

Management strategy evaluation for the Indian Ocean skipjack tuna fishery

Nokome Bentley¹ and M. Shiham Adam²

1. Trophia Limited, New Zealand nbentley@trophia.com
2. Marine Research Centre, Maldives msadam@mrc.gov.mv

Draft 2016-05-23

1. Introduction

2. Model

2.1. Structure and assumptions

2.1.1. Dimensions

2.1.1.1. Time

2.1.1.2. Regions

2.1.1.3. Fish age and size

2.1.1.4. Fishing methods

2.1.2. Population dynamics

2.1.2.1. Numbers

2.1.2.2. Growth

2.1.2.3. Weight and maturity

2.1.2.4. Spawning and recruitment

2.1.2.5. Natural mortality

2.1.2.6. Movement

2.1.3. Harvest dynamics

2.2. Parameters priors and sensitivity ranges

2.2.1. Spawning and recruitment

2.2.2. Mortality

2.2.3. Growth

2.2.4. Weight and maturity

2.2.5. Movement

2.2.6. Selectivity

2.3. Implementation

2.4. Outputs

2.4.1. Weight

2.4.2. Maturity

2.4.3. Growth

2.4.4. Mortality

2.4.5. Movement

2.4.6. Selectivities

2.4.7. Biomass and recruitment trajectories

2.4.8. Fishery related trajectories

2.5. Fits

2.5.1. Maldivian pole and line (M-PL) CPUE

2.5.2. Western purse seine (W-PS) CPUE

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

2.5.4. Size frequencies

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

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

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

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

2.6. Yield curve and types of reference point

2.7. Conditioning
2.8. Management procedures
2.8.1. BRule class
2.8.2. FRange class
2.8.3. IRate class
2.9. Evaluation methods
2.9.1. Management objectives, performance measures, performance statistics
2.9.2. Simulation methods and terminology
2.10. Evaluation results
2.10.1. Comparison of classes
2.10.2. IRate
2.10.3. FRange
2.10.4. BRule
2.10.5. Mald2016
3. Acknowledgments
4. References

1. Introduction

This report describes the development of an operating model of the Indian Ocean skipjack tuna fishery for use in management strategy evaluation (MSE). This work 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).

This document outlines the structure of the model, describes prior probability distributions and sensitivity ranges for model parameters, lists performance statistics to be used for evaluations and introduces some example management procedures. Each section of this report is "living documentation" of the model and its outputs - most have been presented to IOTC working parties previously but where necessary, based on feedback from those working parties, have been updated and revised.

2. Model

2.1. Structure and assumptions

The following convention is used for assigning symbols in the following model equations: Greek lower case letters (e.g. α for the intercept of the length-weight relationship) for model parameters, Roman capital letters (e.g. N for numbers) for model variables, 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 (which are independent of other parameters or variables and that are usually estimated) from model variables (which are dependent upon parameter values).

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

Four regions (r) are defined, South-West (sw), North-West (mw), 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 Maldivian 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 for future models, 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.

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, ..., 23. Fish size (s) is represented in forty, 2cm bins, 0 – 2, 2 – 4, ..., 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
sw	South-west region
nw	North-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 four 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 Maldives 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).

$$\mu = \lambda \left(1 - e^{-\kappa_2(a-a_0)} \left(1 + \frac{e^{-\phi \cdot (a-a_0-\delta)}}{1 + e^{\delta \cdot \phi}} \right)^{-\frac{\kappa_2 - \kappa_1}{\phi}} \right)$$

where a_0 age 0, ϕ is the steepness, δ is the inflection

The standard deviation of length at age is based ,

$$cv = growth_c v_{old} + \frac{growth_c v_0 - growth_c v_{old}}{24}$$

$$sd = \mu \cdot \zeta$$

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

$$L_s = 2s + 1$$

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

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

$$W_a = \sum_s W_s P_{a,s}$$

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,

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

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, v_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,

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

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" in 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, \bar{R} according to the Beverton-Holt stock recruitment function,

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

where η is steepness, θ and \dot{E} are 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,

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

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

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,

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

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 sensitivity 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 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 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 $B(\cdot)$ 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 comparison, 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 and 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 v 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, v , 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 $M_{i,r}$.

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 ranges 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
v	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]
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				
$\omega_{i,r}$	Proportion of fish moving from region i 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/iotcwpmpm/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://iotcwpmpm.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 following 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 struture.

2.4.1. Weight

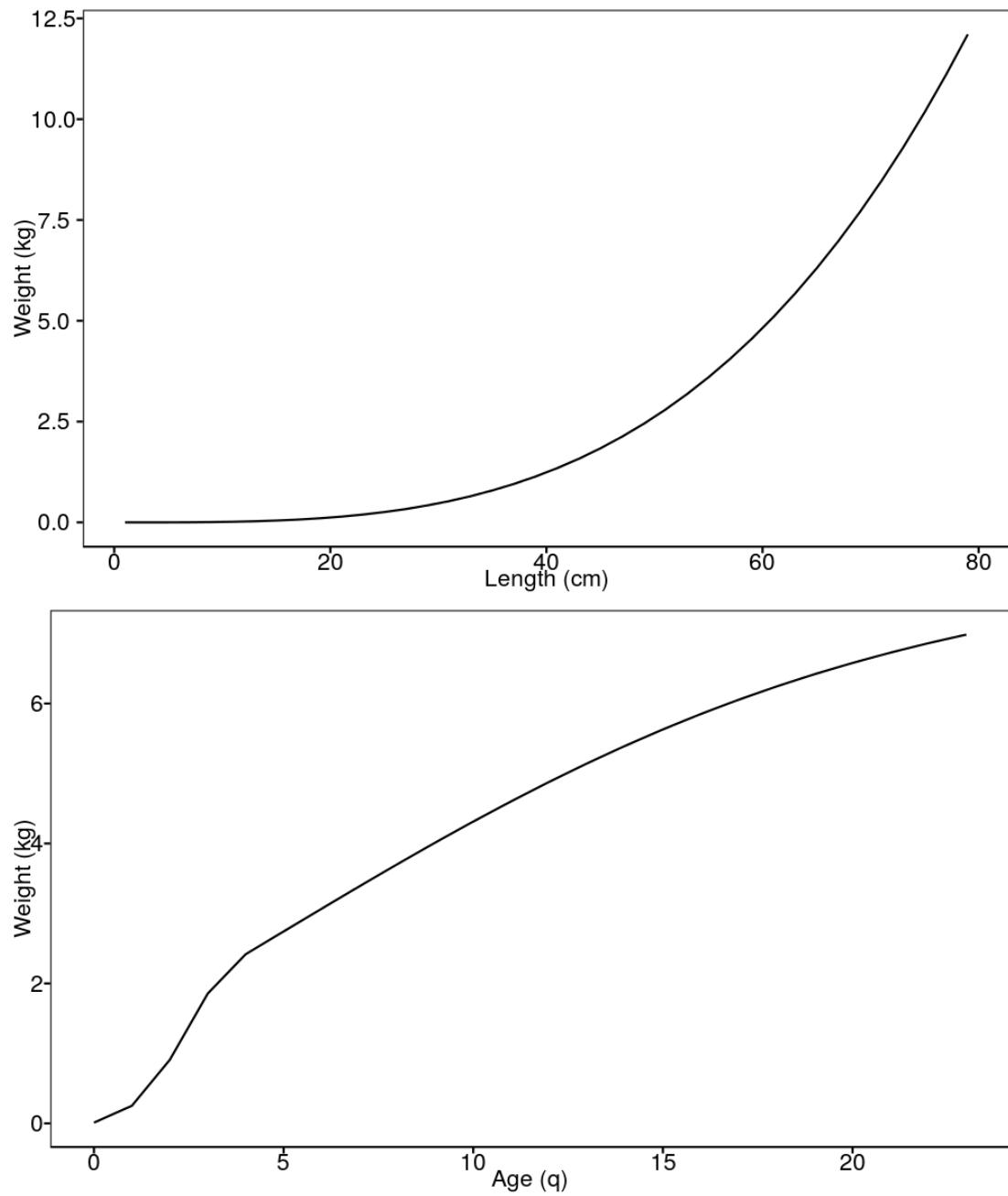


Figure 2: Predicted weight (kg) at length (top) and age (bottom)

2.4.2. Maturity

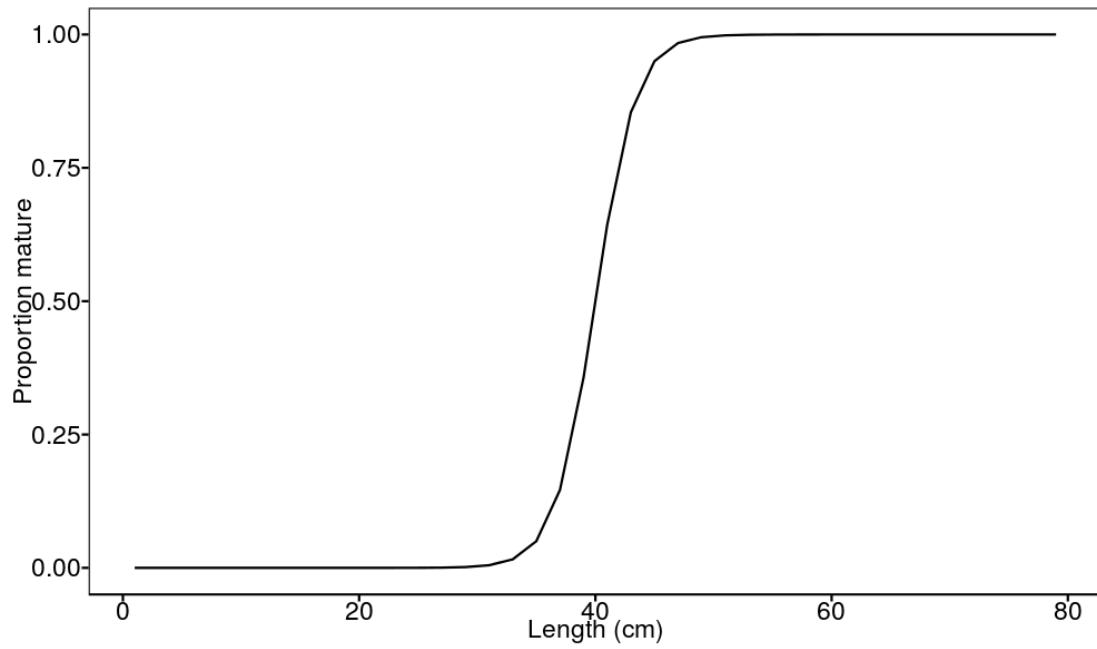


Figure 3: Maturity at length.

2.4.3. Growth

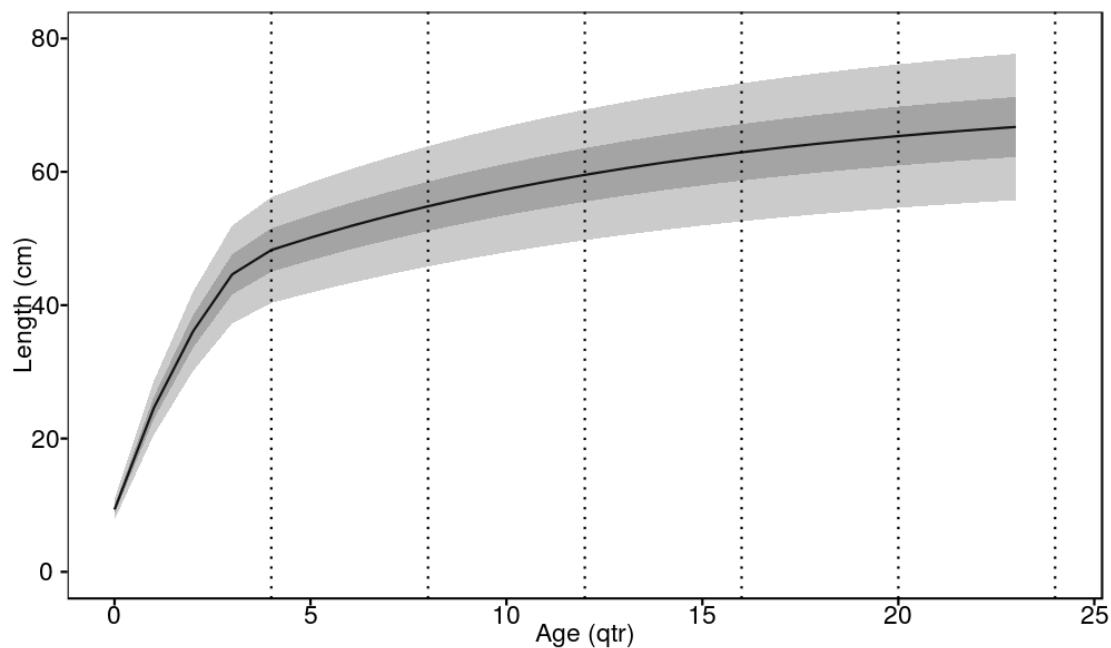


Figure 4: Length at age. Bands represent 50% (inner) and 90% (outer) of lengths for a particular age.

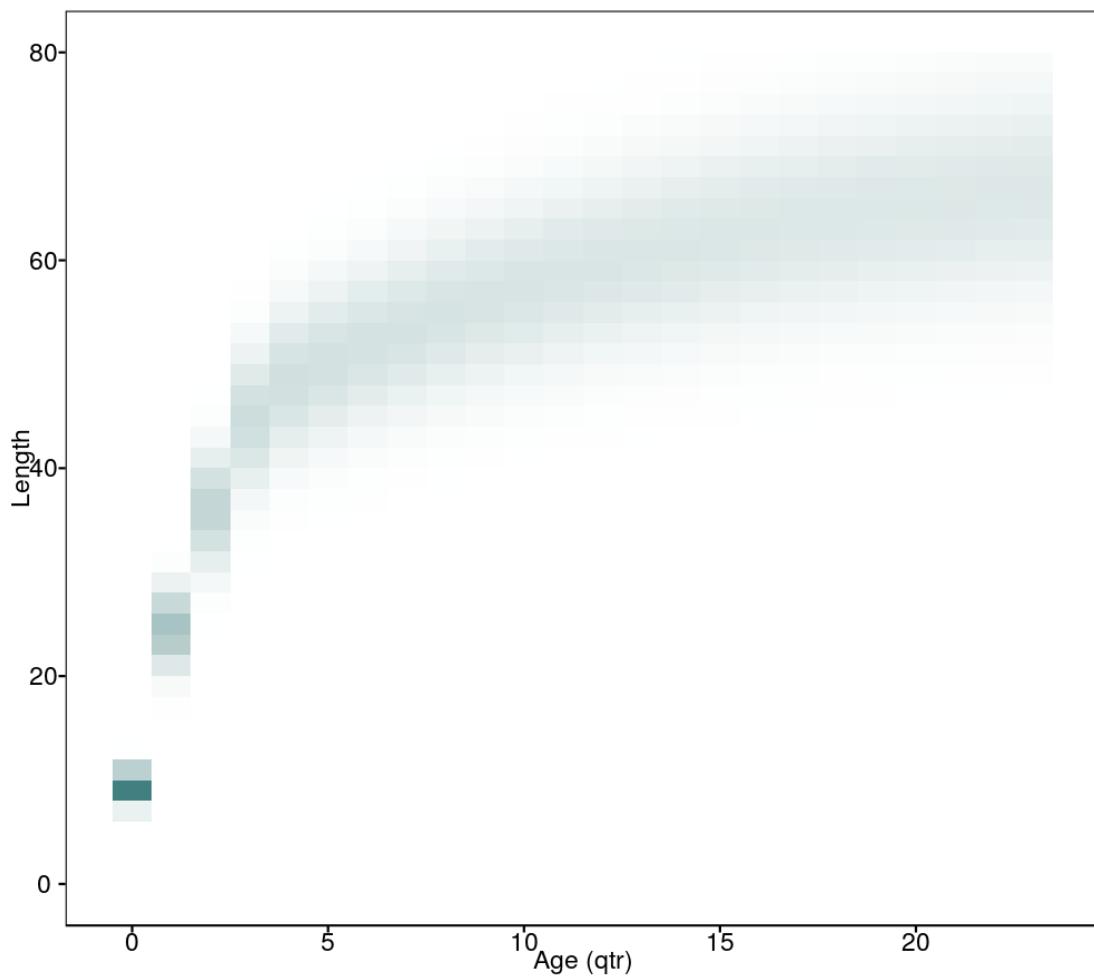


Figure 5: Length distribution at age. Proportion of fish within each size bin by age. Text values are only shown where proportion > 0.01

2.4.4. Mortality

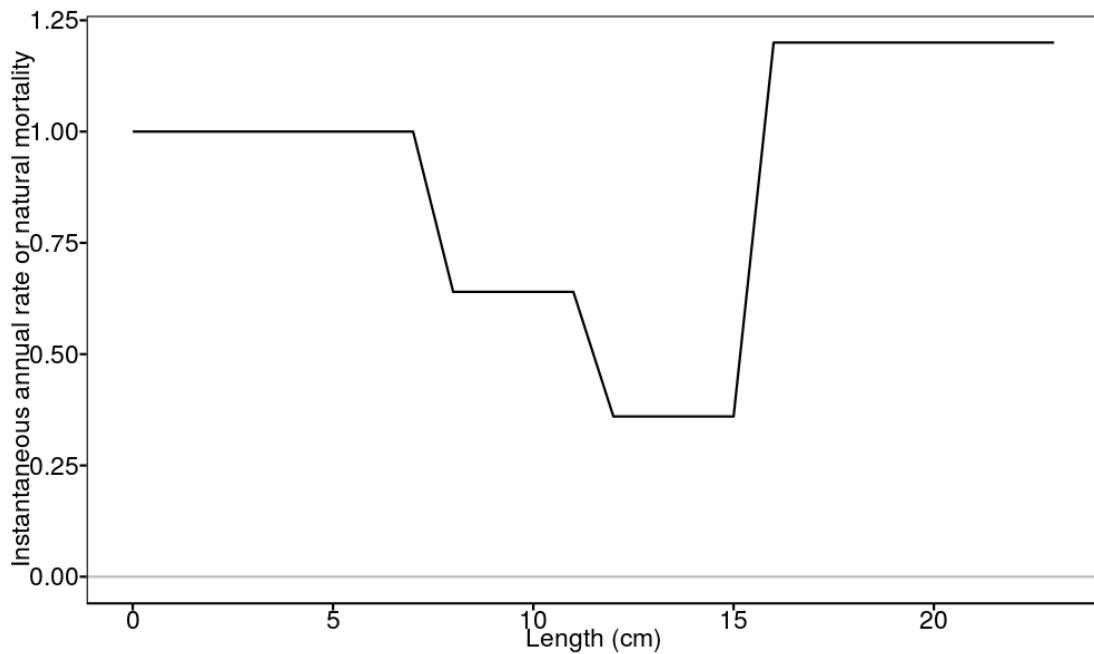


Figure 6: Mortality at length.

2.4.5. Movement

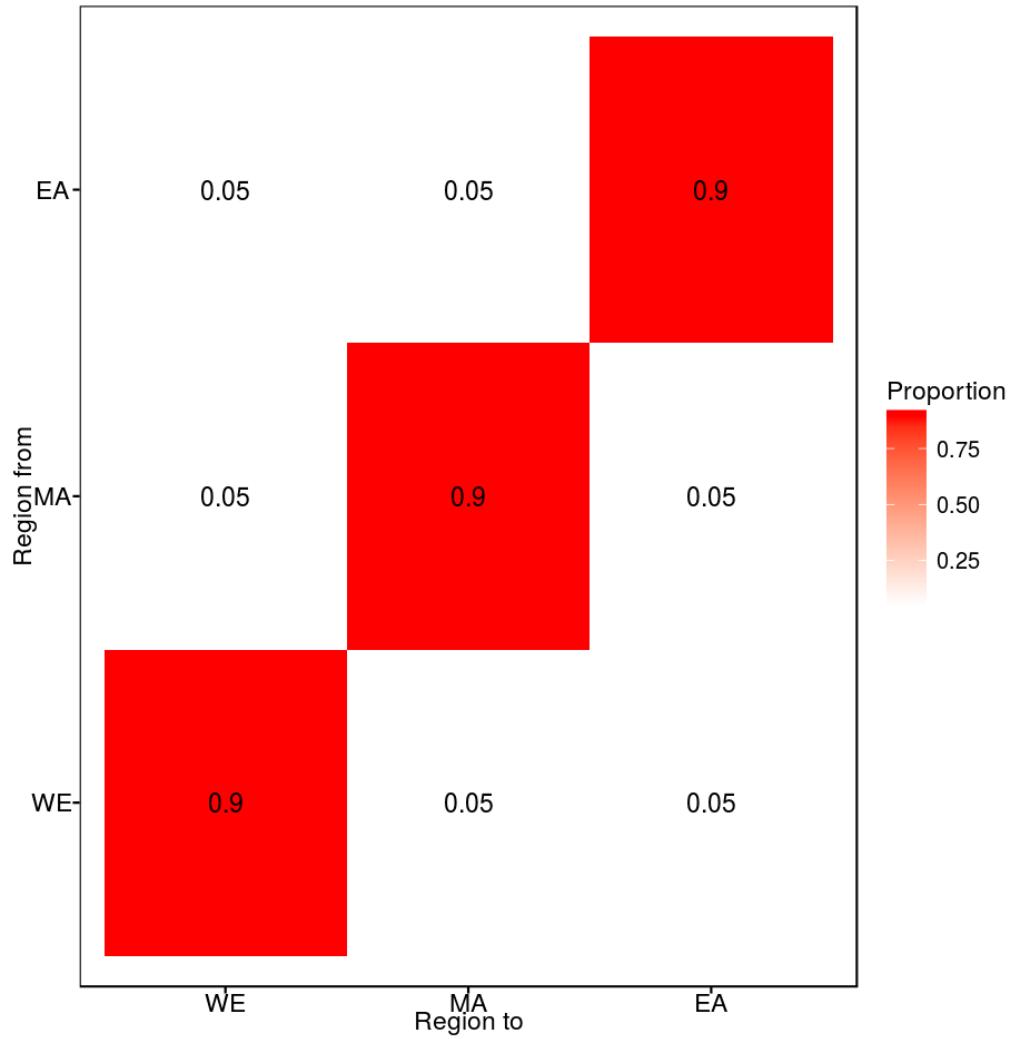


Figure 7: Movement proportion by quarter. Each cell indicates the proportion of fish moving from one region to another in one quarter.

2.4.6. Selectivities

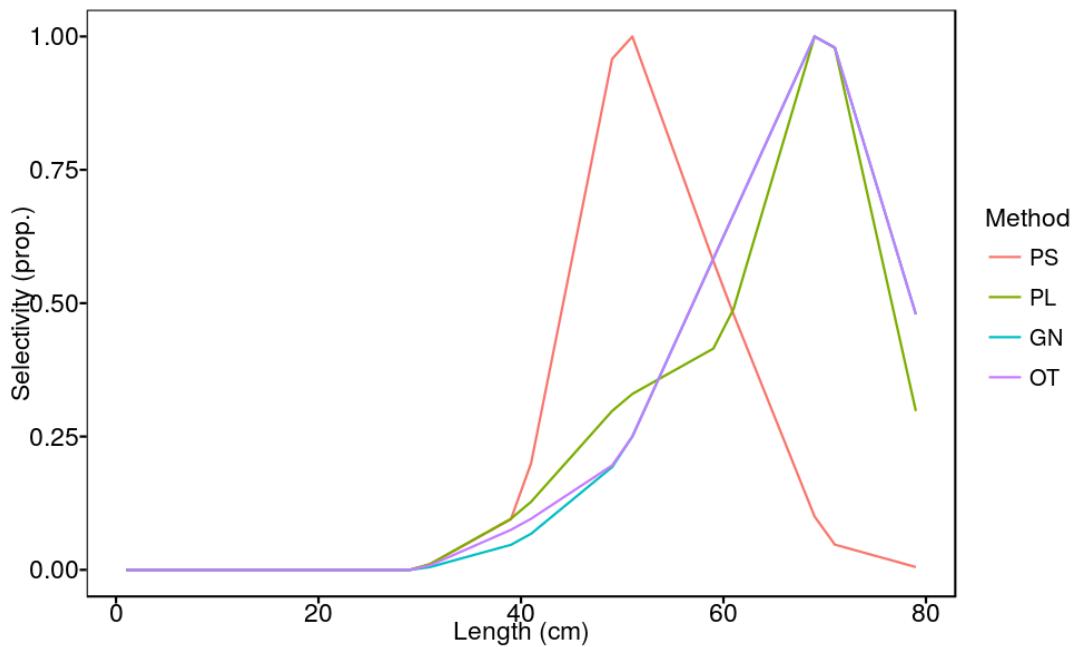


Figure 8: Selectivity at length by fishing method.

2.4.7. Biomass and recruitment trajectories

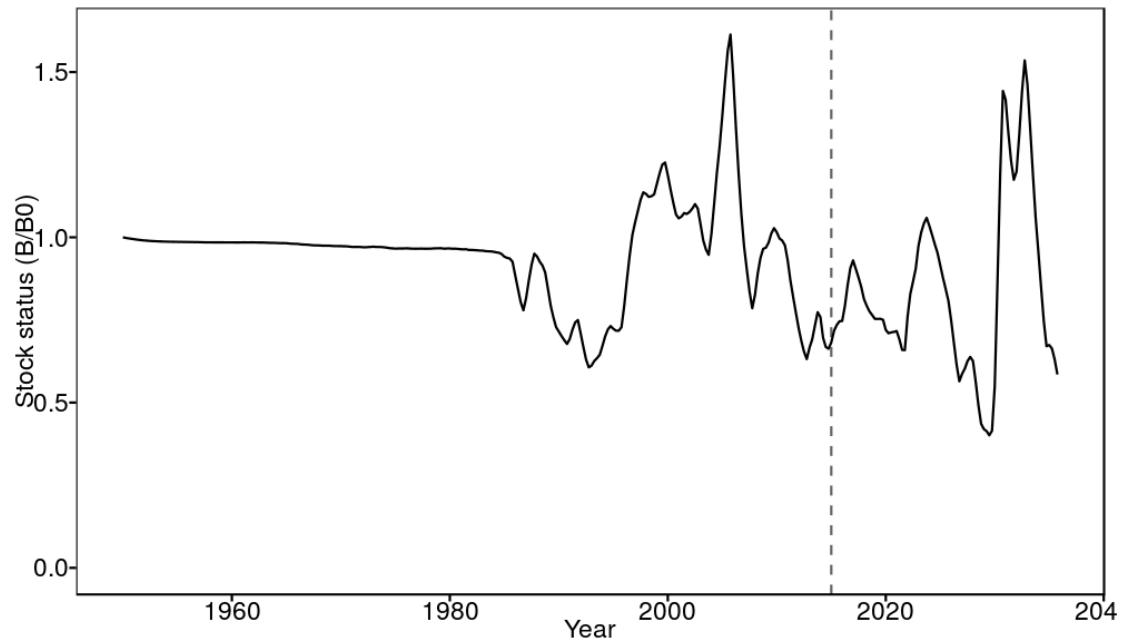


Figure 9: Stock status trajectory.

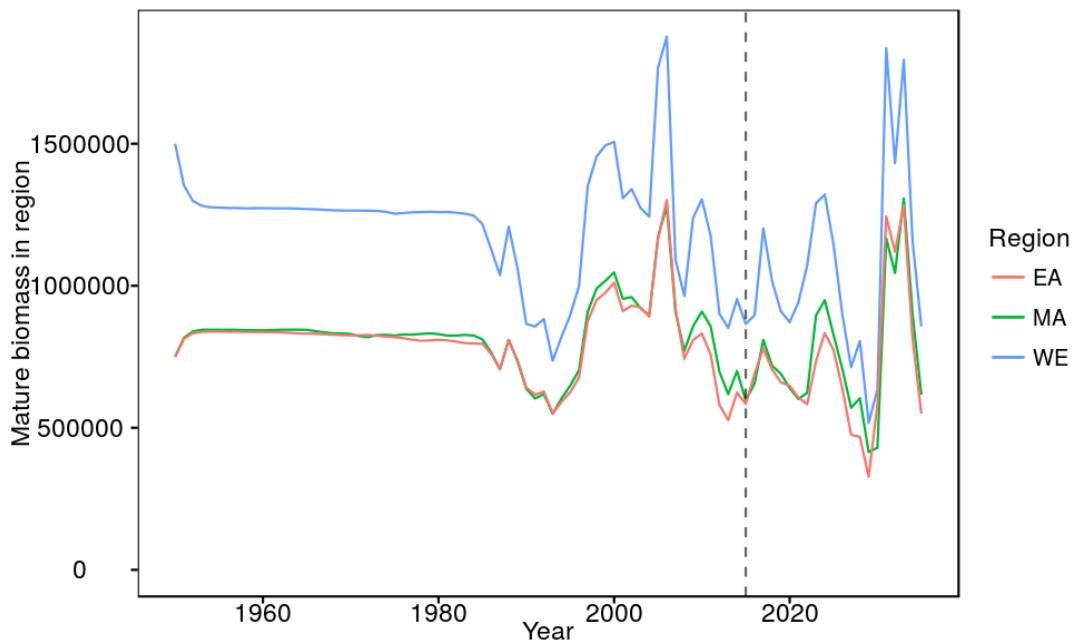


Figure 10: Biomass of spawners by region (first quarter).

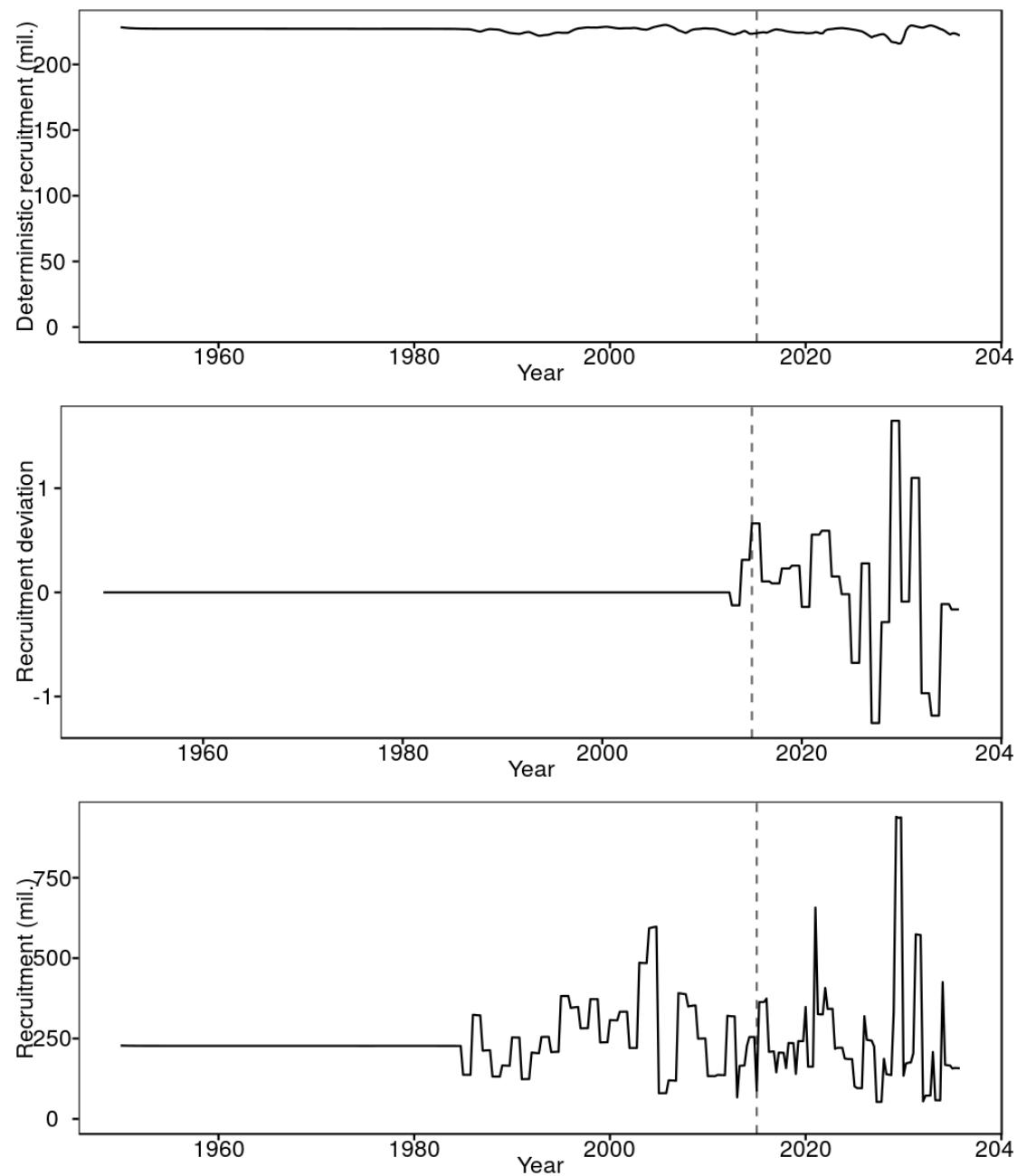


Figure 11: Recruitment trajectories

2.4.8. Fishery related trajectories

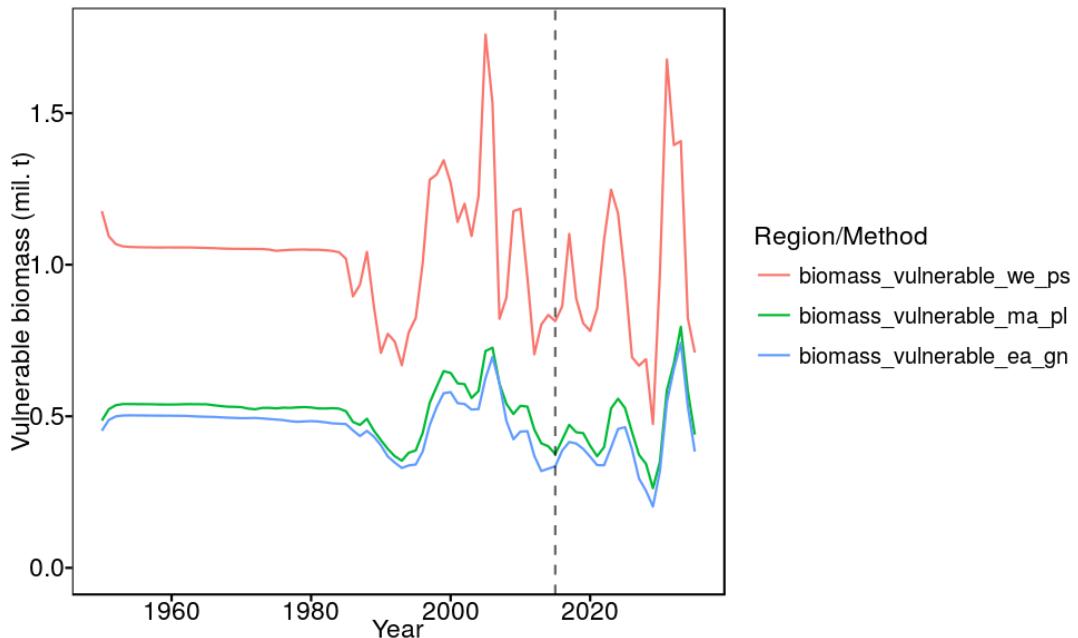


Figure 12: Vulnerable biomass trajectories for the three main fisheries

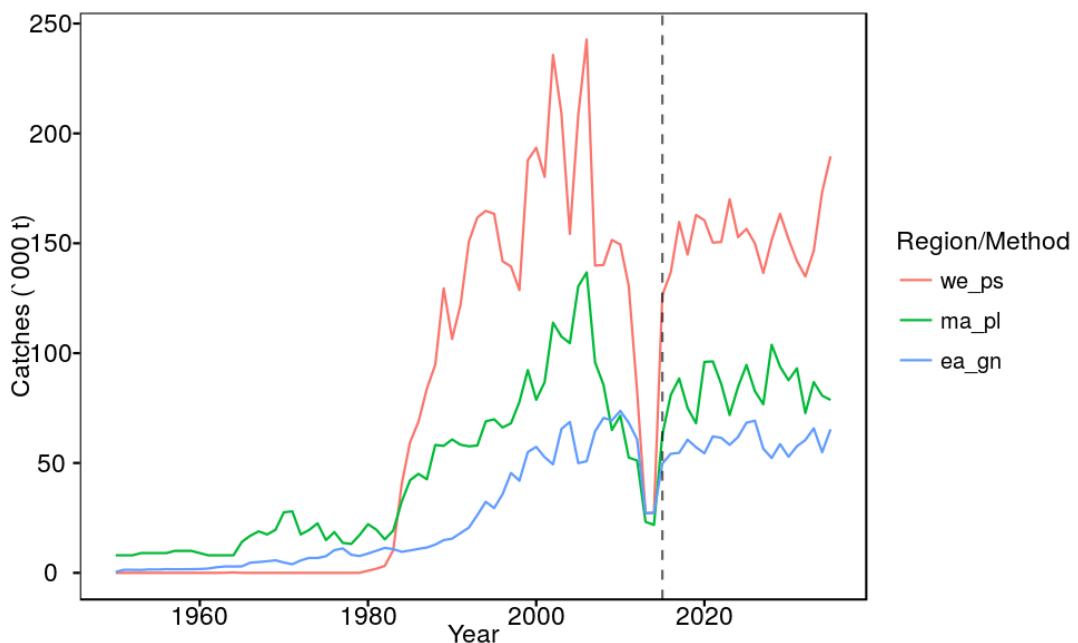


Figure 13: Catch trajectories for the three main fisheries

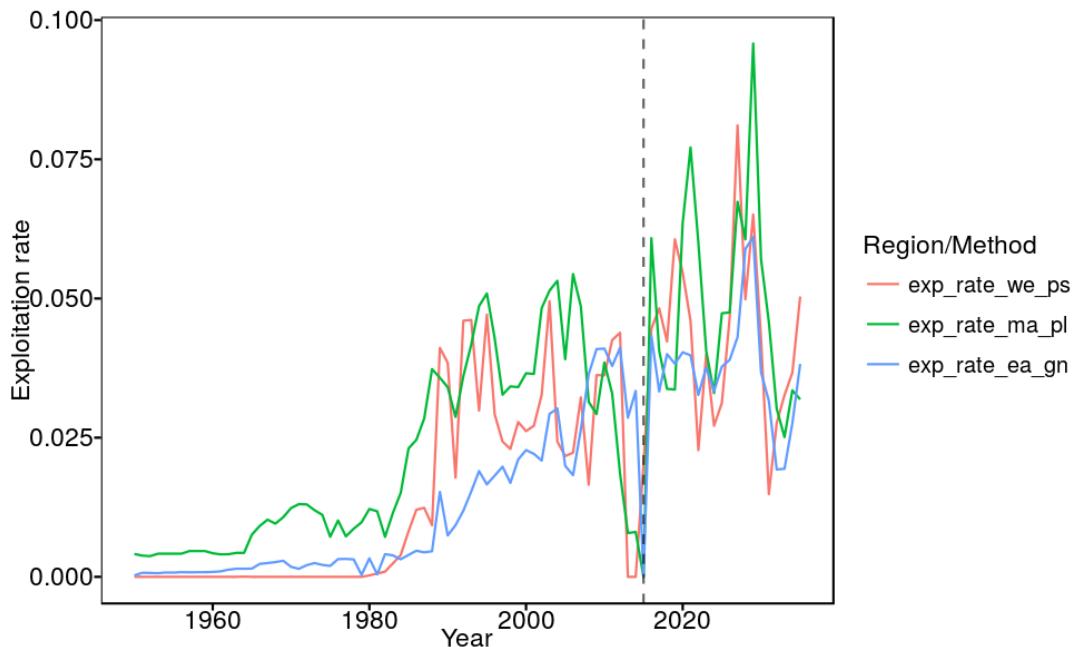


Figure 14: Exploitation rate trajectories for the three main fisheries

2.5. 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.

2.5.1. Maldives pole and line (M-PL) CPUE

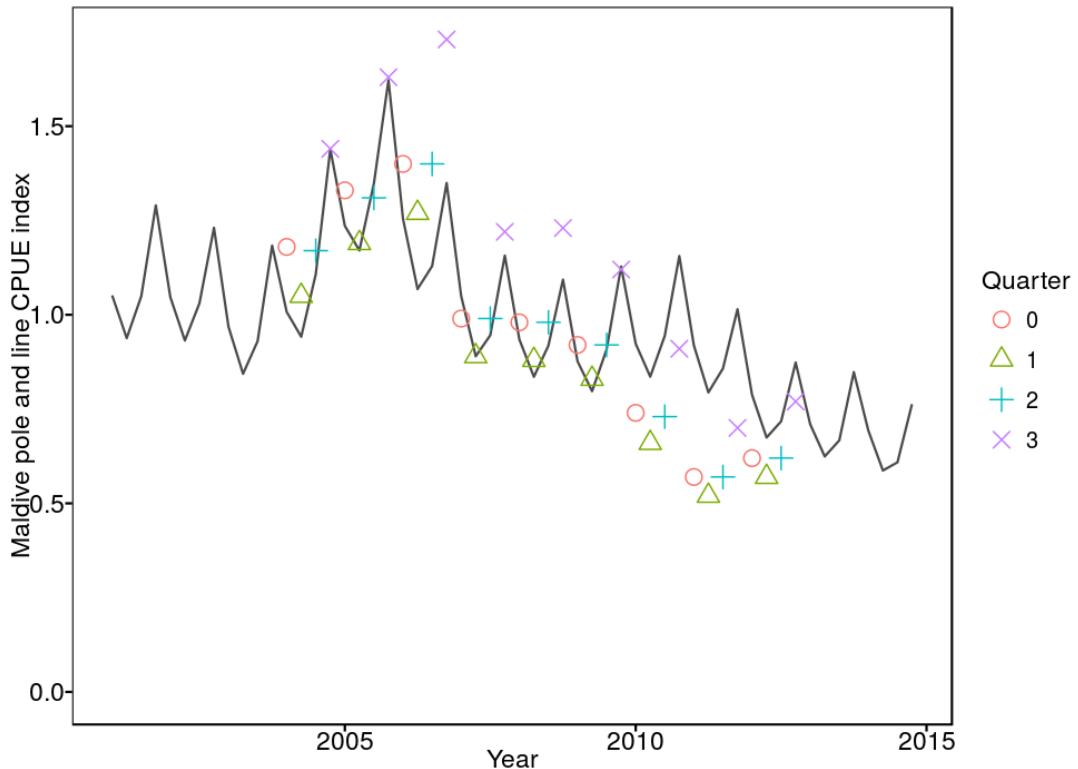


Figure 15: Observed (points) and expected (lines) Maldives (M) pole and line (PL) CPUE.

2.5.2. Western purse seine (W-PS) CPUE

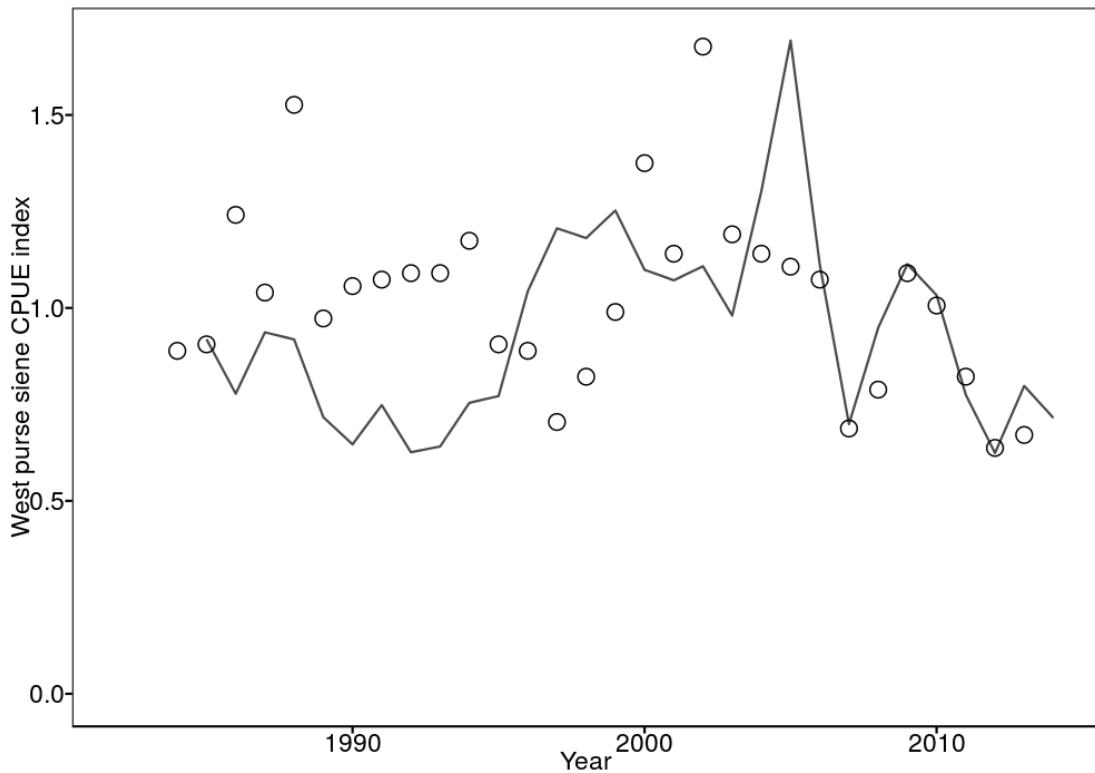


Figure 16: Observed (points) and expected (lines) western (W) purse seine (PS) CPUE.

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

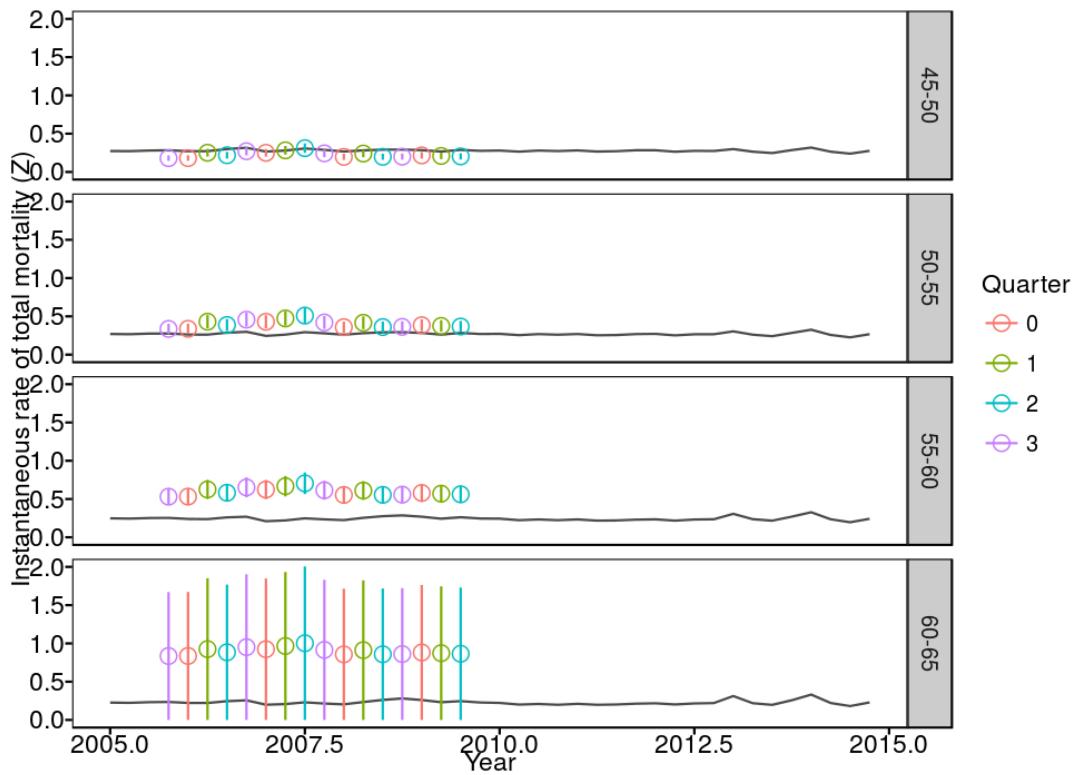


Figure 17: Observed (points) and expected (lines) western (W) purse seine (PS) tagging Z estimates. Error bars indicate ± 1 standard error in estimates.

2.5.4. Size frequencies

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

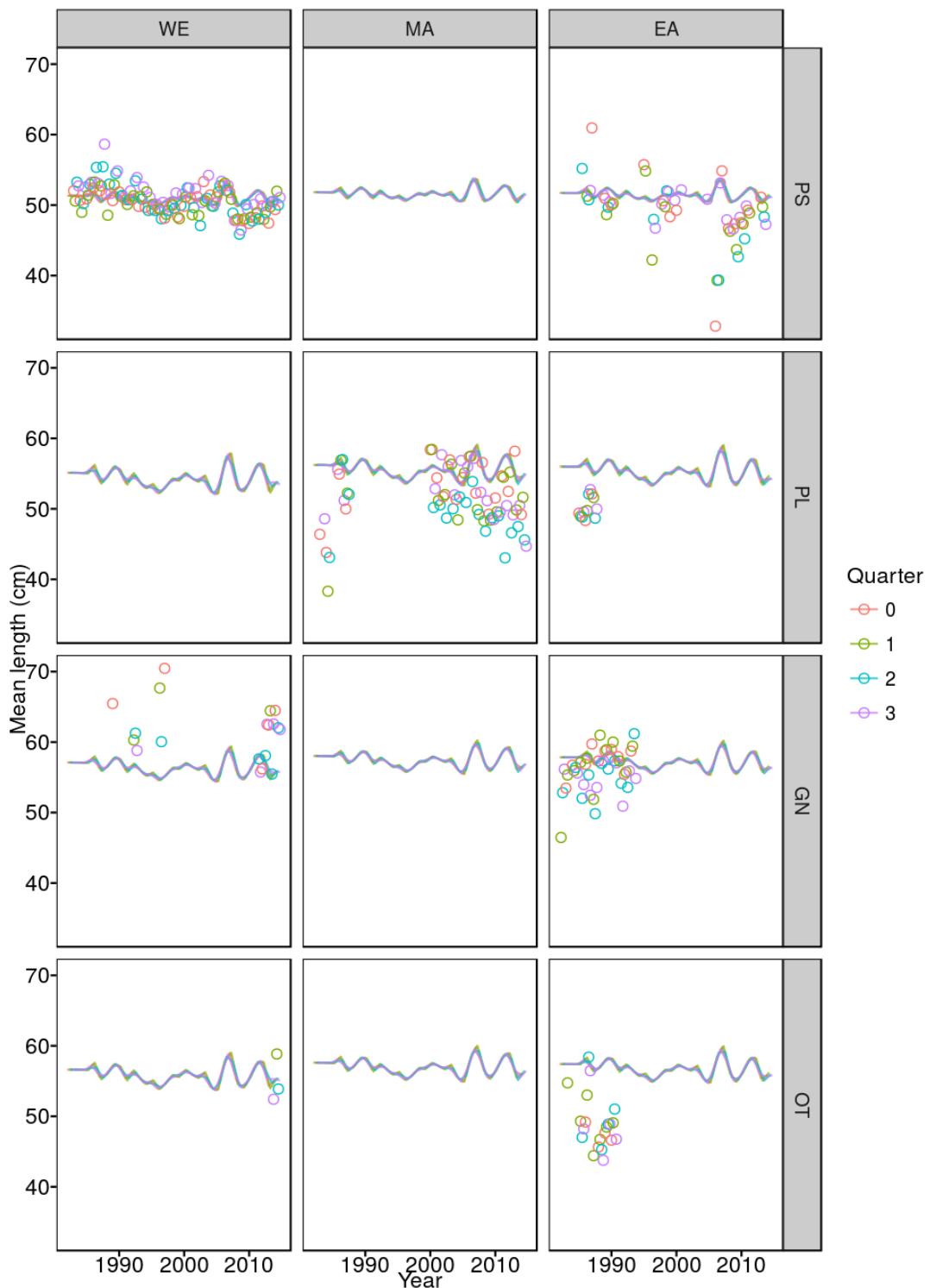


Figure 18: Observed (points) and expected (lines) mean length of catch by region, method, year and quarter.

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

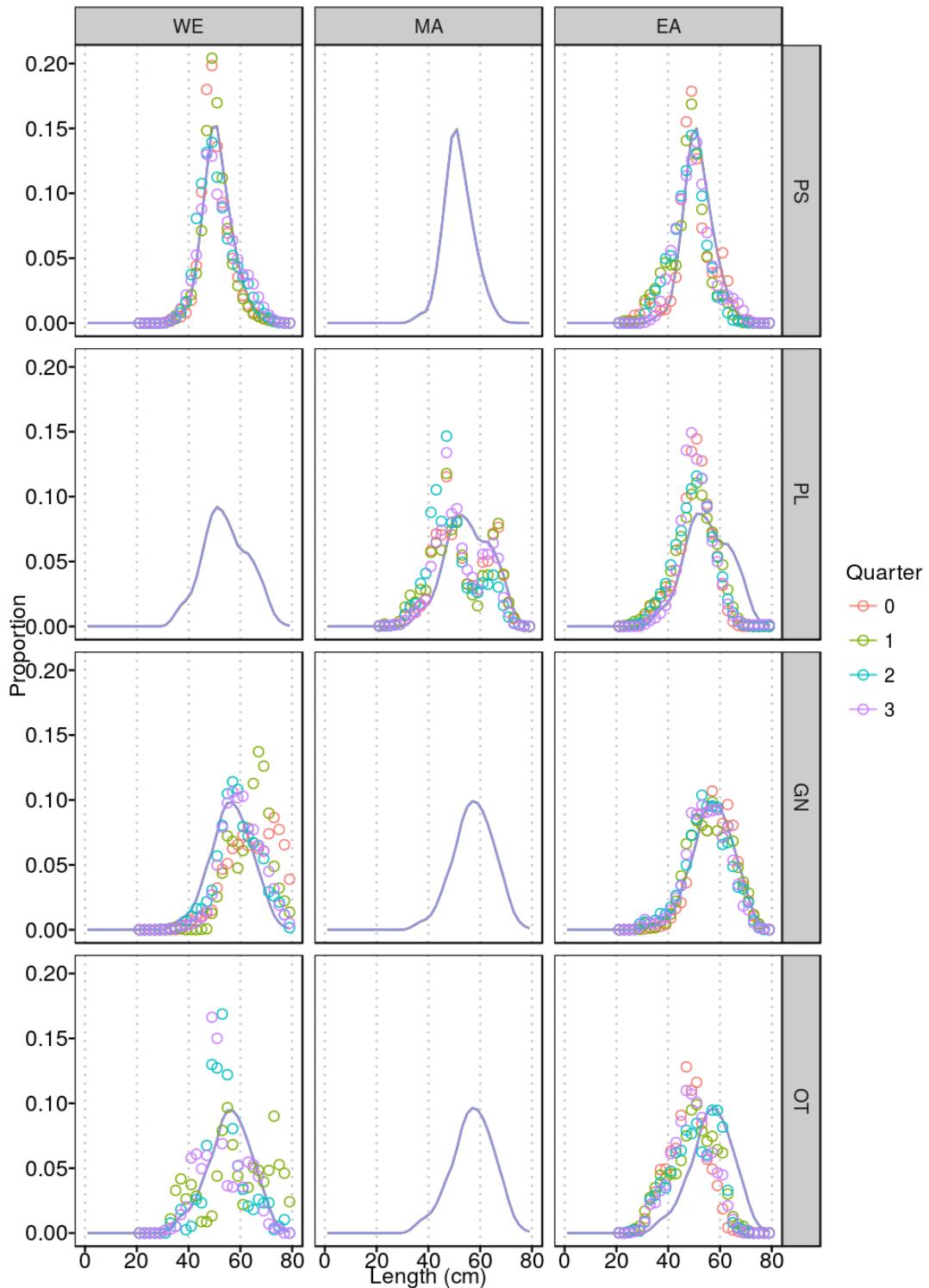


Figure 19: Observed (points) and expected (lines) proportion of catch in each length class by region, method & quarter (aggregated over years).

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

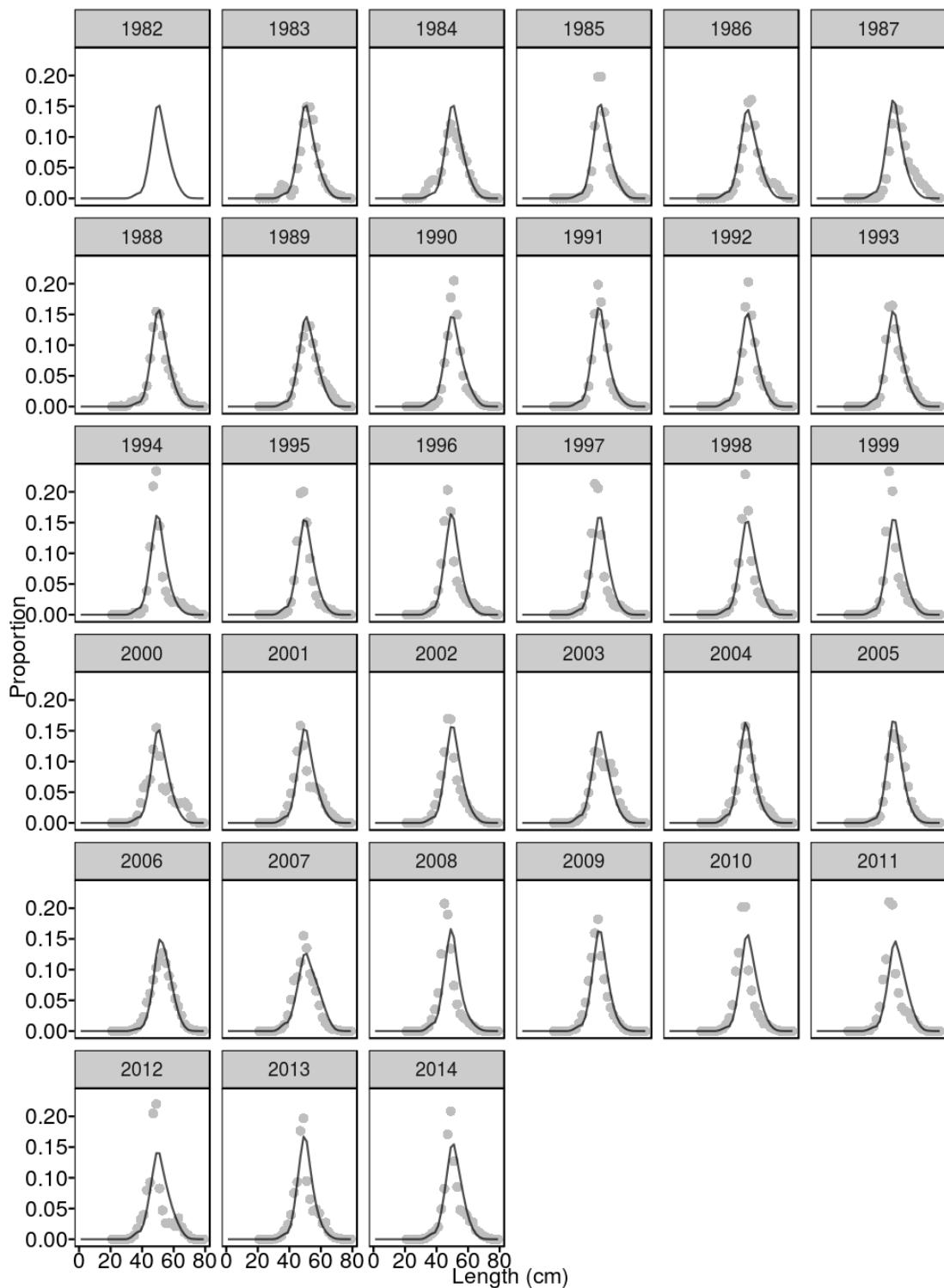


Figure 20: Observed (points) and expected (lines) size frequency distributions for purse seine (PS) in the western region (WE) aggregated over quarters.

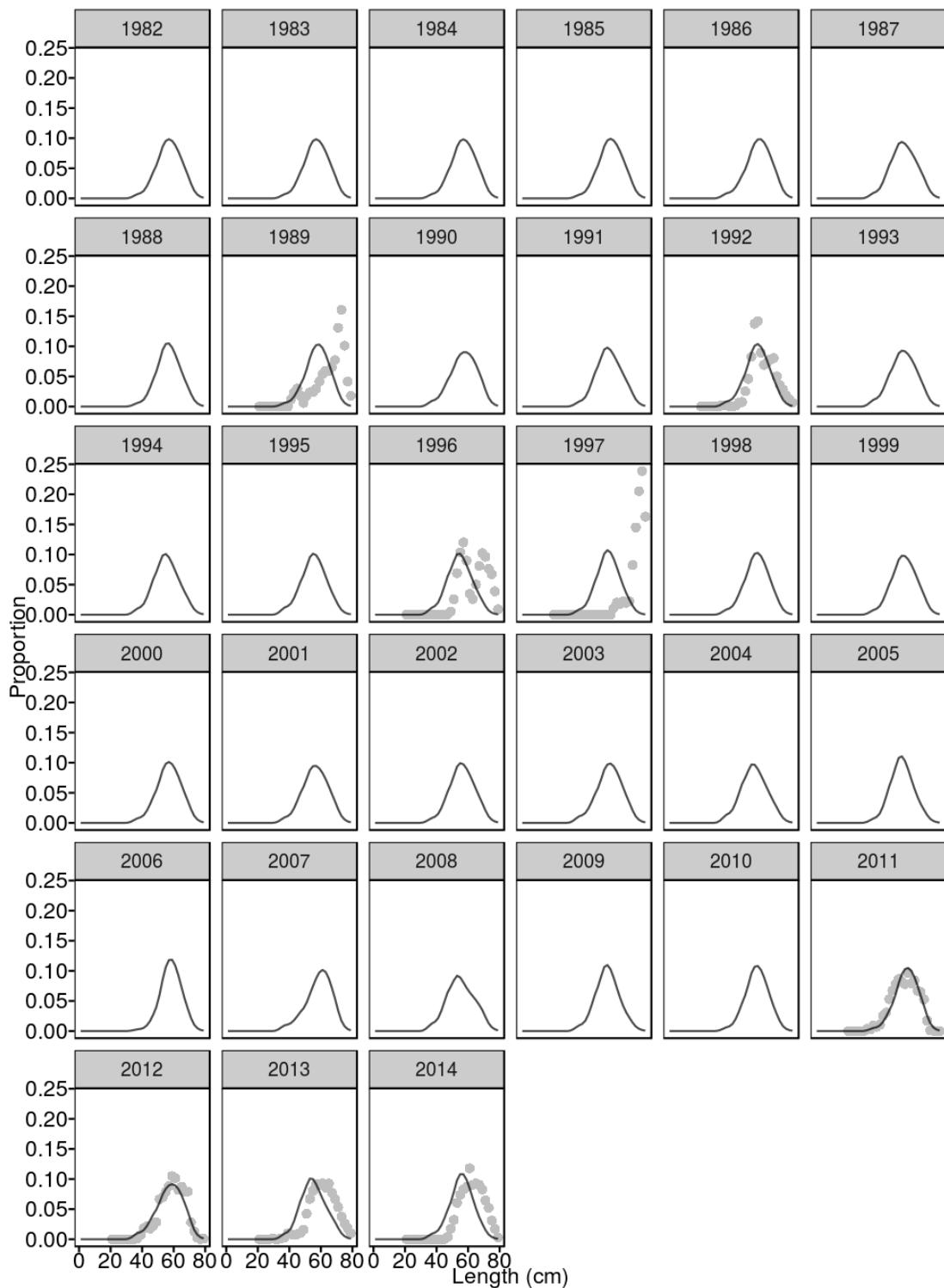


Figure 21: Observed (points) and expected (lines) size frequency distributions for gillnet (GN) in the western region (WE) aggregated over quarters.

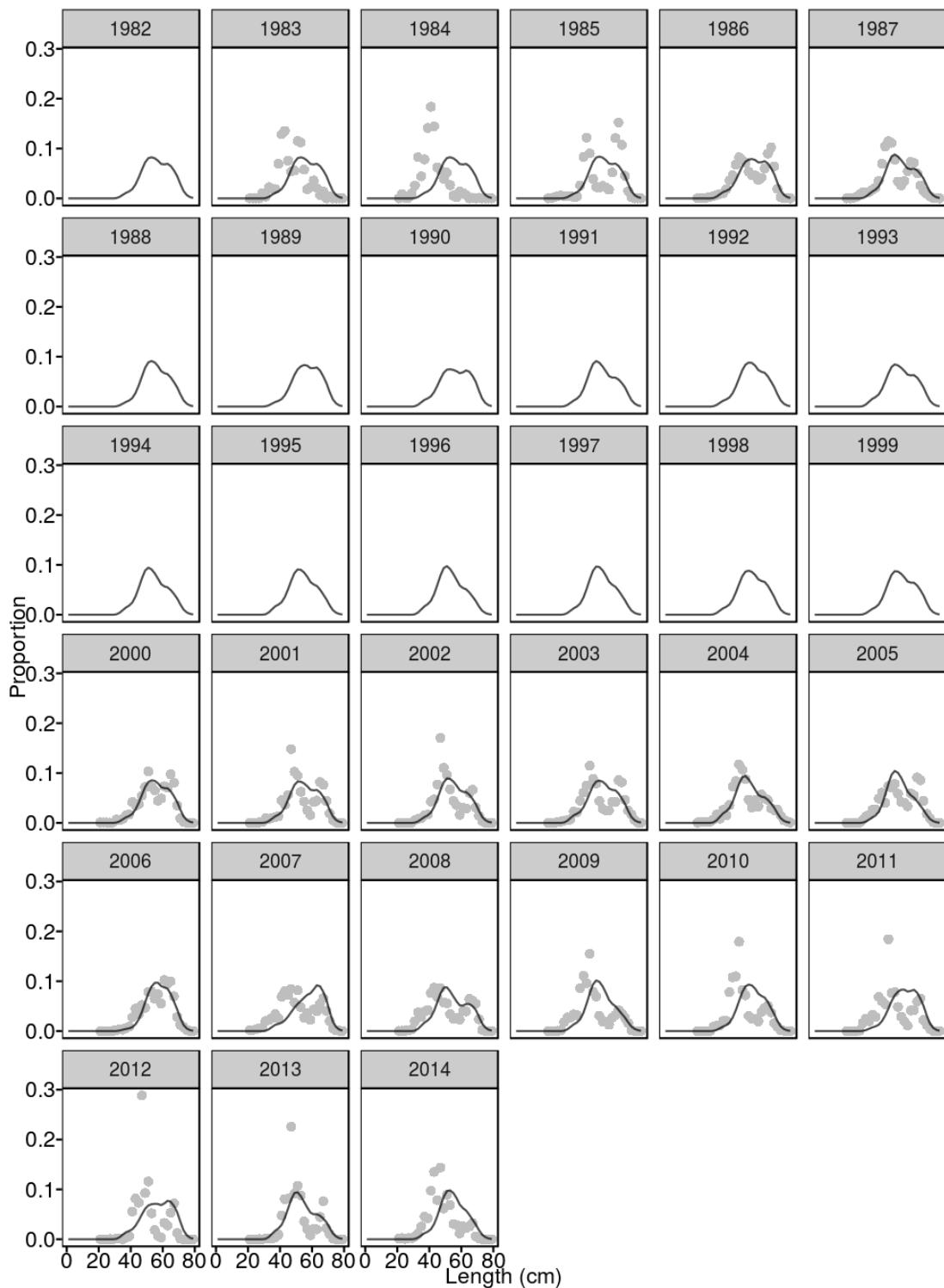


Figure 22: Observed (points) and expected (lines) size frequency distributions for pole and line (PL) in the Maldives region (MA) aggregated over quarters.

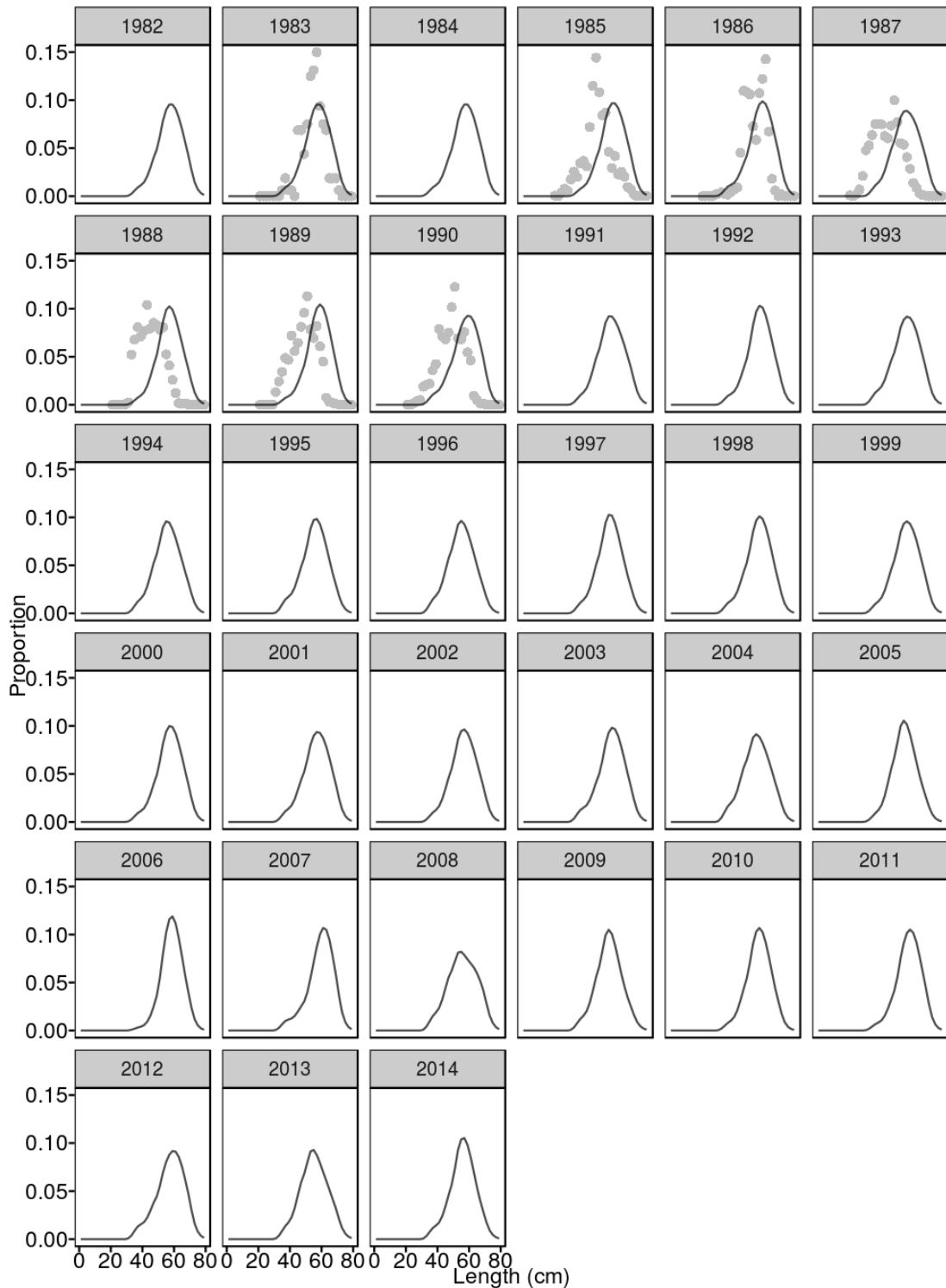


Figure 23: Observed (points) and expected (lines) size frequency distributions for other methods (OT) in the eastern region (EA) aggregated over quarters.

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

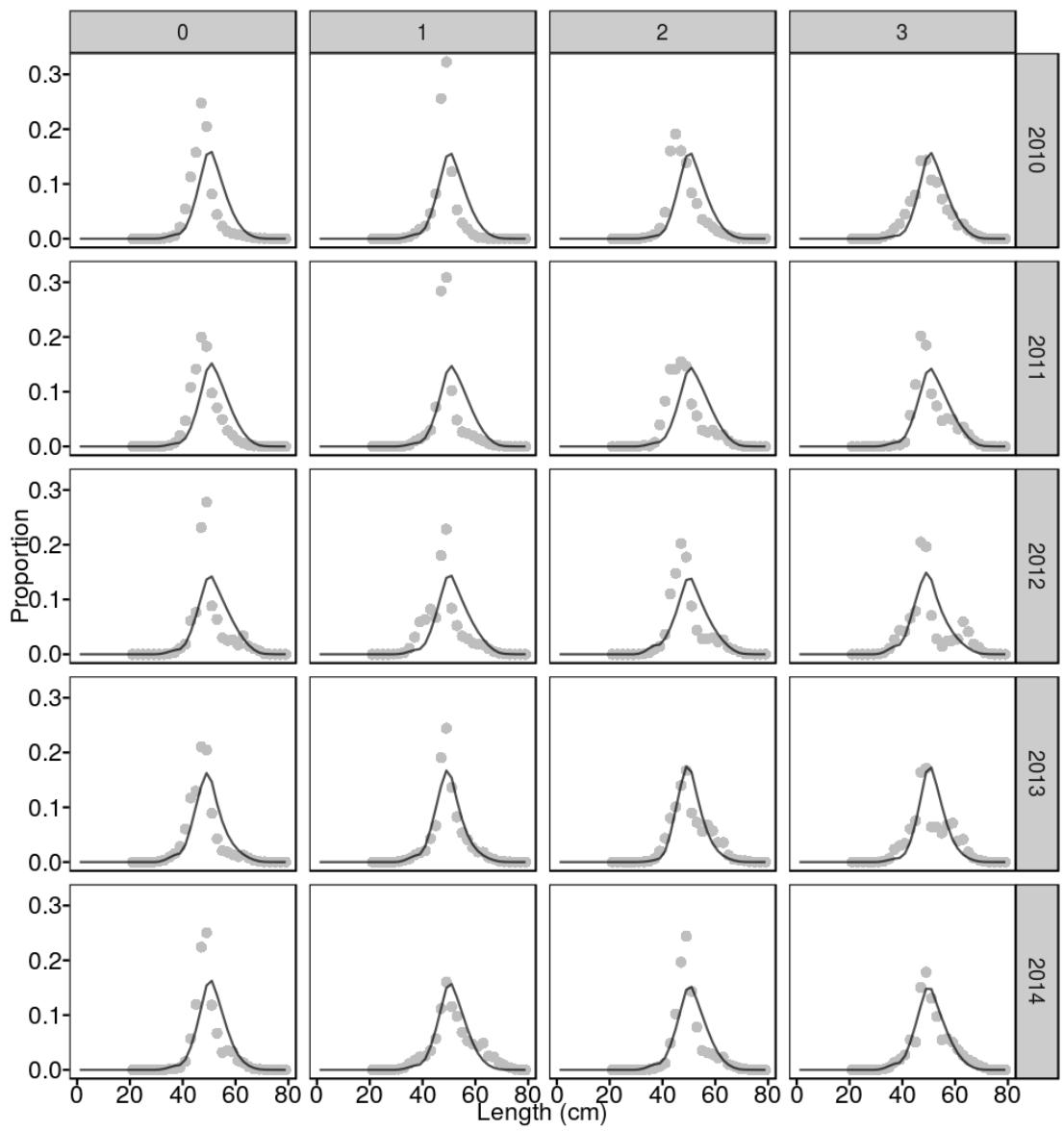


Figure 24: Observed (points) and expected (lines) size frequency distributions for purse seine (PS) in the western region (WE) by year and quarters since 2010.

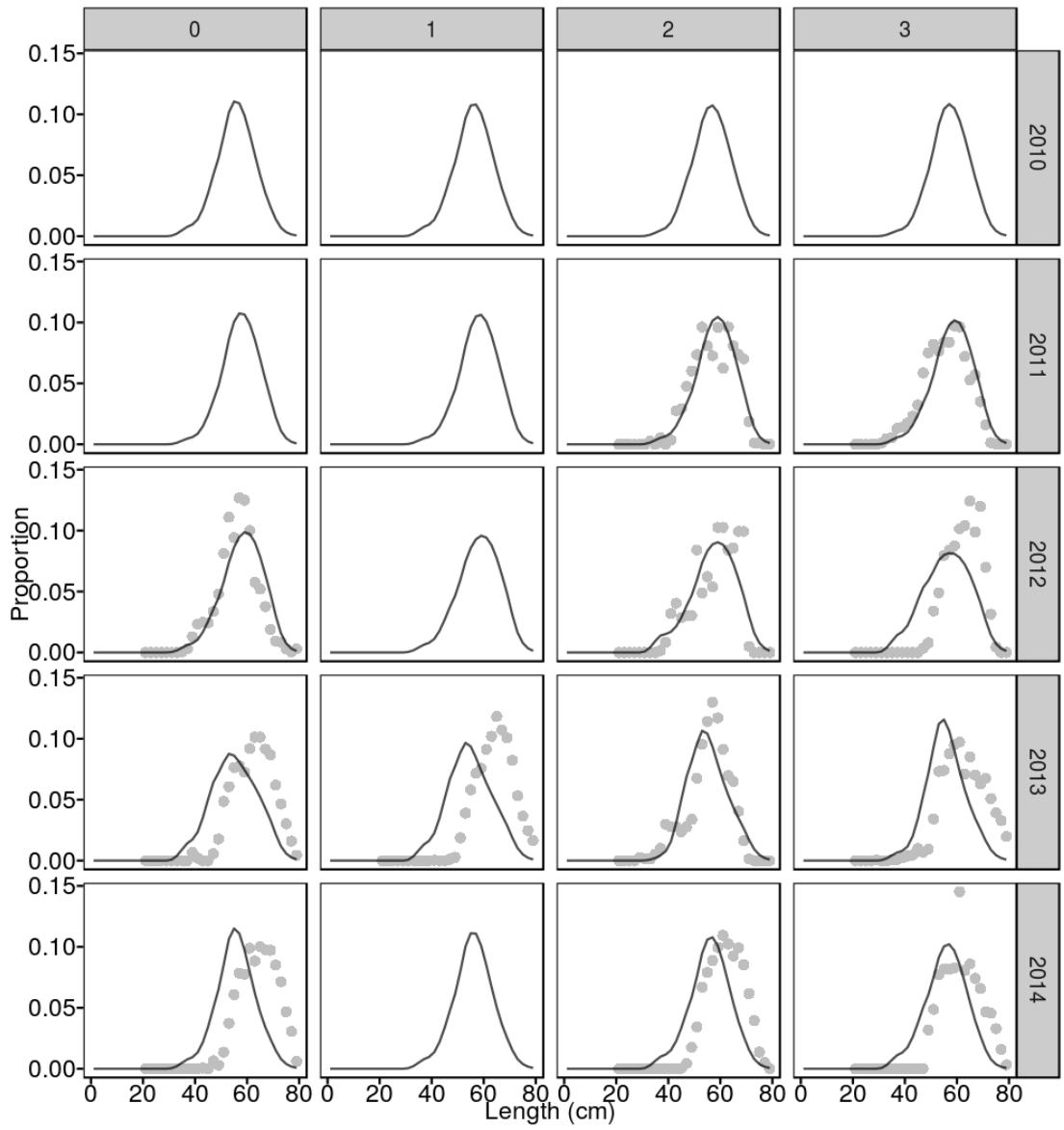


Figure 25: Observed (points) and expected (lines) size frequency distributions for gillnet (GN) in the western region (WE) by year and quarters since 2010.

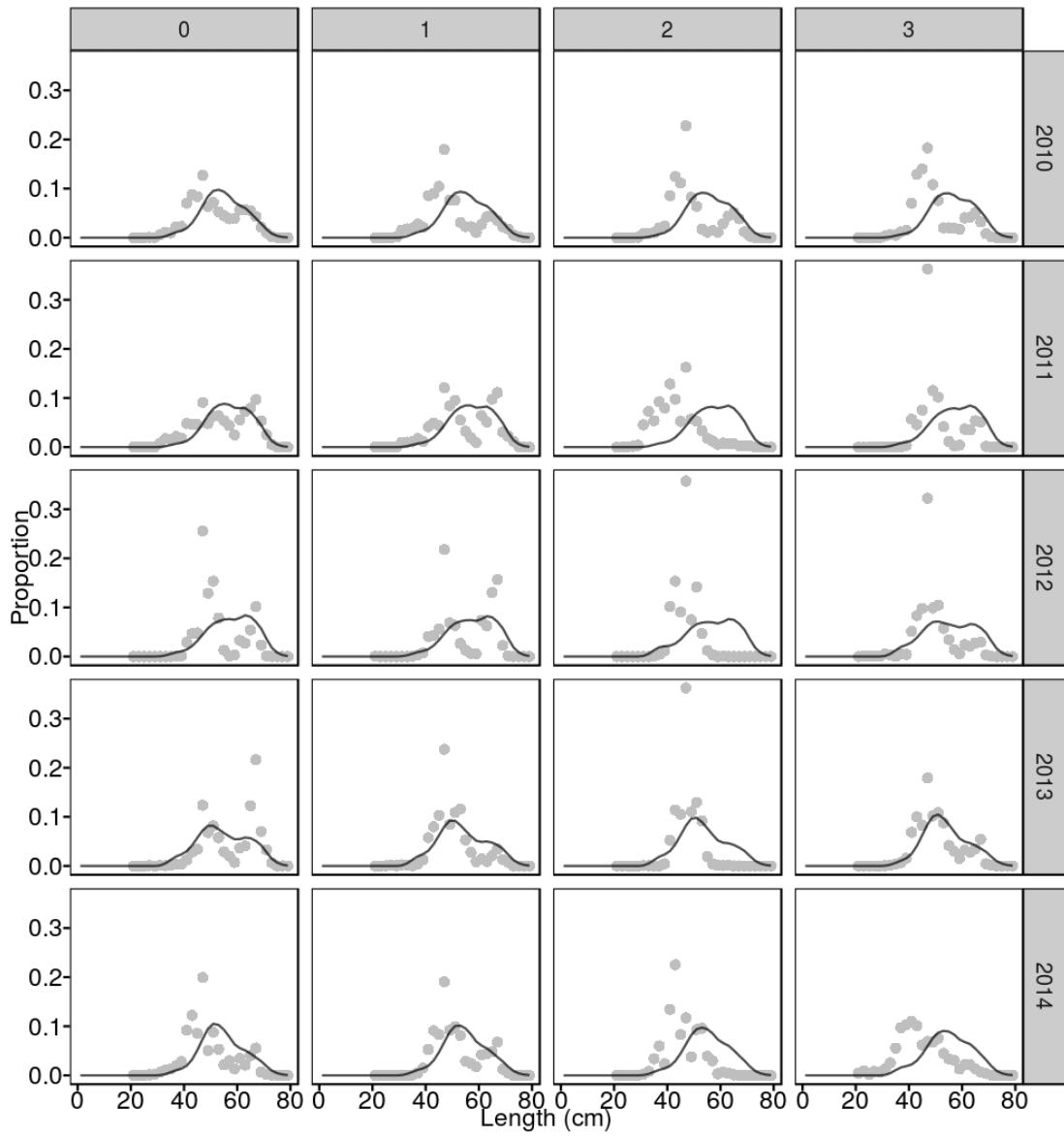


Figure 26: Observed (points) and expected (lines) size frequency distributions for pole and line (PL) in the Maldives region (MA) by year and quarters since 2010.

2.6. Yield curve and types of reference point

The `ioskj.exe` executable has a `yield` task which generates outputs related to:

- the yield curve
- maximum sustainable yield (MSY)
- yield per recruit.

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), Maldives 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 curve can be derived.

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).

The results presented here are **illustrative only**. They are based on the reference parameter set only. Ideally their sensitivity to alternative parameter values should be investigated. Also, further checking and testing of the model's equilibrium dynamics used for generating these results should be done. The main intention of this section is to promote discussion regarding 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.

This section describes the overall yield curve and reference points related to maximising sustainable yield. [Table 3](#) provides MSY related reference points and [Table 4](#) provides reference points associated with alternative biomass levels. [Figure 27](#) presents plots of various variables related to the yield curve.

Table 3: Yield curve related variables determined from the reference parameter set.

Symbol	Description	Value
E_{msy}	Exploitation rate which produces MSY (quarterly)	0.225
F_{msy}	Instantaneous rate of fishing mortality which produces MSY (quarterly)	0.255
C_{msy}	Maximum sustainable yield (quarterly)	107118
B_{msy}	Overall spawner biomass associated with maximum sustainable yield	617467
B_{msy} / B_0	B_{msy} as a percentage of pristine biomass	20.6
-	Number of iterations used to find MSY	11

Table 4: 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.

Biomass level	Exploitation rate (quarterly)	Fishing mortality rate (quarterly)	Yield (quarterly)	Yield/MSY	B / B_{msy}	Effort/Effort at MSY
B_{msy}	0.225	0.255	107118	1	1	1
30 % B_0	0.15	0.1	103103	0.96	1.46	0.665
40 % B_0	0.1	0.065	92577	0.86	1.99	0.444
50 % B_0	0.07	0.045	79953	0.75	2.47	0.31

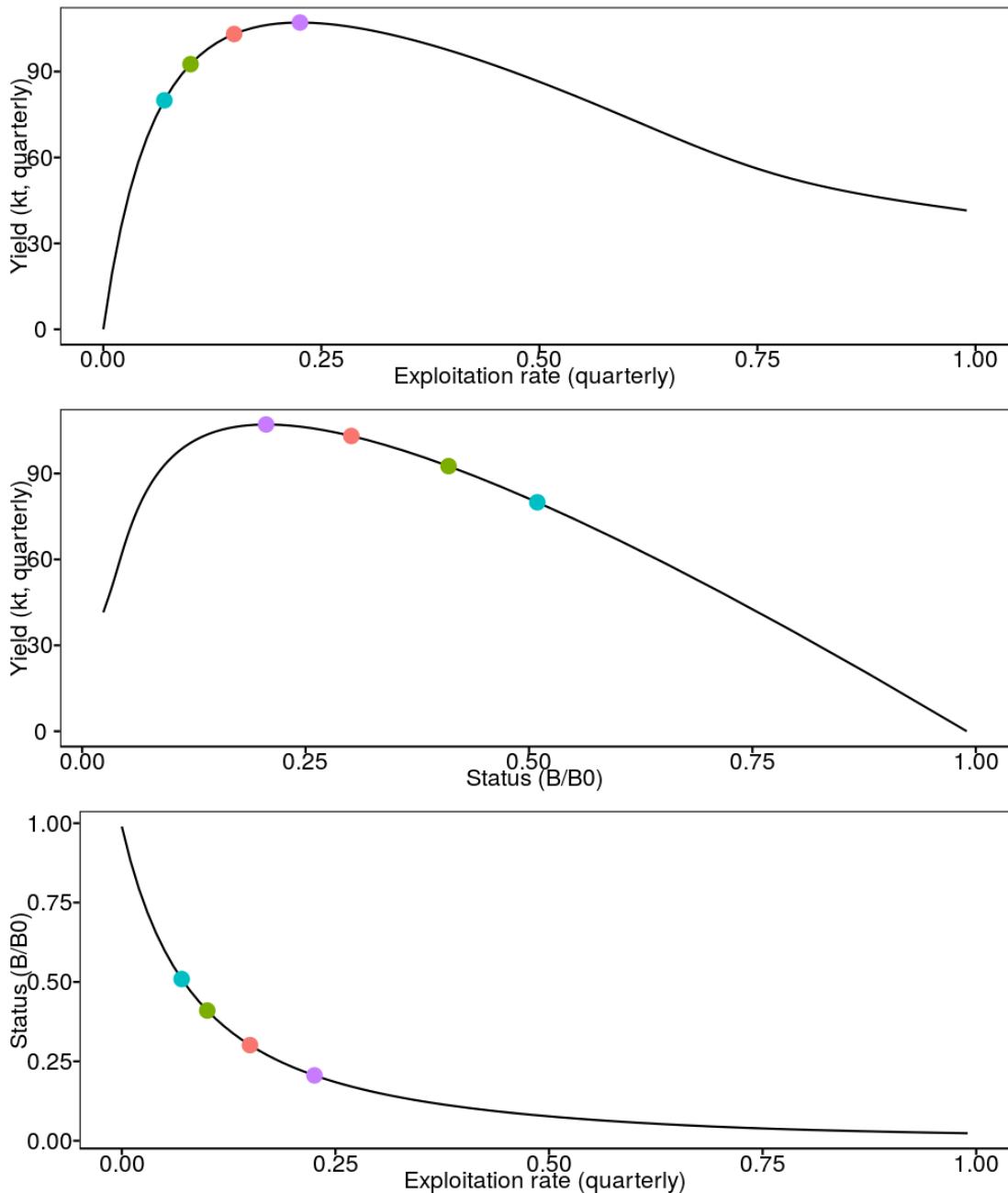


Figure 27: Relations between equilibrium yield, stock status and exploitation rate.(top) Equilibrium yield versus equilibrium exploitation rate. (middle) Equilibrium yield versus equilibrium stock status. (bottom) Equilibrium stock status versus equilibrium exploitation rate.

2.7. 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 5: Feasibility criteria used in the FST algorithm

Code	Criterion	Percentage of trials failing this criterion
1	Overall stock status must always be $\geq 10\%$ BO	1.06
2	Overall stock status must be between 40% and 80% BO since in 2013	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. 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.

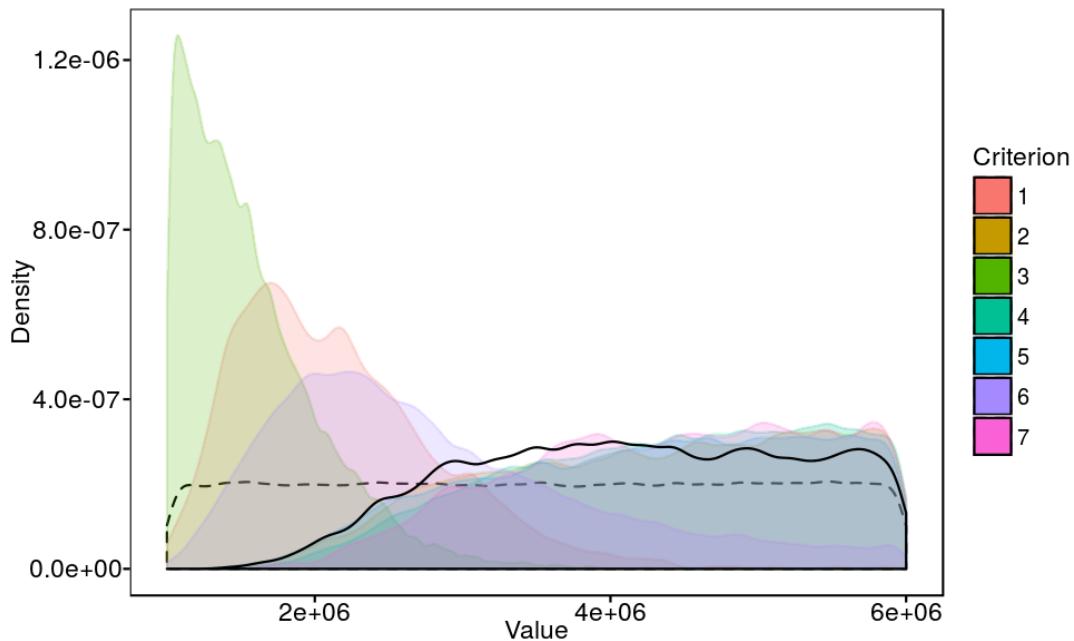


Figure 0: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawners_unfished`. The rejection probability density represent the probability of a parameter values being rejected by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

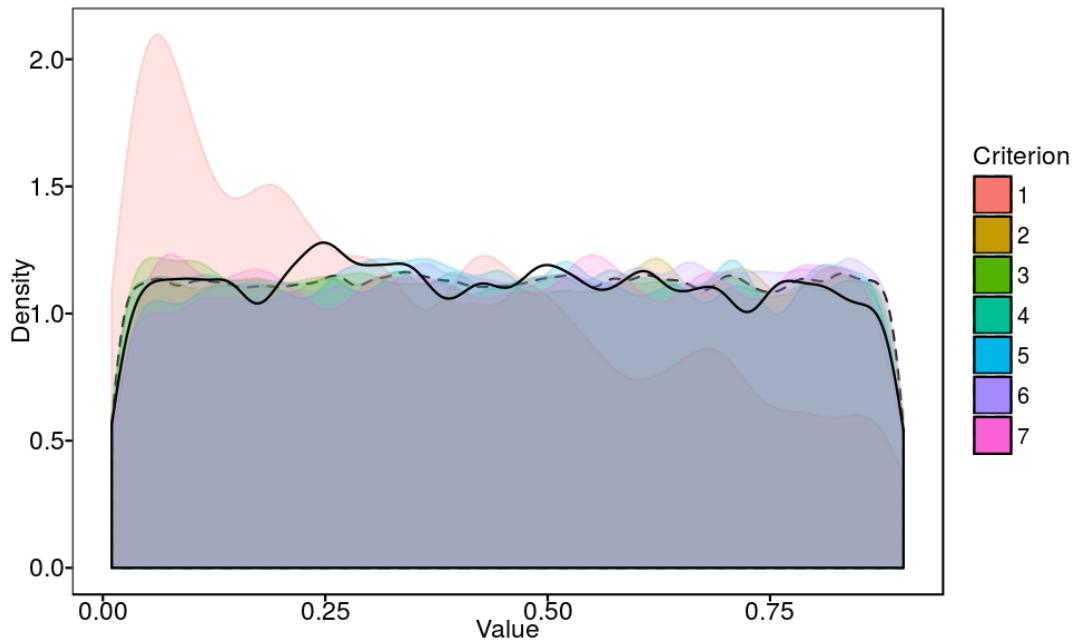


Figure 1: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawners_ma`. The rejection probability density represent the probability of a parameter values being rejected by one of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

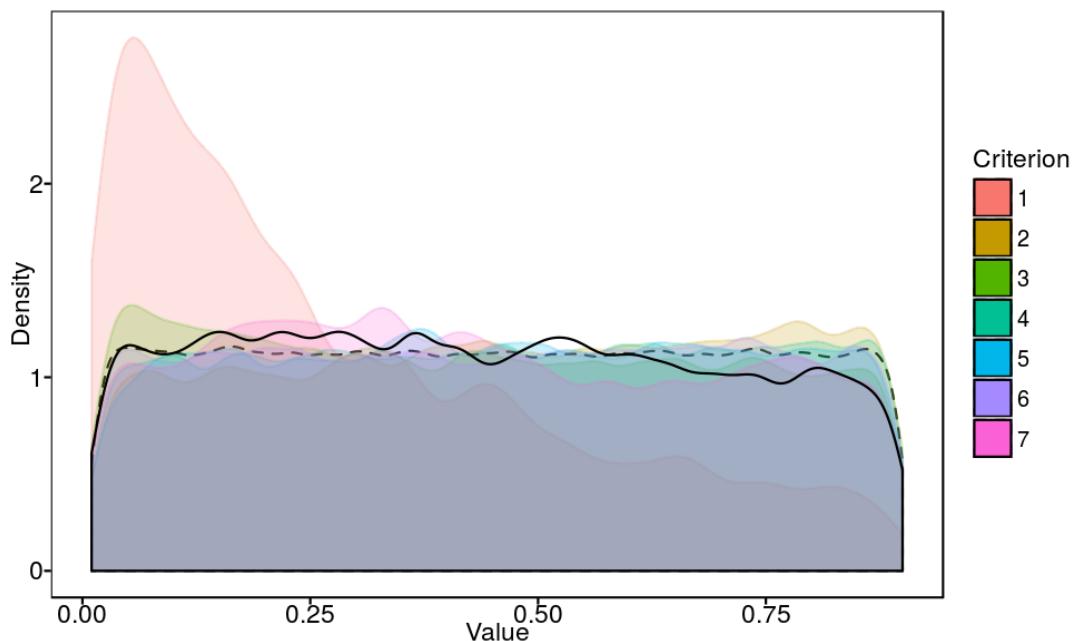


Figure 2: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawners_ea`. The rejection probability density represent the probability of a parameter values being rejected by one of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

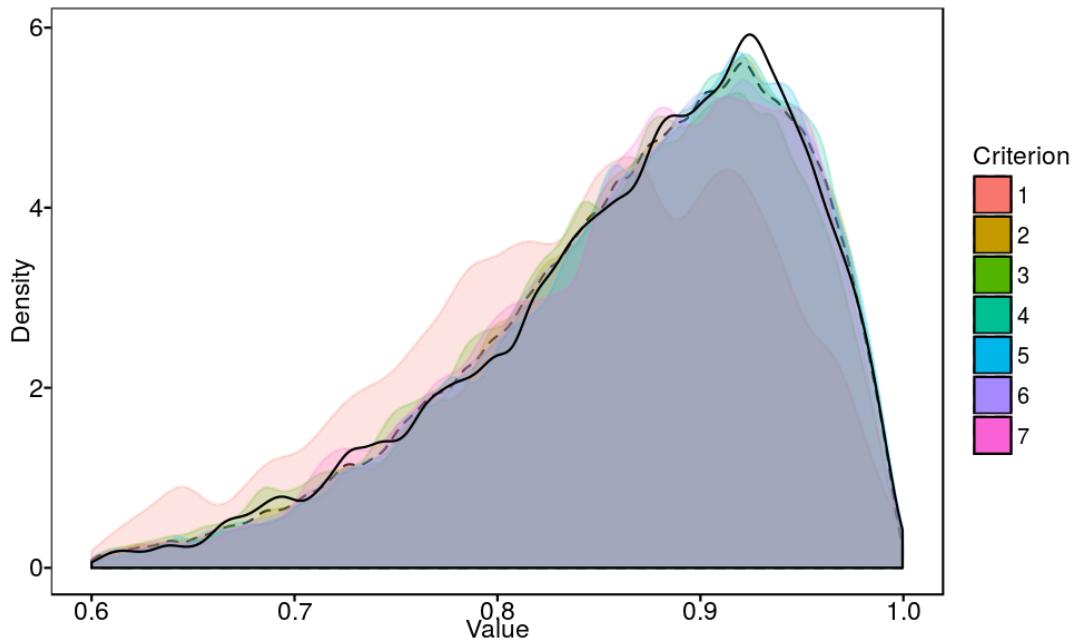


Figure 3: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `recruits_steeplness`. The rejection probability density represent the probability of a parameter values being rejected by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

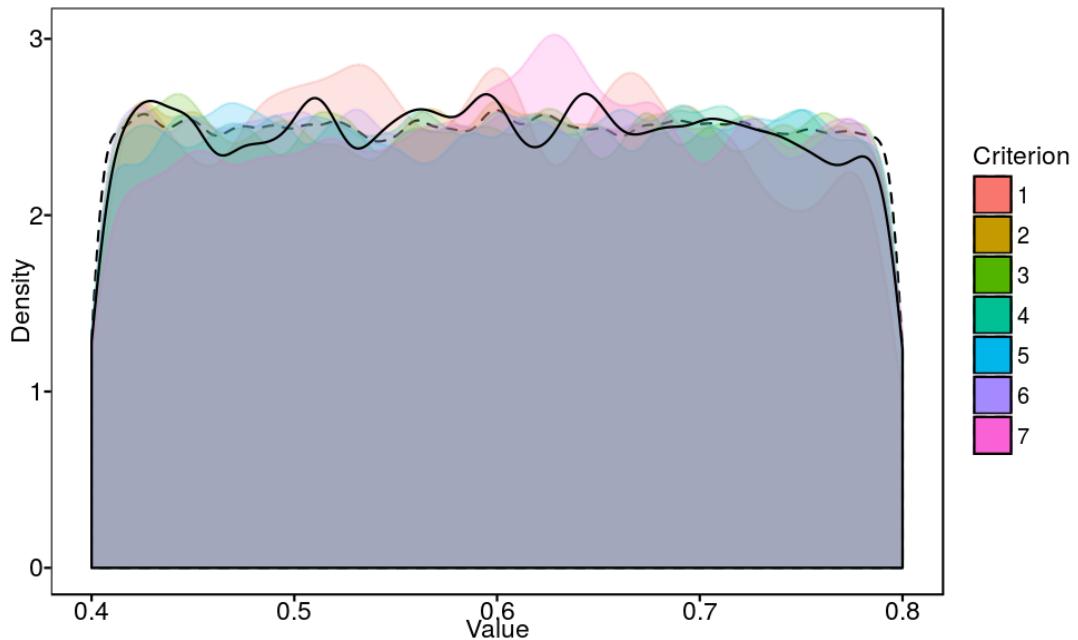


Figure 4: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `recruits_sd`. The rejection probability density represent the probability of a parameter values being rejected by one of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

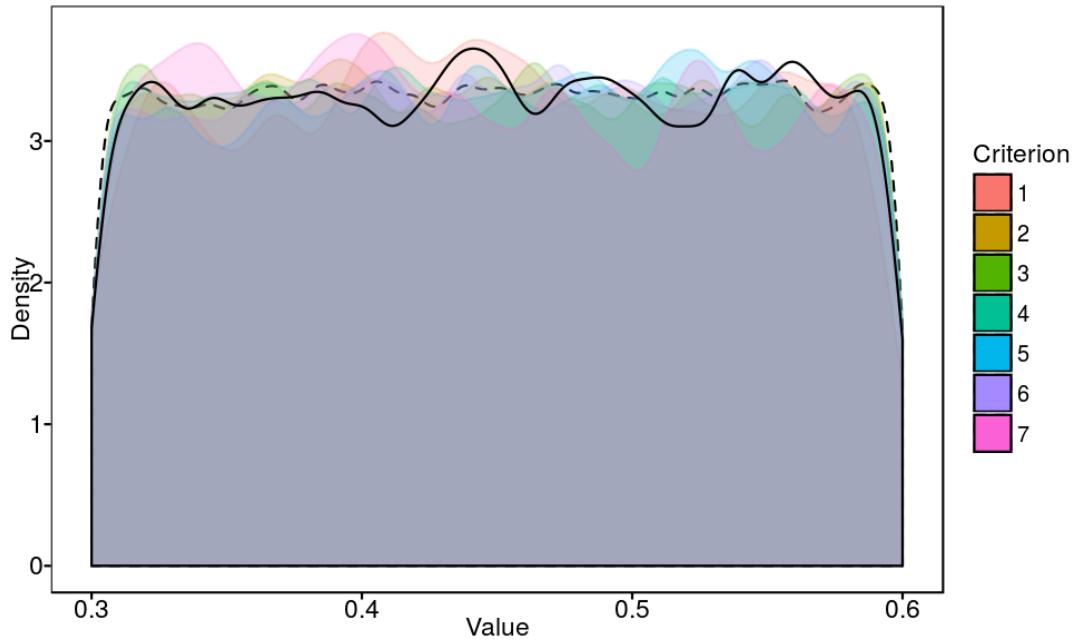


Figure 5: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `recruits_autocorr`. The rejection probability density represent the probability of a parameter values being rejected by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

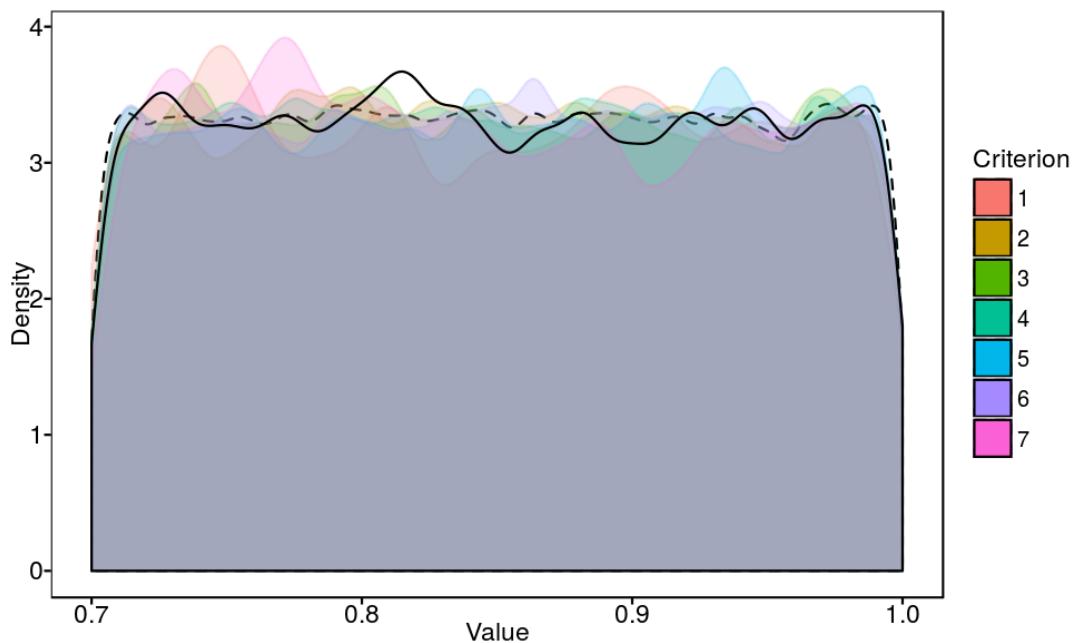


Figure 6: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawning_0`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

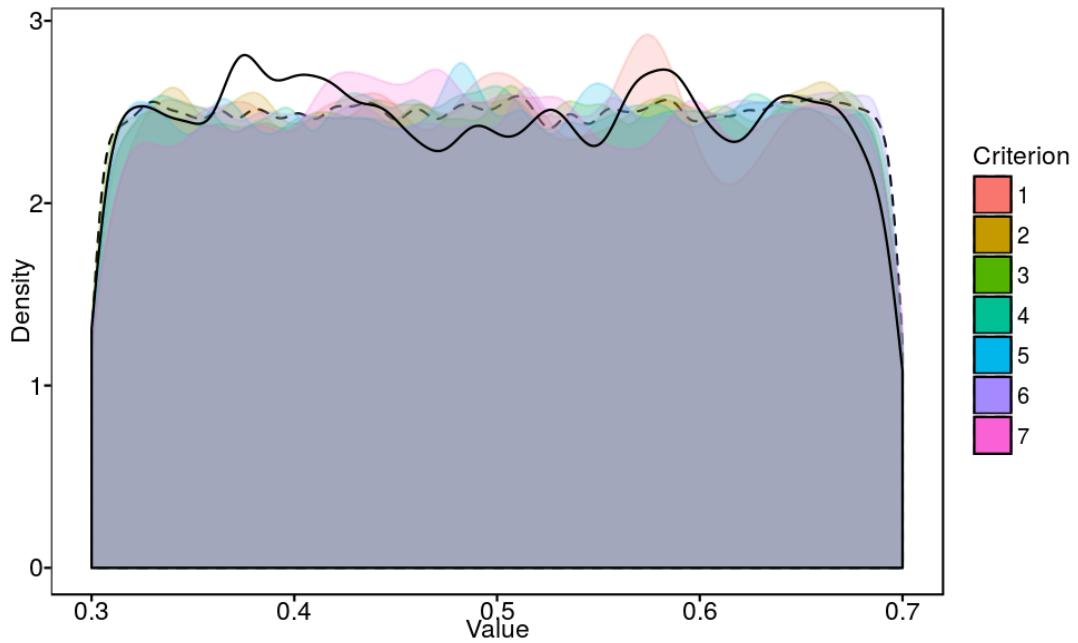


Figure 7: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawning_1`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

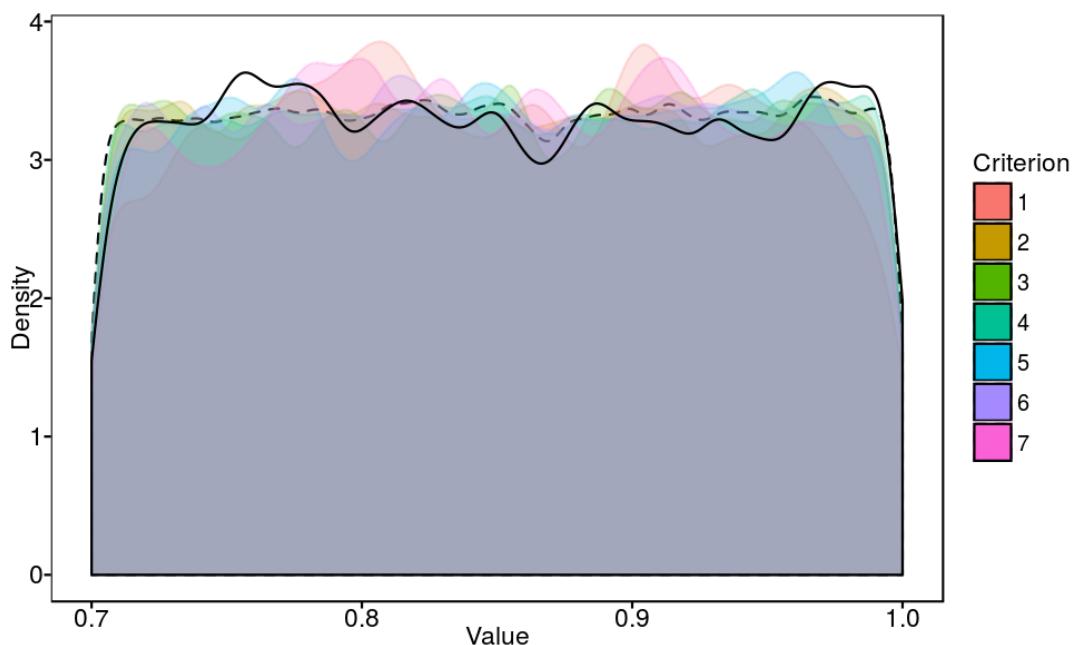


Figure 8: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawning_2`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

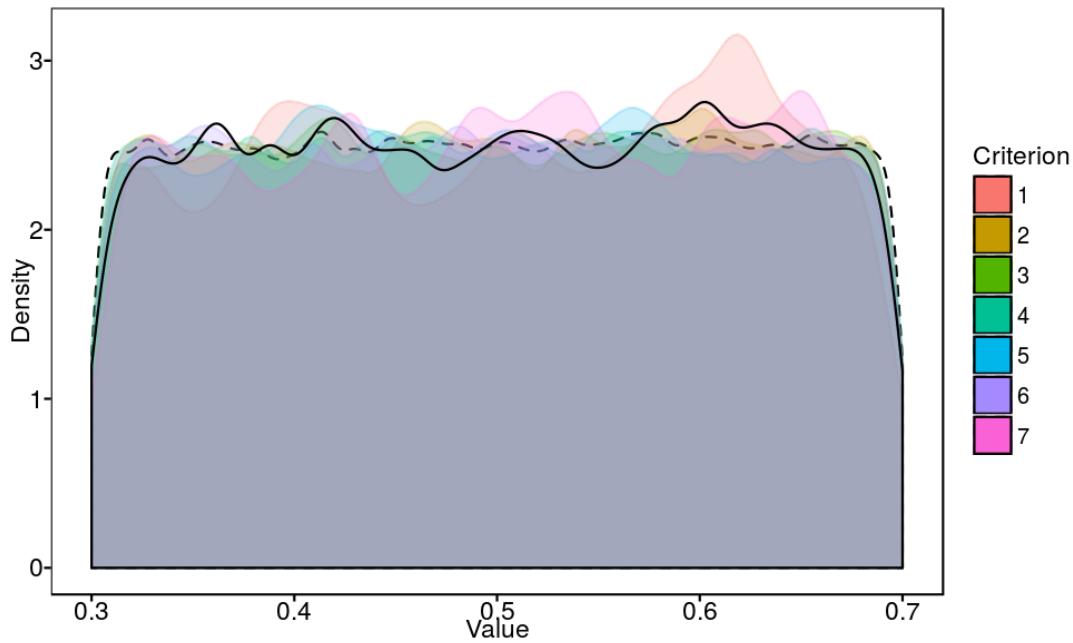


Figure 9: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `spawning_3`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

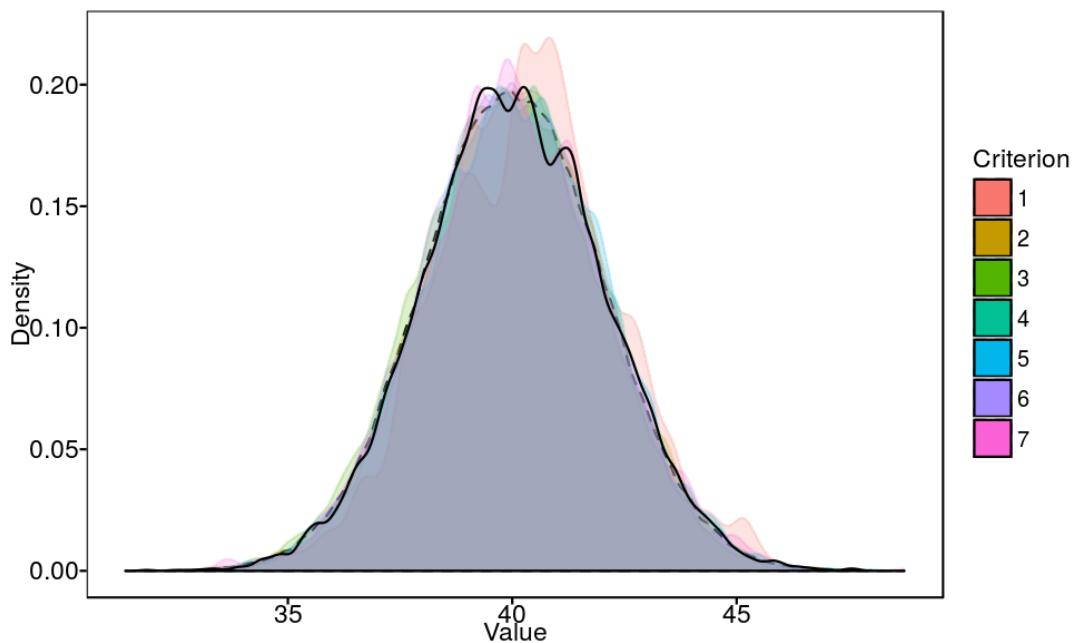


Figure 10: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `maturity_inflection`. The rejection probability density represent the probability of a parameter values being rejected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

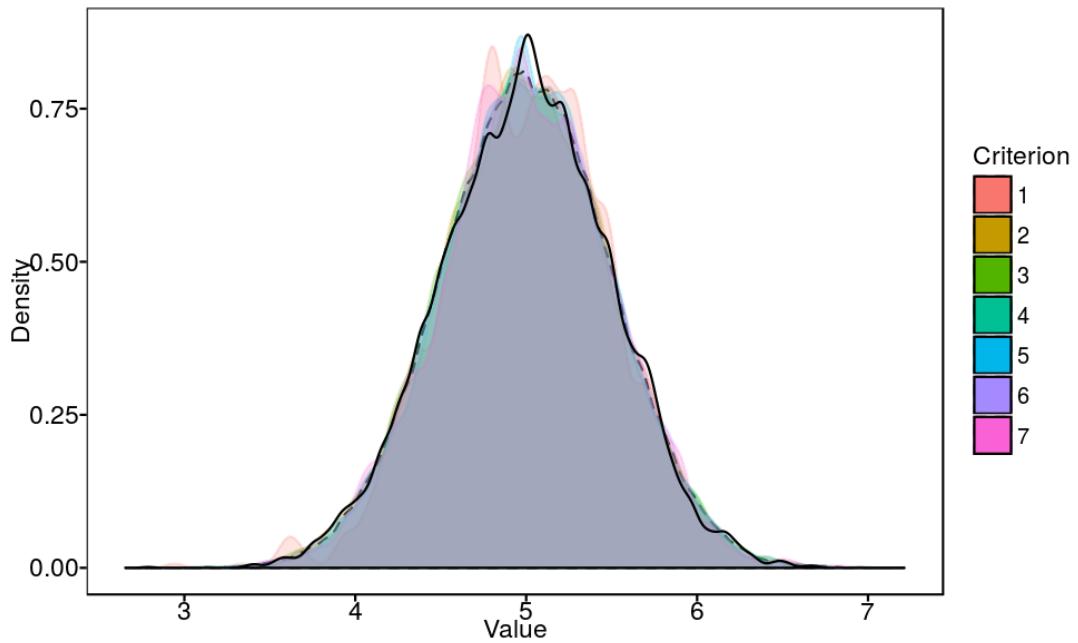


Figure 11: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `maturity_stEEPNESS`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

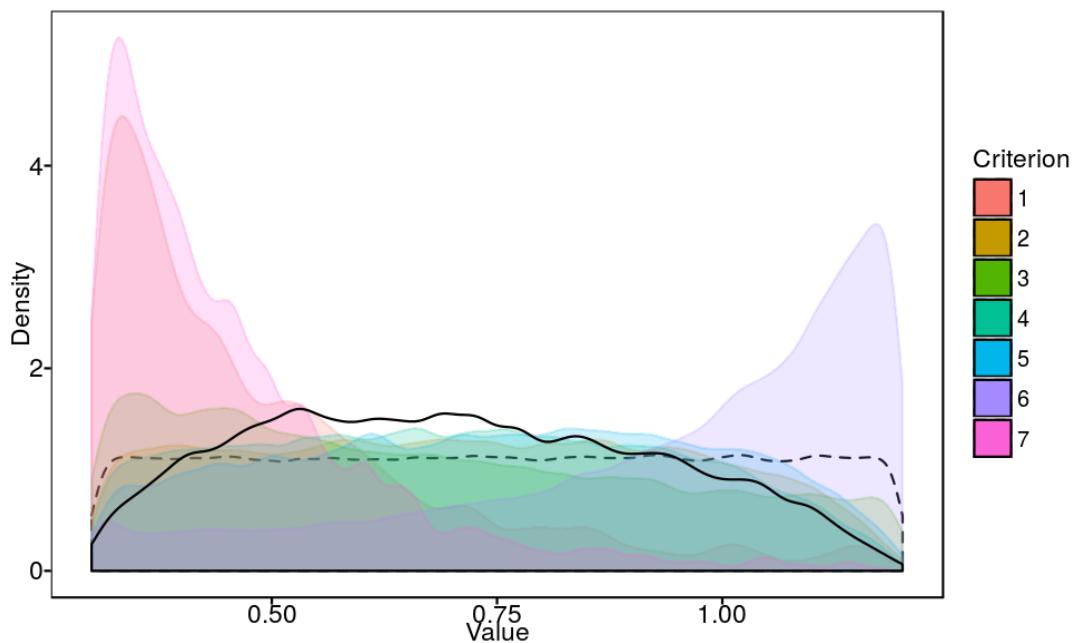


Figure 12: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `mortality_mean`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

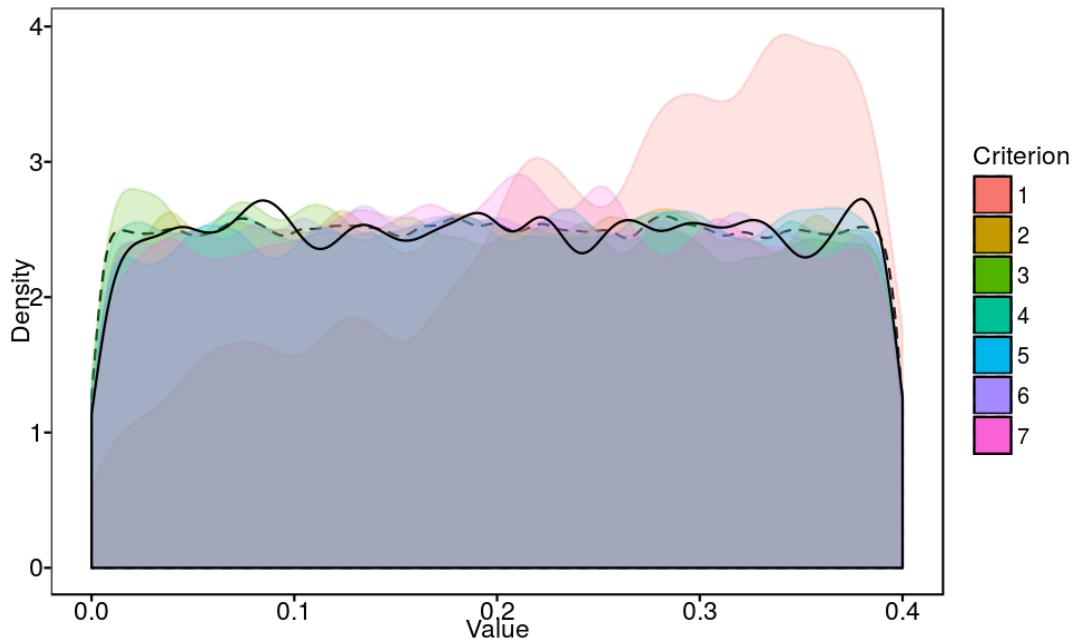


Figure 13: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `movement_we_ma`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

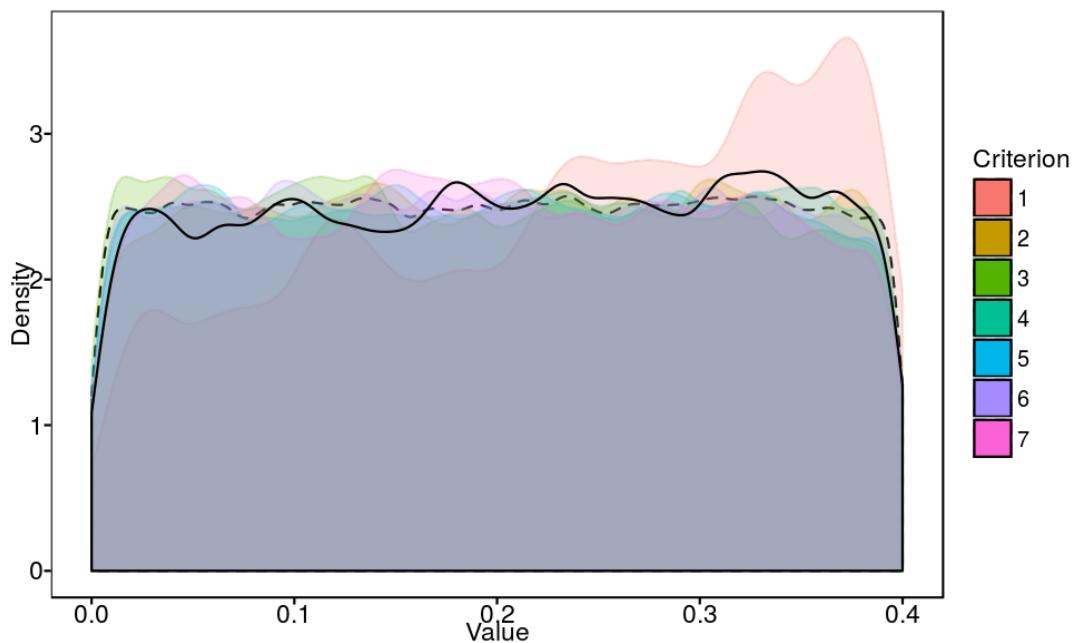


Figure 14: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `movement_we_ea`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

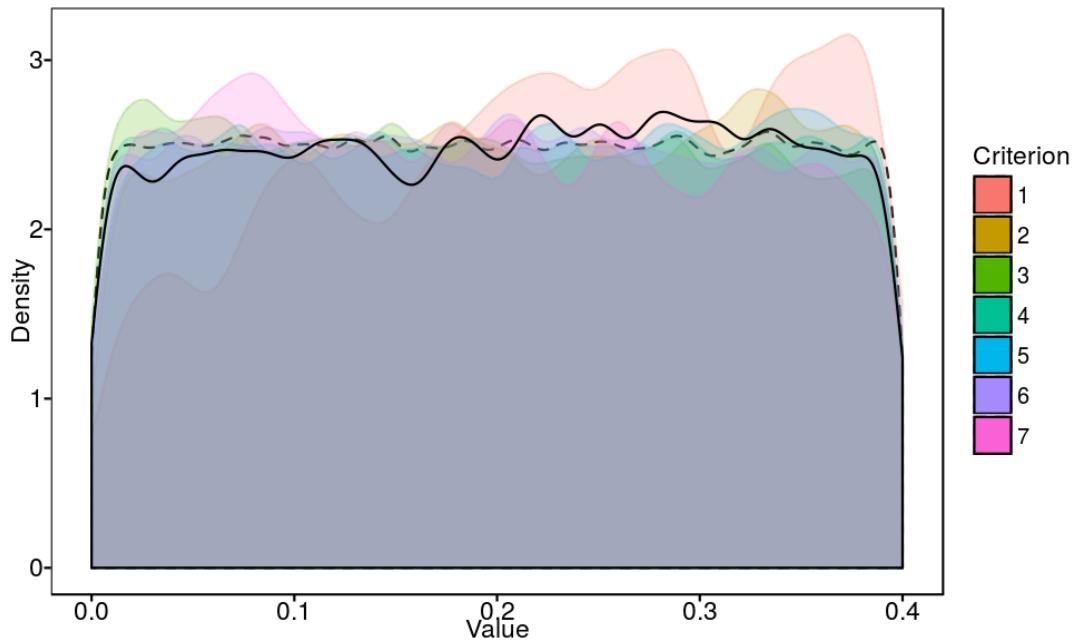


Figure 15: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `movement_ma_ea`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

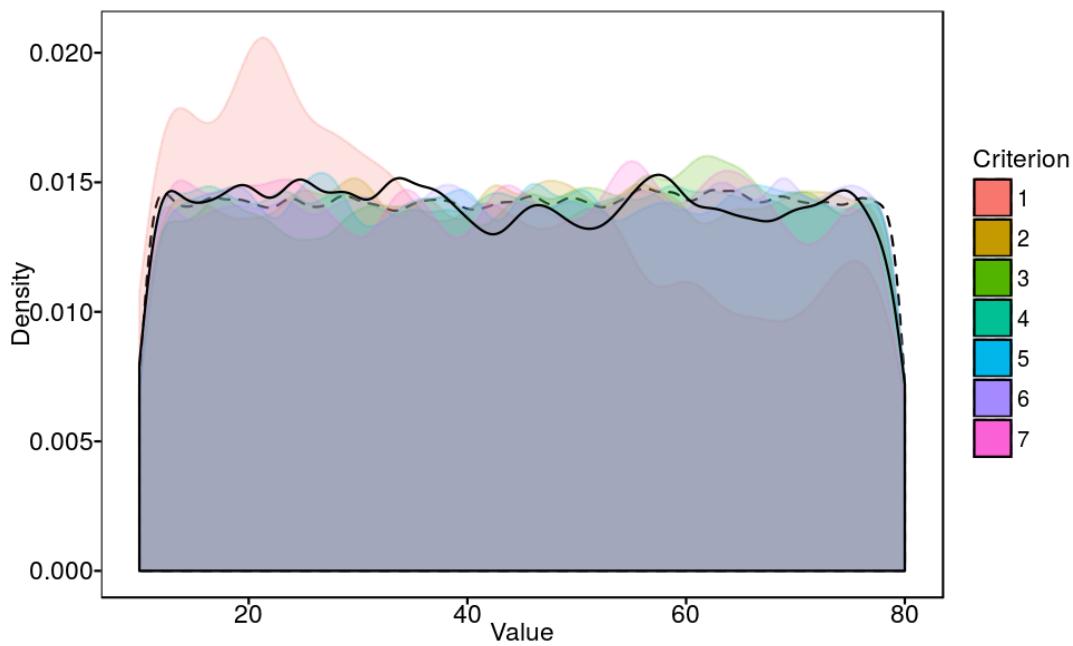


Figure 16: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter `movement_length_inflection`. The rejection probability density represent the probability of a parameter values being rejected by one of the feasibility criteria.

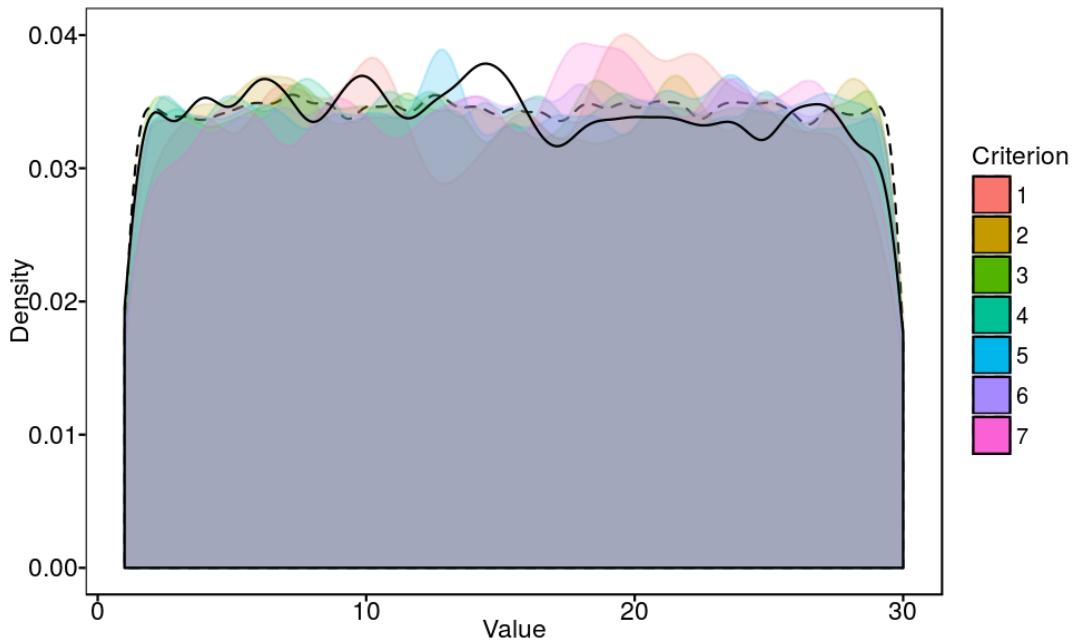


Figure 17: Prior probability density (dashed line), rejection probability densities (coloured fill) and resulting posterior probability density (solid line) for the model parameter movement_length_steeplness. The rejection probability density represent the probability of a parameter values being rejected 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 management 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 pristine 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 (\bar{F}) is calculated. If $\hat{S} < s_l$ then,

$$\bar{F} = 0$$

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

$$\bar{F} = f$$

Otherwise,

$$\bar{F} = \frac{f}{s_t - s_l} (\hat{S} - s_l)$$

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

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

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 6: 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

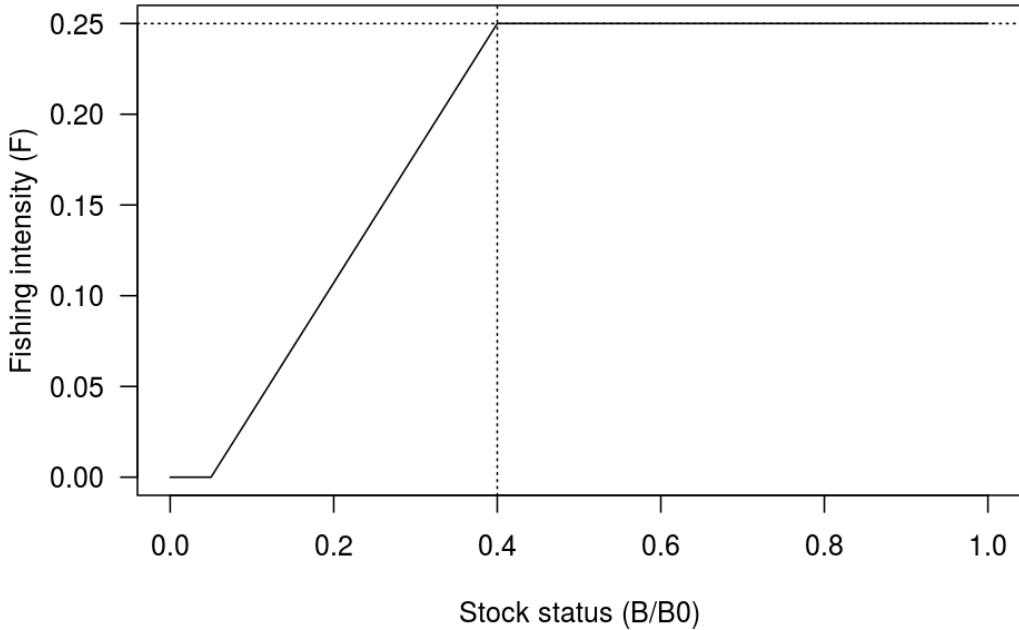


Figure 46: An example instance of the BRule management procedure with $s_l = 0.05$, $s_t = 0.4$, $f = 0.25$ showing the relation between \hat{S} and \bar{F} .

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 ,

$$\hat{F} = F\varepsilon$$

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 7: 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 percentage change in effort	0.4

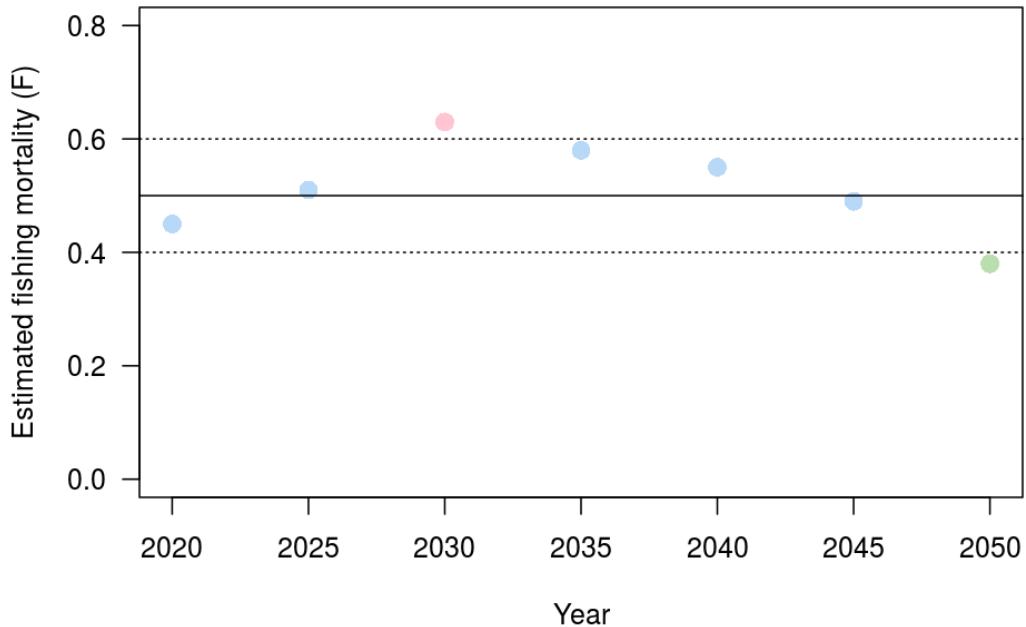


Figure 47: An example instance of the BRule management procedure with $i = 5, f = 0.5, b = 0.1$ illustrating how total allowable catches are increased (green circles) or decreased (red circles) when the estimated fishing mortality is below or above the target range.

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.

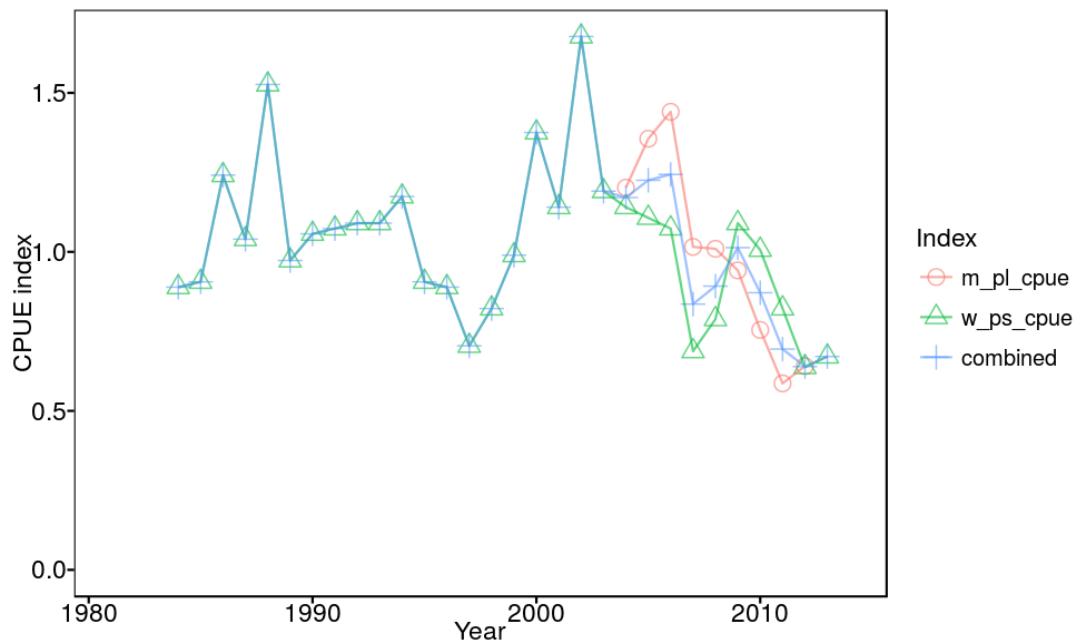


Figure 48: Western purse seine, Maldives pole and line and combined CPUE series.

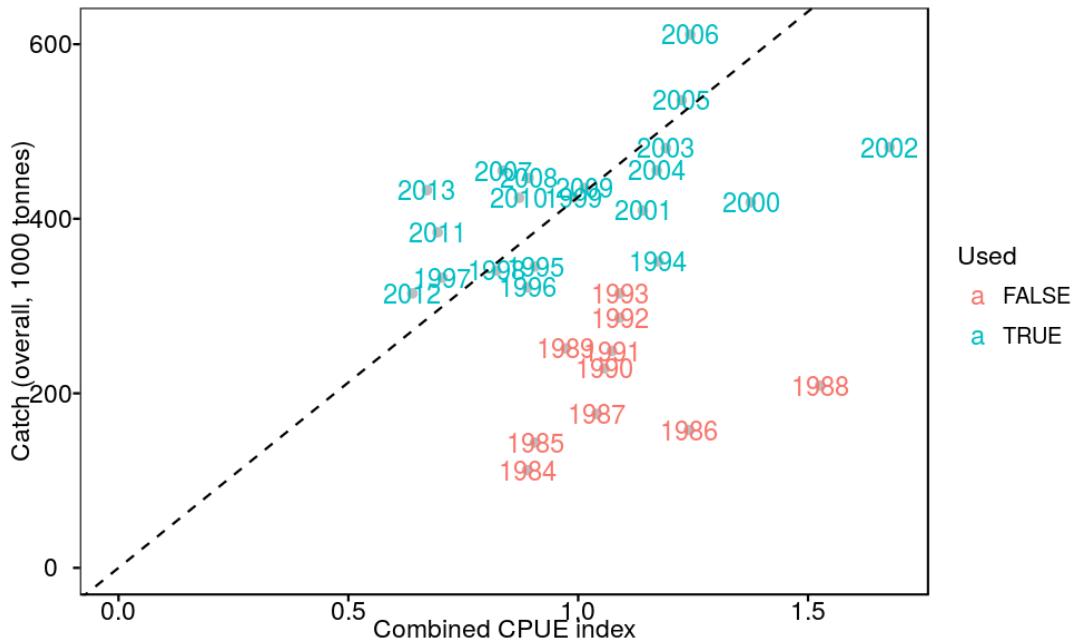


Figure 49: Historical relation between combined CPUE and overall catch. The dashed line has a slope of the catch scalar = 424.93 (geometric mean of the ratio of catches over CPUE).

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

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

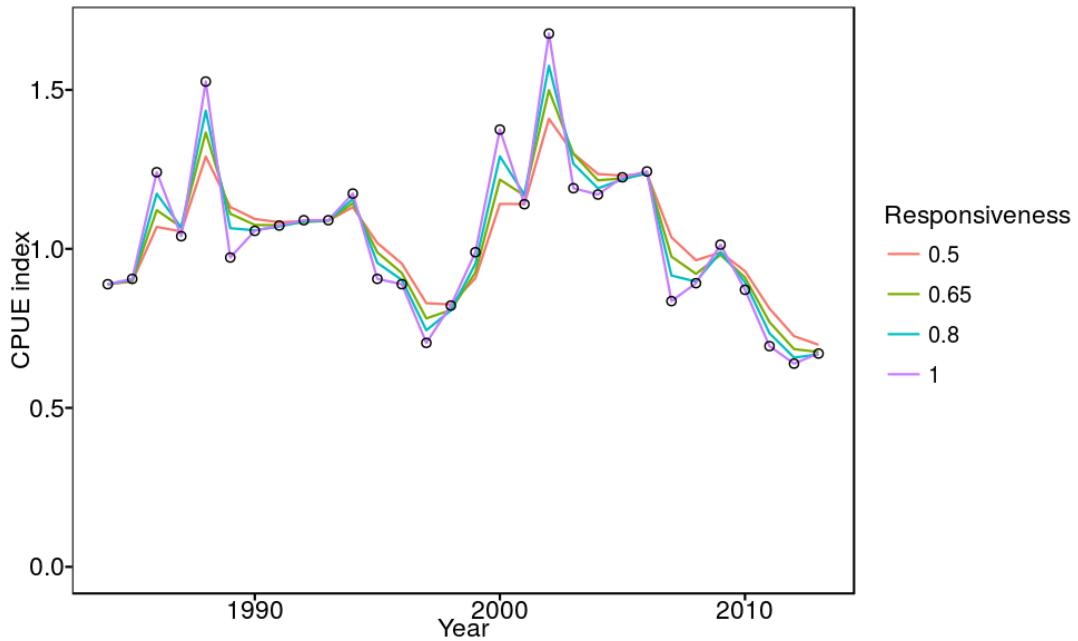


Figure 50: Illustration of the alternative smoothing of CPUE index using the responsiveness parameter.

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 to catchability or operational variations. However, smoothing also reduces adds a lag to the index.

Using \bar{I} the recommended catch scalar (\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,

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

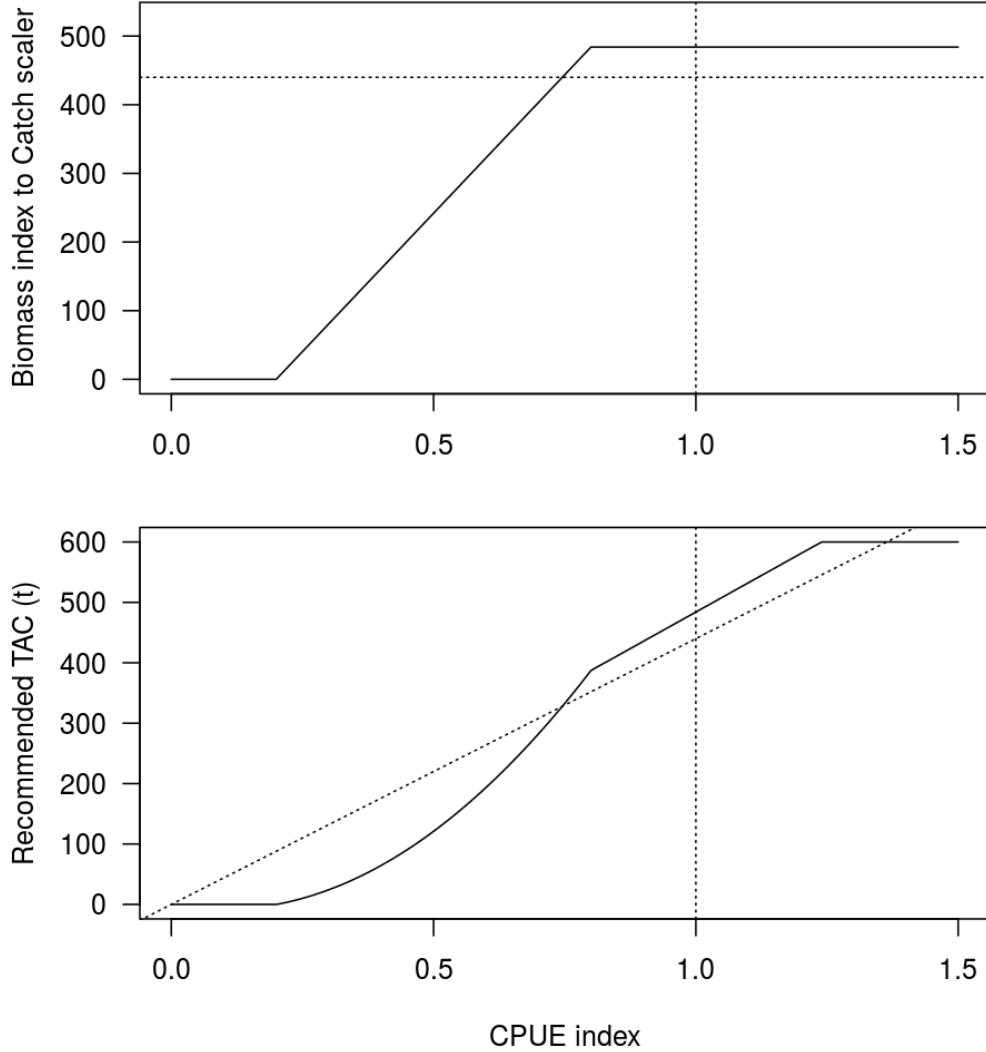


Figure 51: An example instance of the IRate management procedure with $i_l = 0.2$, $i_t = 0.8$, $m = 1.1$, $u = 600$ showing the relation between the CPUE index (\bar{I}) and the catch scalar (\bar{S}) and the recommended TAC.

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

$$\bar{C} = \min(\bar{S}\bar{I}, u)$$

which is applied to the fishery in the following year,

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

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

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

Table 8: 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 multiplier	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 biomass 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 biomass index is at 20% of historic levels	0.05, 0.1, 0.2
Maximum change	f	Maximum allowable percentage change in effort	0.4
Maximum TAC	u	Maximum total allowable catch (thousand tonnes)	300, 400, 500, 600

2.9. Evaluation methods

This section describes the methods used to evaluate alternative candidate management procedures.

2.9.1. 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 9). 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%BO we use the "safety" related statistic, the probability of being **above** 10%BO.

Table 9: Management objectives, performance statistics and performance measures. [This table has not yet been updated to reflect recent changes agreed 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 $B \geq B_{tar} \text{ and } F \leq F_{tar}$
Probability of being in Kobe red quadrant	B, F	Proportion of years that $B < B_{tar} \text{ and } F > F_{tar}$
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 Maldives 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 decrease %) : the percentage of years in which there is a decrease in the recommended catch limit (note that the changes in catch limit only occur every 3 years)
- Stability (Years 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)

2.9.2. 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 52](#)).

The primary purpose of MPE is not to provide forecasts 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 53](#)). This allows us to compare the performance of alternative MPs under exactly the same set of assumptions. Notice in ([Figure 53](#)) 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.

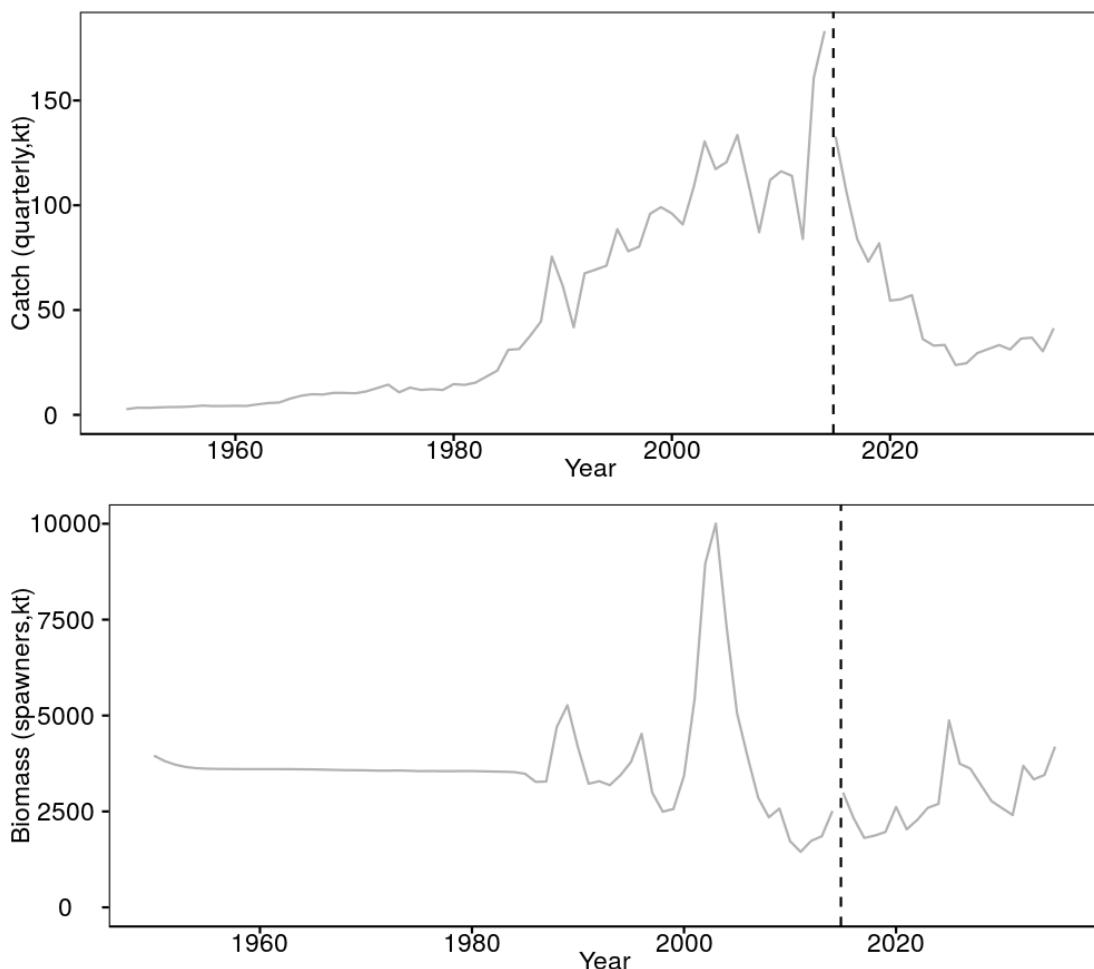


Figure 52: Catch and biomass trajectories from a single evaluation of a single management procedure using a single parameter replicate.

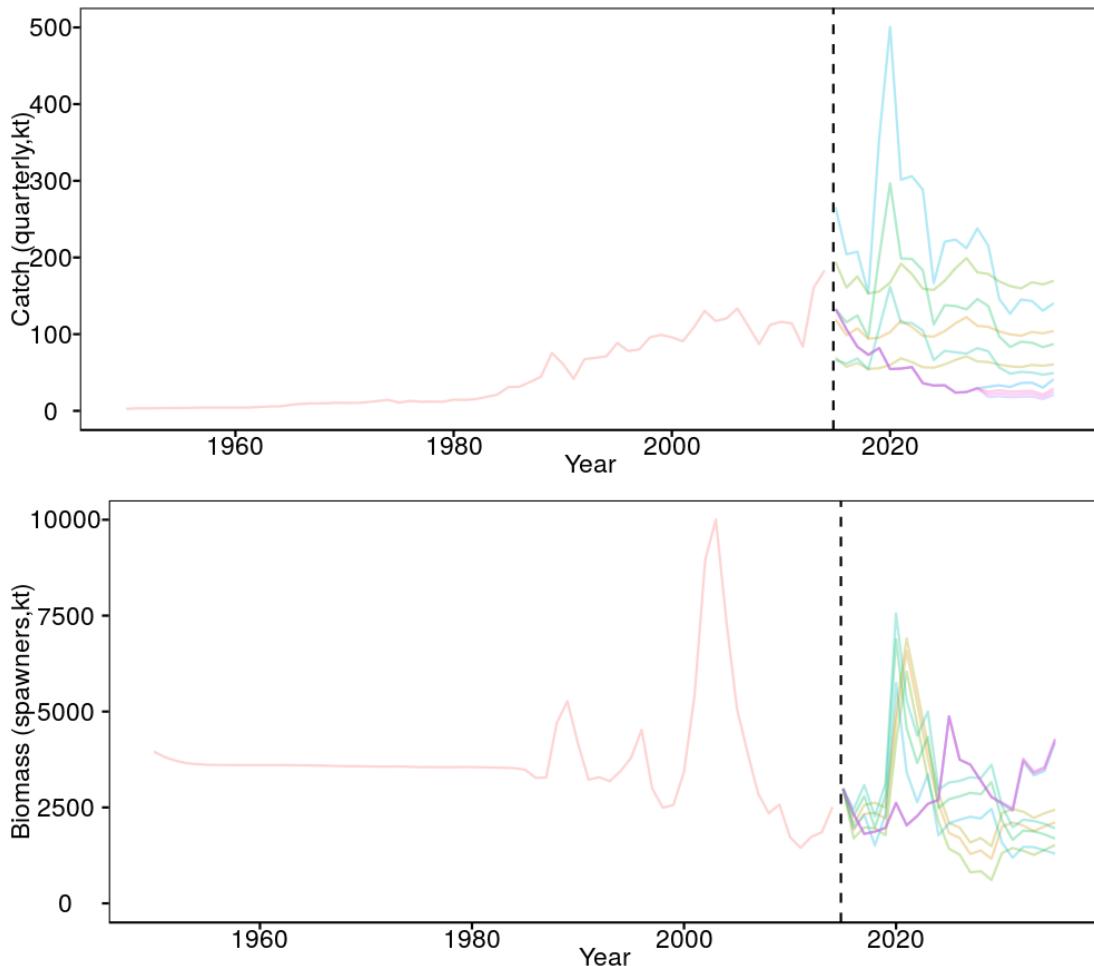


Figure 53: Catch and biomass trajectories from multiple evaluations of multiple management procedure using a single parameter replicates. Each of the coloured future trajectories arises from applying one candidate management procedure.

To be able to assess and compare the robustness of management procedures to uncertainty it is necessary to run evaluations for many replicates. Figure 54 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 55). The ribbons show the bands where 50%, 80% and 90% 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.

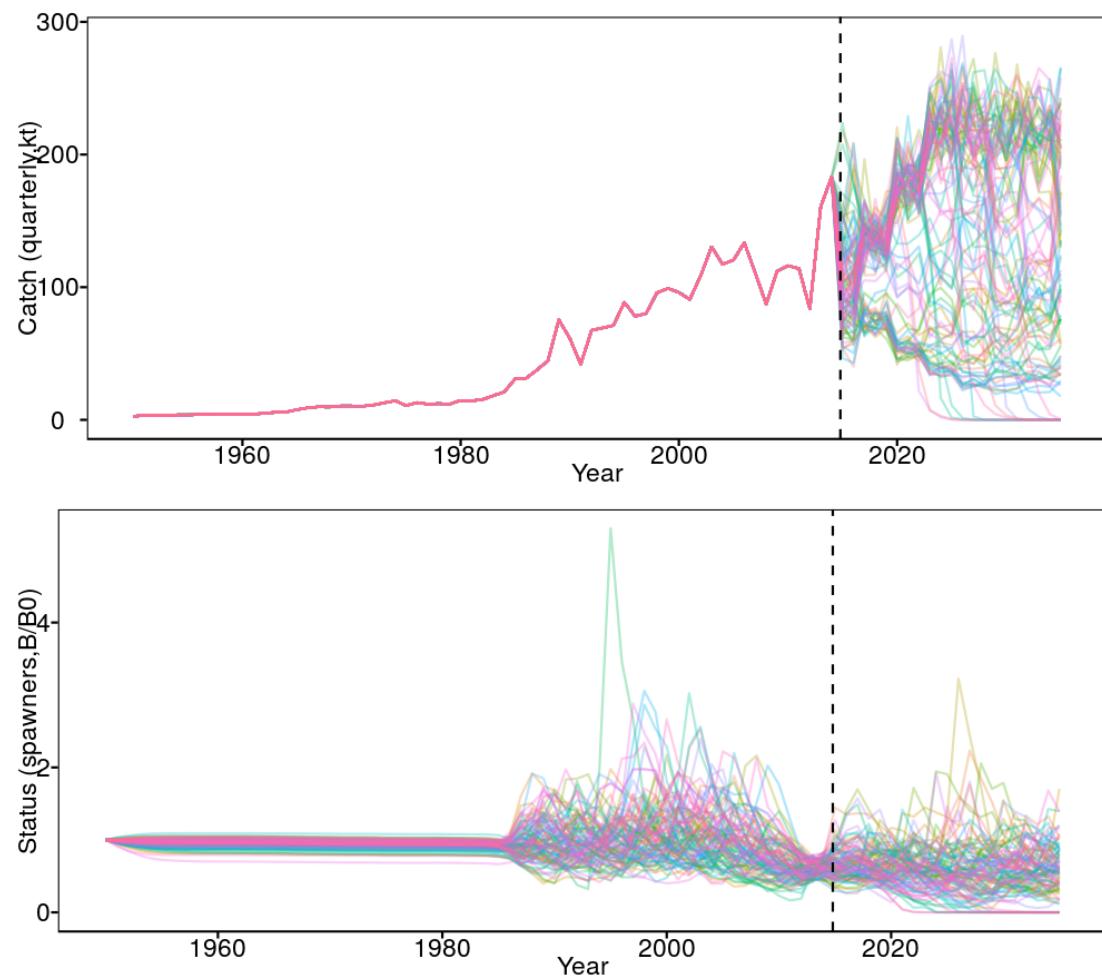


Figure 54: Catch and biomass trajectories from multiple evaluations of a single management procedure using multiple parameter replicates. Each of the coloured trajectories arises from alternative replicate.

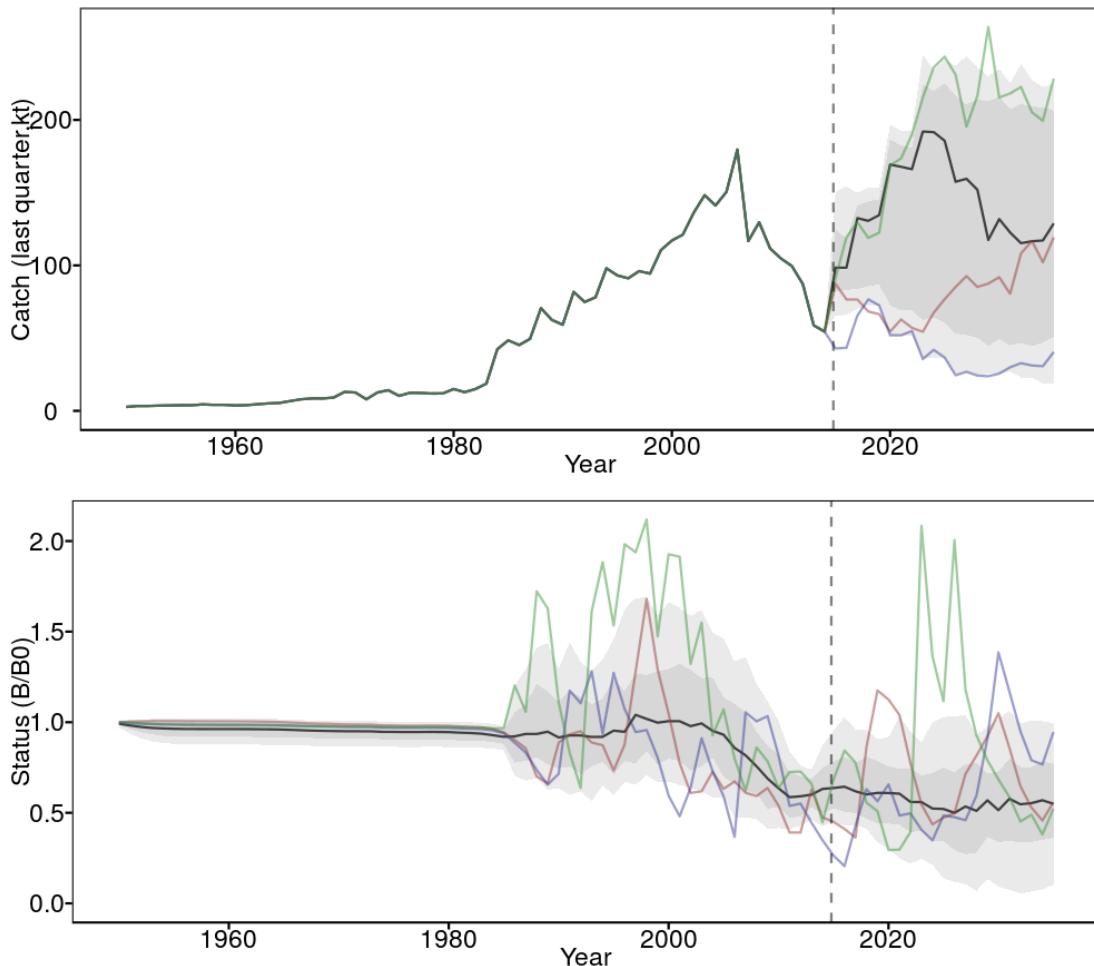


Figure 55: Catch and biomass trajectories from multiple evaluations of a single management procedure using multiple parameter replicates summarised into percentile ribbons

2.10. Evaluation results

2.10.1. Comparision of classes

TODO

2.10.2. IRate

TODO

2.10.3. FRange

TODO

2.10.4. BRule

TODO

2.10.5. Mald2016

This section summarizes the performance of the Mald2016 management procedure. 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 10](#) and catch and biomass trajectories are shown in [Figure 56](#).

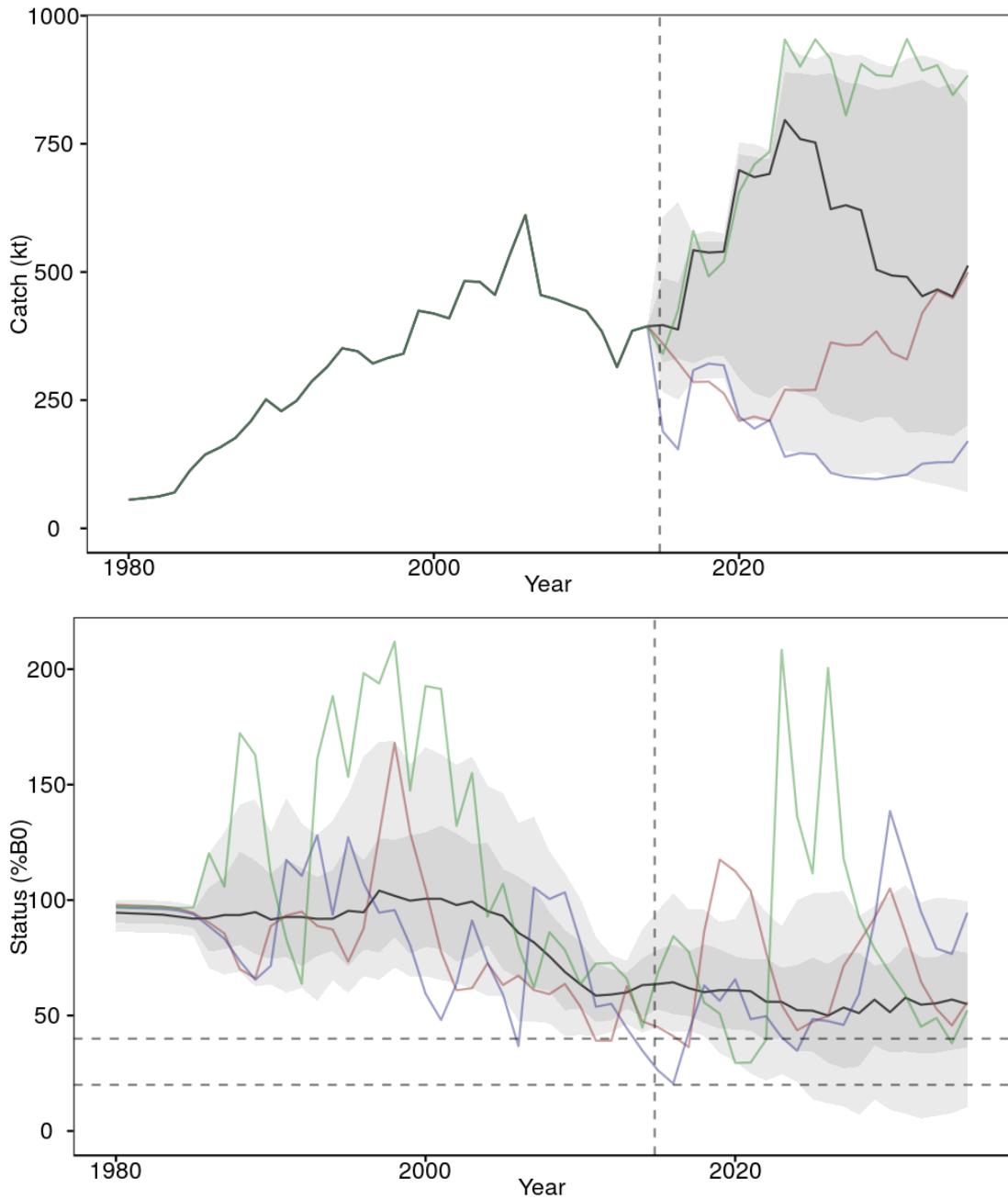


Figure 56: Projected catch and stock status trajectories for the Mald2016 management procedure with the "base case", suggested values for control parameters. The black line indicates the median and the grey ribbons the 10-90th and 25-75th percentiles. The coloured lines represent three individual simulations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

Table 10: 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	Mean	Percentiles				
		10th	25th	50th	75th	90th
Status (Mean %B0)	60.42	38.93	50.03	60.44	71.85	82.9
Fishing intensity (F/F40%BO)	0.73	0.12	0.23	0.54	0.97	1.6
Kobe green (Years %)	68.47	25.58	48.84	76.74	97.67	100.0
Kobe top-right (Years %)	17.90	0.00	0.00	0.00	27.91	72.1
Kobe red (Years %)	5.58	0.00	0.00	0.00	6.98	20.9
Kobe bottom-left (Years %)	8.05	0.00	0.00	0.00	9.30	30.2
Safety (Prop. years B>20%BO)	96.38	88.37	100.00	100.00	100.00	100.0
Yield (Mean catch; kt)	523.46	245.17	354.70	618.48	666.58	691.8
Yield (Years catch>=425kt %)	63.70	0.00	23.26	81.40	97.67	100.0
Stability (MAPC %)	17.13	11.60	13.64	16.24	19.51	23.3
Probability of shutdown (Years catch<1kt %)	0.23	0.00	0.00	0.00	0.00	0.0
Stability (Years TAC decrease %)	7.80	0.00	0.00	0.00	12.50	25.0
Stability (Years TAC increase %)	17.20	0.00	12.50	25.00	25.00	25.0
Western purse seine CPUE (relative to 2000-2015)	0.97	0.57	0.75	0.96	1.17	1.4
Maldives pole and line CPUE (relative to 2000-2015)	1.00	0.60	0.78	0.99	1.20	1.4
Eastern gill net CPUE (relative to 2000-2015)	0.98	0.56	0.75	0.96	1.18	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.

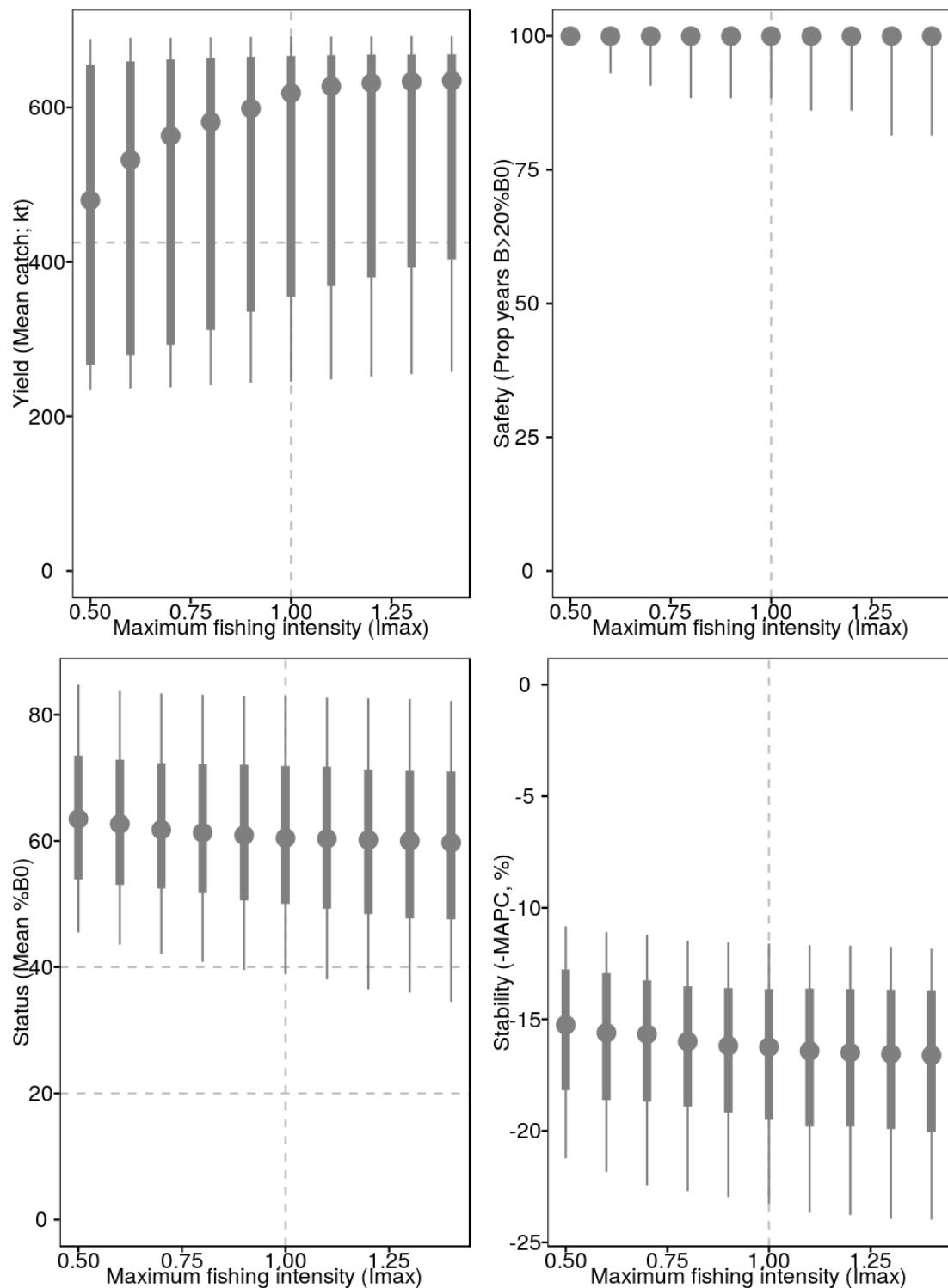


Figure 57: Key performance statistics versus the maximum fishing intensity (l_{max}) control parameter

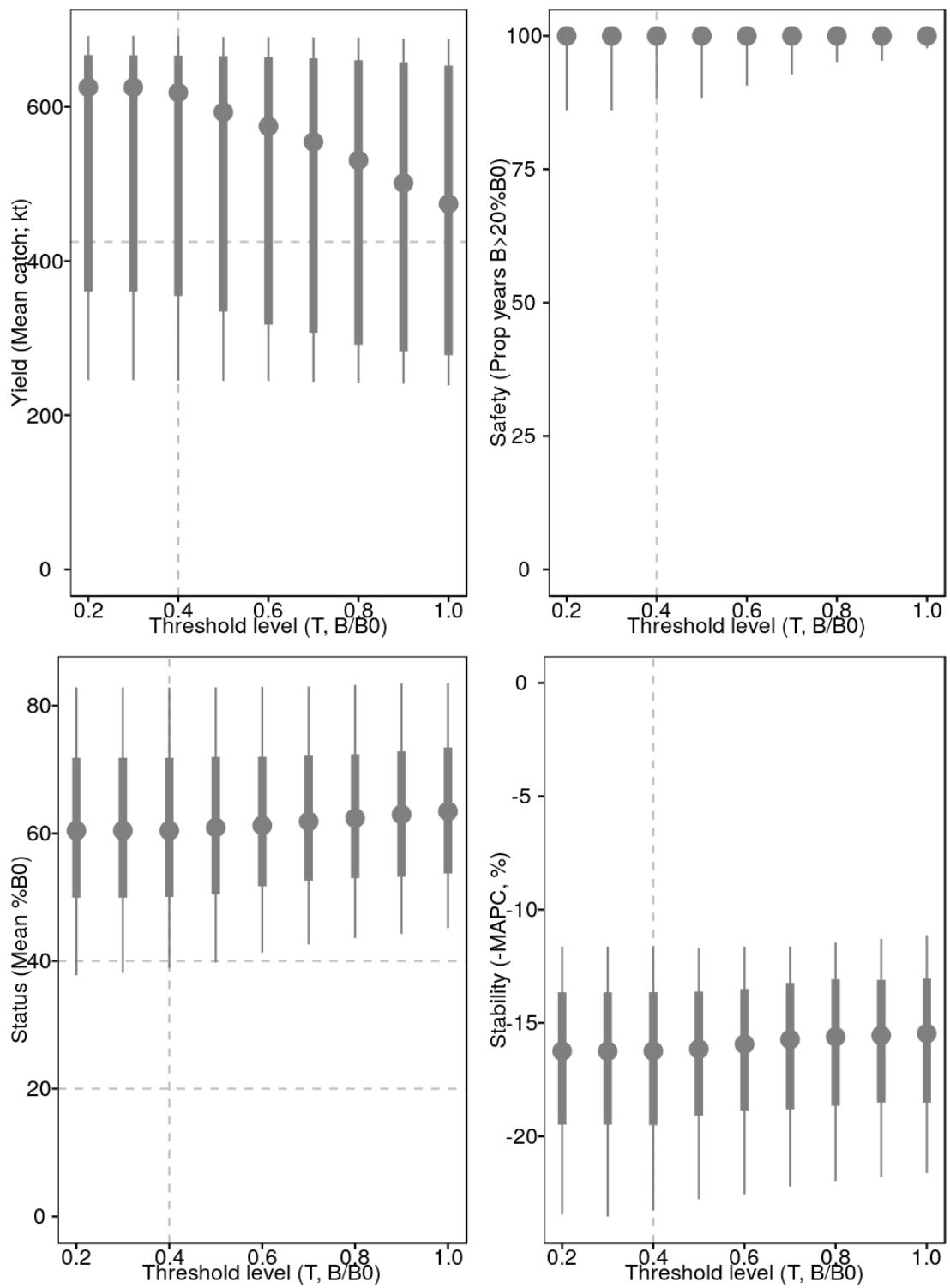


Figure 58: Key performance statistics versus the threshold level (T) control parameter

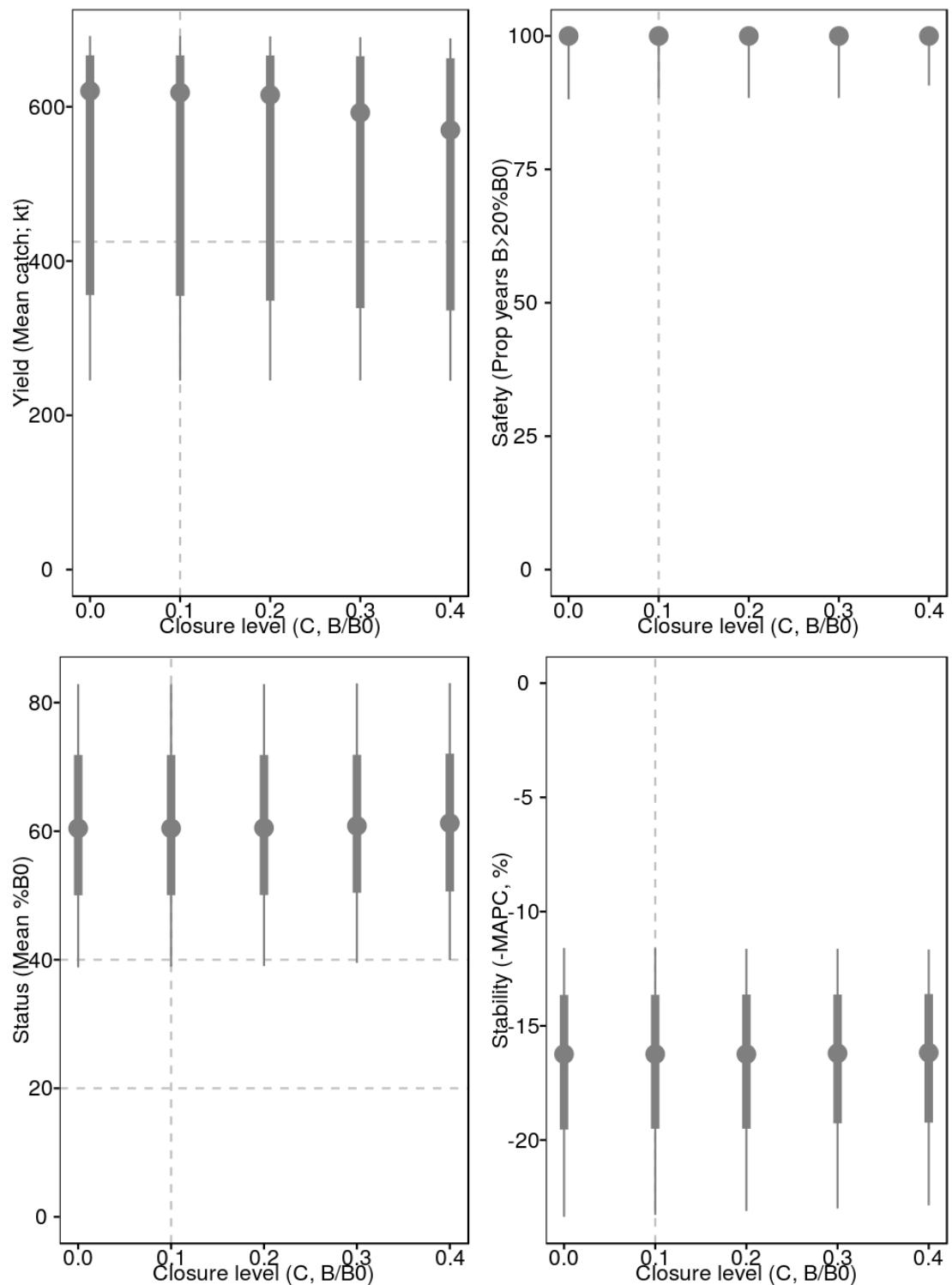


Figure 59: Key performance statistics versus the safety (closure) level (X) control parameter

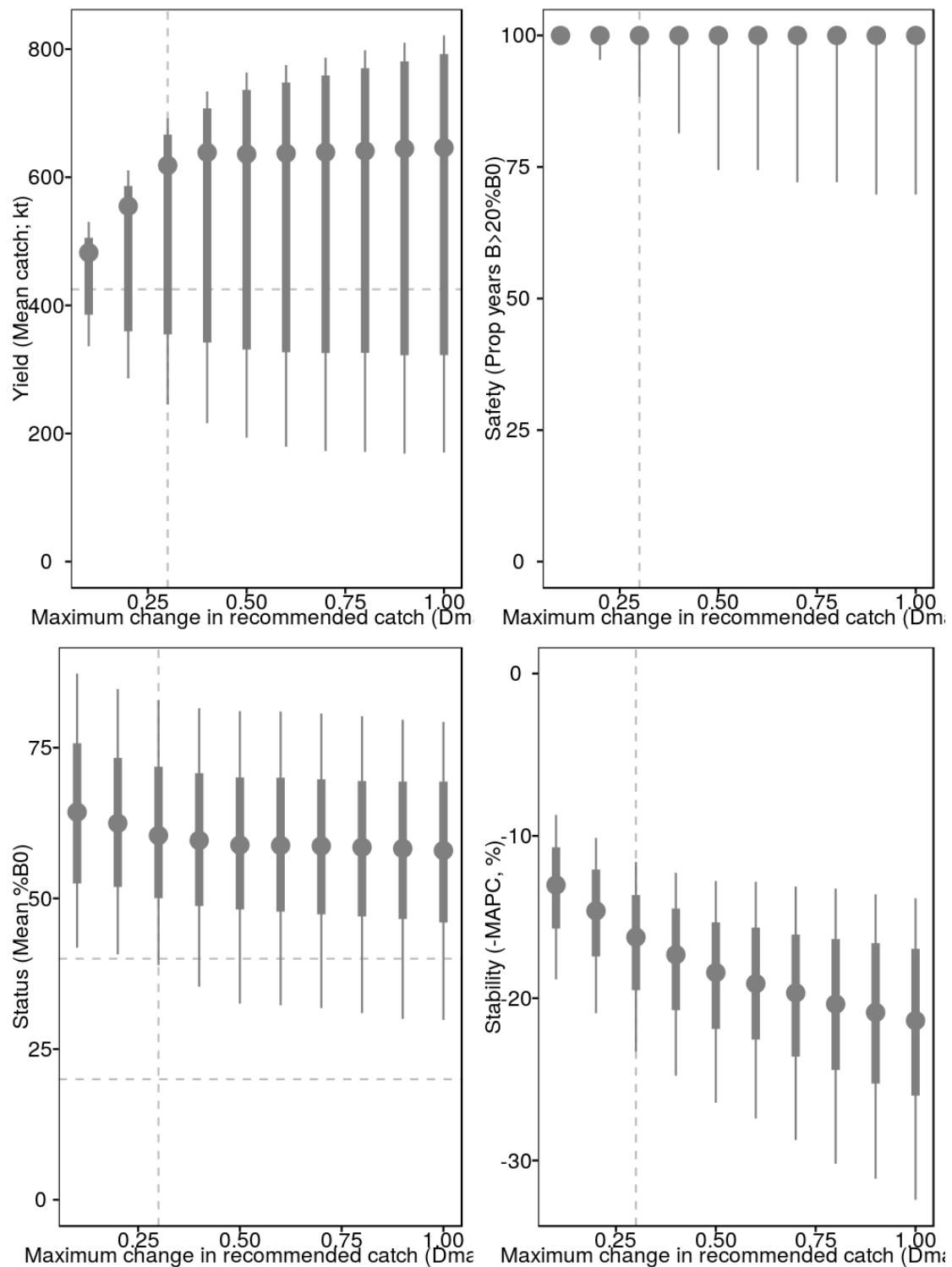


Figure 60: Key performance statistics versus the maximum change (D_{max}) control parameter.

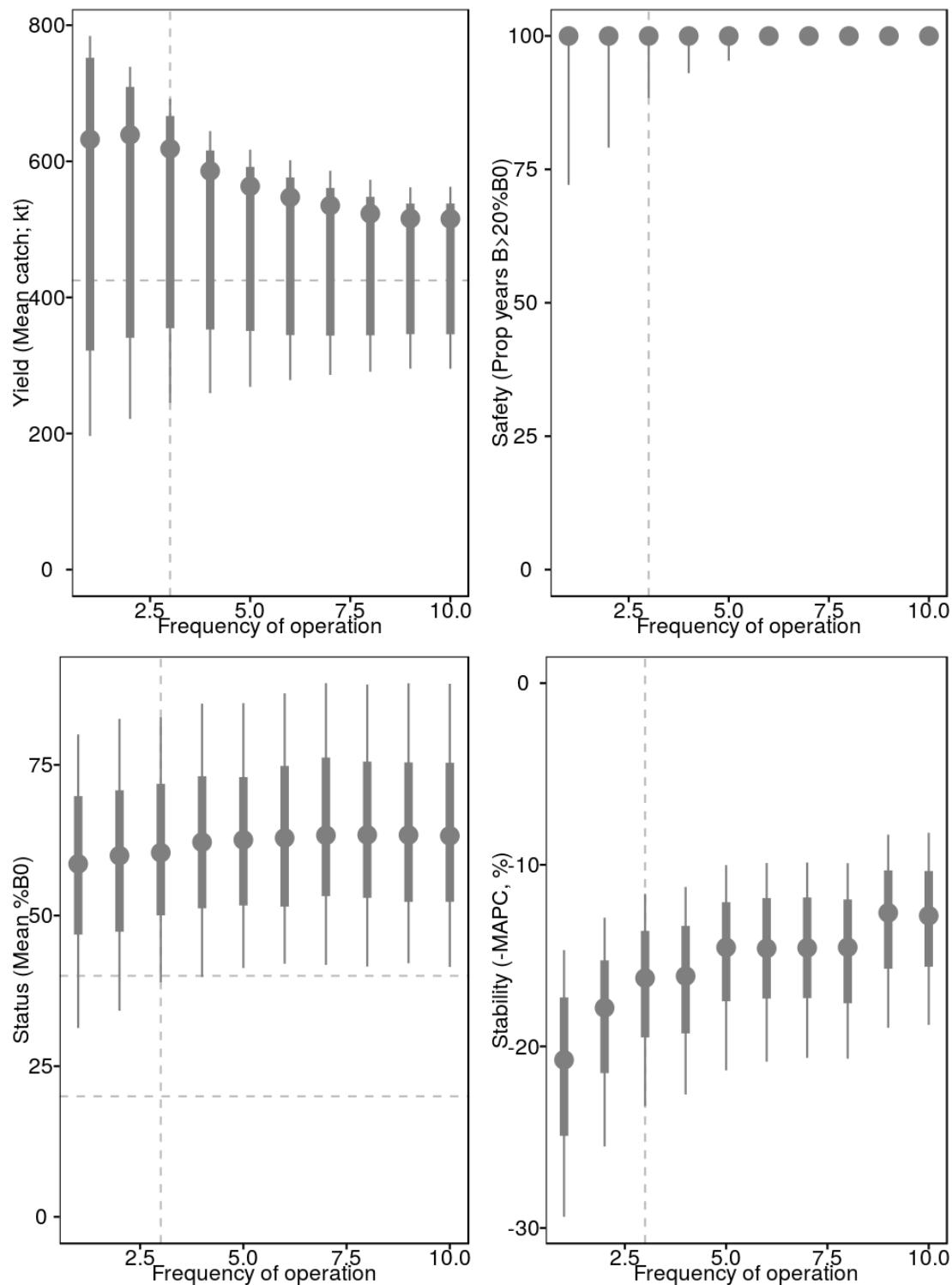


Figure 61: Key performance statistics versus the frequency of operation (assessments) control parameter.

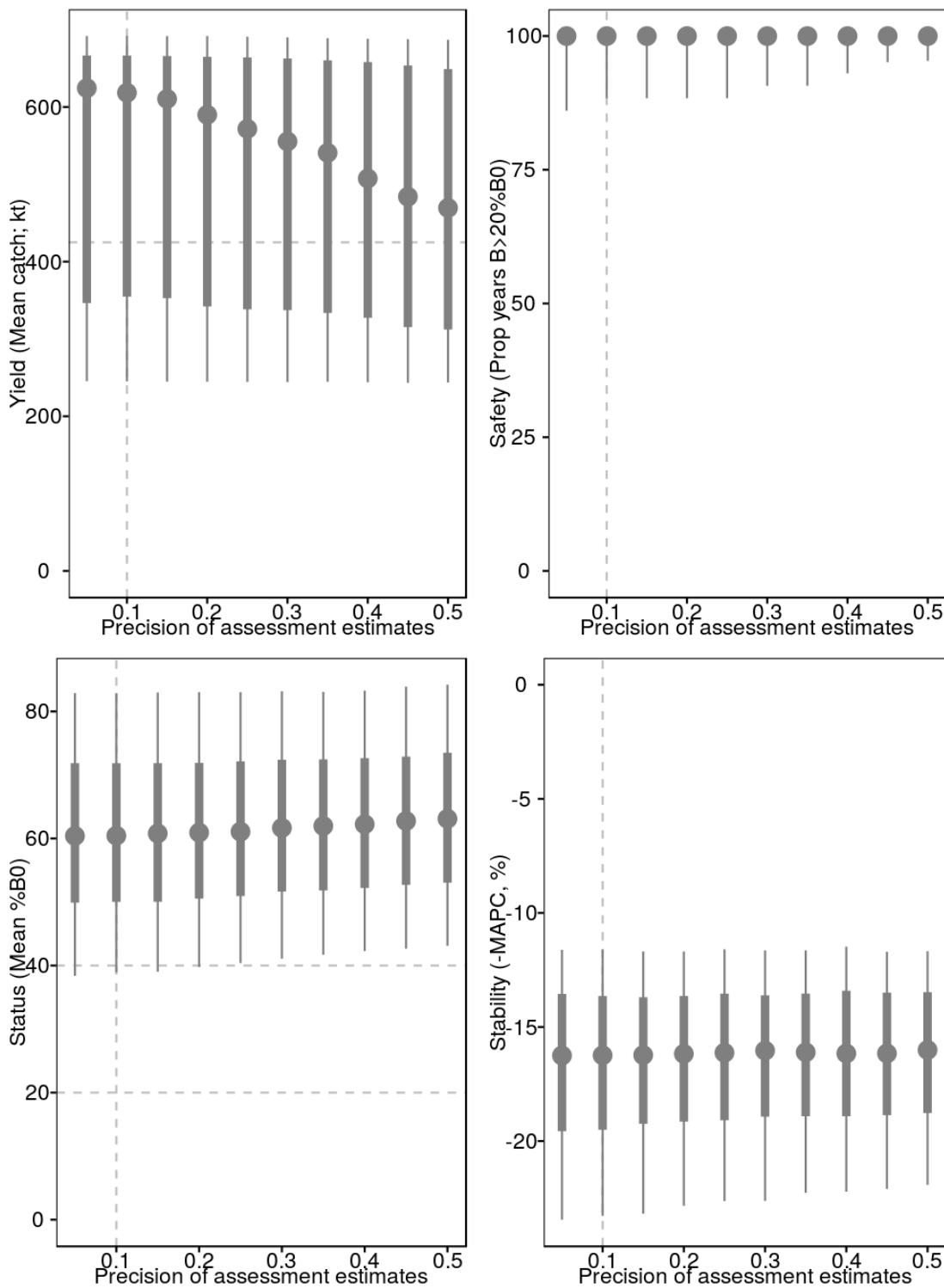


Figure 62: Key performance statistics versus the precision of assessments estimate used by the management procedure. In other results presented, it is assumed that the precision of assessment estimates is 0.1.

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 present in the suggested base set.

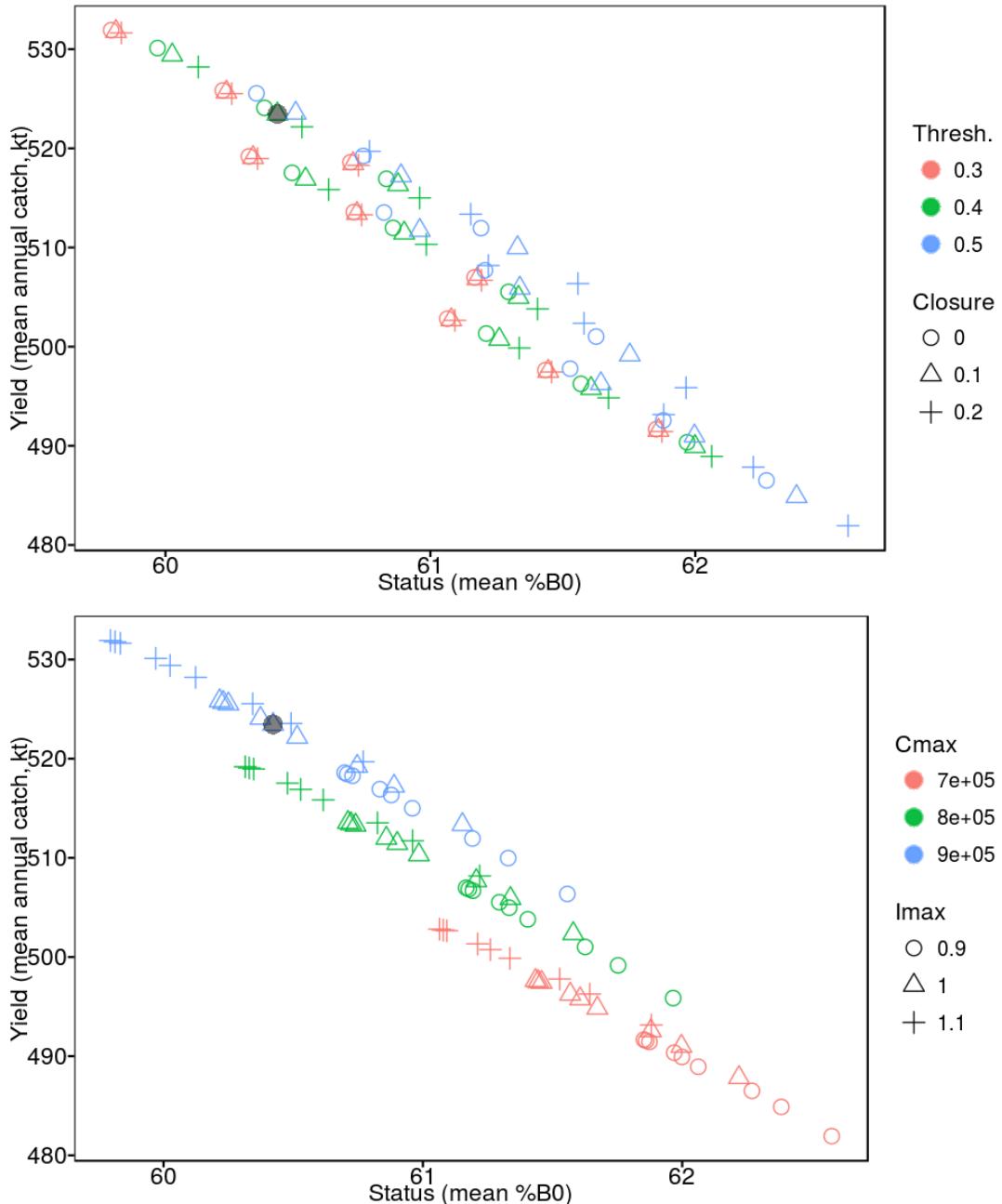


Figure 63: Tradeoff plot between stock status (mean %BO) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates the suggested base set of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

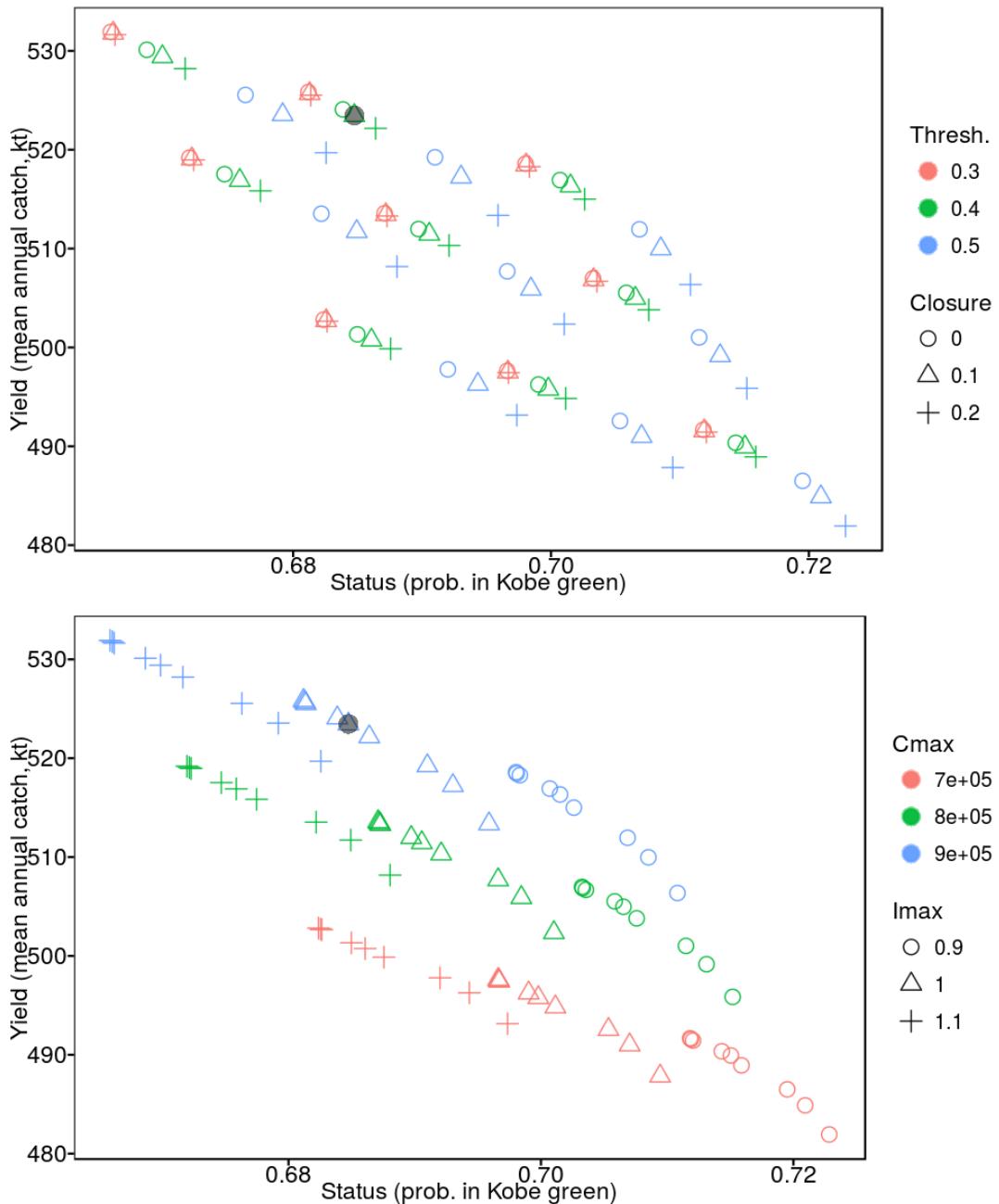


Figure 64: Tradeoff plot between stock status (probability of being in Kobe green quadrant) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates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

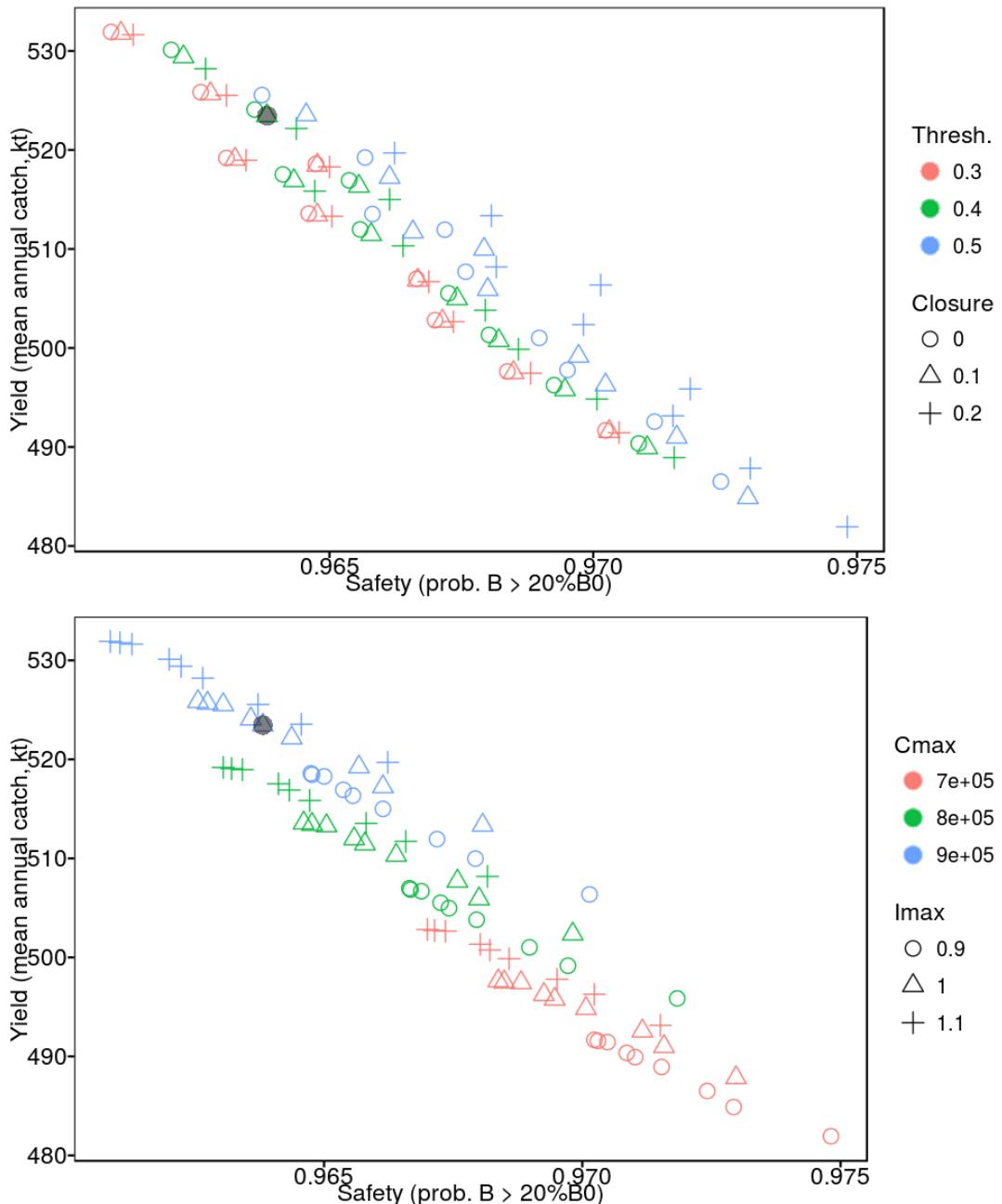


Figure 65: Tradeoff plot between safety (probability that stock status is greater than 20% B_0) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates the suggested base set of control parameter values.

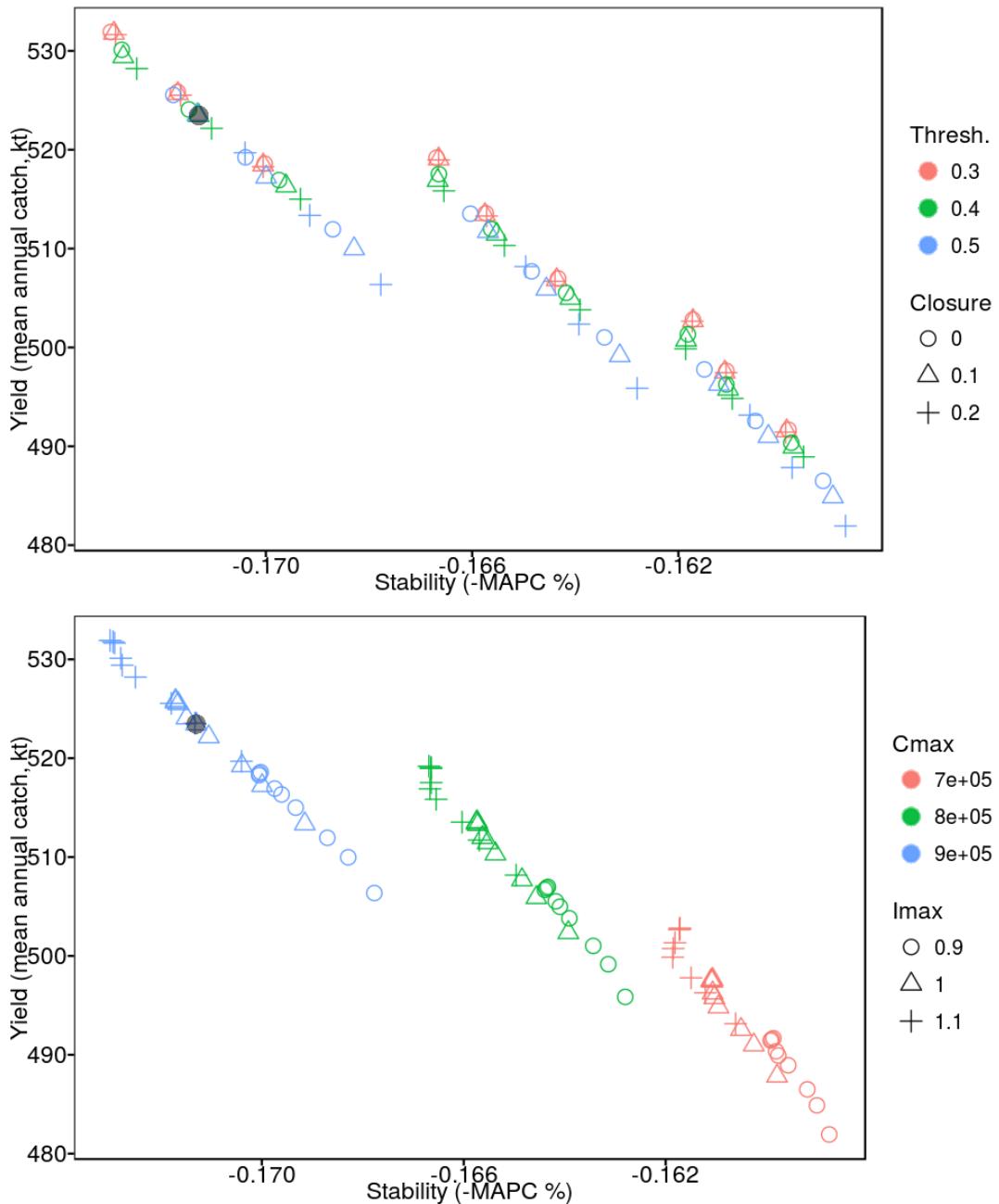


Figure 66: Tradeoff plot between stability (mean absolute proportional change in catch) and yield across the grid of alternative control parameter values. Each panel shows exactly the same points but with different mappings between color and shape and control parameters. The black filled circle indicates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

3. 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).

4. References

Adam, M.S., Sharma, R., Bentley, N. (2013) Progress and Arrangements for Management Strategy Evaluation Work of Indian Ocean Skipjack Tuna.IOTC-2013-WPTT15-42.

Bentley, N., Langley, A.D. (2012) Feasible stock trajectories: a flexible and efficient sequential estimator for

use in fisheries management procedures. Canadian Journal of Fisheries and Aquatic Sciences 69 (1), 161-177.

Everson, J.P., Million, J., Sardenne, F., Le Croizier, G. (2012) Updated growth estimates for skipjack, yellowfin and bigeye tuna in the Indian Ocean using the most recent tag-recapture and otolith data. IIOOTC-2012-WPT14-23 Rev-1

Fonteneau, A. (2014) On the movements and stock structure of skipjack (*Katsuwonus pelamis*) in the Indian ocean. IOTC-2014-WPTT16-36

Grande, M (2013). The reproductive biology, condition and feeding ecology of the skipjack, *Katsuwonus pelamis*, in the Western Indian Ocean PhD Thesis. Department of Zoology and Animal Cell Biology, Universidad del País Vasco.

IOTC (2014) Report of the 3rd IOTC WPM small working group on Management Strategy Evaluation.IOTC-2014-WPTmT05-INF03. <http://www.iotc.org/documents/report-3rd-iotc-wpm-small-working-group-management-strategy-evaluation>

ISSF (2014) Report Of The 2014 Meeting Of The Indian Ocean Skipjack MSE Advisory Committee. <http://iss-foundation.org/resources/downloads/?did=548>

Kolody, D., Polacheck, T., Basson, M., & Davies, C. (2008). Salvaged pearls: lessons learned from a floundering attempt to develop a management procedure for Southern Bluefin Tuna. *Fisheries Research*, 94(3), 339-350.

Lorenzen, K. (1996). The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. *Journal of fish biology*, 49(4), 627-642.

Myers, R.A. (2002) Recruitment: understanding density-dependence in fish populations.

SCRS, 2011. Report of the 2011 joint meeting of the ICCAT Working Group on Stock Assessment Methods and Bluefin tuna Species Group to analyze assessment methods developed under the GBYP and electronic tagging. http://www.iccat.int/Documents/Meetings/Docs/2011_WG%20METHODS-ENG.pdf

Scott, G. P., Gorka Merino, Haritz Arrizabalaga, Hilario Murua, Josu Santiago and Victor R. Restrepo, 2013. A Framework for Promoting Dialogue on Parameterizing a Harvest Control Rule with Limit and Target Reference Points for North Atlantic Albacore. SCRS/2013/120

Sharma, R., Herrera, M., Million, J. (2012) Indian Ocean skipjack tuna stock assessment 1950-2011 (Stock Synthesis). IOTC-2012-WPTT14-29 Rev-1