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Evaluation of three harvest control rules for bigeye tuna (*Thunnus obesus*) fisheries in the Indian Ocean

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Abstract

Bigeye tuna (*Thunnus obesus*) in the Indian Ocean supports an important international fishery that is estimated to be fully exploited, and the relevant management body, the Indian Ocean Tuna Commission, does not have any explicit management decision framework in place to prevent over-fishing. This study describes a simple Management Strategy Evaluation (MSE) for this fishery, comparing three harvest control rules: i) constant fishing mortality, ii) constant catch, and iii) constant escapement. The population dynamics in the operating model are conditioned to the most recent stock assessment, with three operating models selected to encompass a range of uncertainty in current stock status and biological parameters. Performance was compared on the basis of three management objectives (over 3, 10 and 25 year time horizons): i) the probability of maintaining spawning stock biomass above the level that can sustain Maximum Sustainable Yield (MSY) on average, and ii) the probability of achieving average catches greater than 0.8 MSY, iii) interannual variability in catches . The feedback-based policies were able to differentially exploit the productivity variability, reducing spawning biomass risk. The constant fishing mortality strategy provided the best performance overall. The results are presented as an example to illustrate the MSE process, and the type of management advice that would be provided.

Keywords: *Thunnus obesus*; bigeye tuna; harvest control rules; Management Strategy

Evaluation; Management Procedure; Fishery management

Introduction

Bigeye tuna, *Thunnus obesus,* is a sashimi-quality tuna of considerable economic importance in the Indian Ocean, and its importance is likely to increase with the decline of the bluefin tuna fisheries (Safina and Klinger, 2008; MacKenzie et al., 2009). It is also ecologically important as one of the top predators in marine ecosystems (Lehodey, 2004). It is harvested by fleets from several countries using various gears, mainly longline and purse seine (> 97% total landing in weight, IOTC database). Longline fisheries target bigger fish in deeper water (usually more than 100m), and yield the highest catch in mass, while purse seine fisheries often land small bigeye as by-catch around fish aggregating devices (FADs) when targeting skipjack and yellowfin tunas. (IOTC Secretariat, 2005).

The Indian Ocean Tuna Commission (IOTC) is responsible for the management of bigeye tuna. While operational reference points have not been agreed by the Commission, there is a general expectation that the spawning stock biomass (SSB) should not fall much below the level that can support the Maximum Sustainable Yield (MSY)(i.e. SSB_{msy}) as prescribed in the UN Fish Stocks Agreement (IOTC, 2010). However, there is no harvest strategy which prescribes what action should be taken if SSB falls below SSB_{msy}. The latest IOTC assessment suggested that the bigeye tuna stock is not likely to be currently in an overfished state, and overfishing is probably not occurring (SSB>SSBmsy, and F<Fmsy), but the stock is near full exploitation, and the uncertainty in the assessment suggests that these reference points could be exceeded. The total annual catch declined from the peak level at around 150,000 t in 1999 to 100,000 t in 2009[1], and Japanese standardized CPUE of longline fishery declined more than a half from 1977 to 2009 (Okamoto and Shono, 2010). Although the most recent catch is likely below MSY (114,000 t, Kolody et al., 2010), there is considerable uncertainty in the assessment, and managers should be preparing appropriate management actions before the fishery is over-exploited. This calls for an evaluation of how the stock may respond to different management strategies in the face of uncertainty in current stock status and key life history characteristics (e.g. stock recruitment dynamics and natural mortality).

Management strategy evaluation (MSE), also referred to as harvest strategy evaluation (Punt et al., 2005), is a general framework to develop and test management procedures (MPs). A fully specified MP includesa harvest control rule (HCRs), and the data collection and analysis methods that feed into the HCR. The HCR is designed to be robust to uncertainty and have a high probability of achieving a reasonable balance among competing biological and socioeconomic objectives (Holland, 2010). Monte Carlo simulations are usually used in an operating model to simulate population dynamics with a broad range of uncertainty (including observation, process, implementation and model specification errors (Butterworth, 2007). MSE has been developed for many fisheries including several species of tuna (Polacheck et al., 1999; Kell et al., 2005a,b; Fromentin and Kell, 2008), however, few international fisheries have adopted a formal MP.

In this study, we developed both short-term, medium-term and long-term performances of three constant harvest control rules with Monte Carlo simulation under pre-specified management objectives for the bigeye tuna. To be consistent with the Stock Synthesis (SS3) based stock assessment, we identified three groups of stock assessment outputs from recent stock assessment, representing different scenarios and assumptions made to cover possible uncertainty in the stock assessment (Kolody et al. 2010).The three groups include low, medium and high productivity. They represent stock assessment outputs considering most uncertainties, and thus may cover the “true” population dynamics. They are used in this study to quantify the stock dynamics in MSE. Although the MSE framework developed in this study is for the bigeye tuna fishery in the Indian Ocean, it is also applicable to other fisheries.

2. Methods

The methods are broken into three sub-sections which describe the main components of the MSE framework:

i) Operating model – a model which simulates the fish population and fishery dynamics, and the data observation process. Alternative plausible hypotheses that encompass the major uncertainties are included;

ii) Harvest Control Rule – the decision algorithm which produces a Total Allowable Catch (TAC) recommendation as a function of the simulated data ; and

iii) Performance measures, which include statistics for stock and fishery indicators and probabilities of achieving/violating management objectives for the simulated performance of the harvest control rules.

2.1 Operating model and Uncertainty

An age-structured population dynamics model was used to make stochastic forward projections. The current stock status and biological parameters were derived from three specifications of the most recent stock assessment (Kolody et al. 2010). Main assumptions included:

1) Iterated on an annual time-step, with age-structured population ($0\text{-}15^+$ year), with catches extracted using the continuous (Baranov) catch equation.
2) Four fishing fleets: combined longline (LL, primarily Japan and Taiwan), unassociated purse seine sets (PSFS), FAD/log associated purse seine sets (PSLS) and all others (Other). Each fleet has stationary age-based selectivity.
3) Beverton-Holt stock-recruitment dynamics with steepness fixed at 3 values (0.55, 0.75, 0.95), with lognormal annual deviates (σ_R in table 3), and Spawning Stock Biomass (SSB) directly proportional to the mass of mature fish.
4) Biological parameters, including length-at-age, weight-at-age, maturity-at-age and M-at-age relationships were stationary within each simulation (however M varied among the 3 operating models)

There were some minor differences between the assessment and the operating models including: i) the assessment was iterated on a quarterly time-step, and ii) the operating model used a slightly different (and preferable) growth equation. The notation, operating model equations, and model parameters are detailed in Tables 1, 2, and 3 respectively.

The largest difference between the stock assessment and the operating model was the treatment of uncertainty. The assessment (Kolody et al., 2010) described a weighted combination of the Maximum Posterior Density (MPD) estimates from 288 model specifications (to reflect the fact that a number of assessment assumptions are inevitably somewhat arbitrary, and some key population parameters cannot be reliably estimated from the available data). The MSE operating model included only 3 MPD specifications which were selected to span the range of productivity (MSY) that was considered to be plausible in the assessment (subsequently referred to as low, medium and high productivity). As such, the MSE was not undertaken with the intention of identifying the most realistic and appropriate representation of uncertainty. It was intended to compare the general performance and robustness of a range of policy options, and to test whether HCRs could be identified that would provide reasonable performance irrespective of the stock productivity.

In this MSE, we did not attempt to simulate the stock assessment process that would provide the input to the HCRs. As described below, the feedback-based HCRs require estimates of SSBMSY, SSB(t) and F(t) to produce TAC recommendations. We used the following estimation errors:

bias_F for constant fishing mortality rule, in different productivity level (please check table 1 for notions): $F_{y,t}^{total,act} = F_{y,t}^{total,act} * bias\_F_{pl}$

bias_SSB for constant escapement rule in different productivity level:

$\mathrm{SSB}_{y}^{obs} = SSB_{y}^{obs} * bias\_SSB_{pl}$

The bias term is specific to each operating model and ensures that the population estimates are initially consistent with the historical data for each of the three productivity scenarios. The bias term was intended to prevent the simulation from having unrealistically informative data. i.e. If the current assessment cannot distinguish the productivity of the stock, the HCR should not be immediately able to distinguish the productivity either. This is a simplification of the sort of biases that would occur if a stock assessment algorithm was embedded within the HCR. The stochastic component of the estimation error is described by σ_{SSB}, σ_F (Table 3). There was no implementation error (i.e. the catch removed was always equal to the TAC), and no observed error (i.e. the observed catch was equal to the catch removed)

For each of the 3 productivity scenarios, 250 Monte Carlo simulation runs were conducted, with each simulation running for 25 years. The MPD stock status for 2009 was used as the starting point in the simulation (Table 4).

2.2 Harvest Control Rules

Three commonly used HCRs were evaluated in this study (Fig.1):

1) Constant Fishing mortality (CF) – fishing mortality is held constant over time for each fleet (allocations among fleets vary depending on selectivity)

Keeping stable fishing mortality rate is easy to be implemented for fishery management and can result in proper stock biomass and long-term yield (Walters and Parma, 1996). There are also some conditional constant fishing mortality rules, with a lower fishing mortality or even fishery closure when stock is below a threshold level. In this study, we only considered strict constant fishing mortality strategy, and three harvest levels were evaluated.

2) Constant Catch (CC) .

Constant catch strategy is also operable and widely implemented in many fisheries to set annual quotas to prevent overcapacity and facilitate long-term planning (Hjerne and Hansson, 2001). However, it may cause stock overfished if stock abundance decline is not detected timely. Annual catch of most recent three years (from 2006 to 2008) fluctuated around 110,000 tons. We considered catch levels from 60,000 to 140,000 tons with an interval of 20,000 tons. This covers the current catch level, allowing us to evaluate if current annual catch is sustainable. The TAC is constant over time, and could only be abandoned when stock biomass was too low to support the annual catch. This management strategy can be written as

$$C_y = \begin{cases} 0 & if \quad SSB_y^{'} > SSB_y^{obs} \\ C_T & if \quad SSB_y^{obs} \geq SSB_y^{`} \end{cases}$$

where C_T is the annual catch target set based on a given constant catch rule; C_y is annual catch to be requested in year y; and $SSB_y^{`}$ is the lowest spawning stock biomass associated with biomass in year y, which could sustain C_T in year y. (calculated by catch equation with F at 5 yr^{-1} while achieving C_T).

3) Constant Escapement

Constant escapement strategy, also referred to as “fraction/minimum biomass strategy” (Ishimura et al., 2005), is a conservative way to keep stock biomass always above its minimum exploitable level in theory (Deroba and Bence 2008, Hjerne and Hansson 2001). It can be defined as

$$C_y = \begin{cases} 0 & if \quad SSB_L > SSB_y^{obs} \\ \alpha(SSB_y^{obs} - SSB_L) & if \quad SSB_y^{obs} \geq SSB_L \end{cases}$$

where α is pre-specified fraction of the difference between spawning stock biomass in year y and relevant limit value. Three scenarios of this strategy were tested in this study.

These control rules were chosen because they are widely used in fisheries management (. Hilborn and Walters, 1992). Fifteen management strategy scenarios were considered, covering five different F levels for the constant fishing mortality rule, five different catch levels for the strict constant catch rule, and five escapement levels for the constant escapement rule (Table 4).

2.3 Performance measures

Several performance measures were calculated to describe the main biological and economic management trade-offs typically considered in a single species context:

1) Mean value (over simulation) of the median catch over 25 years;
2) Median value (over simulation) of the 25-year interannual catch variability (AAV), defined as:

$$AAV = 100 \frac{\sum_y \left| C_y - C_{y+1} \right|}{\sum_y C_y}$$

where C_y is the catch in year y. A lower value corresponds to a more stable fishery, and is generally preferable for industry.

3) Median value (over simulation) of the ratio of spawning biomass at the end of the projection years (SSB_{2034}) to SSB_{msy};
4) Median value (over simulation) of the ratio of the average spawning biomass over 25 years to SSB_{msy};
5) Probabilities of the annual spawning biomass above SSB_{msy} over 3 years, 10 years and 25 years; and
6) Probabilities of the annual catch between 0.8MSY to MSY over 3 years, 10 years and 25 years.

As the total variance of catch during all projection years are not so meaningful, AAV is used in our study instead of coefficient of variance or standard deviation of annual catch, exploring the variability of interannual catch. Because most of the scenarios in this study tend to approach equilibrium at the end of 25-year simulations, SSB_{2034} was considered to represent the equilibrium SSB. When calculating the probabilities of achieving management goals, durations of 3 years, 10 years and 25 years were used to represent the short, medium and long terms, respectively.

3. Results

3.1. Constant fishing mortality rate rule

For all CF scenarios, AAVs were low and catches were different in the first year (2010), and tended to be constant from 2020 (Table 5; Fig. 2a). Comparing to the lower constant catch at 95,000 to 105,000 for scenario CF_0.2, equilibrium catch of other scenarios was around 115,000 to 130,000 after 2020. The SSBs behaved similarly from 2015, almost stayed at constant levels if Fs were higher than 0.3, and increased gradually for the two lower F scenarios (Fig. 2b).

As all the constant F scenarios could eventually result in almost constant catches without much difference at different equilibrium SSBs, SSB at the end of projection year (SSB_{2034}) was critical for comparing those scenarios. When harvesting at 0.6 yr^{-1} and 0.5 yr^{-1}, SSB_{2034} would be $0.69SSB_{msy}$ and $0.98SSB_{msy}$ respectively, which also lead to low mean SSBs (Table 5). In contrast, SSB_{2034} could reach $1.83SSB_{msy}$ and $2.49SSB_{msy}$ for scenarios CF_0.3 and CF_0.2, and mean SSB were also as high as $1.68SSB_{msy}$ and $2.24SSB_{msy}$, but its median catch was lower (Table 5). Keeping F constant at 0.4 yr^{-1} seemed to be optimal, because its median SSB and SSB_{2034} were not less than the SSB_{msy} level and the median (around 126,000 tons) and equilibrium catch (around 130,000 tons) levels were higher than those obtained for scenarios CF_0.3 and CF_0.2, and was also higher than the 2009 level (101,982 tons; Table 5; Fig. 2a,b).

3.2. Constant catch rule

The result showed that highertotal allowable catch would result in higher AAVs (Table 5), and the stock could be sustainable when annual catch was80,000 tons, as the stock increased from the third year (2012) at $0.77SSB_{msy}$ to$2.48SSB_{msy}$ at 2034, and its median SSB was at $2.20SSB_{msy}$, obtaining higher median catch than the most other constant catch scenarios (Fig. 2c,d). In contrast, higher annual catches at 140,000 tons would cause the median SSB below SSB_{msy} during the simulation years. Although keeping annual catches at 60,000 tons could ensure high stock abundance, mean annual catches were much lower than keeping annual catch at 8,000 tons. Thus, scenario CC_80000 was desirable of the five constant catch scenarios.

3.3. Constant escapement rule

In the constant escapement strategies, five exploitation rates considered were 0.3 to 0.7 by a step of 0.1 with pre-set limit SSB at $0.5SSB_{msy}$ (Table 4). For all constant escapement scenarios catch declined from the beginning year to 2012 at 37,000 to

55,000 tons, and then increased to maximum values at 113,000 to 151,000 tons at 2016.The stock declined again till 2019. All constant escapement scenarios kept a steady catch and equilibrium SSB after 2019 (Fig. 2e,f). The results also showed that AAVs were higher for the scenarios with higher exploitation rates (Table 5).

As median SSBs were kept above SSB_{msy} for all scenarios, scenarios CE_0.3 and CE_0.4 were not appropriate for their low catch. For scenario CE_0.5, median catch was slightly below (around 2,000 tons) those of scenarios CE_0.6, but the mean SSB was much higher ($>0.1SSB_{msy}$, Table 5). This suggests that the scenario of CE_0.5 was most rational among the five constant escapement scenarios.

4. Discussion

Among the five scenarios in each of the three groups of constant harvest control rules considered, optimal choices for the bigeye fishery in the Indian Ocean were scenarios CF_0.4, CC_100000 and CE_0.5, which could result in the median SSBs above SSB_{msy} and mean catches ranging from 80,000 to 126,000 tons (Table 5). The highest mean catch was achieved at 126,000 tons when fishing mortality was kept at 0.4 yr^{-1}, while the highest mean SSB was reached at $2.20SSB_{msy}$ for scenario CC_80000. Comparing to the three scenarios above by Kobe II strategy matrix, keeping escapment rate at 0.5 is not a appropriate choice for its lowest median catch and only slightly higher probability of achieving SSB target in short, medium and long runs, although its mean SSB are higher than that of CF_0.4 (Tables 5 and 6). If management goal is to harvest more fish, scenario CF_0.4 and CC_80,000 should be the choices. However, if management goal focuses on conservation, scenario CE_0.5 is most appropriate for its highest probability of ensuring SSB more than SSB_{msy} in short, medium and long term (Tables 5 and 6).

Basing on our study, annual catch should be kept at a level lower than that in 2009. Although the updated resolution stated ad hoc management strategy of keeping the catch under MSY level (114,000 tons; IOTC, 2010), we believe that the annual catch at 80,000 tons is a better choice, while setting MSY as target catch often result in the stock overfished (Punt, 2001). This is because scenario CC_80000 was shown to be optimal when comparing with other constant catch scenarios. We also need to consider catch history. Annual catch records were higher than 114,000 tons during 1995 to 2007, which probably had induced the stock overfished. Although past stock assessment suggests that the stock was slightly above biomass target, there was large uncertainty associated with such assessments.

There is a significant difference between our constant fishing mortality rule and common one, in which “true” fishing mortality rate is estimated from biomass by stock assessment and catch simulated with mean catch at preset level by Monte Carlo simulation. However, common constant fishing mortality rule will be impacted seriously by big actual stock assessment errors, because such a big stock assessment error could inflence the result seriously when estimating fishing mortality by catch equation. Comparatively, keeping a constant fishing effort directly is considered in this study, which will not influenced by stock assessment error, it could be applied by controlling fishing effort, although it has a disadvantage of solving fishing effort standardization problem.

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Reference

Butterworth, D.S., 2007. Why a management procedure approach? Some positives and negatives. ICES J. Mar. Sci. 64, 613-617.

Deroba, J. J., Bence, J. R., 2008. A review of harvest policies: Understanding relative performance of control rules. Fish. Res. 94, 210-223.

Fromentin J. M., Kell L. T., 2008. Evaluation of the performance and robustness of VPA-based stock assessment and MSY-based management strategy to process error: The Atlantic bluefin tuna case study. Col. Vol. Sci. Pap. ICCAT, SCRS/2008/094, 14p.

Hjerne, O., Hansson, S., 2001. Constant catch or constant harvest rate? - The Baltic Sea cod (*Gadus morhua* L.) fishery as a modelling example. Fish. Res. 53, 57-70.

Holland D. S., 2010. Management Strategy Evaluation and Management Procedures: Tools for Rebuilding and Sustaining Fisheries, OECD Food, Agriculture and Fisheries Working Papers, No. 25, OECD Publishing.

IOTC Secretariat, 2005. A review of the situation of bigeye tuna (*Thunnus obesu*s) in the Indian Ocean. Col. Vol. Sci. Pap. ICCAT, 57(2): 201-217

IOTC, 2008. Growth of tropical tunas using the Laslett, Polacheck and Eveson (LEP)

IOTC, 2010. For the conservation and management of tropical tunas stocks in the IOTC area of competence (Resolution 10/01). In: Collection of resolution and recommendations by the Indian Ocean tuna commission. Resolution 10/01, 2010: 164-168. http://www.iotc.org/files/proceedings/misc/ComReportsTexts/resolutions_E.pdf

IOTC database: www.iotc.org/English/data/databases.php

Ishimura, G., Punt, A.E., Huppert, D.D., 2005. Management of fluctuating fish stocks: the case of Pacific whiting. Fish. Res. 73, 201-216.

Kell L. T., Pastoors M. A., Scott R. D., 2005a. Evaluation of multiple management objectives for Northeast Atlantic flatfish stocks: sustainability vs. stability of yield. ICES J. Mar. Sci., 62: 1104-1117.

Kell L. T., Pilling G. M., Kirkwood G. P., et al., 2005b. An evaluation of the implicit management procedure used for some ICES roundfish stocks. ICES Journal of Marine Science, 62: 750-759.

Kolody D., Herrera M., 2010. Exploration of Indian Ocean Bigeye Tuna Stock Assessment Sensitivities 1952-2008 using Stock Synthesis. IOTC-2010-WPTT-04, 75p.

Lehodey P., 2004. A Spatial Ecosystem And Populations Dynamics Model (SEAPODYM) for tuna and associated oceanic top-predator species: Part II - Tuna populations and fisheries. 17th meeting of the Standing Committee on Tuna and Billfish, Majuro, Republic of Marshall Islands, 9-18 Aug. 2004, Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia, Working Paper: ECO-2: 36 p.

MacKenzie B R, Mosegaard H, Rosenberg N A, 2009. Impending collapse of bluefin tuna in the northeast Atlantic and Mediterranean. Conservation Letters, 2: 25-34.

Method. IOTC-2008-WPTT-09, 8p.

Nishida, T., Shono, H., Okamoto, H., Suzuki, z., 2002. Updated bigeye tuna (*Thunnus obesus*) resource analyses in the Indian Ocean- CPUE, ASPM (MSY) and projections. IOTC-WPTT-2002-35, 7p.

Okamoto H., Shono H., 2010. Japanese longline CPUE for bigeye tuna in the Indian Ocean up to 2009 standardized by GLM. IOTC-2010-WPTT-29, 14p.

Polacheck, T., Klaer, N. L., Millar, C., Preece, A. L., 1999. An initial evaluation of management strategies for the southern bluefin tuna fishery. ICES J. Mar. Sci. 56, 811-826.

Punt A. E., 2001. The gospel of maximum sustainable yield in fisheries management: birth, crucifixion and reincarnation [M]. In: J.D. Reynolds, G.M. Mace, K.H. Redford and J.G. Robinson, Editors, Conservation of Exploited Species, Cambridge University Press: 67 - 86.

Punt A. E., Pribac F., Taylor B. L., et. al., 2005. Harvest strategy evaluation for school and gummy shark. J. Northwest Atl. Fish. Sci, 35: 387-406.

Ricard, D., Basson, M., 2002. Application of an age-structured production model (ASPM) to the Indian Ocean bigeye tuna (*Thunnus obesus*) resource.

IOTC-WPTT-02-07, 14p.

Roel B. A., DeOliveira J. A. A., 2007. Harvest control rules for the Western horse mackerel (*Trachurustrachurus*) stock given paucity of fishery-independent data. ICES Journal of Marine Science, 64: 661–670.

Safina C, Klinger D H, 2008. Collapse of bluefin tuna in the Western Atlantic. Conservation Biology, 22: 243-246.

Shono, H., Nishida, T., Okamoto, H., 2004. Future projections for bigeye tuna in the Indian Ocean. IOTC-WPTT-04-19. 14p.

Shono, H., Okamoto, H., Senba, K., 2006. Preliminary Stock Assessment for Bigeye Tuna in the Indian Ocean using Stock Synthesis II (SS2). IOTC-2006-WPTT-18. 12p.

Shono, H., Satoh, K., Okamoto, H., Nishida, T., 2009. Updated stock assessment for bigeye tuna in the Indian Ocean up to 2008 using Stock Synthesis III (SS3). IOTC-2009-WPTT-20. 9p.

Tong Y H, Chen Y., Chen X J., Xu L X., Zhang Y Y, Tian S Q, 2011. Management strategy evaluation for bigeye tuna, *Thunnus obesus*, in the Indian Ocean. Fish. Res. (in published)

Table 1 Symbols and descriptions of variables used in the stochastic simlation model (Table 2)

Symbol	**Description**
Index variable	
y	Year (2009-2034)
t	Age (0-15^{+})
State and control variable	
N	Abundance
R	Recruitment
R_0	Virgin recruitment
SSB	Actual spawning stock biomass (tons)
SSB^{obs}	Observed spawning stock biomass (tons)
SSB_0	Unfished spawning stock biomass (tons)
C^{act}	Actual catch in weights (tons)
F	Wanted Instantaneous fishing mortality (yr^{-1})
F^{act}	Actual instantaneous fishing mortality (yr^{-1})
r, p, q	Ratios of F_{2009}^{LL}, F_{2009}^{PSFS}, F_{2009}^{PSLS} to F_{2009}^{total} respectively
pl	Productivity levels (low, med, high)
S	Fishery selectivity
L	Mean length at the very beginning year (cm)
W	Mass-at-length at the very beginning year (tons)
$W_{t+0.5}$	Mass-at-length in the middle of year (tons)
Mat	Maturity-at-length at the very beginning year
Structural parameter	
h	Steepness in B-H stock-recruitment relationship
L_∞, $k1$, $k2$, α, β, t_0	VB log K growth function parameters (constant)
a, b	Mass-at-length parameters (constant)
m	Maturity-at-lengthparameter,slope(constant)
L_{50}	Maturity-at-lengthparameter,half-saturation(constant)
M	Instantaneous Natural mortality rate (yr^{-1}; constant)
Distributional parameter	
σ_{SSB}	Standard deviation for SSB (constant)
σ_R	Standard deviation for R (constant)
σ_F	Standard deviation for F (constant)
Harvest control rule	
γ	Pre-specified fraction of the difference between spawning stock biomass in year y and relevant limit value

Table 2. Equations used in stochastic simulation model

Population model equations

$$N_{y,t} = \begin{cases} R_y & if\ \ t=0 \\ N_{y-1,t-1} e^{-(M_{t-1}+F^{total}_{y-1,t-1})} & if\ \ 1 \le t \le 14 \\ N_{y-1,t-1} e^{-(M_{t-1}+F^{total}_{y-1,t-1})} + N_{y-1,t} e^{-(M_t+F^{total}_{y-1,t})} & if\ \ t=15^{+} \end{cases} \tag{T.2.1}$$

Where

$$F^{total}_{y,t} = S^{LL}_t rF^{total}_y + S^{PSFS}_t pF^{total}_y + S^{PSLS}_t qF^{total}_y + S^{OTHER}_t (1-r-p-q)F^{total}_y \tag{T.2.2}$$

Recruitment

$$R_y = \frac{4hR_0 SSB_y}{SSB_0(1-h)+SSB_y(5h-1)} e^{\varepsilon-\sigma_R^2/2}, \quad \varepsilon \sim \boldsymbol{N}\,(\mathbf{0}, \sigma_R^2) \tag{T.2.3}$$

Observation and implementation

$$SSB_y = \sum_{t=1}^{15} N_{y-1,t-1} e^{-(M_{t-1}+F^{total}_{y-1,t-1})} Mat_t W_t + N_{y-1,15} e^{-(M_{15}+F^{total}_{y-1,15})} Mat_{15} W_{15} \tag{T.2.4}$$

$$SSB^{obs}_y = SSB_y e^{\varepsilon-\sigma_{SSB}^2/2}, \quad \varepsilon \sim \boldsymbol{N}\,(\mathbf{0}, \sigma_{SSB}^2) \tag{T.2.5}$$

$$F^{total,act}_y = F^{total}_y e^{\varepsilon-\sigma_F^2/2}, \quad \varepsilon \sim \boldsymbol{N}\,(\mathbf{0}, \sigma_F^2) \tag{T.2.6}$$

$$C^{act}_y = \sum_{t=0}^{15} N_{y,t}(1-e^{-(M_t+F^{total,act}_{y,t})}) W_{t+0.5} F^{total,act}_{y,t} / (M_t + F^{total,act}_{y,t}) \tag{T.2.7}$$

Growth

$$L_t = L_\infty \left(1 - e^{-k_2(t-t_0)} \left\{ \frac{1+e^{-\beta(t-t_0-\alpha)}}{1+e^{\beta\alpha}} \right\}^{-(k_2-k_1)/\beta} \right) \tag{T.2.1.8}$$

Weight-Length relationship

$$W_t = aL_t^b \tag{T.2.9}$$

Maturity

$$Mat_t = \frac{1}{1+e^{(-m(L_t-L_{50}))}} \tag{T.2.10}$$

Table 3 Values defined for various parameters used in the simulation

	Parameter	**3 different productive sets**		
		low	medium	high
Uncertainty	σ_R	0.6	0.6	0.6
			Growth	
	L_∞ (cm)	160	160	160
	$k1$	0.071	0.071	0.071
	$k2$	0.4207	0.4207	0.4207
	α	5.6033	5.6033	5.6033
Biological parameter	β	2.999	2.999	2.999
	t_0	-3.09	-3.09	-3.09
			Maturity	
	m	0.25	0.25	0.25
	L_{50} (cm)	110.888	110.888	110.888
			W-L relationship	
	a	0.00003661	0.00003661	0.00003661
	b	2.90182	2.90182	2.90182
			Natural mortality	
	M (age=0; yr^{-1})	0.74	0.925	1.11
	M (age=1; yr^{-1})	0.42	0.525	0.63
	M (age>=2; yr^{-1})	0.32	0.4	0.48
			S-R relationship	
	R_0	71105000	110381700	170807000
	SSB_0 (tons)	1610510	1103270	793953
	h (steepness)	0.55	0.75	0.95
	SSB_{2009} (tons)	525256	347980	244364
	F^{LL}_{2009} (yr^{-1})	0.219	0.249	0.308
Stock status	F^{PSFS}_{2009} (yr^{-1})	0.015	0.018	0.023
	F^{PSLS}_{2009} (yr^{-1})	0.221	0.163	0.151
	F^{OTHER}_{2009} (yr^{-1})	0.022	0.038	0.064
BRP	MSY (tons)	87723	118226	139825
	SSB_{msy} (tons)	574016	320775	171883
Other	Weight	0.333	0.333	0.333
	bias_F	1.434	1	0.862
	bias_SSB	0.907	1	1.198

Table 4 Management scenarios and associated parameter values

HCR	Scenario Abbreviation	Specified Value
CF	CF_0.6	F = 0.6 yr^{-1}
	CF_0.5	F = 0.5 yr^{-1}
	CF_0.4	F = 0.4 yr^{-1}
	CF_0.3	F = 0.3 yr^{-1}
	CF_0.2	F =0.2 yr^{-1}
CC	CC_140000	C_T = 140000 tons
	CC_120000	C_T = 120000 tons
	CC_100000	C_T = 100000 tons
	CC_80000	C_T = 80000 tons
	CC_60000	C_T = 60000 tons
CE	CE_0.7	$\gamma = 0.7$
	CE_0.6	$\gamma = 0.6$
	CE_0.5	$\gamma = 0.5$
	CE_0.4	$\gamma = 0.4$
	CE_0.3	$\gamma = 0.3$

Table 5 Equal weighted values of performance measures derived from 250 simulation runs of three models covering three levels of productivity, for a simulated bigeye tuna fishery managed with different management strategy scenarios for 25 years of simulation duration. The scenarios were defined in Table 1.

Scenarios	**C (tons)**	**AAV**	**r_SSB**	**r_SSB$_{2034}$**
CF_0.6	120,660.52	7.99	0.70	0.69
CF_0.5	125,554.93	7.71	0.94	0.98
$\boxed{\textbf{CF\_0.4}}$	$\boxed{126{,}039.55}$	7.62	1.26	1.34
CF_0.3	118,276.33	7.54	1.68	1.83
CF_0.2	98,301.65	7.41	2.24	2.49
CC_140000	93,366.67	63.57	0.74	0.91
CC_120000	80,033.33	38.79	1.12	1.21
CC_100000	66,700.00	23.03	1.71	2.03
$\boxed{\textbf{CC\_80000}}$	80,000.00	4.54	2.20	2.48
CC_60000	60,000.00	$\boxed{0.00}$	$\boxed{2.72}$	$\boxed{3.32}$
CE_0.7	119,718.30	27.97	1.11	1.10
CE_0.6	122,449.87	25.49	1.23	1.21
$\boxed{\textbf{CE\_0.5}}$	120,157.60	22.34	1.35	1.37
CE_0.4	117,786.04	19.26	1.53	1.57
CE_0.3	114,617.17	16.77	1.83	1.80

Note: Optimal scenarios and data are marked in frame.

Table 6 Kobe II strategy matrix derived from the management objective grid with models weighted equally as in Table 3.

Probability of achieveing management objective	**Projection Time frame**	**Weighted proportion of scenarios that achieve the management objectives**		
		CF_0.4	CC_80000	CE_0.5
$P(SSB_y/SSB_{msy}>1)$	In 3 years	0.11	0.11	0.22
	In 10 years	0.40	0.43	0.54
	In 25 years	0.60	0.61	0.63
$P(0.8<Catch_y/MSY<1)$	In 3 years	0.35	0.33	0.00
	In 10 years	0.33	0.33	0.12
	In 25 years	0.27	0.28	0.15
Median Catch	In 3 years	85,768	80,000	51,927
	In 10 years	102,095	80,000	113,531
	In 25 years	126,040	80,000	120,158

Figure captions

Fig. 1. Graphic representations of constant harvest control rules considered in this study.

Fig. 2. Temporal trajectories of relative mean catch ratio and SSB ratios under different management strategies.

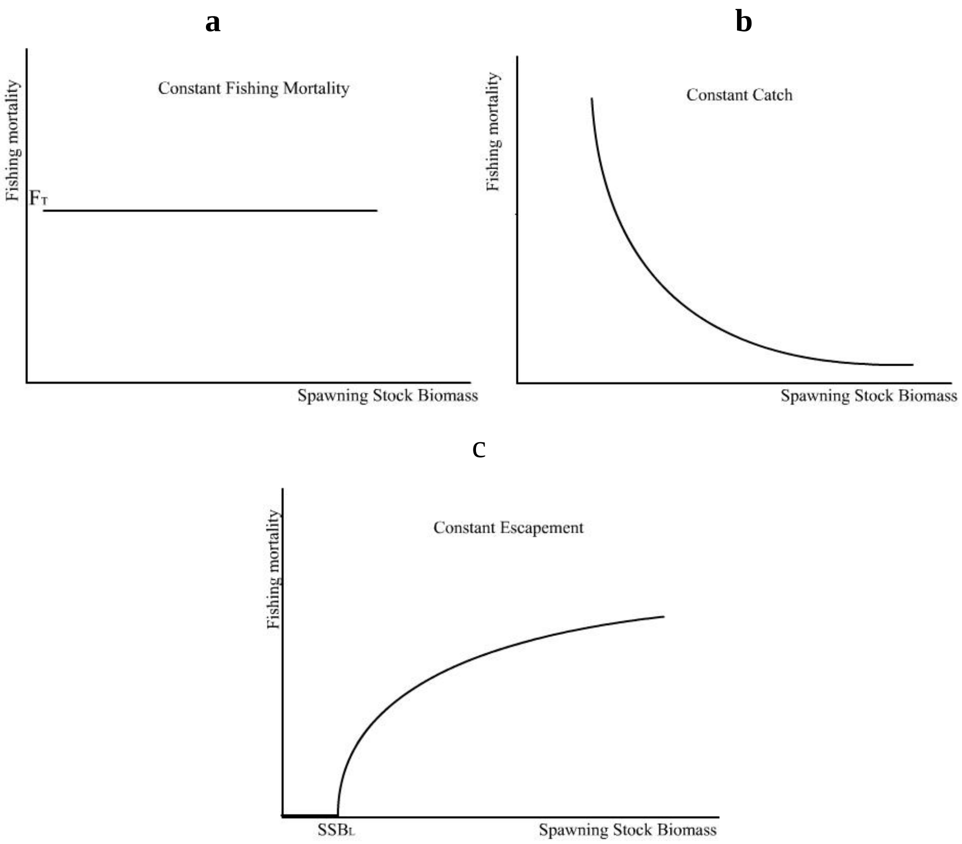
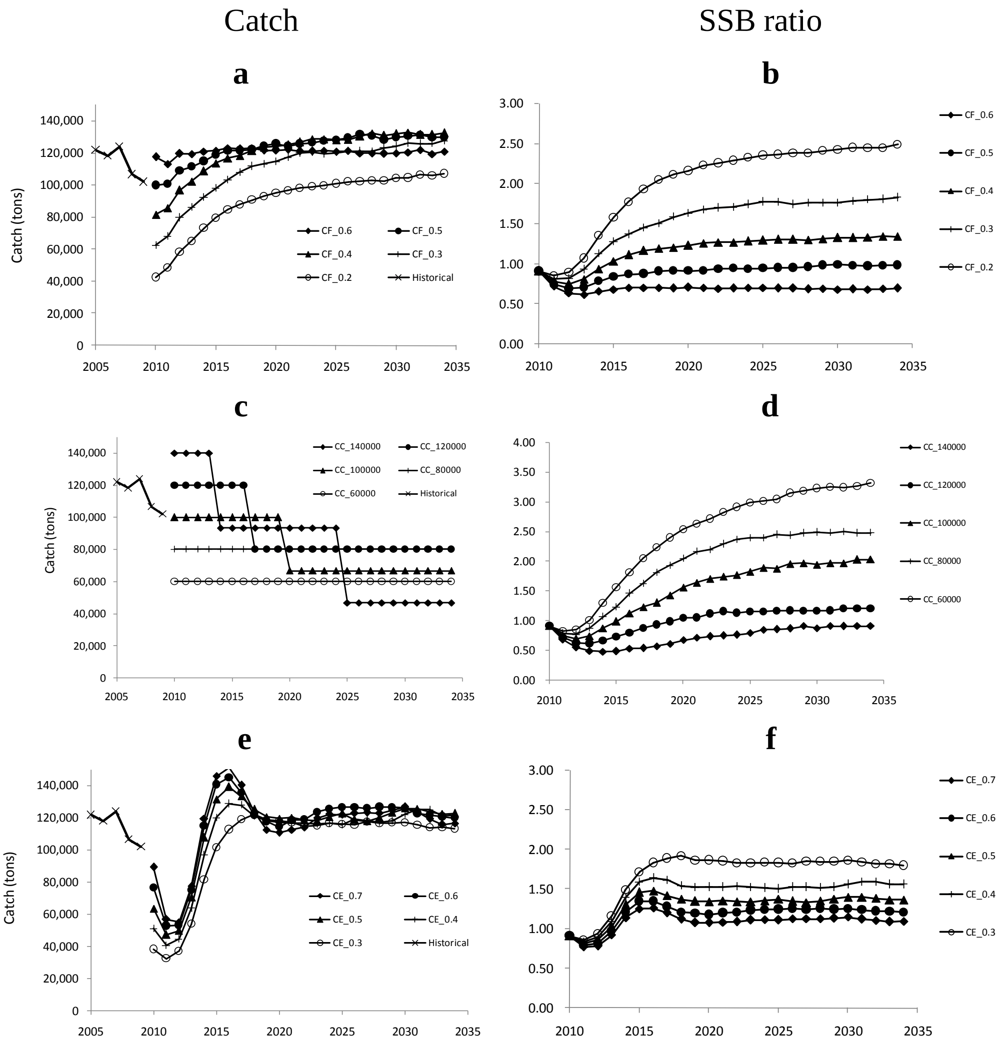


Fig. 1 Graphic representations of harvest control rules considered in this study.



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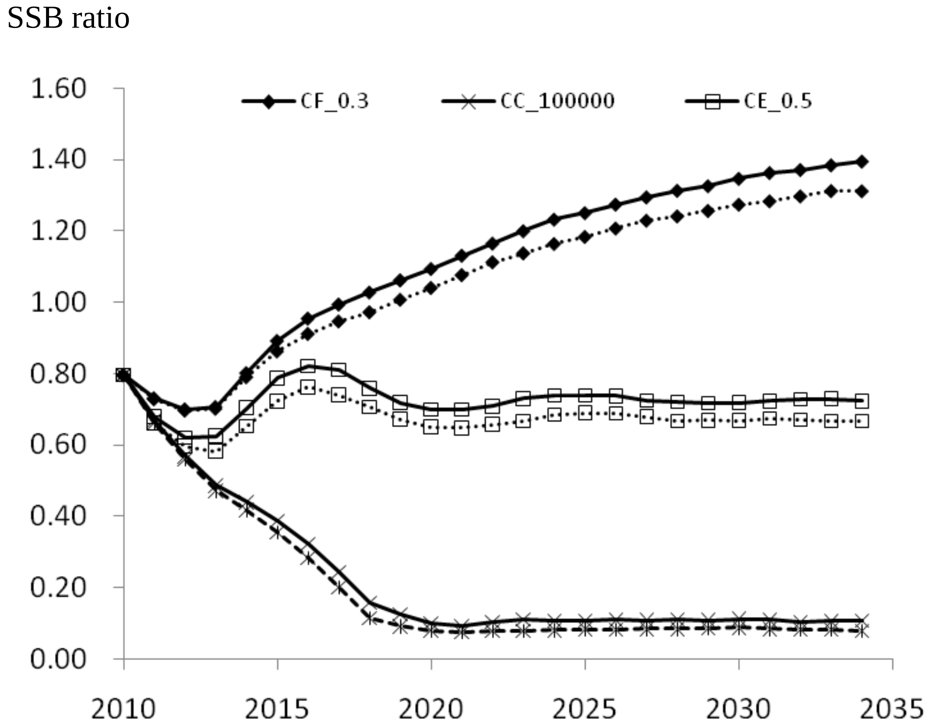

Fig. 4 Results for the low producitivity operating model for the “true” median SSB (solid lines) and the 10th percentile SSB (dashed lines) of three optimal management scenarios.