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An operating model for the Indian Ocean skipjack tuna fishery

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Abstract

A simulation model of the Indian Ocean skipjack tuna fishery was developed for the evaluation of alternative fisheries management procedures. The model partitions the population by region, age, and size and the fishery by region and gear (purse seine, pole-and-line, gill net, others). Prior probability distributions and sensitivity ranges are defined for model parameters for use in conditioning and robustness testing. Performance statistics are defined based and linked to broader management objectives. Three contrasting classes of management procedure (MP) are provided as examples: BRule (a generic harvest control rule based on an estimate of stock status), FRange (a MP which adjusts effort when fishing mortality is outside a target range) and IRate (a MP which recommends a total allowable catch using a CPUE-based biomass index).

Outline

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. Implementation and usage

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.

3. 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-weigth 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. Often these potential changes would make the model more complex but are likely to better reflect reality.

3.1. Dimensions

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

3.1.1. 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 ($q \in 0, 1, 2, 3$).

3.1.2. 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 is 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 pol-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. However, 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.

3.1.3. 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, $0-2, 2-4, ..., 78-80cm$.

3.1.4. 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

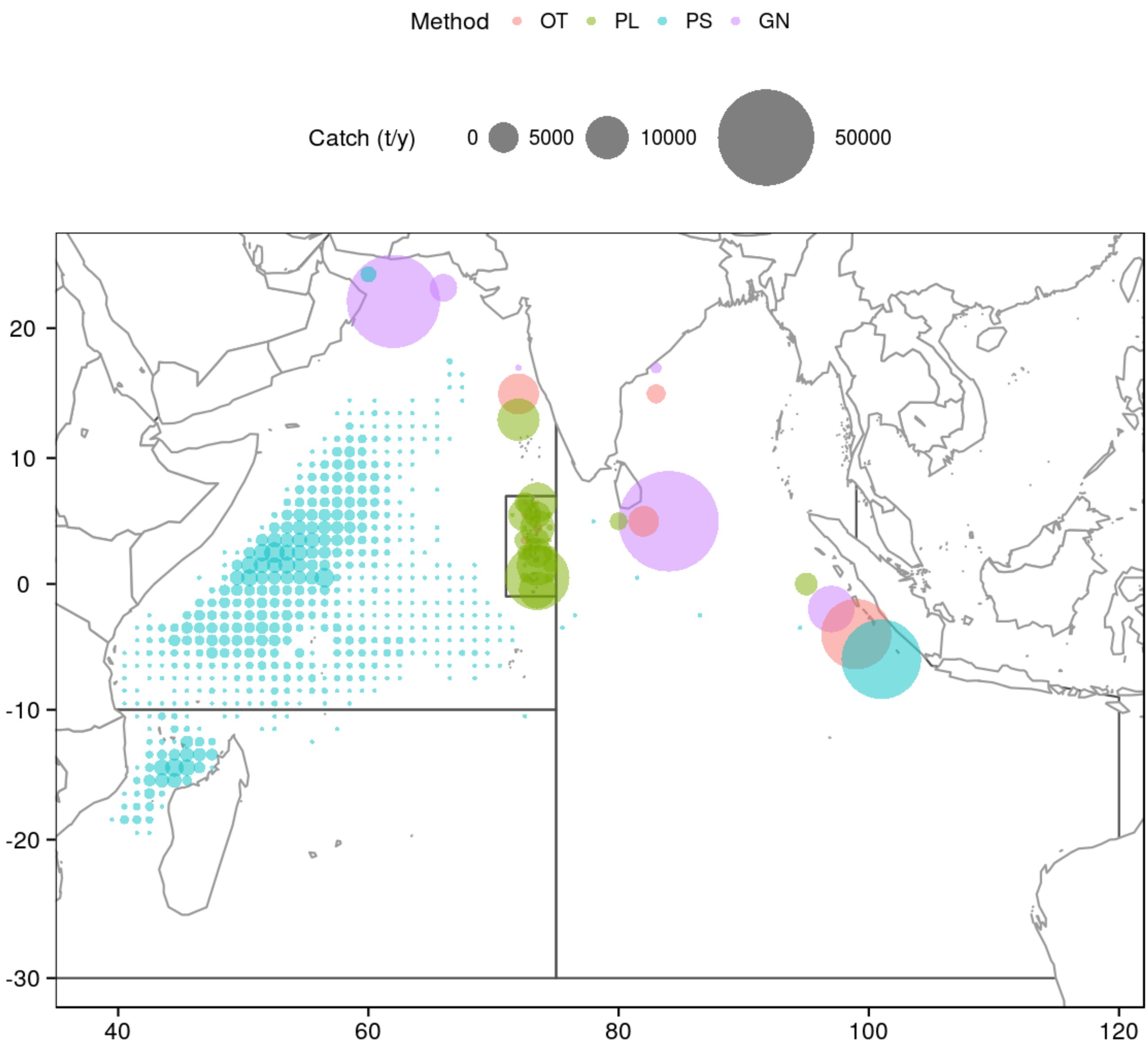

Figure 1: Map of the four regions defined for the model and the spatial distribution of average annual catch by method, 2005-2014. The position of catches from the western purse-seine and the Maldive pole-and-line fisheries is based on reported latitude and longitudes. The position of other catches is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

3.2. Fish population dynamics

3.2.1. Numbers

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

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

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

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

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

For age 0, recruitment occurs,

$$N_{r,0,s} = R_{r,s}$$

where $R_{r,s}$ is the number of fish recruiting to age 0 in region r at size s.

Numbers are updated by applying growth, survival, exploitation and movement. The numbers in each region, in each age class and size class are determined by summing over all regions and size classes,

$$N_{r,a,s} = \sum_{\dot{r} \in \{we,ma,ea\}, \dot{s}=0...\vec{s}} \left(\dot{N}_{\dot{r},a,\dot{s}} G_{\dot{s},s} D_s \left(1 - E_{\dot{r},\dot{s}}\right) M_{\dot{r},r} \right)$$

where G is the growth transition matrix, D is the natural survival rate, E is the exploitation rate, and M is the movement transition matrix (all described below).

3.2.2. Length, weight and maturity

The length of fish of size s is the midpoint of the 2mm bin size,

$$L_s = 2s + 1$$

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.

3.2.3. 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,

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

3.2.4. 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,

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

3.2.5. Growth

Growth is described using a size transition matrix which is calculated based on the von Bertallanfy growth function. The mean increment in one quarter is,

$$I_s = (\lambda - L_s)\left(1 - e^{-0.25\kappa}\right)$$

Variation in growth is modelled as a normal distribution with a constant standard deviation, ζ, and a coefficient of variation, φ, on the increment. The standard deviation of the growth increment for a fish of size s is thus,

$$J_s = \sqrt{\zeta^2 + (\varphi I_s)^2}$$

The proportion of fish growing from size $\dot{s}$ to size s in one quarter is thus,

$$G_{\dot{s},s} = \int_{l=2s}^{l=2(s+1)} \frac{1}{\sqrt{2\pi}J_{\dot{s}}} \frac{e^{-\left(L_{\dot{s}}+I_{\dot{s}}-l\right)^2}}{2\left(J_{\dot{s}}\right)^2}$$

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, κ_t.

An alternative to the von Bertallanfy function would be to use the two-stanza growth model and parameter estimates of Everson et al (2012, 2014).

3.2.6. 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:

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

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.

3.3. Fishing 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,

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

4. Parameters

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.

4.1. 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.

4.2. 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.

4.3. 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).

4.4. 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).

4.5. 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 $M_{\dot{r},r}$

4.6. 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]
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

5. Performance measures, performance statistics and management objectives

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 3). 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 3: Management objectives, performance statistics and performance measures

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 $\lvert C_t/C_{t-1} - 1 \rvert$
Variance in catch	C	Variance over years
Probability of shutdown	C	Proportion of years that $C = = 0$

6. Example 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.

6.1. 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 4: 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

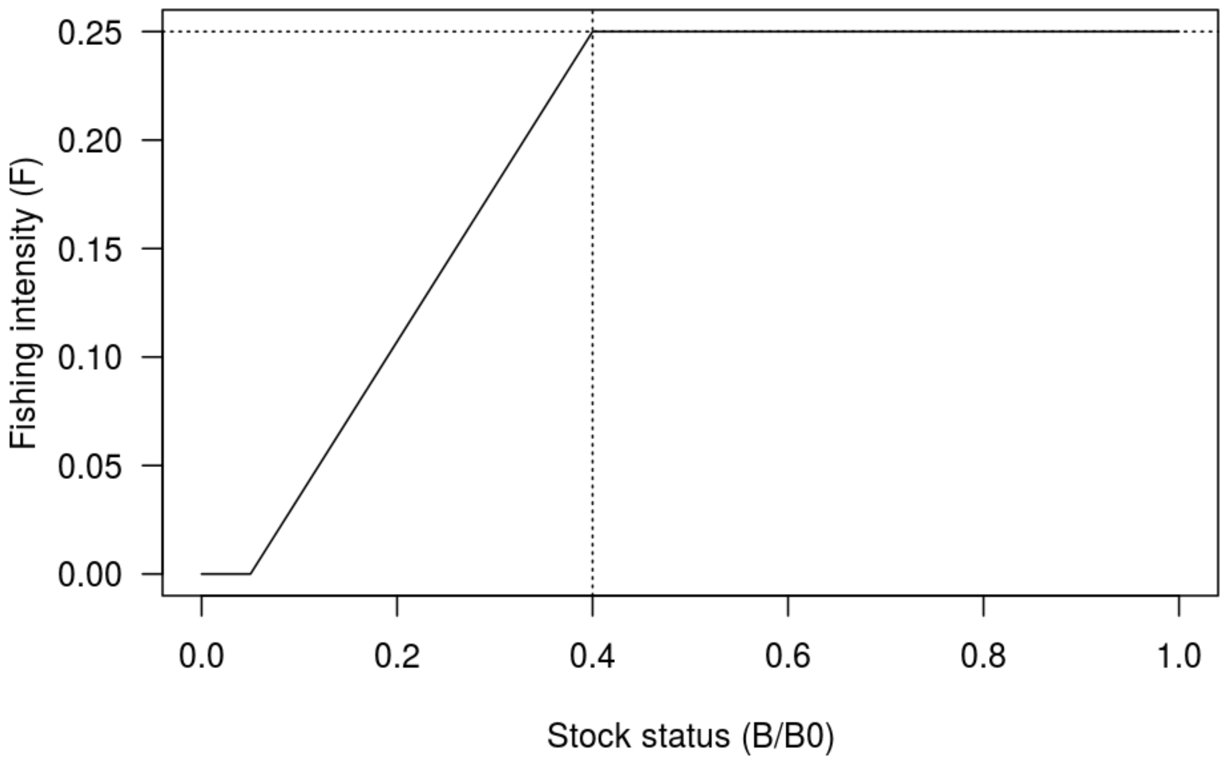

Figure 2: An example instance of the BRule management procedure with $s_l = 0.05$, $s_t = 0.4$, $f = 0.25$ showing the relation between $\widehat{S}$ and $\overline{F}$.

6.2. 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 5: 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

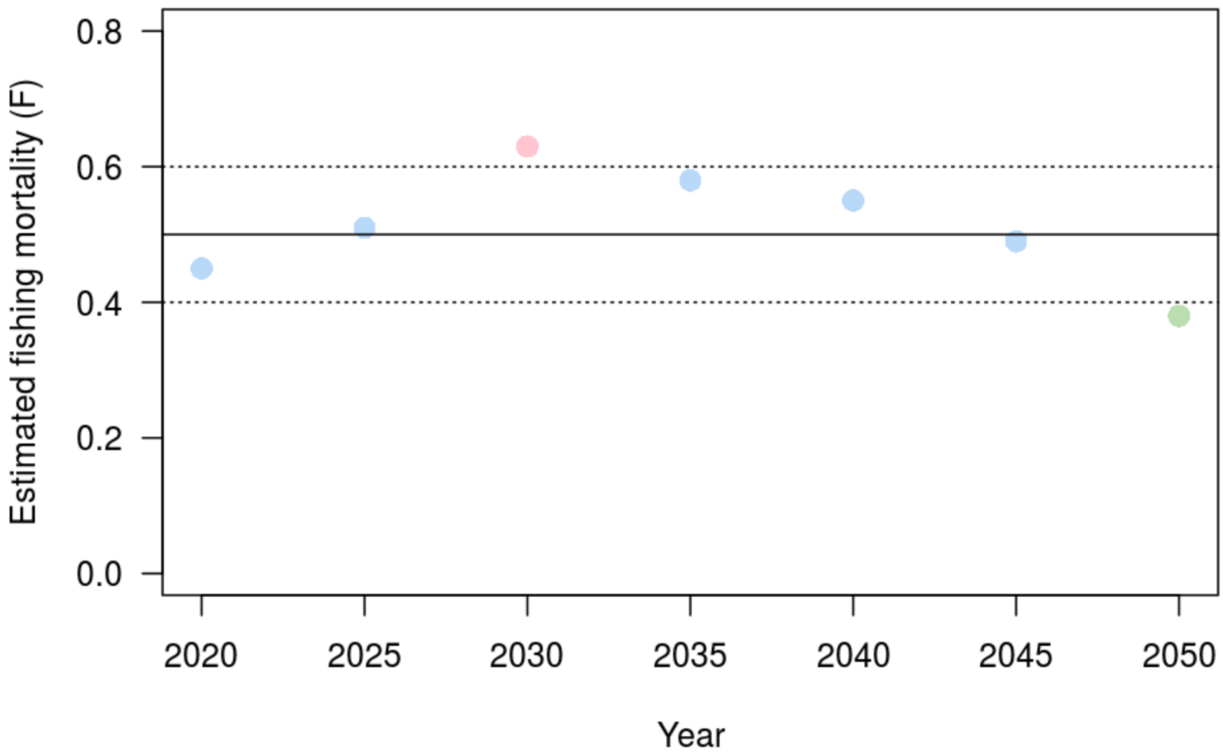

Figure 3: An example instance of the BRule management procedure with $i = 5, f = 0.5, b = 0.1$ illustrating how total allowable catches are increased (green circles) or decreased (red circles) when the estimated fishing mortality is below or above the target range.

6.3. 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.

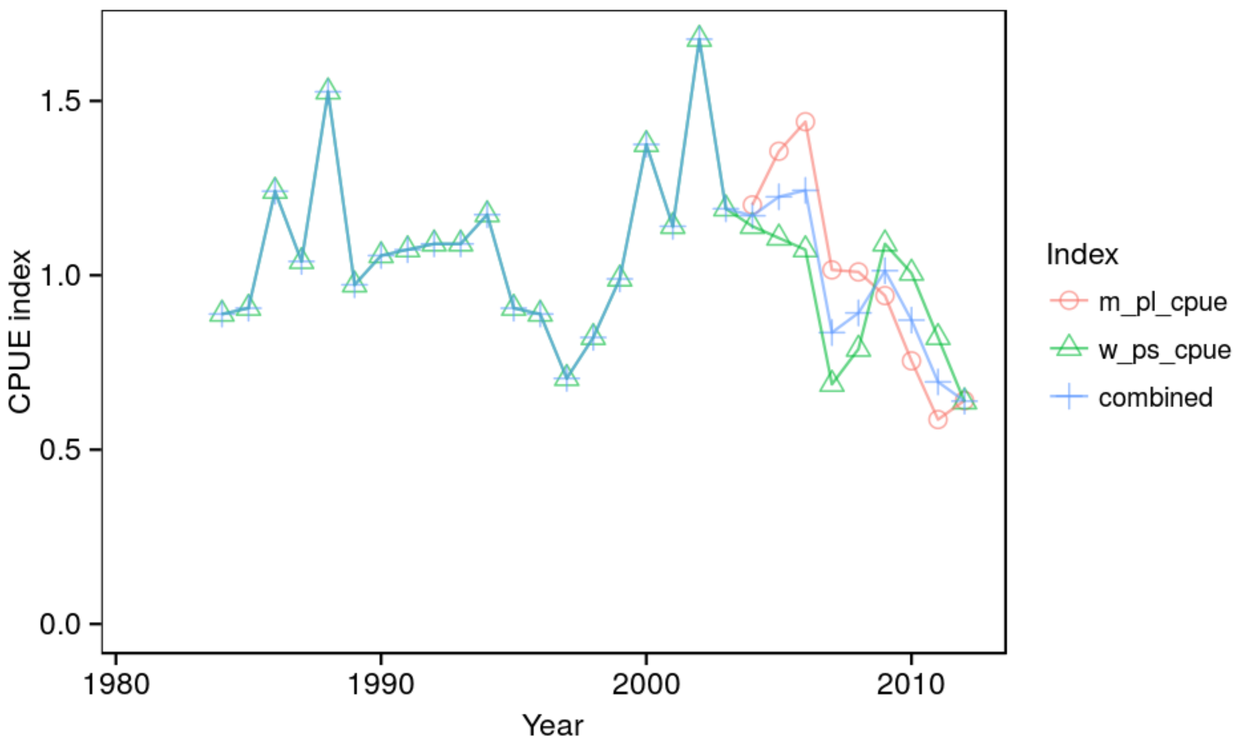

Figure 4: Western purse seine, Maldive pole and line and combined CPUE series.

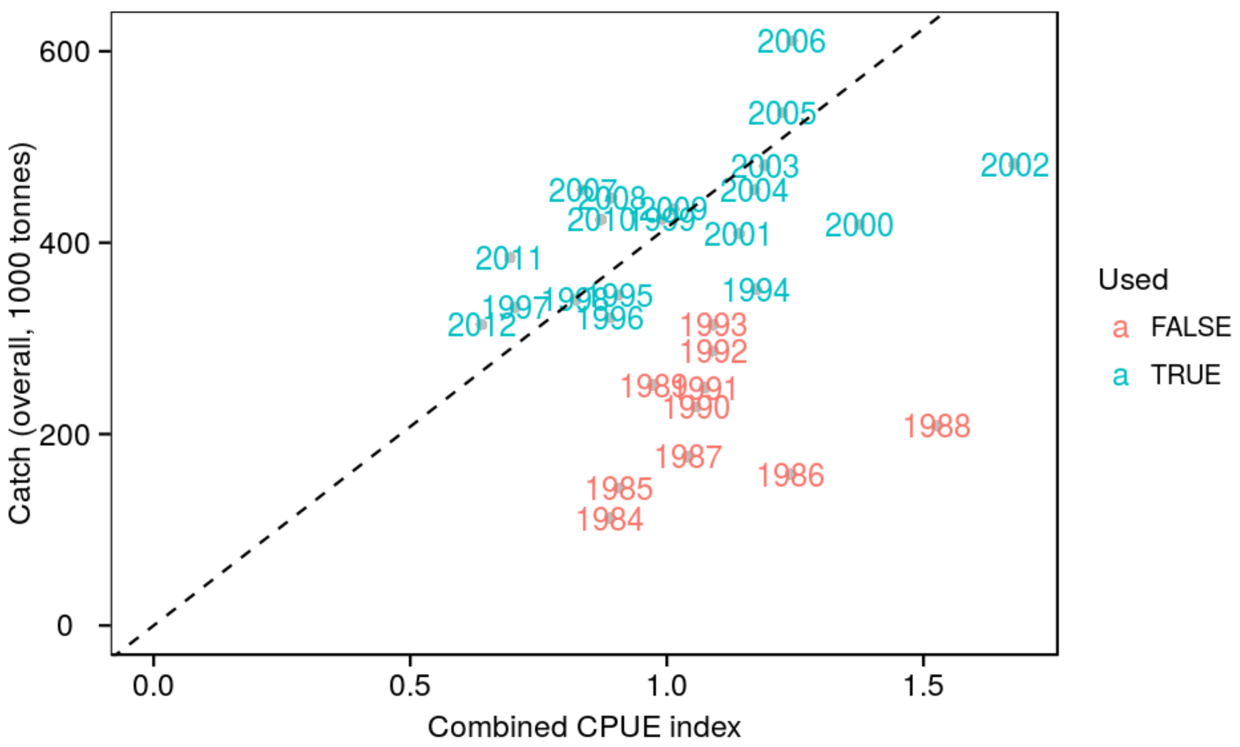

Figure 5: Historical relation between combined CPUE and overall catch. The dashed line has a slope of the catch scalar = ~round(scalar,2)~ (geometric mean of the ratio of catches over CPUE).

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

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

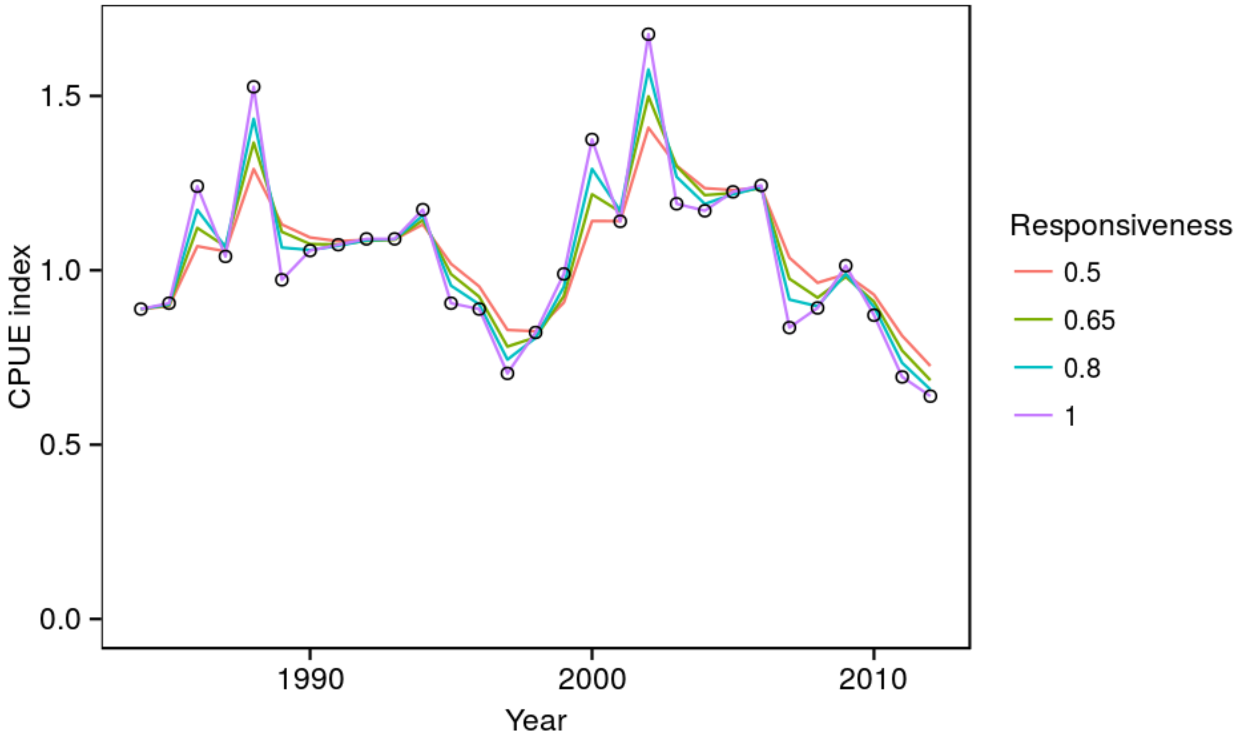

Figure 6: Illustration of the alternative smoothing of CPUE index using the responsiveness parameter.

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,

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

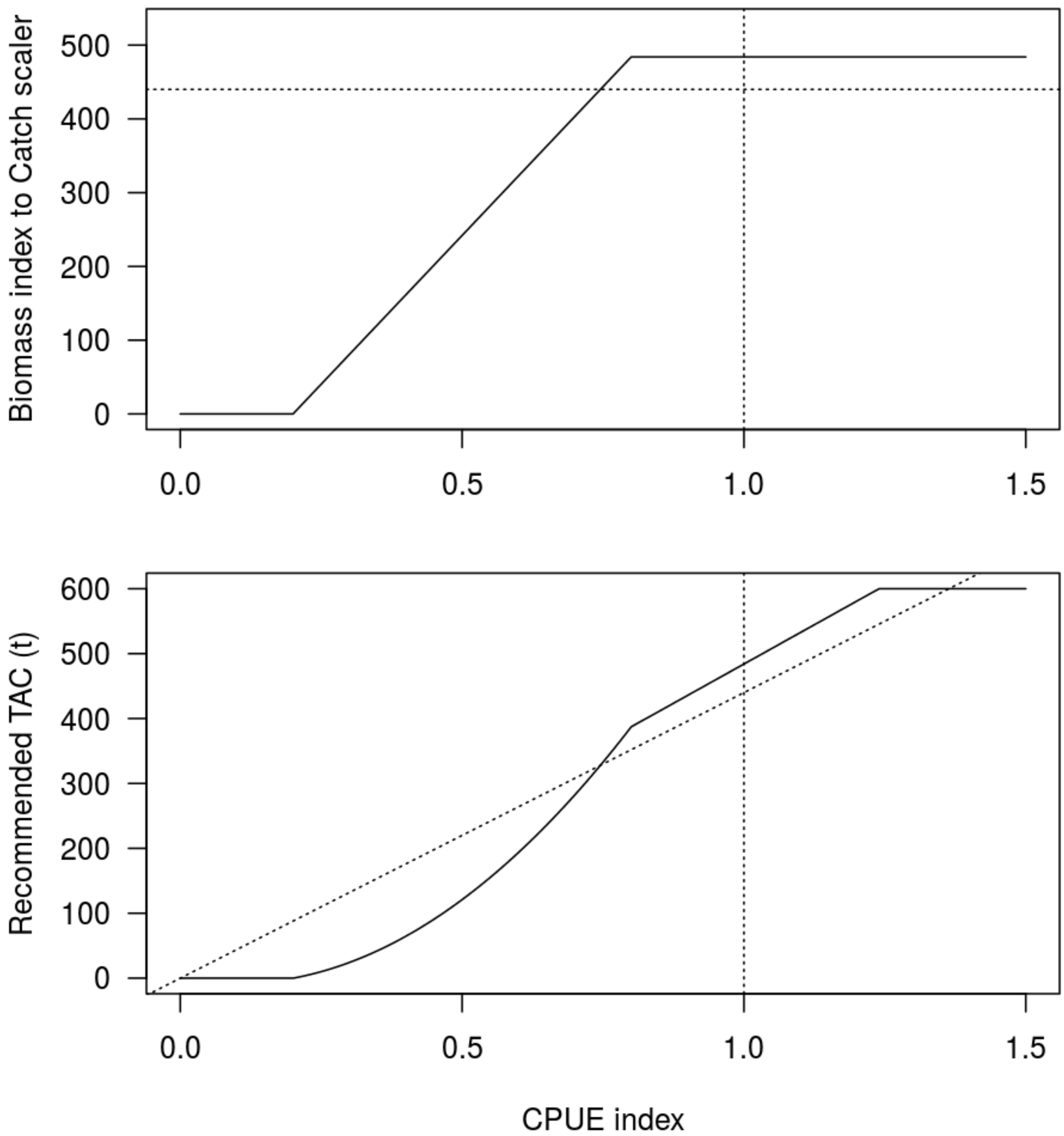

Figure 7: An example instance of the IRate management procedure with $i_l = 0.2$, $i_t = 0.8$, $m = 1.1$, $u = 600$ showing the relation between the CPUE index ($\overline{I}$) and the catch scalar ($\overline{S}$) and the recommended TAC.

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 6: 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

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