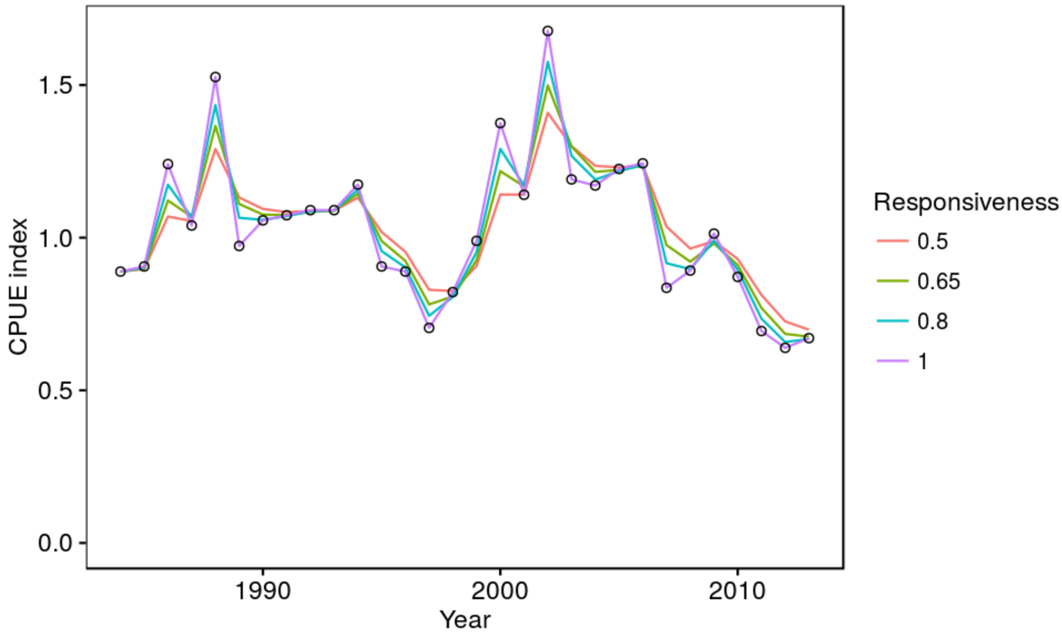


Figure 45: Illustration of the alternative smoothing of CPUE index using the responsiveness parameter.

Higher values of r produce greater responsiveness because they put more weight on more recent values of CPUE and produce a index that is less smoothed. When $r = 1$ there is no smoothing and $\bar{I}_t = rI_t$. Smoothing may be advantageous in that it reduces the influence of annual random variation in CPUE due catchability or operational variations. However, smoothing also reduces adds a lag to the index.

Using $\bar{I}$ the recommended catch scaler ($\bar{S}$) is calculated. If $\bar{I} < i_l$ then,

$$\bar{S} = 0$$

If $\bar{I} > i_t$ then,

$$\bar{S} = m\hat{S}$$

Otherwise,

$$\bar{S} = \frac{m\hat{S}}{i_t - i_l}\left(\bar{I} - i_l\right)$$

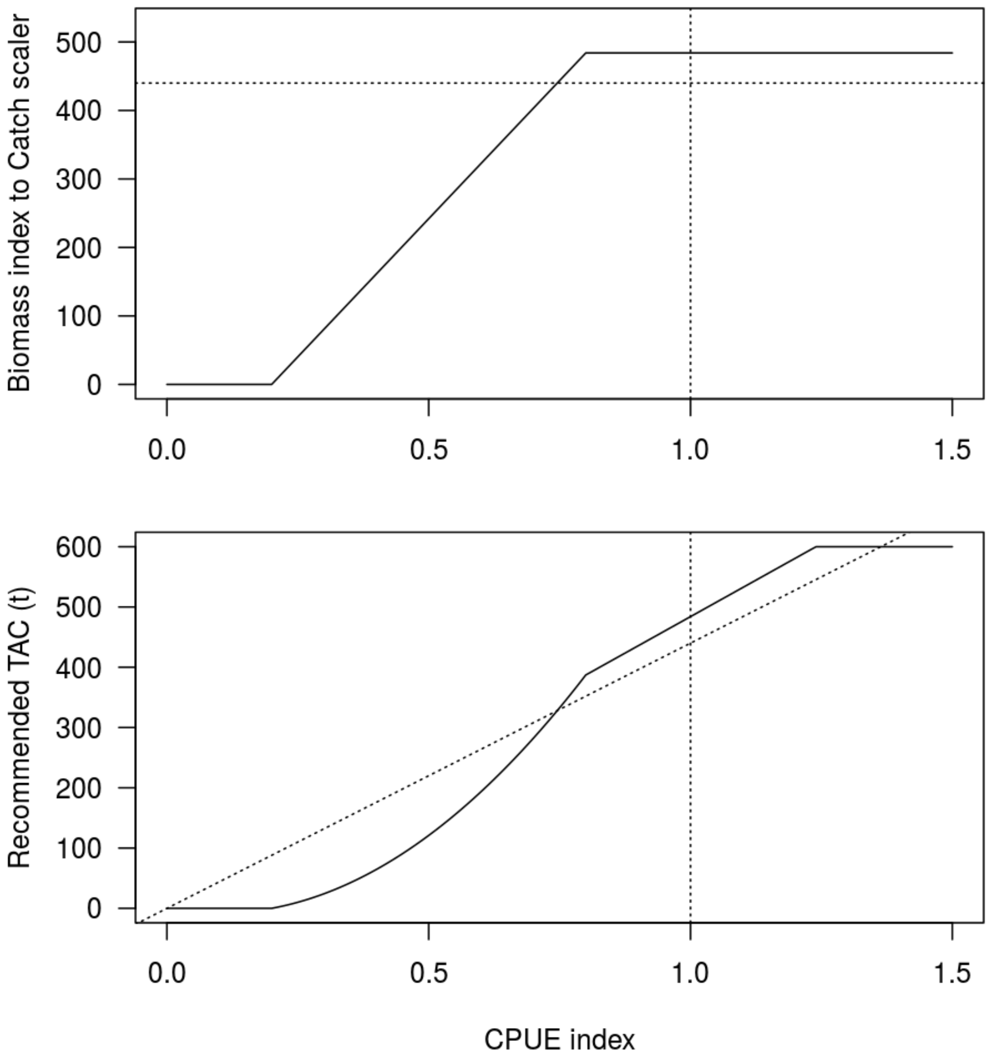


Figure 46: An example instance of the IRate management procedure with $i_l = 0.2, i_t = 0.8, m = 1.1$, $u = 600$ showing the relation between the CPUE index ($\overline{I}$) and the catch scalar ($\overline{S}$) and the recommended TAC.

The recommended catch scaler is used to calculate a recommended TAC, $\overline{S}$, by multiplying the harvest rate by the biomass index,

$$\overline{C} = \min\left(\overline{S}\overline{I}, u\right)$$

which is applied to the fishery in the following year,

$$C_{t+1} = \overline{C}\phi$$

where ϕ is a lognormally distributed multiplicative error with mean of 1 and standard deviation of e,

$$\phi \sim LN(1, e)$$

Table 7: Control parameters of the IRate management procedure : descriptions and values evaluated.

Parameter	Symbol	Description	Values evaluated
Responsiveness	r	Degree of smoothing in biomass index	0.5
Target harvest rate muliplier	m	Target harvest rate relative to historic levels i.e 0.9 = 90% of historic average	0.8, 0.9, 1.0, 1.1
Threshold biomass index	i_t	Biomass index at which the harvest rate is reduced relative to historic levels i.e. 0.7 = reduce harvest rate when the biomas index is at 70% of historic levels	0.5, 0.6, 0.7, 0.8
Limit biomass index	i_l	Biomass index at which harvest rate is zero relative to historic levels i.e. 0.2 = close the fishery when the biomas index is at 20% of historic levels	0.05, 0.1, 0.2
Maximum change	f	Maximum allowable percenatge change in effort	0.4
Maximum TAC	u	Maximum total allowable catch (thousand tonnes)	300, 400, 500, 600

2.8.4. Mald2016 class

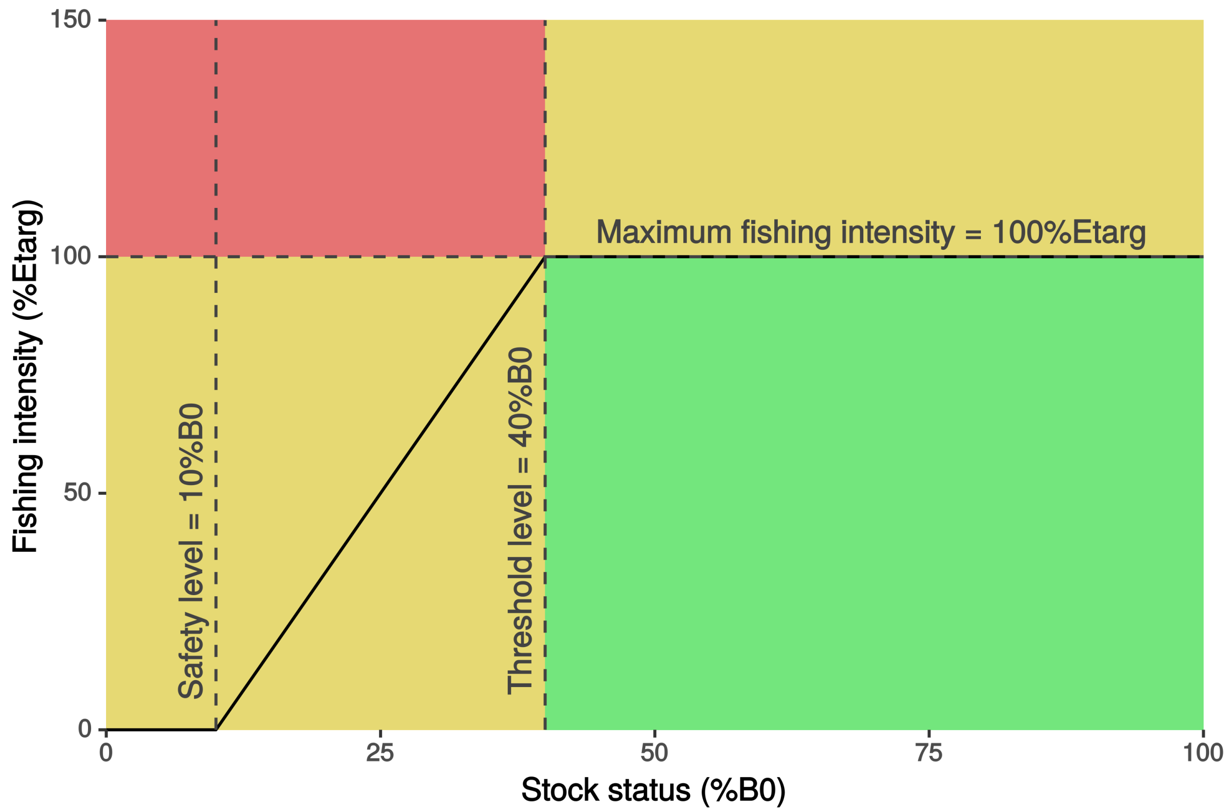
In February 2016, the "Indian Ocean Coastal Meeting on Harvest Control Rules" was held in the Maldives. This two day workshop was designed to engage stakeholders in the process of narrowing down the options for a management procedure for Indian Ocean skipjack tuna. After considering alternatives, the workshop concluded that, in the short term, a management procedure similar to the `BRule` MP described above was most appropriate. This was largely because the workshop felt that none of the existing data series for the fishery were sufficiently reliable to be the sole basis for a management procedure. IOTC members were already comfortable with the assessment process which incorporated as much of the available data as possible including the data from tagging programmes.

During, and subsequent to, the meeting, the `Mald2016` management procedure was developed as a refinement of `BRule` and became the basis of "Resolution 16/02 On harvest control rules for skipjack tuna in the IOTC area of competence". Paragraphs 6 to 10 of that resolution form the core of the `Mald2016` MP:

- The Skipjack tuna stock assessment shall be conducted every three (3) years, with the next stock assessment to occur in 2017. Estimates of 7(a–c) shall be taken from a model-based stock assessment that has been reviewed by the Working Party on Tropical Tunas and endorsed by the Scientific Committee via its advice to the Commission.
- The Skipjack tuna HCR shall recommend a total annual catch limit using the following three (3) values estimated from each Skipjack stock assessment. For each value, the reported median from the reference case adopted by the Scientific Committee for advising the Commission shall be used.
    - a) The estimate of current spawning stock biomass (Bcurr);
    - b) The estimate of the unfished spawning stock biomass (B0);
    - c) The estimate of the equilibrium exploitation rate (Etarg) associated with sustaining the stock at Btarg.
- The HCR shall have five control parameters set as follows:
    - a) Threshold level, the percentage of B0 below which reductions in fishing mortality are required, Bthresh = 40%B0. If biomass is estimated to be below the threshold level, then fishing mortality reductions, as output by the HCR, will occur.
    - b) Maximum fishing intensity, the percentage of Etarg that will be applied when the stock status is at, or above, the threshold level Imax = 100%. When the stock is at or above the threshold level, then fishing intensity (I) = Imax

- c) Safety level, the percentage of B0 below which non-subsistence catches are set to zero i.e. the non-subsistence fishery is closed Bsaftey= 10%B0.
- d) Maximum catch limit (Cmax), the maximum recommended catch limit = 900,000t. To avoid adverse effects of potentially inaccurate stock assessments, the HCR shall not recommend a catch limit greater than Cmax. This value is based upon the estimated upper limit of the MSY range in the 2014 Skipjack stock assessment.
- e) Maximum change in catch limit (Dmax), the maximum percentage change in the catch limit = 30%. To enhance the stability of management measures the HCR shall not recommend a catch limit that is 30% higher, or 30% lower, than the previous recommended catch limit.

- The recommended total annual catch limit shall be set as follows:
  - a) If the current spawning biomass (Bcurr) is estimated to be at or above the threshold spawning biomass i.e., Bcurr >= 0.4B0, then the catch limit shall be set at [Imax x Etarg x Bcurr]
  - b) If the current spawning biomass (Bcurr) is estimated to be below the threshold biomass i.e, Bcurr < 0.4B0, but greater than the safety level i.e., Bcurr > 0.1B0, then the catch limit shall be set at [I x Etarg x Bcurr]. See Table 1 in Appendix 1 for values of fishing intensity (I) for specific Bcurr/B0.
  - c) If the spawning biomass is estimated to be at, or below, the safety level, i.e. Bcurr <= 0.1B0 then the catch limit shall be at 0 for all fisheries other than subsistence fisheries.
  - d) In the case of (a) or (b), the recommended catch limit shall not exceed the maximum catch limit (Cmax) and shall not increase by more than 30% or decrease by more than 30% from the previous catch limit.
  - e) In the case of (c) the recommended catch limit shall always be 0 regardless of the previous catch limit.
- The HCR described in 8(a-e) produces a relationship between stock status (spawning biomass relative to unfished levels) and fishing intensity (exploitation rate relative to target exploitation rate) as shown below :



3. Evaluations

3.1. Methods

This section describes the methods used to evaluate alternative candidate management procedures. Evaluation results are provided in the following section.

3.1.1. Management objectives, performance measures, performance statistics

This section uses the following terminology. A *performance measure* is any model variable that is used as a basis for a *performance statistic* . That is, a performance statistic, summarises a performance measure over the evaluation period, in this case 25 years.

The main performance measures used are catches C, relative catch rates A, and spawner biomass B. For convenience, where the performance measure represents a summation across all possible model dimensions (e.g. region, method) for the variable we exclude subscripts in mathematical notation. e.g.

$$C = \sum_{r,m} C_{r,m}$$

We have grouped performance statistics according to broad categories of management objectives : yield, abundance, stability, status and safety (Table 8). We use these labels in the following summaries and for each category focus on the first performance statistic. For example, when presenting evaluation results relating to the stability management objective we mostly summarise the MAPC performance statistic. In accordance with the desire to maximise these objectives we present "positive" versions of each of performance statistics in the following figures and tables. For example, rather than presenting a "risk" related statistic such as the probability of being below 10%B0 we use the "safety" related statistic, the probability of being **above** 10%B0.

Table 8: Management objectives, performance statistics and performance measures. [This table has not yet been updated to reflect recent changes agrred to during WPM]

Performance statistic	Performance measure/s	Summary statistic
Status : maximize stock status		
Mean spawner biomass relative to pristine	B/B_0	Geometric mean over years
Minimum spawner biomass relative to pristine	B/B_0	Minimum over years
Mean spawner biomass relative to B_{msy}	B/B_{msy}	Geometric mean over years
Mean fishing intensity relative to target	F/F_{tar}	Geometric mean over years
Mean fishing mortality relative to F_{msy}	F/F_{msy}	Geometric mean over years
Probability of being in Kobe green quadrant	B,F	Proportion of years that $B \geq B_{tar} \& F \leq F_{tar}$
Probability of being in Kobe red quadrant	B,F	Proportion of years that $B < B_{tar} \& F > F_{tar}$
Safety : maximize the probability of remaining above low stock status (i.e. minimize risk)		
Probability of spawner biomass being above 20% of B_0	B	Proportion of years that $B > 0.2B_0$
Probability of spawner biomass being above 10% of B_0	B	Proportion of years that $B > 0.1B_0$
Yield : maximize catches across regions and gears		
Mean catch	C	Mean over years
Mean purse siene catch	$\sum_r C_{r,ps}$	Mean over years
Mean pole and line catch	$\sum_r C_{r,pl}$	Mean over years
Mean gillnet catch	$\sum_r C_{r,gn}$	Mean over years
Abundance : maximize catch rates to enhance fishery profitability		
Mean relative catch rates for western purse siene	$A_{we,ps}$	Geometric mean over years
Mean relative catch rates for Maldive pole and line	$A_{ma,pl}$	Geometric mean over years
Mean relative catch rates for eastern gillnet	$A_{ea,gn}$	Geometric mean over years
Stability : maximize stability in catches to reduce commercial uncertainty		
Mean absolute proportional change (MAPC) in catch	C	Mean over years of $\|C_t/C_{t-1} - 1\|$
Variance in catch	C	Variance over years
Probability of shutdown	C	Proportion of years that $C = \;= 0$

Additional performance statistics have been added as requested by stakeholders:

- Yield (years catch>=425kt %) : the percentage of years in which catches are above the nominal baseline of 425kt per annum.

- Stability (years where decrease %) : the percentage of years in which there is an decrease in the recommended catch limit (note that the changes in catch limit only occur every 3 years)
- Stability (years where increase %) : the percentage of years in which there is an increase in the recommended catch limit (note that the changes in catch limit only occur every 3 years)

3.1.2. Simulation methods and terminology

This section provides an overview of the methods and terminology used for evaluating management procedures (i.e. management procedure evaluation, MPE). We provide examples of the types of figures and tables that are used in the following, more detailed, descriptions of evaluation results for each class of management procedure.

Each *evaluation* of a management procedure is based on a *replicate*. Each replicate incorporates *parameter uncertainty* through the random selection of a set of model parameters as well as *stochastic uncertainty* through the random generation of *process uncertainty* (e.g. recruitment variation) and *observation uncertainty* (e.g. CPUE error). The parameter set for a replicate is drawn from all the possible parameter sets determined from model conditioning. For each evaluation, the particular management procedure is used to determine future simulated management which affects catches, which in turn affects stock biomass and other *performance measures* (Figure 47).

The primary purpose of MPE is not to provide forecats of catch, biomass or other performance measures. Rather, it is to compare the performance, relative to management objectives, of alternative candidate management procedures. Thus, for each replicate, each of the candidate management procedures is evaluated (Figure 48). This allows us to compare the performance of alternative MPs under exactly the same set of assumptions. Notice in (Figure 48) that the biomass trajectories resulting from using alternative MPs often fluctuate in parallel. This is due to the same recruitment variations being used for each evaluation.

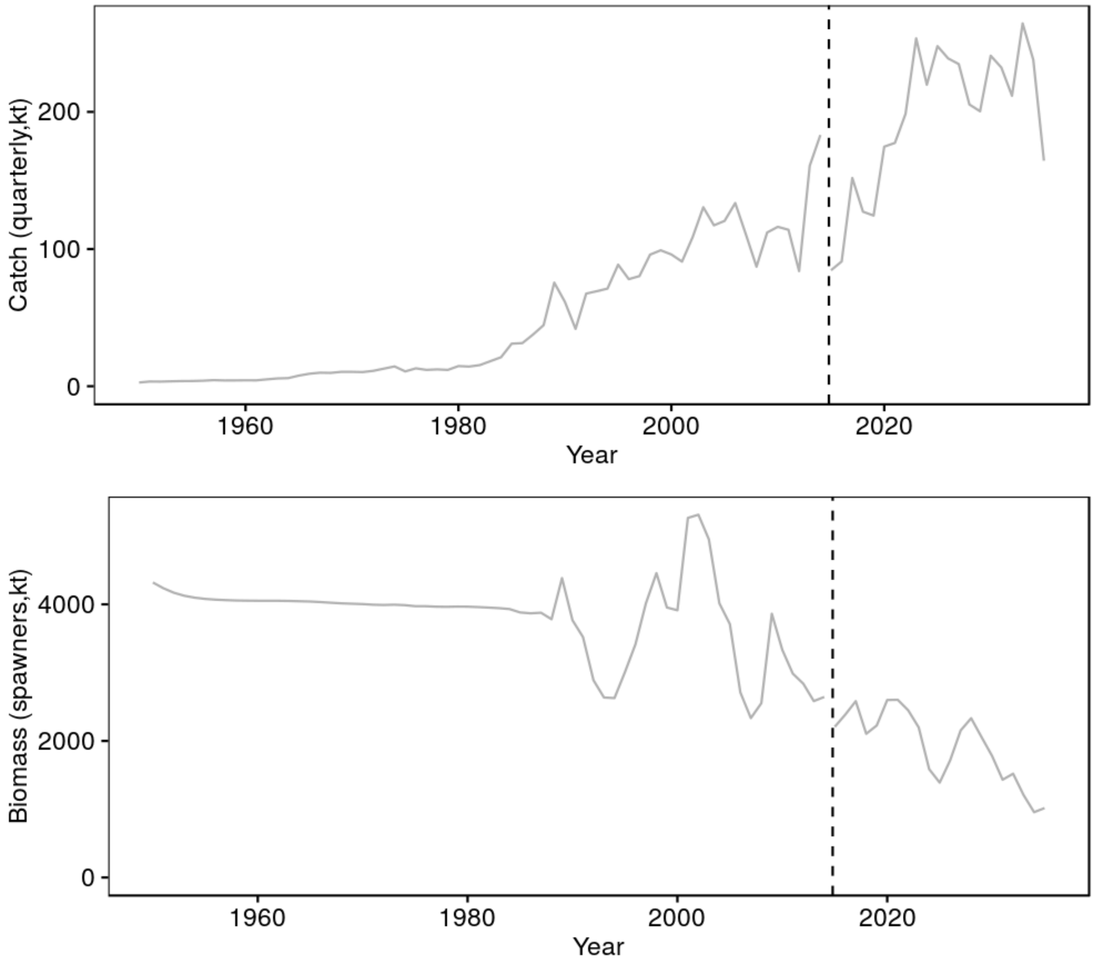


Figure 47: Catch and biomass trajectories from a single evaluation of a single management procedure using a single parameter replicate.

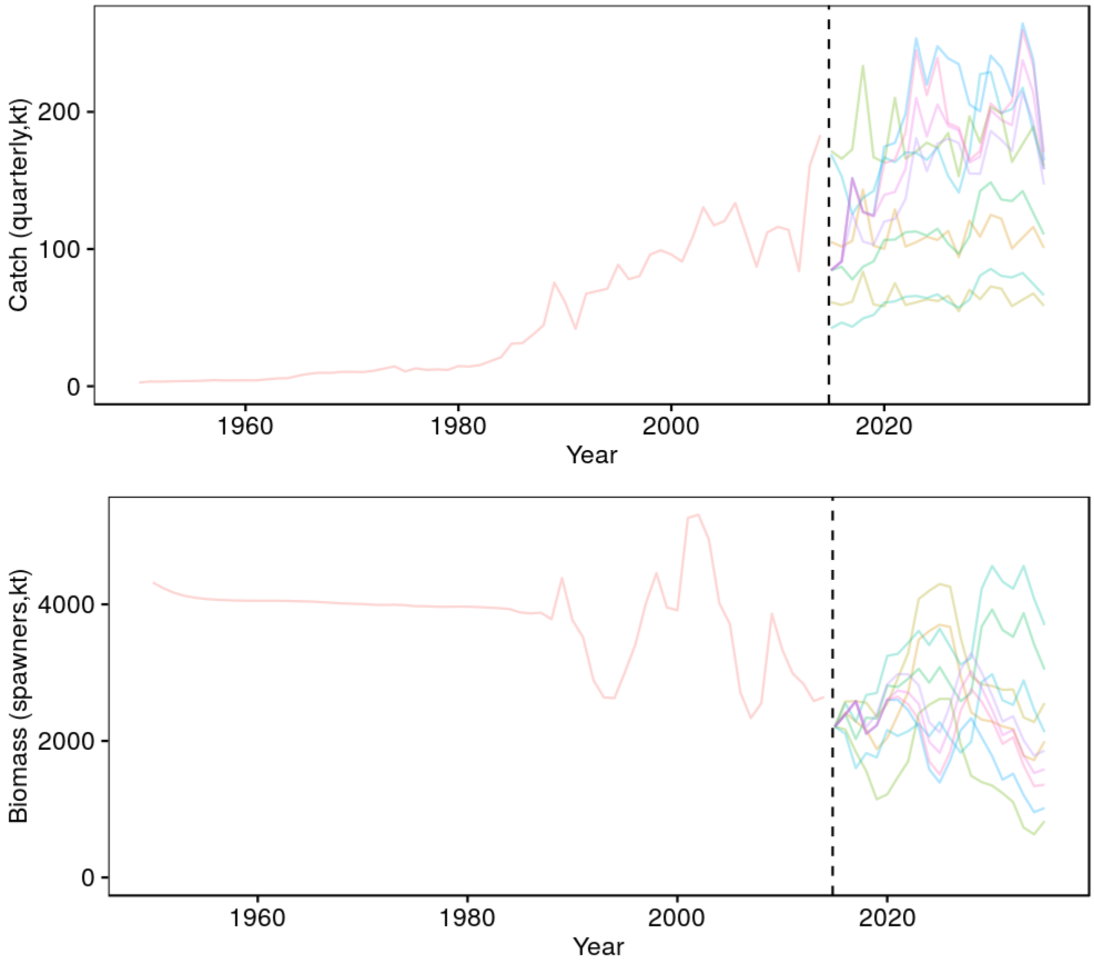


Figure 48: Catch and biomass trajectories from multiple evaluations of multiple management procedure using a single parameter replicates. Each of the coloured future trajectories arises from applying one candidate management procedure.

To be able to assess and compare the robustness of management procedures to uncertainty it is necessary to run evaluations for many replicates. Figure 49 shows one hundred evaluations, each based on a different replicate, for a single management procedure. When presenting the trajectories from muliple evaluations, it is usually easier to ascertain both the central tendency and the variability of trajectories using quantile ribbons (Figure 50). The ribbons show the bands within which 50% and 80% of trajectories fall. In addition, to indicate the expected inter-annual variability, the trajectories from three example replicates are shown separately. These example replicates were chosen as those that produced the 20th (red), 50th (blue) and 80th (green) percentile of average biomass of spawners under the constant effort management procedure.

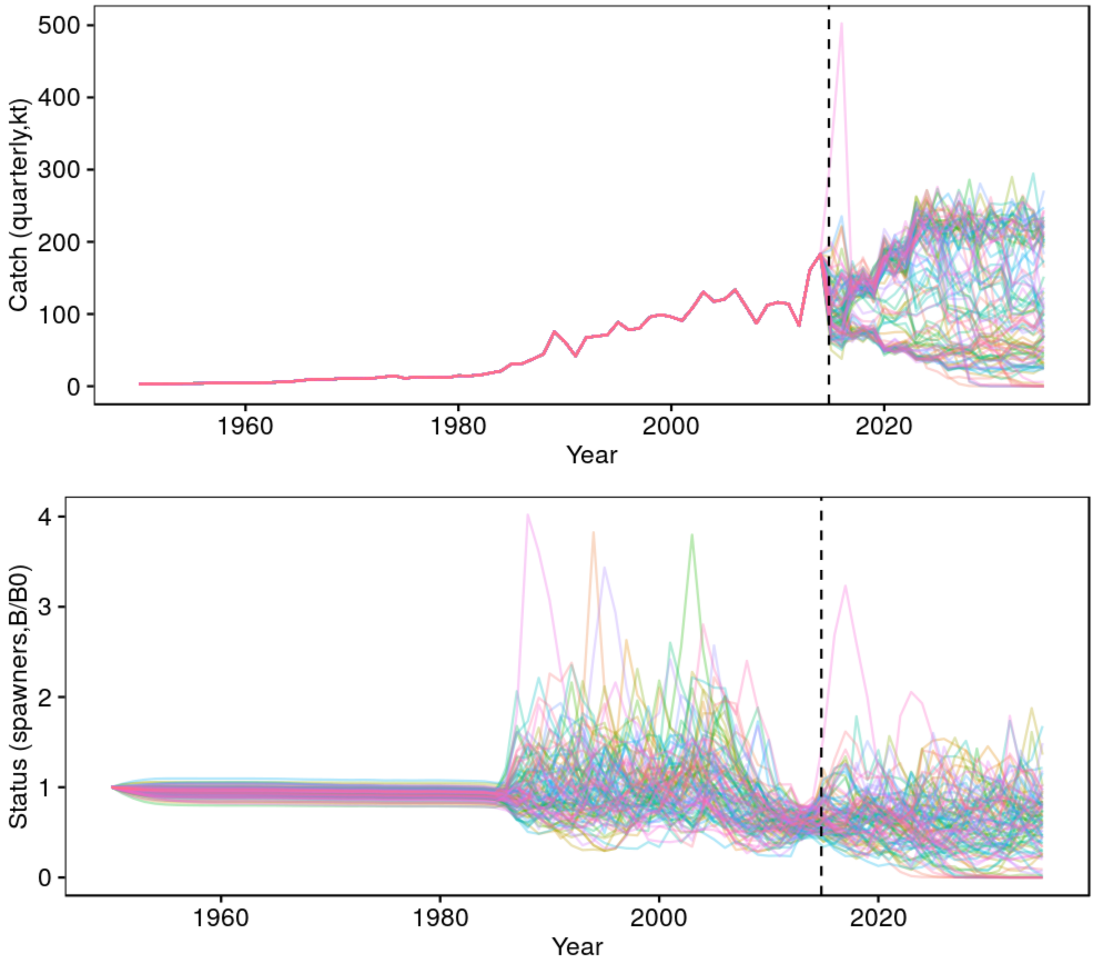


Figure 49: Catch and biomass trajectories from multiple evaluations of a single management procedure using multiple parameter replicates. Each of the coloured trajectories arises from alternative replicate.

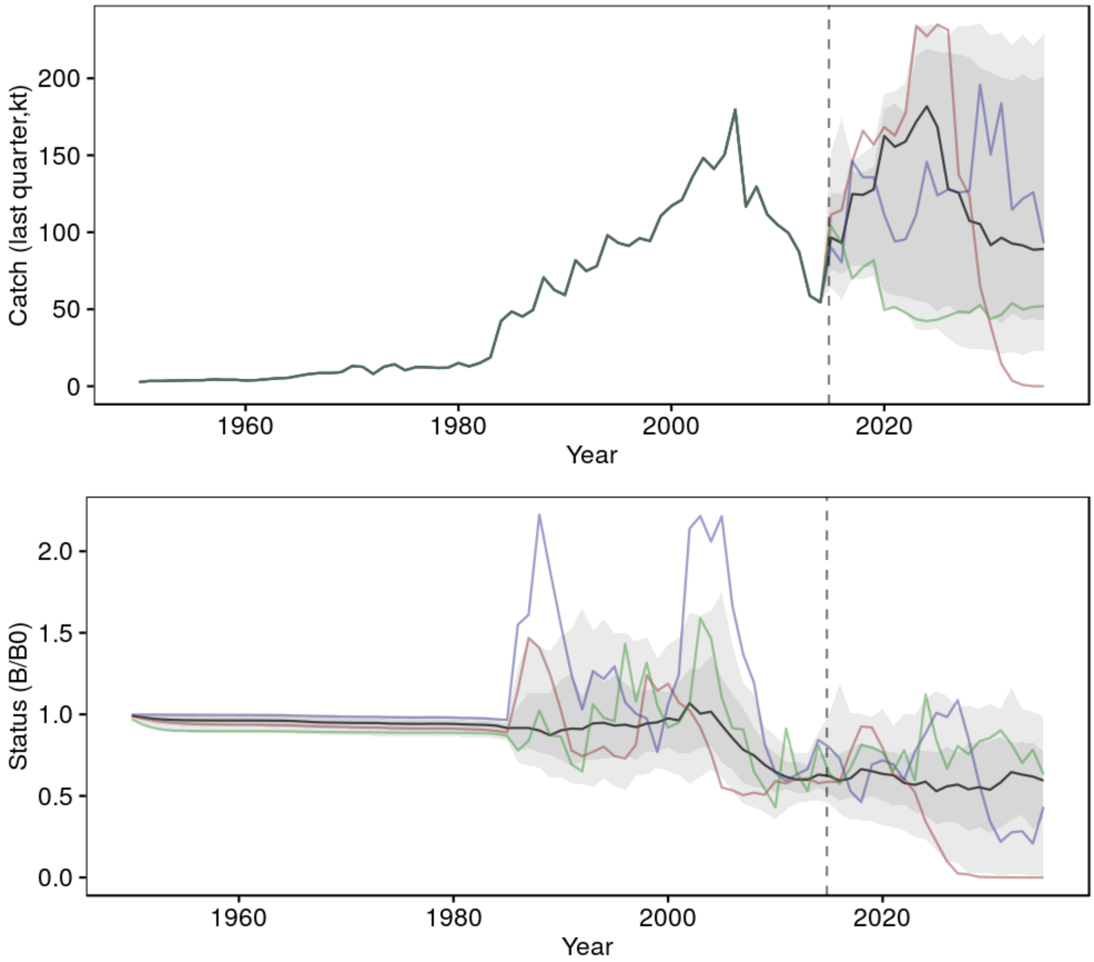


Figure 50: Catch and biomass trajectories from multiple evaluations of a single management procedure using multiple parameter replicates summarised into percentile ribbons

3.2. Results

3.2.1. General

In this section we provide a general comparison of the performance of the various classes of management procedures developed during this study relative to the performance statistics introduced above. In the following section we provide more detailed result for the `Mald2016` mangement procedure which was the focus of interest for evaluations.

The following figures illustrate the trade offs between pairs of performance statistics representing key management objectives:

- Figure 51 : yield v status
- Figure 52 : yield v safety
- Figure 53 : yield v stability

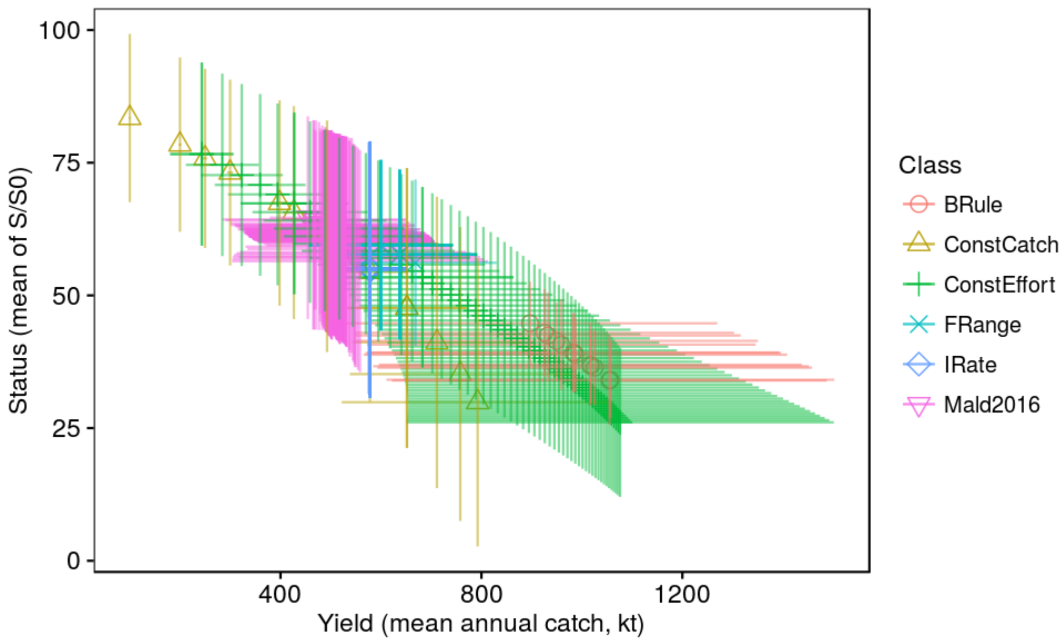


Figure 51: Trade-off between yield and status related performance statistics across all the management procedures evaluated. Each point represents the mean of the performance statistic over all replicate simulations. The horizontal and vertical lines represent one standard deviation o

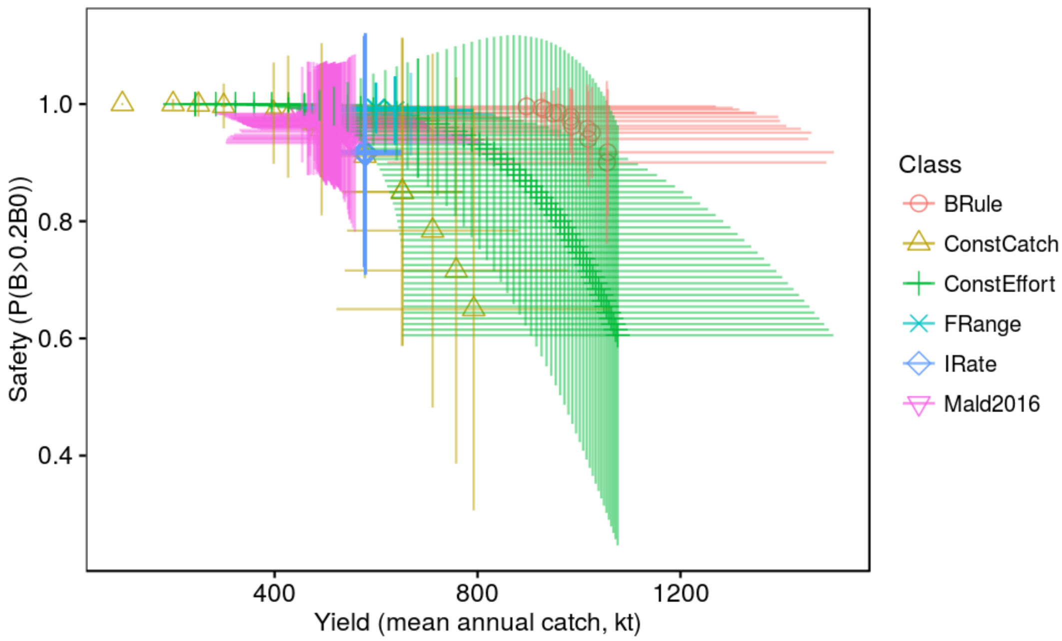


Figure 52: Trade-off between yield and safety related performance statistics across all the management procedures evaluated. See Figure 52 for more details.

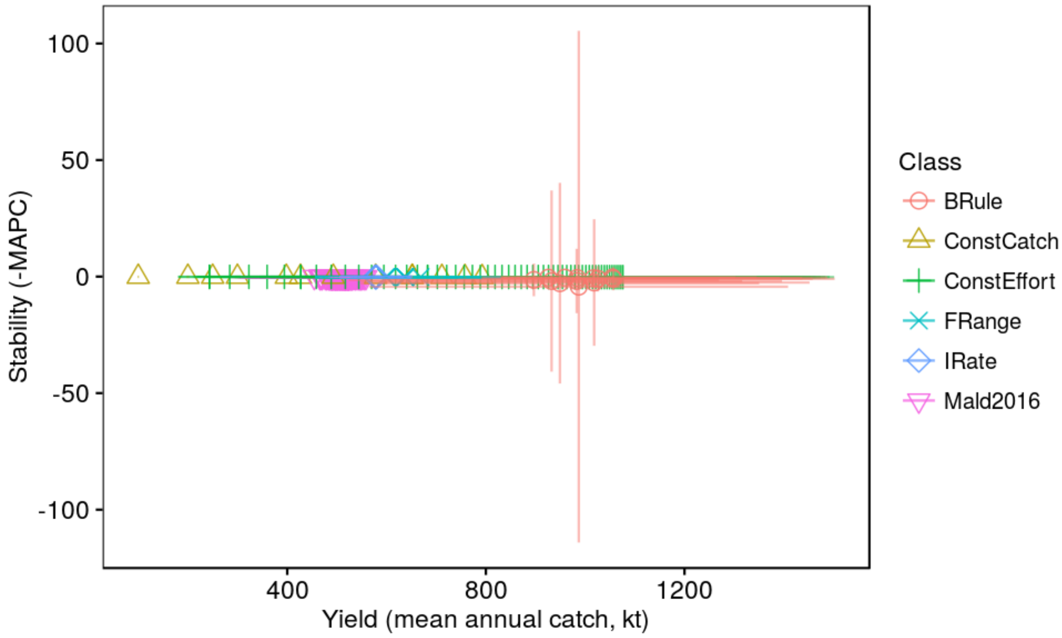


Figure 53: Trade-off between yield and stability related performance statistics across all the management procedures evaluated. See Figure 52 for more details.

There is an unsurprising performance trade off between yield and abundance (Figure 54). In general, higher catches lead to higher exploitation rates and reduced biomass which in turn leads to reduced catch rates. Generally there is a high correlation between the abundance performance statistics for each of the main fisheries (Figure 55). Note however, that some MPs, particularly those resulting in overall higher abundance do result in higher relative abundance for M-PL and E-GN. This is most likely a result of the lower exploitation rates under these MPs which in turn creates an increase in the biomass of larger sized skipjack which are more fully selected by these fisheries.

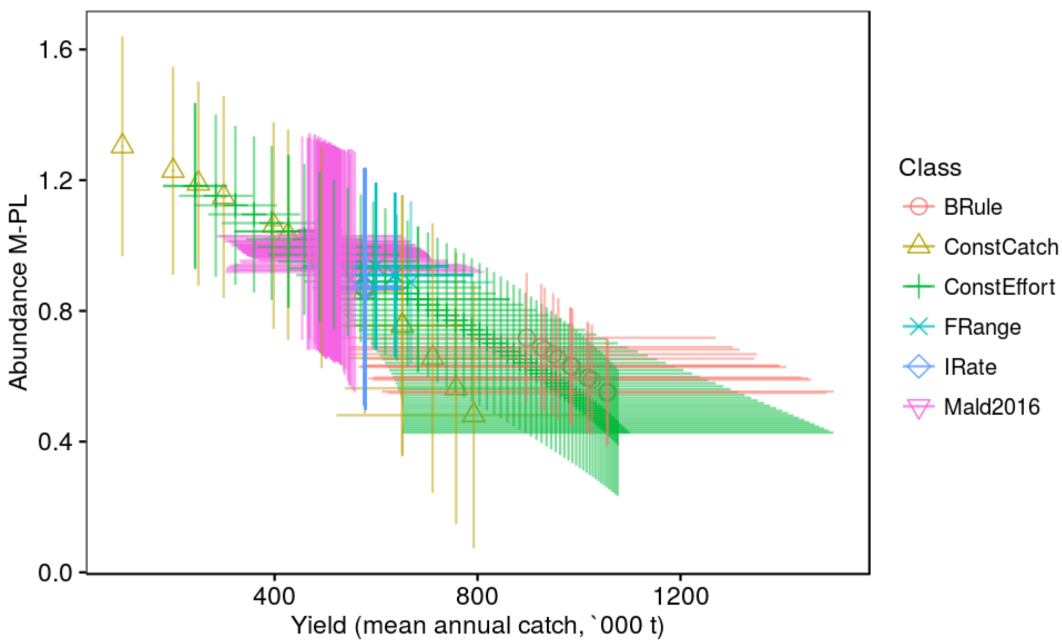


Figure 54: Trade-off between yield and abundance related performance statistics (here the CPUE for the Maldive pole and line fishery) across all the management procedures evaluated.

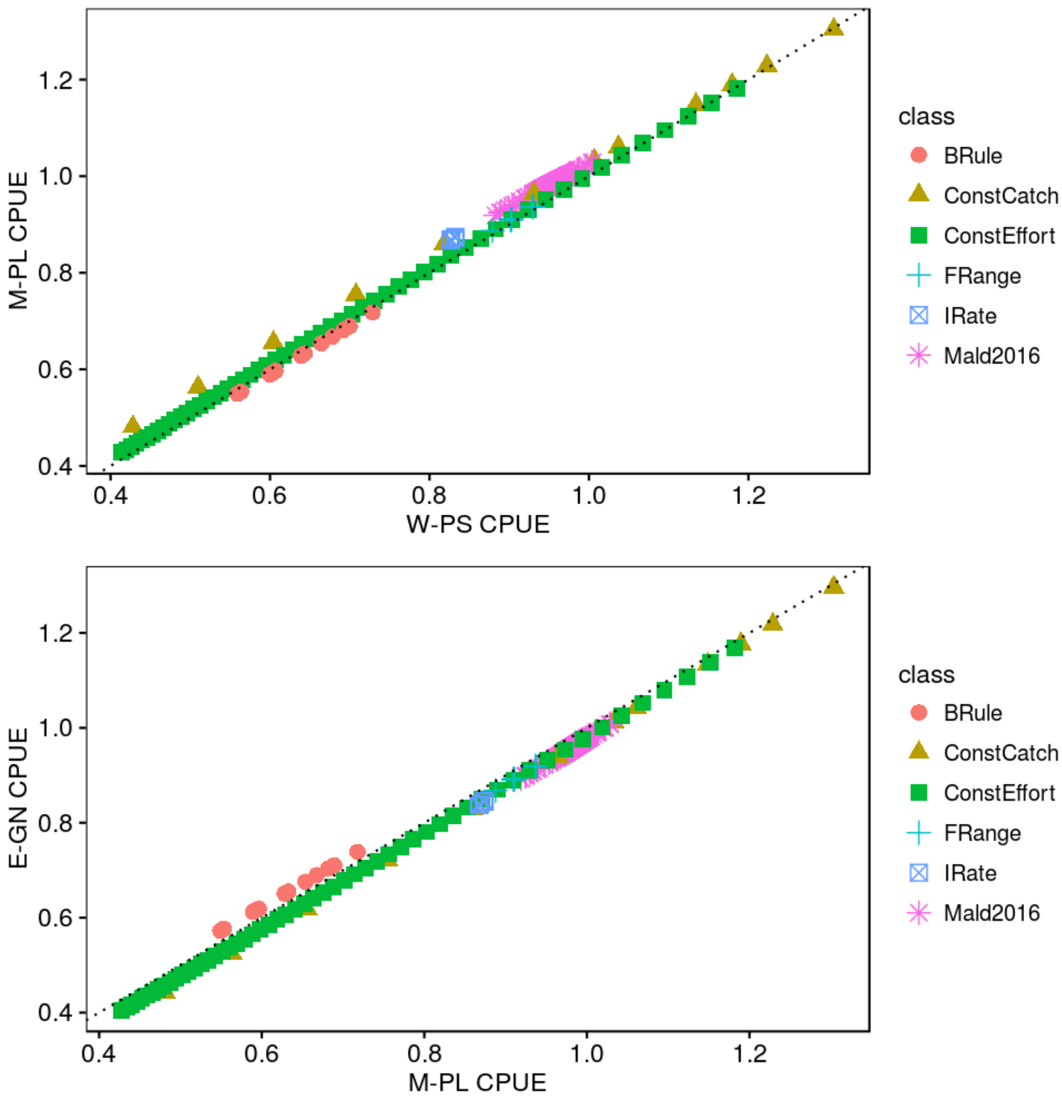


Figure 55: Correlation between the abundance performance statistics between the three main fisheries.

3.2.2. Mald2016

This section summarizes the performance of the `Mald2016` management procedure using the evaluation methods described above. It is important to note that `Mald2016` is based on the results of stock assessments performed every three years. However the management procedure does not specify how that assessment should be conducted (e.g. what data weightings should be used). As such, it can be considered to be a Harvest Control Rule (HCR), rather than a full managment procedure.

In these evaluations we did not attempt to simulate a fixed stock assessment process (e.g. by assuming a simple assessment done using a biomass dynamics model, or by simulating a full Stock Synthesis based assessment). There is likely to be variation, perhaps substantial, in the methods and data used in assessments and subsequently variation in both the accuracy and precision (both unknown) of future assessments. We assumed that there was a no bias and a 10% coefficient of variation in the precision of assessment estimates of stock status. However, even given these optimistic assumptions, the evaluation results show a deterioration in the performance of the MP in the long term (there is a significant proportion of simulations where after 25 years stock biomass falls below 25% B0). In the Discussion we suggest alternative ways that these issues could be addressed.

The suggested base control parameter values for this MP are:

- Maximum fishing intensity $I_{\max} = 100\ \%$

- Threshold level $T = 40\ \%$
- Safety (closure) level $X = 10\ \%$
- Maximum TAC $C_{\max} = 900,000t$
- Maximum change in TAC $D_{\max} = 30\ \%$

The resulting performance statistics given this set of control parameters are provided in Table 9 and catch and biomass trajectories are shown in Figure 56.

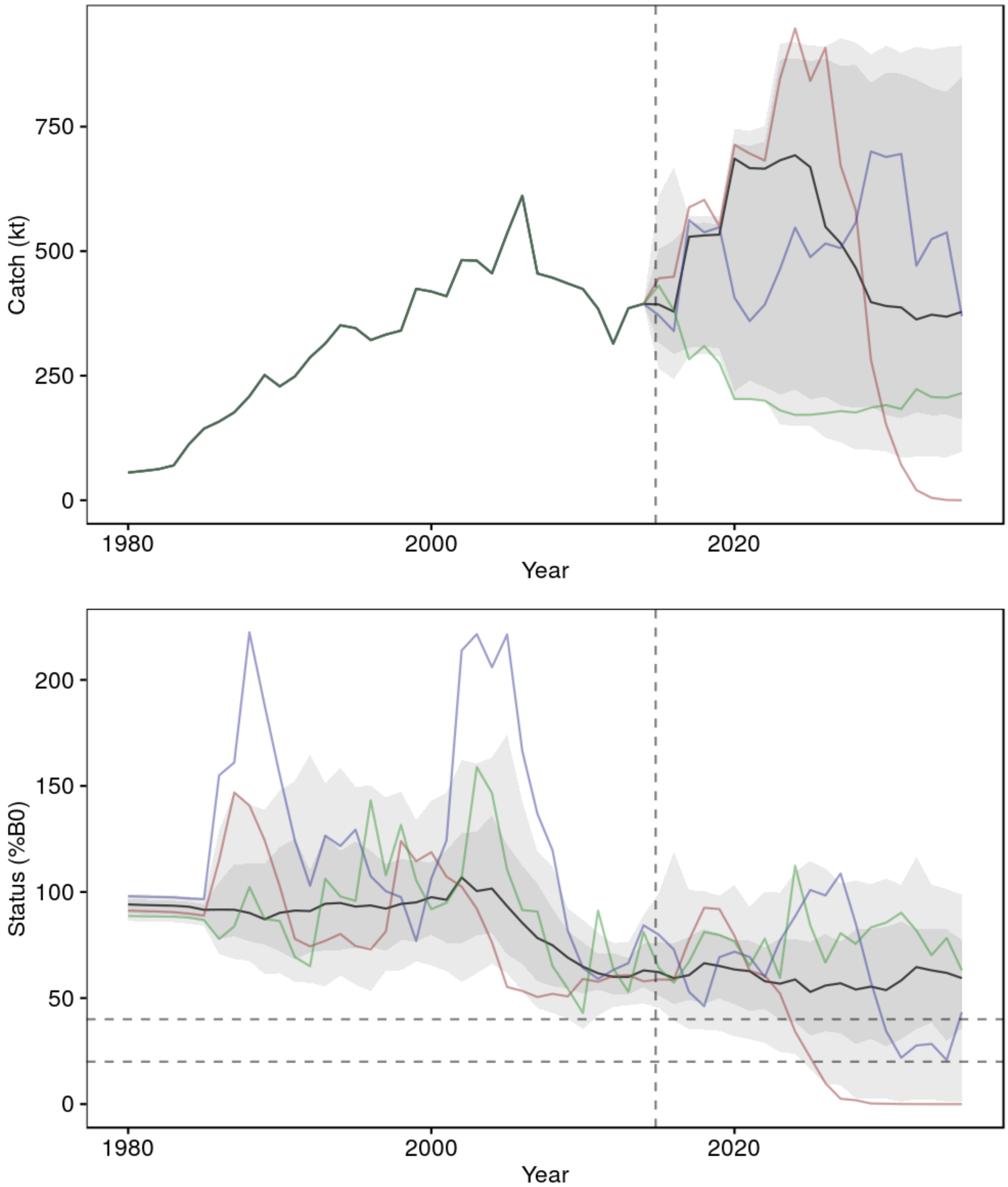


Figure 56: Projected catch and stock status trajectories for the Mald2016 management procedure with the "base case", suggested values for control parameters. The black line indicates the median and the grey ribbons the 10-90th and 25-75th percentiles. The coloured lines represent three individual simulations which correspond to the 25th, 50th and 75th percentiles of stock status over the projection period under a constant effort strategy.

Table 9: Performance statistics values for the `Mald2016` management procedure with the suggested base control parameter values. Performance statistics relate to the first 10 years of simulations 2015 to 2025. See previous section for

	Performance statistic		Percentiles				
		Mean	10th	25th	50th	75th	90th
	Status (Mean %B0)	60.74	38.76	49.97	60.83	72.0	83.5
	Fishing intensity (F/F40%B0)	0.74	0.11	0.23	0.54	1.0	1.6
	Kobe green (Years %)	68.65	23.26	46.51	76.74	100.0	100.0
	Kobe top-right (Years %)	18.04	0.00	0.00	0.00	25.6	72.1
	Kobe red (Years %)	5.40	0.00	0.00	0.00	7.0	18.6
	Kobe bottom-left (Years %)	7.91	0.00	0.00	0.00	9.3	30.2
	Safety (Prop. years B>20%B0)	96.51	88.37	100.00	100.00	100.0	100.0
	Yield (Mean catch; kt)	522.39	242.75	335.78	612.92	667.2	692.6
	Yield (Years catch>=425kt %)	63.52	0.00	18.60	81.40	97.7	100.0
	Stability (MAPC %)	16.88	11.37	13.44	16.15	19.3	22.9
	Probability of shutdown (Years catch<1kt %)	0.16	0.00	0.00	0.00	0.0	0.0
	Stability (Years TAC decrease %)	8.22	0.00	0.00	0.00	12.5	25.0
	Stability (Years TAC increase %)	16.77	0.00	12.50	25.00	25.0	25.0
	Western purse seine CPUE (relative to 2000-2015)	0.94	0.57	0.75	0.93	1.1	1.3
	Maldives pole and line CPUE (relative to 2000-2015)	0.97	0.61	0.78	0.96	1.1	1.4
	Eastern gill net CPUE (relative to 2000-2015)	0.95	0.56	0.75	0.93	1.1	1.4

This section examines the sensitivity of the performance statistics to alternative values of control parameters for the `Mald2016` management procedures. This was done by individually varying each of the control parameters whilst keeping the remainder at their base value. In the following figures, distributions for four key performance statistics are presented at each level of each control parameter.

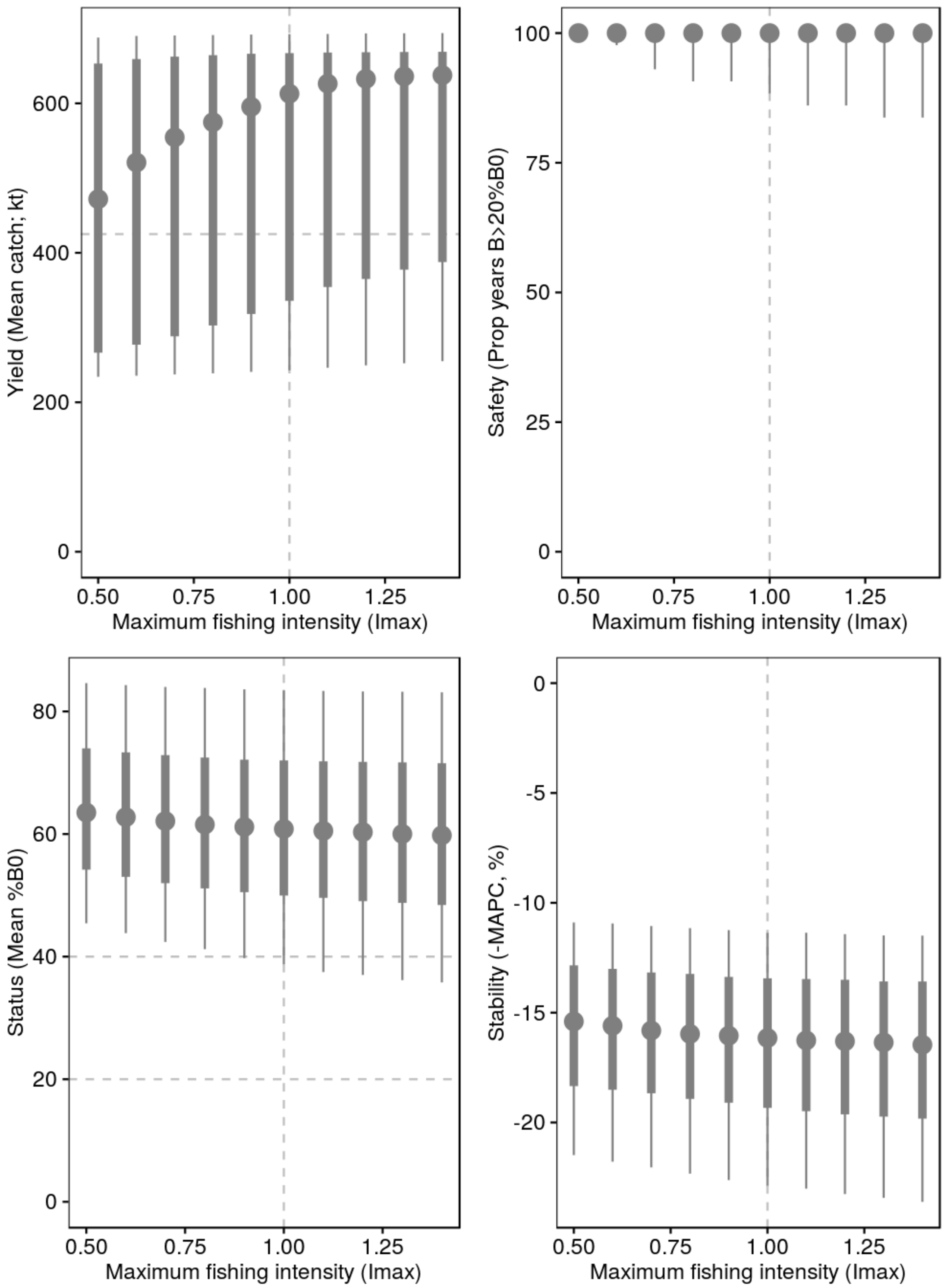


Figure 57: Key performance statistics versus the maximum fishing intensity (Imax) control parameter

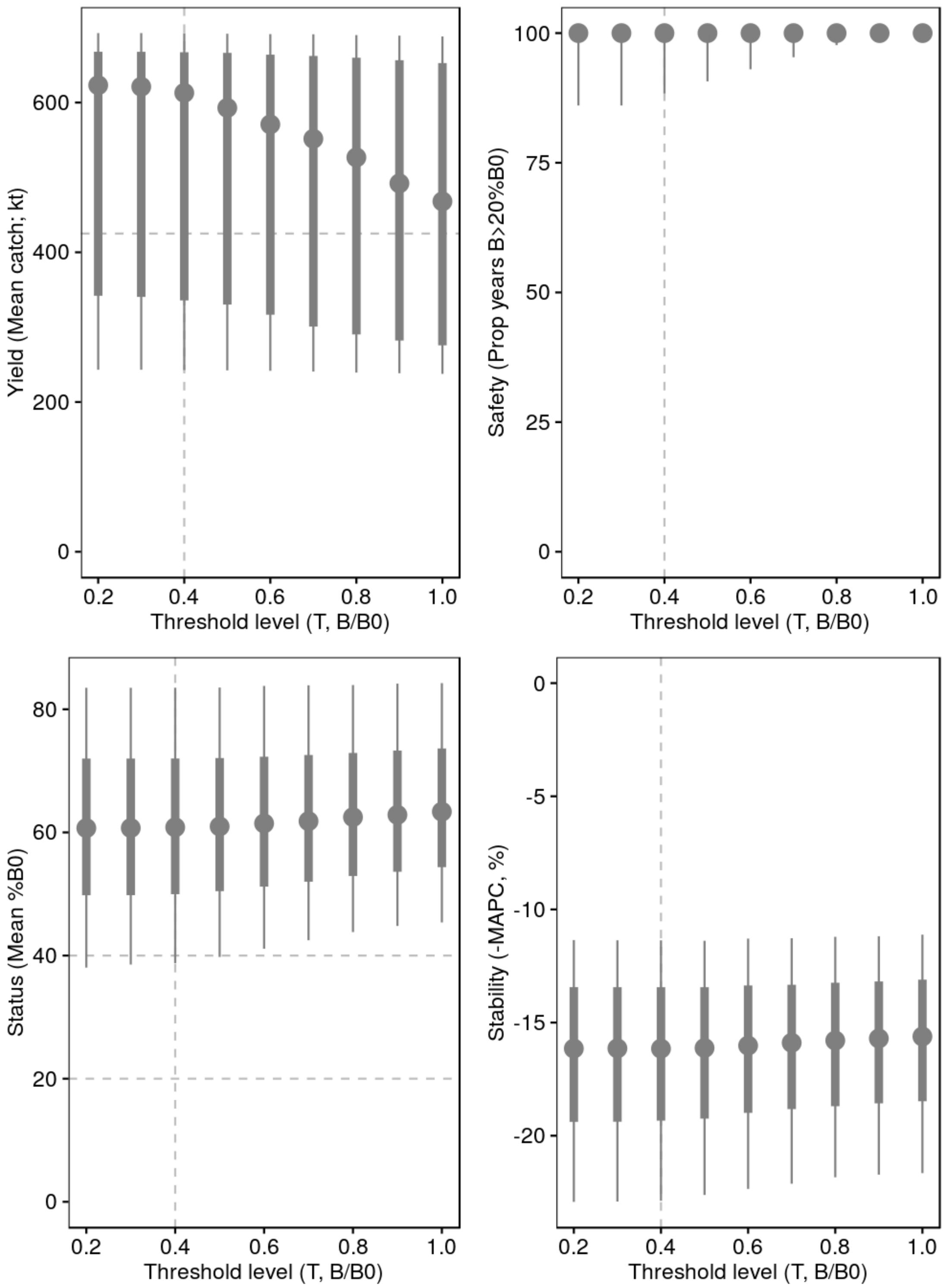


Figure 58: Key performance statistics versus the threshold level (T) control parameter

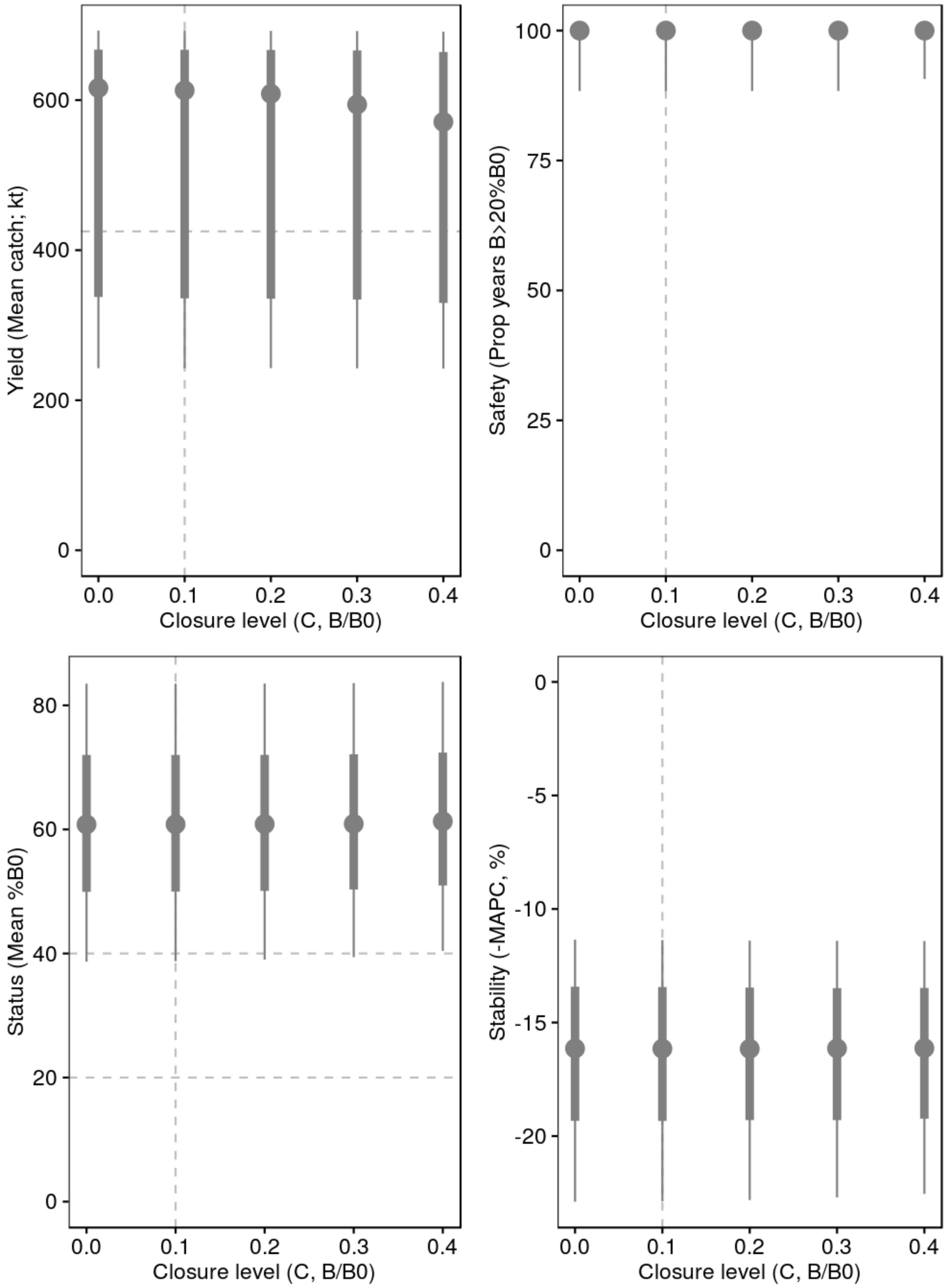


Figure 59: Key performance statistics versus the safety (closure) level (X) control parameter

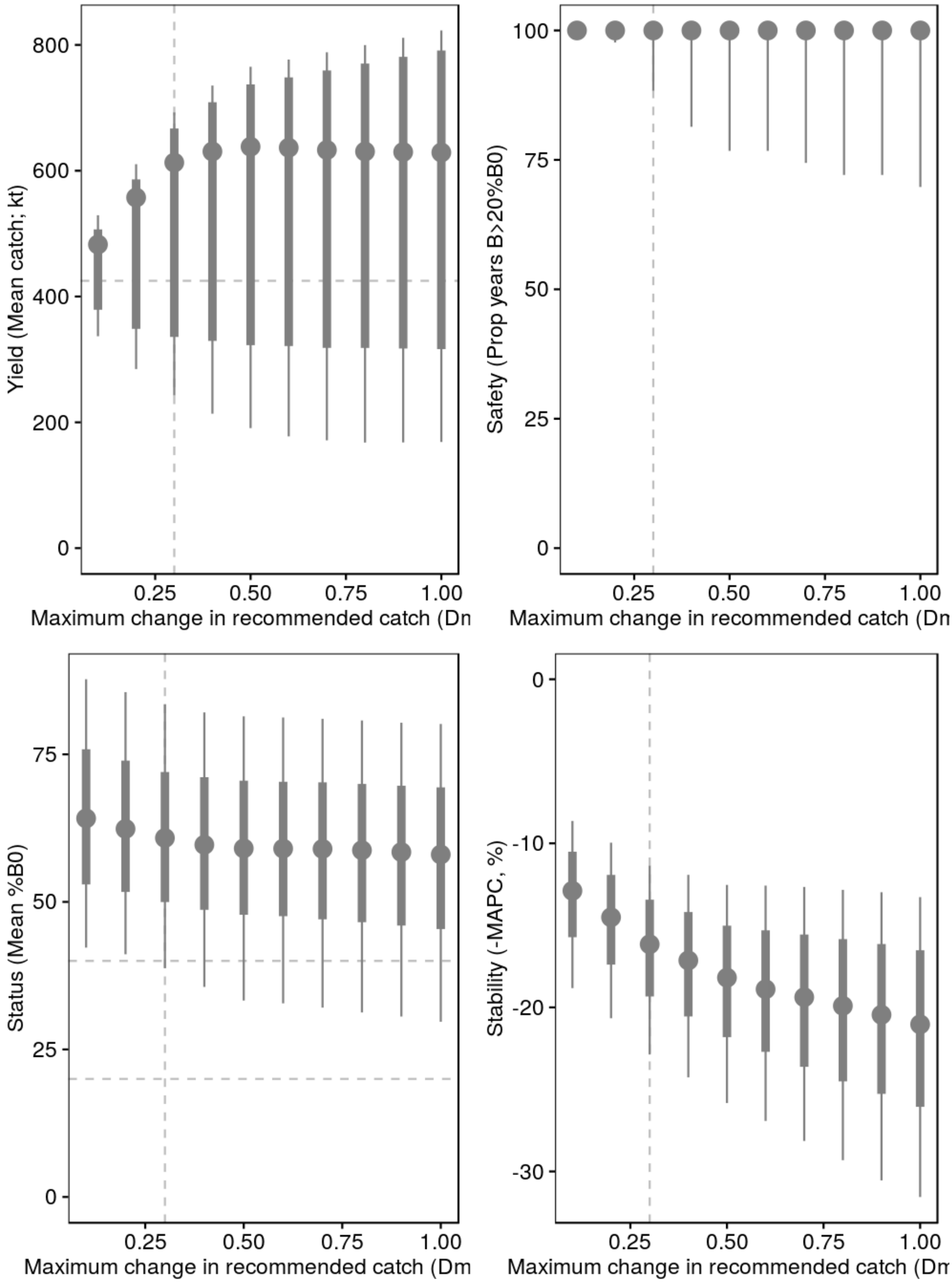


Figure 60: Key performance statistics versus the maximum change (Dmax) control parameter.

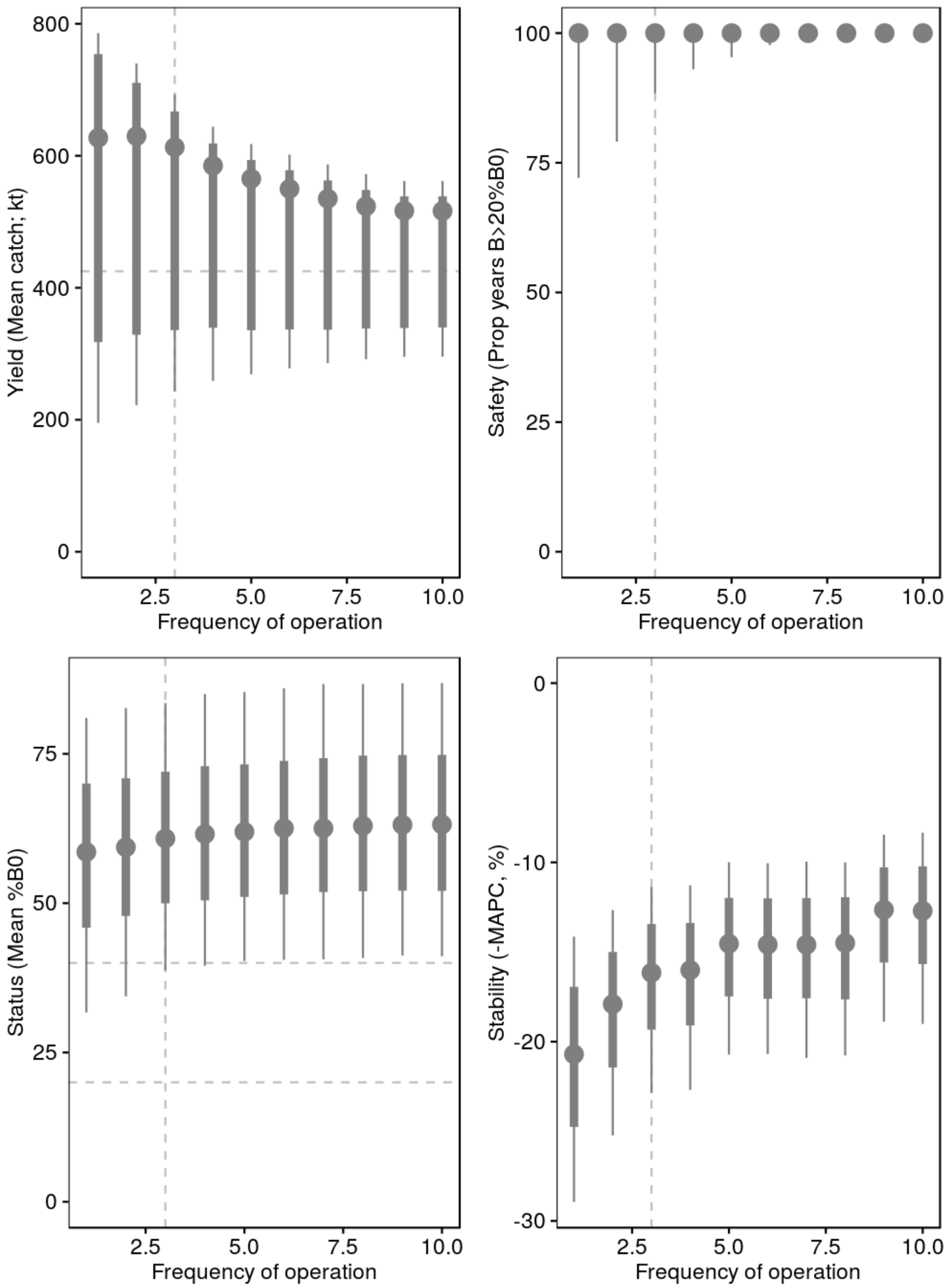


Figure 61: Key performance statistics versus the frequency of operation (assessments) control parameter.

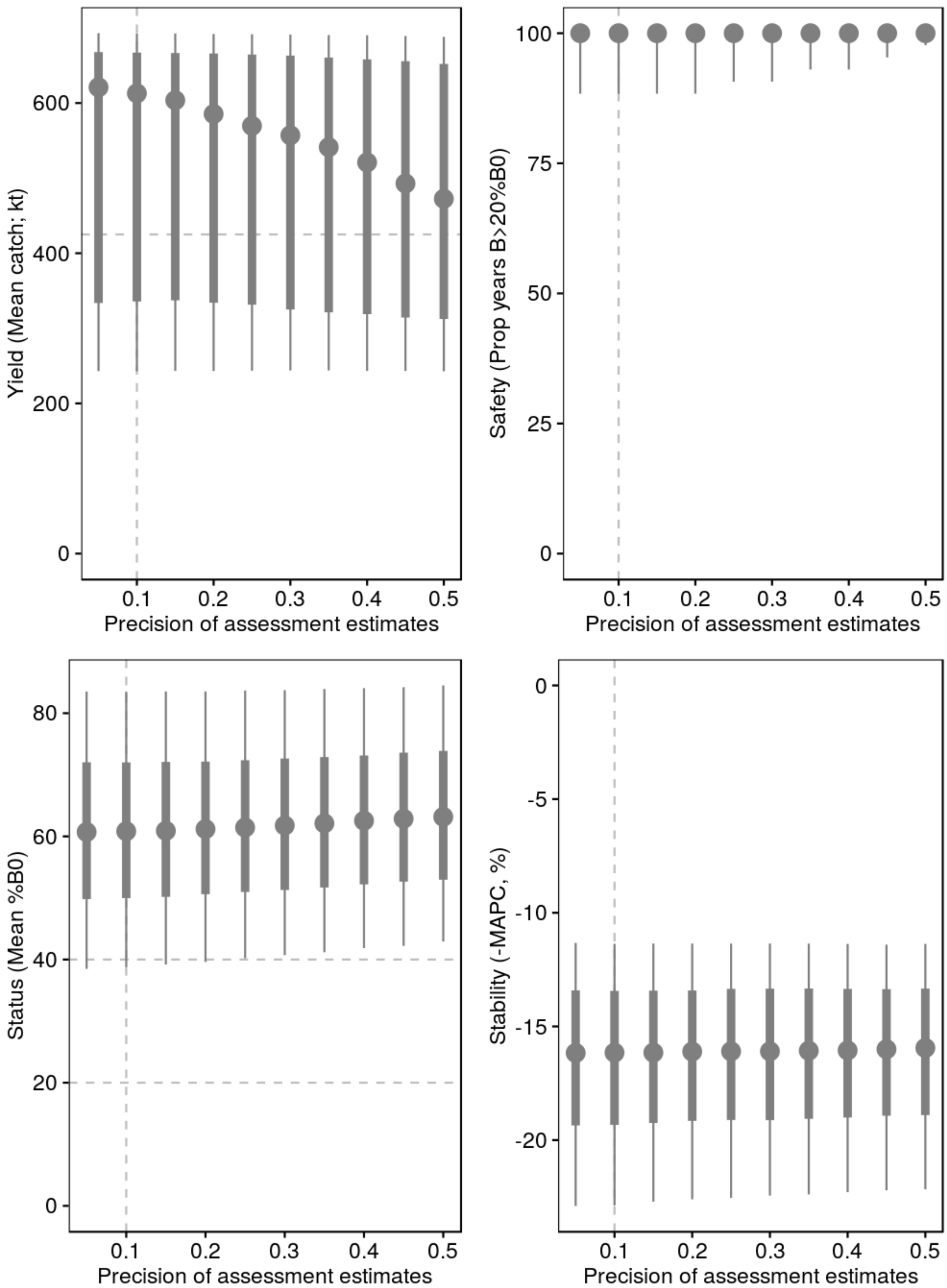


Figure 62: Key performance statistics versus the precision of assessments estimate used by the management procedure. In other results presented, it is assumed that the precision of assessment estimates is 0.1.

In addition to "one-by-one" changes in each of the control parameters, a grid of values was evaluated using every combinations of the following set of values:

- Maximum fishing intensity $I \max = 0.9, 1.0, 1.1$
- Threshold level $T = 0.3, 0.4, 0.5$
- Safety (closure) level $X = 0.0, 0.1, 0.2$
- Maximum TAC $C_{\max} = 700000, 800000, 900000$

This allows for identification of combinations of parameters that may be preferred over the combination of parameters presente din the suggested base set.

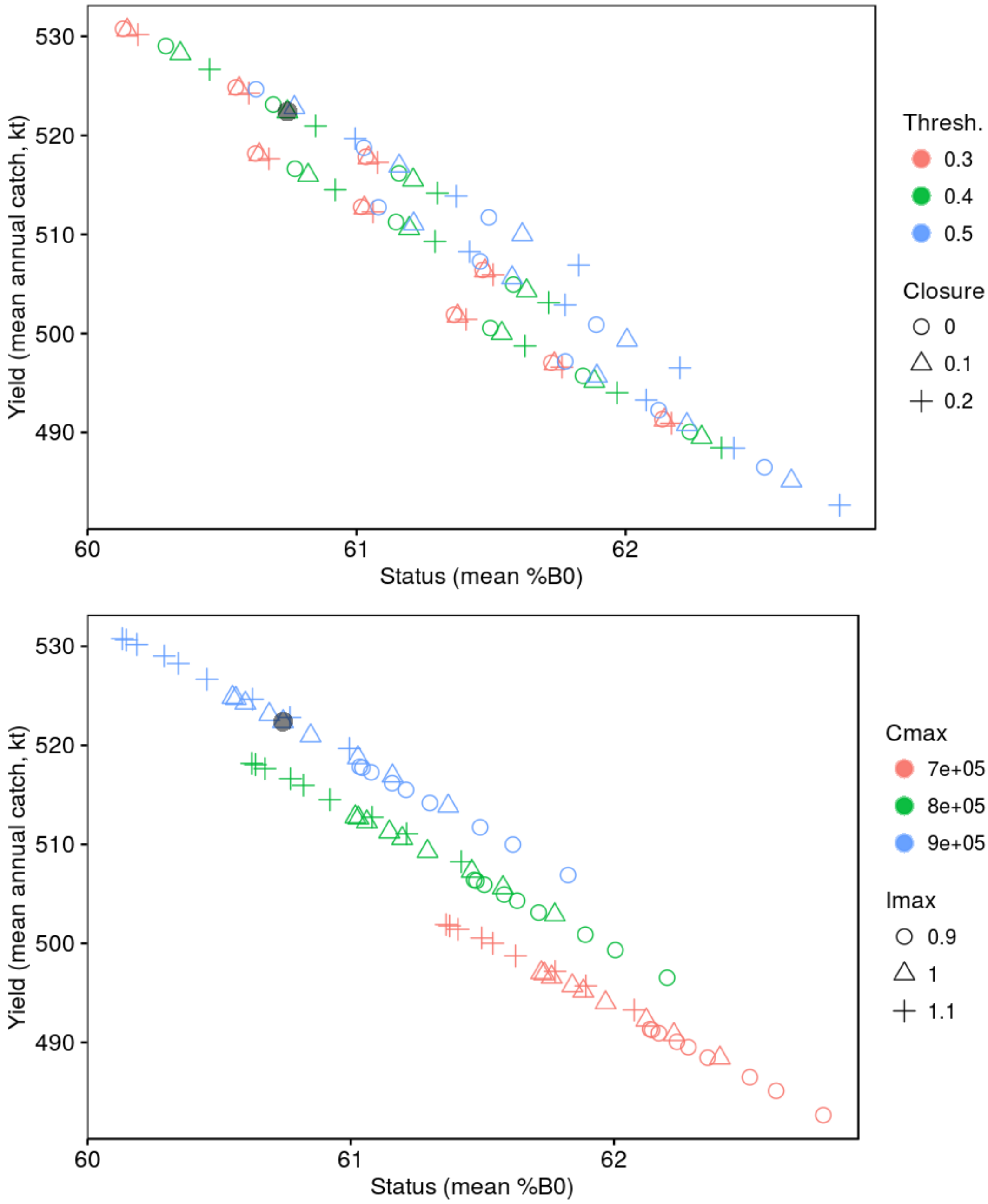
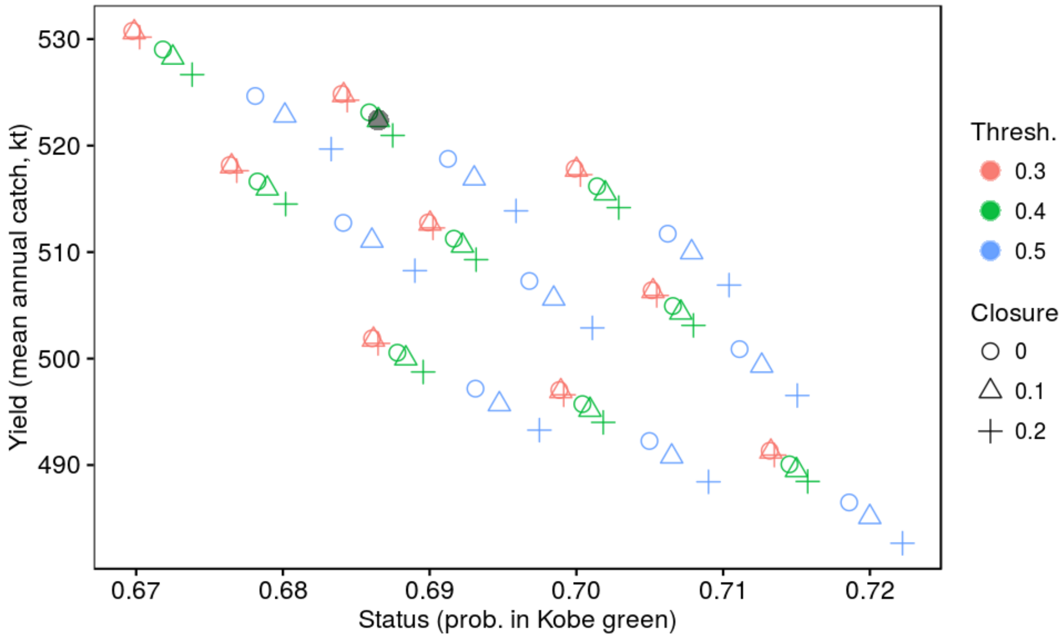


Figure 63: Tradeoff plot between stock status (mean %BO) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates the suggested base set of control parameter values.



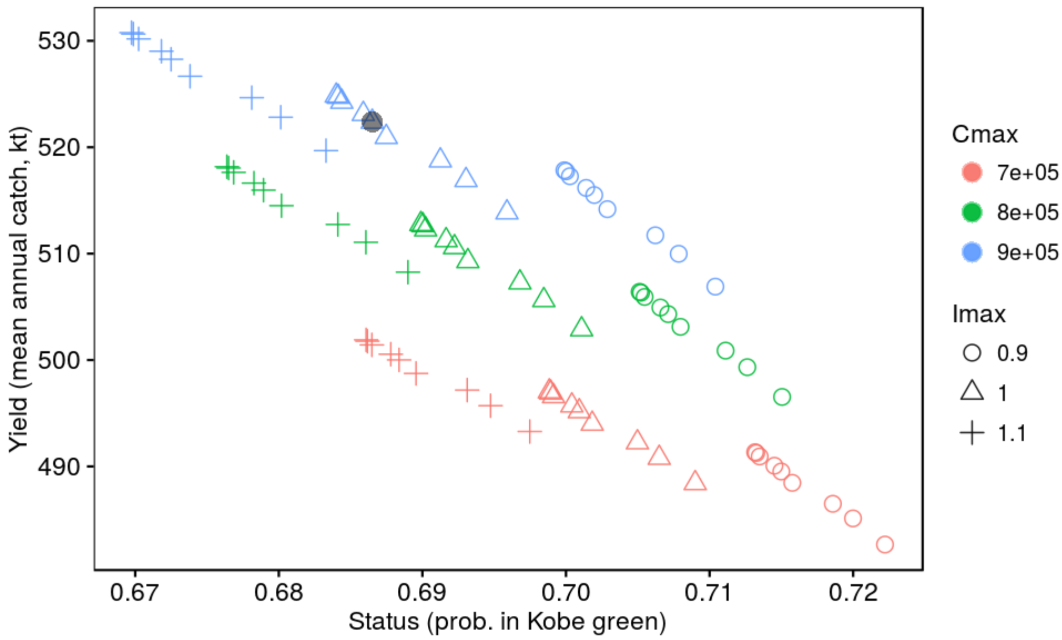
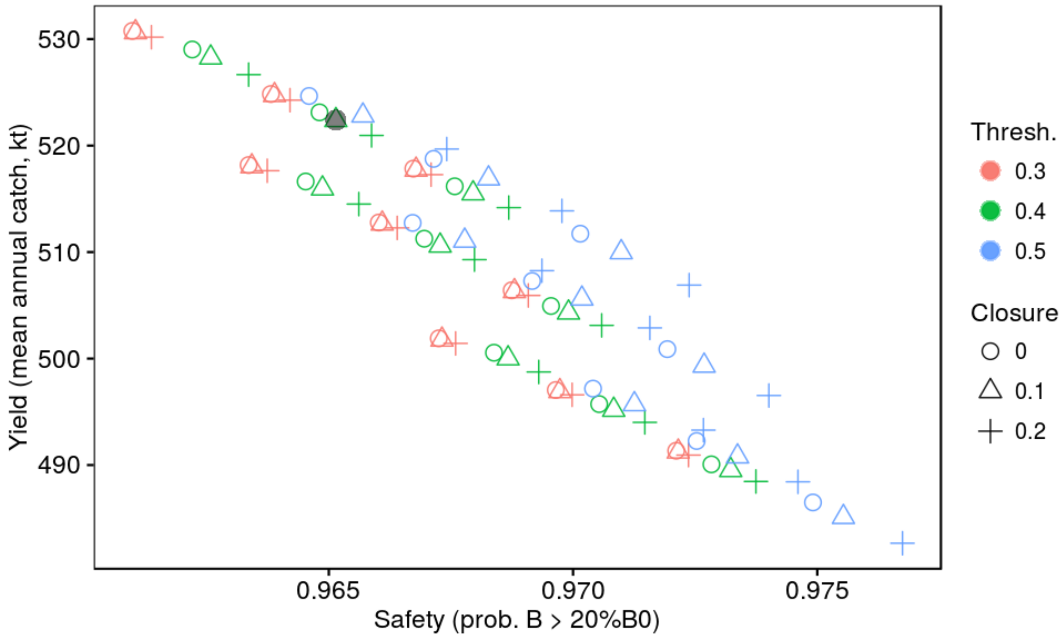


Figure 64: Tradeoff plot between stock status (probability of being in Kobe green quadrant) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates the suggested base set of control parameter values.



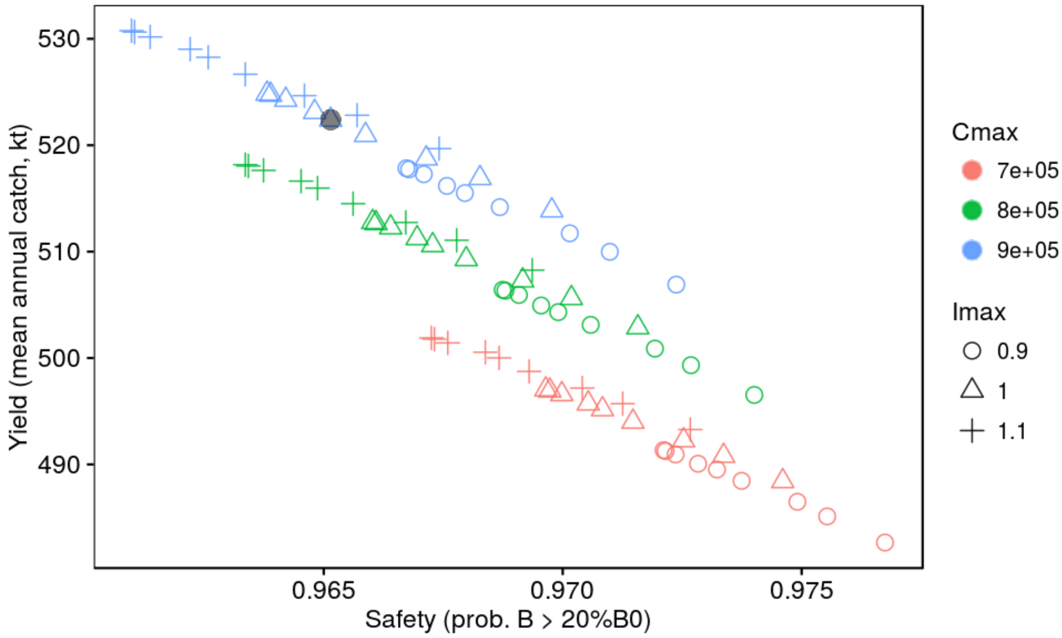


Figure 65: Tradeoff plot between safety (probability that stock status is greater than 20%B0) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates the suggested base set of control parameter values.

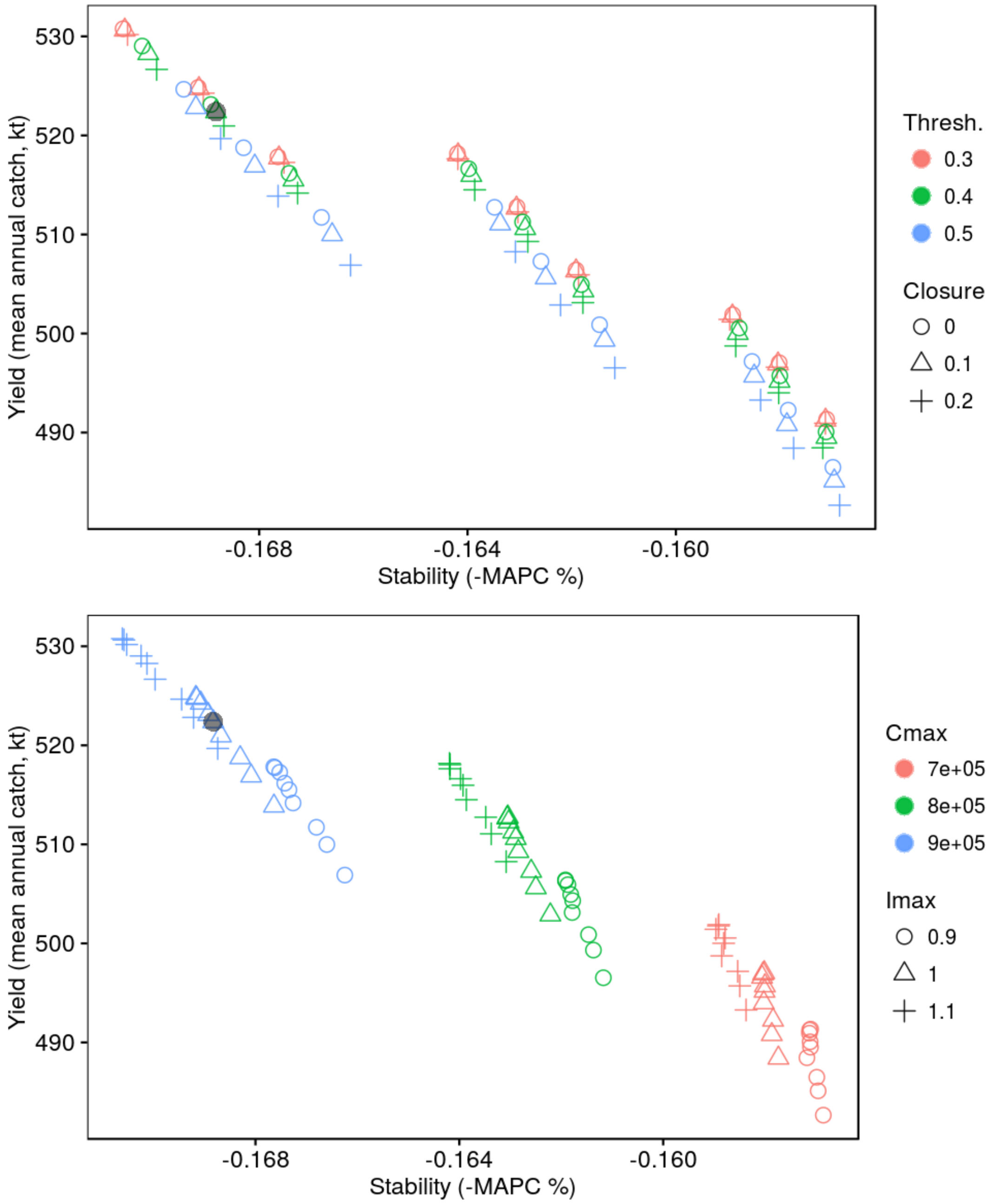


Figure 66: Tradeoff plot between stability (mean absolute proportional change in catch) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates the suggested base set of control parameter values.

4. Discussion

This project established a simulation framework for the evaluation of management procedures for the Indian Ocean skipjack tuna fishery. In addition to representing a significant investment in the IOTC's scientific capabilities, alongside the IOTC's other MSE work programmes and the Management Procedure Dialogue (MPD), it also helped introduce the member states and other stakeholders to management strategy evaluation.

However, the work presented here should only be considered the start of an ongoing programme of MSE for skipjack in the Indian Ocean. There is significant potential for building upon the investments in development of an operating model and in familiarizing the Commission with MSE.

In particular, the `Mald2016` MP adopted as part of resolution 16/02 should only be considered a starting point for continued refinement of MPs for the skipjack fishery. As previously discussed, although the MP is based on a stock assessment, the resolution does not specify the exact methods to be undertaken in each stock assessment and as such it could not be fully evaluated in this MSE. There are significant time lags associated with collecting the data, conducting and reviewing a stock assessment. For short lived, highly fluctuating species like skipjack tuna, these lags severely degrade the performance of management procedures. Instead of attempting to improve the evaluation of assessment based management procedures, it will probably be more fruitful in the long term to consider, alternative model-free, data-based management procedures for the fishery. That will require a strategic analysis of the utility of both current, and potential, data collection regimes.

The simulation model developed here does not capture the multispecies nature of the fishery. This is important because fishing effort, both industrial and artisinal, is able to switch targetting between species, especially between skipjack and yellowfin tuna. Thus, a reduction in allowable catch for one species may result in an increase in effort on another. We recommend that, in the future, a multispecies operating model be developed for management strategy evaluation of tropical tunas in the Indian Ocean.

5. Acknowledgments

This work has been funded by the International Pole and Line Foundation (IPNLF), the Maldives Seafood Processors and Exporters Association (MSPEA), the Areas Beyond National Jurisdiction Program (ABNJ) and WWF with support and oversight of the Maldives Marine Research Centre (MRC). Support for the project's Advisory Committee has been provided by the International Seafood Sustainability Foundation (ISSF).

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6. References

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