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(Indian Ocean Tuna Commission - Working Party on Methods)

A simulation approach developed to assess reference points and risk on Indian Ocean Tuna Populations

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Abstract

A simulation approach was developed using the life-history characteristics of Albacore, Skipjack, Bigeye and Yellowfin Tuna, and tested the interim target and limit reference points recommended by the Commission. The effect of fishing at optimal rates, and the risk of going below these reference points is evaluated, and the trade-off between the harvest rates, the limit reference points, the auto-correlation of the process error and the time to recovery to the target and limit abundance levels is evaluated. Managers eventually have to evaluate a trade-off on the risk to the resource and the optimal catch levels on the long-term for the stock being managed. The approach presented here displays the probability of adverse events occurring and evaluates different outcomes based on the specified thresholds and rates at which the stocks are fished. A concept of type I and type II errors is introduced, primarily defining the probability of taking a management action when it was not needed (a false positive, risk to taking a management action on a fishery) versus failing to take a management action when it is needed (a false negative, risk to fail to protect the resource when needed). For illustrative uses, we demonstrate how well it would work for a theoretical albacore, skipjack, bigeye and yellowfin stocks similar to the ones used in models in the Indian Ocean based on life history parameters.

Risks of falling below 40% of S_{MSY} are below 7% and 10% for Albacore and Skipjack respectively if fished at optimal levels. For bigeye and yellowfin these risks are less than 1% respectively to fall below 50% of S_{MSY} and 40% S_{MSY} respectively. Thus, based on these limit reference points, managers should be willing to take a management action every 15 years for albacore, every 10 years for skipjack, and every 100 years for bigeye and yellowfin respectively provided fishing is kept at optimal levels. Risks of failing to detect an issue with overfishing is less than 2% for albacore at levels exceeding optimal fishing levels, about 40% for skipjack, and about 60% for bigeye and yellowfin at these reference points. If managers wish to minimize the risks of failing to detect overfishing for skipjack, yellowfin and bigeye, these stocks should be managed at levels higher than 40% of S_{MSY} for SKP and YFT, and >50% of S_{MSY} for BET. The other reference point, namely F_{MSY} indicates that when exceeded by a factor of 1.5, all tuna stocks will rarely recover to optimal levels of spawning stock size or yield, unless severe harvest controls are applied on these stocks. Minor controls have insignificant effects on recovery times indicating that when fishing exceeds F_{MSY} levels, a longer recovery time to both the threshold and limit recovery times can be expected. Based on the results of this study, a more robust approach for critical reference points for management would be in the realm of 0.6-0.8 of S_{MSY} and not to exceed 1.2 F_{MSY} for all tuna stocks. This would keep the type II error (risk of overfishing to less between 10-20%) for all Indian Ocean Tuna stocks, and ensure recovery to optimal yield levels within 2-3 generations for all stocks other than skipjack and bigeye tuna with simple harvest control rules.

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A Simulation Approach Developed to Assess Thresholds and Risk on Tuna Populations in the Indian Ocean

Background within the IOTC

At the Commission meeting in 2012, a resolution was adopted (i.e. Resolution 12/01 followed by Resolution 13/10 in 2013). The key points of this resolution cover the following tenets below:

"*The Resolution 12/01:*

- *AGREES, in accordance with paragraph 1 of Article IX of the IOTC Agreement, to the following:*
  - *To apply the precautionary approach, in accordance with relevant internationally agreed standards, in particular with the guidelines set forth in the UNFSA, and to ensure the sustainable utilization of fisheries resources as set forth in Article V of the IOTC Agreement.*
  - *In applying the precautionary approach, the Commission shall adopt, after due consideration of the advice supplied by the Scientific Committee, stock-specific reference points (including, but not necessarily limited to, target and limit reference points), relative to fishing mortality and biomass, and associated harvest control rules, that is, management actions to be taken as the reference points for stock status are approached or if they are breached"*

In Resolution 13/10 the following were agreed to:

ACKNOWLEDGING that continuing dialog between scientists and managers is necessary to define appropriate HCRs for the IOTC tuna and tuna-like stocks;

ADOPTS in accordance with paragraph 1 of Article IX of the IOTC Agreement, that:

1. *When assessing stock status and providing recommendations to the Commission, the IOTC Scientific Committee should apply the following interim target[2] and limit reference points[3] for the species of tuna and tuna-like species listed in **Table 1**. B_{MSY} refers to the biomass level for the stock that would produce the Maximum Sustainable Yield; F_{MSY} refers to the level of fishing mortality that produces the Maximum Sustainable Yield.*

***Table 1**. Interim target and limit reference points.*

Stock	*Target Reference Point*	*Limit Reference Point*
Albacore	B_{MSY}; F_{MSY}	$B_{LIM} = 0.40\ B_{MSY}$; $F_{LIM} = 1.40\ F_{MSY}$
Bigeye tuna	B_{MSY}; F_{MSY}	$B_{LIM} = 0.50\ B_{MSY}$; $F_{LIM} = 1.30\ F_{MSY}$
Skipjack tuna	B_{MSY}; F_{MSY}	$B_{LIM} = 0.40\ B_{MSY}$; $F_{LIM} = 1.50\ F_{MSY}$
Yellowfin tuna	B_{MSY}; F_{MSY}	$B_{LIM} = 0.40\ B_{MSY}$; $F_{LIM} = 1.40\ F_{MSY}$
Swordfish	B_{MSY}; F_{MSY}	$B_{LIM} = 0.40\ B_{MSY}$; $F_{LIM} = 1.40\ F_{MSY}$

2. *These interim target and limit reference points shall be assessed and further reviewed by the IOTC Scientific Committee and the results shall be presented to the Commission for adoption of species-specific reference points. If applicable, the IOTC Scientific Committee should endeavour to apply the interim reference points in the provision of advice on the status of stocks and on recommendations for management measures.*

Rationale/Objective

In 2012 (Mosqueira and Kitakado 2012) identified the needs and issues of evaluating these reference points in the context of risk and time to recovery if any adverse impacts occurred on these stocks. Before developing an Operating Model (OM) and some generic harvest control rules (HCR) that may meet some generic management objectives (MO), a simple exercise needs to be conducted about

[2] FAO reference manual on stock assessment states, "The **Target Reference Points**, TRP are Biological Reference Points defined as the level of fishing mortality or of the biomass, which permit a long-term sustainable exploitation of the stocks, with the *best possible catch* (Cadyma 2003). For this reason, these points are also designated as *Reference Points for Management*. They can be characterized as the *fishing level* F_{target} (or by the *Biomass*, B_{target})".

[3] A **limit reference point** "…indicates a state of the fishery and/or resource which is considered to be undesirable and which management action should avoid" (Caddy and Mahon, 1995).

how relevant some of these reference points are for management (Mosqueira and Kitakado 2012) . The objective of this work is to evaluate within a very simple framework the interim reference points (assuming they can be estimated perfectly, which in itself is a big assumption). If they were estimable with perfect knowledge, then how good are the reference points with respect to different errors in either detecting a problem with a false cause, or failing to detect a problem when it was required. Time to recovery to the target and limits are also key in assessing these points, and are also evaluated with this work.

Introduction to equilibrium reference points

There remains a conceptual commitment (sensu Khun 1996) among some fisheries and wildlife managers to the idea that nature is in balance even though ecologists have been questioning this perception for several decades (Egerton 1973, DeAngelis and Waterhouse 1987). Balance or stability has been defined in many ways following a disturbing force including presence/absence of species (persistence), distance from which populations or communities can recover to equilibria (amplitude), and time for this recovery to take place (resilience) (Connell and Sousa 1983, Grimm and Wissel 1997). Stability has been searched for in metrics ranging from the collective biomass of communities to species densities or relative abundances. Individual populations seldom adhere to or even cycle regularly around equilibrium abundances (Connell and Sousa 1983, Tilman 1996). Although, population stability may increase when ample resources are available to younger life stages but are limited to adults (in theory; Mueller and Huynh 1994), persistence of species may stabilize at large spatial scales due to several hypothesized steadying mechanisms (DeAngelis and Waterhouse 1987), and in some studies the collective biomass of the community was shown to be more or less constant (Rodriguez 1994, Tilman 1996, Doak et al. 1998). Regardless, most research suggests that it may be more reasonable to conceptualize individual populations as fluctuating stochastically within bounds (Connell and Sousa 1983). The density-dependence we observe with respect to mortality and natality in some species (e.g., Beverton and Holt 1957, Ricker 1975) implies there is a carrying capacity, which defines the upper bound.

Researchers studying exploited populations have recently shifted their attention to identifying the lower bound or threshold abundance below which a population cannot return within a reasonable amount of time. Setting thresholds too low limits future production and yield and can expose populations to greater risk of extinction; setting thresholds too high unduly limits harvest. Understanding how long it takes for populations to recover from low abundances and that recovery cannot be defined as adherence to equilibrium will help managers and resource stakeholders set limits on the extent to which populations can be exploited.

The approach presented here takes into account these ideas of stochastic variation around some equilibrium points, and the underlying consequences of fishing at rates that are near optimal for a stock (in this case tuna). Undesirable events are quantified in a probabilistic sense, and the eventual time to recover to these thresholds and limits is also evaluated. As presented in subsequent pieces of this paper, managers really need to pay attention to four things:

1) Risk of an adverse event occurring (probability of a population going below a threshold assuming a certain harvest policy).
2) The amount of time it may take a species to recover to the target and limit reference points given additional management actions (AMA) as proposed through Harvest Control Rules (HCR’s), and
3) Setting these threshold limits that may be risk averse or pro-risk that eventually boils down to a policy decision.

4) Setting a target harvest rate policy that may minimize these adverse events occurring, once again a policy choice.

Using these four ideas and building a simulator to address this is presented in further sections of this report. Finally, balancing these 4 ideas along with biological aspects of the stock being studied as well as aspects of the fishery targeting these stocks is accounted for in this simulation model.

The Dilemma of Low Spawning Biomass

In a managed fishery (fishery system), spawning biomass may drop to lower than desirable levels because:

1) harvest rates have been higher than desirable thought;
2) productivity, i.e. recruitment has been lower than estimated; or
3) chance resulting from natural variation around a mean production (process error).

The appropriate management response to the first and second circumstances is the same: reduce harvest rates such as is the result from and Additional Management Action (AMA). The appropriate response to the third circumstance is to maintain a sustainable and well-estimated harvest rate, and in all three cases, invoke a rebuilding strategy (another essential piece of the MSE) through a set of Harvest Control Rules (HCR's).

A lower bound can be used as a threshold below which a high frequency of low Spawning Biomass would be an unlikely event, given what we know of harvest rates and productivity. If such an unlikely event occurs, we would conclude, more probably, that either harvest rates have been consistently higher than estimated, or productivity consistently lower than estimated. Our knowledge of fishing mortality rates and productivity are both based on parameters estimated with uncertainty, meaning that our knowledge may be faulty. Also, past productivity could have been accurately assessed, but current productivity of the stock may have declined due to changes in environment. Regardless of the circumstance, the logical response to unexpectedly low Spawning Biomass would be to lower harvest rates (implement AMA). Otherwise, the stock might suffer recruitment overfishing and be placed at higher risk of further declines in abundance.

One should note, however that low Spawning Biomass can and do occur from chance alone with no shift in productivity or average harvest rates. Restricting harvest under this circumstance would be unnecessary, pushing average Spawning Biomass above the level that produces maximum sustained yield (MSY) and the average yields below MSY, though using the precautionary principle (Richards et. al. 1996) would not necessarily be bad for the fishery.

This dilemma defines the two types of risk associated with management based on Spawning Biomass. The first (Type I Risk) is the risk of unnecessarily restricting fishing-induced mortality when Spawning Biomass is <u>below</u> a threshold, that is, when chance alone has lowered Spawning Biomass, i.e. in an easily reversible situation. The second (Type II Risk) is the risk of not restricting fishing-induced mortality even though productivity has declined irreversibly, but chance has kept Spawning Biomass <u>above</u> the threshold. Fortunately, the tradeoff between these two types of risk can be quantified and used to set a rational lower bound using available information and reasonable intuition.

Estimating Risk

Estimating risk of management error through AMA begins with the probability that a stock "requires response" in a particular year. If probabilities of each event "requiring response" are independent over time (assumed when there is no evidence of dependence), the probability no "response" is needed is:

Prob (No Stock "Requires Response") = $1 - p_i$ eq. 1

where p_i is the probability that the stock (i) "requires response". Therefore, the probability of AMA is the complement of the equation above: p_i eq. 2

Accordingly:

1) ***Type II Risk is zero and Type I Risk equals eq. 2 whenever a stock is not overfished; or***
2) ***Type I Risk is zero and Type II Risk equals eq. 1 whenever a stock is overfished***

If the p_i were known, risk would be known. However, risk of both types must be estimated because the p_i must be estimated for each set of conditions implicitly assuming a set harvest rate policy.

The probability p that a stock would meet the criterion of being overfished in a given year can be estimated with the simulation approach presented here. These simulations would:

1) be based on an estimated stock-recruit relationship;
2) be stochastic with variation in:

    2a) process error;
    2b) maturation and selectivity rates;
    2c) harvest rates; and
    2d) measurement error in estimates of future Spawning Biomass;

Note in our scenario developed, we are only varying process error, as maturation and selectivity rates are assumed constant over time, and harvest rate is varied and is a specified management control. Finally, in the simulation developed we assumed spawning biomass could be estimated perfectly. However stochastic variations within bounds could be introduced on all these variables.

3) have an optimal harvest rate as estimated using stable state assumptions of the age structure of the stock;
4) have many iterations;
5) be robust to initial conditions; and
6) have a specific lower bound for future Spawning Biomass.

Average harvest rate in each simulation is set to the estimated optimal rate to be consistent with the management goal of MSY, which can be estimated using equilibrium assumptions. Influence of initial conditions on the simulations is reduced by disregarding results from earlier iterations (a "burn-in" period). Probability p_i is estimated from the remaining iterations (*M* "years" in the simulations) by dividing the number of years in which the criterion was met (*m events that show the stock goes below a threshold*) by *M*. While this calculation ignores that "years" in each simulation are not independent, this dependence should be inconsequential with large numbers of iterations. Figure 1 is a graphical representation of the results of a series of such simulations of an optimally fished stock across a spectrum of lower bounds.

With one modification, simulations as described above can represent overfished stocks. If all other factors are as before, including the average harvest rate, overfishing can be simulated by reducing the density-independent parameter h in the estimated stock-recruit relationship. Remembering that overfishing occurs with a reduction in productivity, a reduction of κ (x100%) in productivity is represented as a change in eq.4:

$$N_{1,t} = \frac{\alpha S_{t-1}}{\beta + S_{t-1}} \qquad \text{eq. 3}$$

Where

$$\alpha = \frac{4hR_0}{5h-1} \qquad \text{eq. 4}$$

and $\beta = \frac{B_0(1-h)}{5h-1}$ eq. 5

Where h is steepness (base case h=0.8 was used in the simulations), R_0 and B_0 are recruitment at Virgin Biomass and Virgin Biomass respectively, α and β are parameters related to the density independent and dependent terms in the Beverton Holt relationship.

Thus

$\alpha' = \frac{\kappa(4hR_0)}{5h-1}$ is used in simulations instead of α. Figure 1b shows the effect on of reducing productivity by 50% on an estimated relationship between π and a lower bound.

Note that for each lower bound and each stock there are two values of π. The first value, call it π', is the probability of meeting the criterion (going below a threshold limit) under optimal fishing. The second value, call it π'', is the probability of meeting the criterion with overfishing. In the example in Figure 1b, overfishing represents a 50% reduction in estimated productivity, while simulated harvest rates remained at levels estimated to optimally harvest a stock with 100% of estimated productivity.

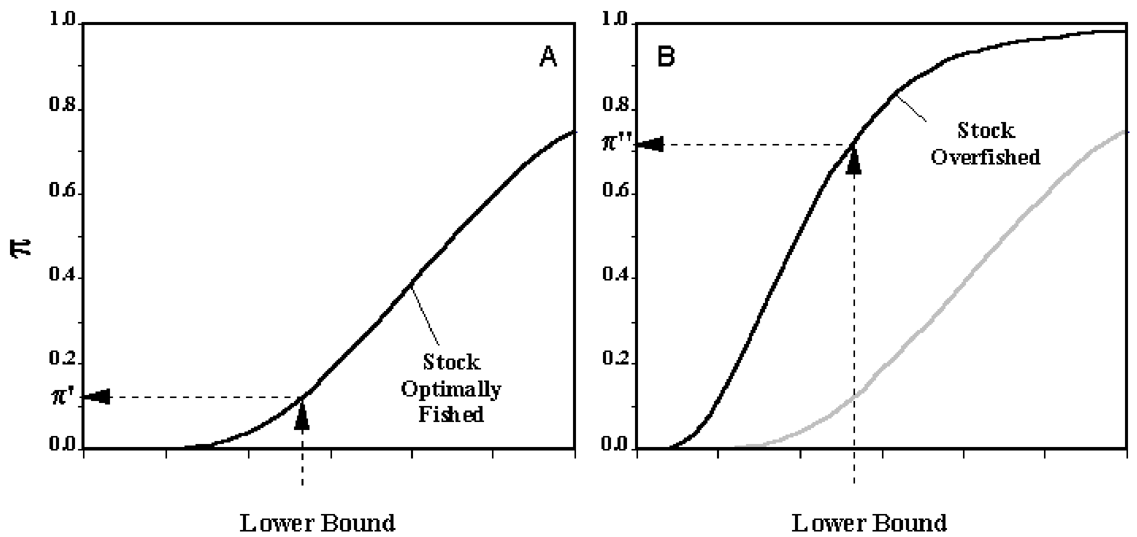


Figure 1. Estimated probability π of a stock meeting the threshold criterion in a particular calendar year as a function of a lower bound in Spawning Biomass under optimal fishing (Panel A) and under overfishing (Panel B) in which productivity has been reduced 50%. Curves are based on interpolations from individual simulations.

As independence is the assumption used to estimate the probability of an event, the chance of being below a threshold given you were below the threshold in the previous year is also p_i and having an event occur 2 years in a row is $(p_i)^2$. Normally such successive events are extremely low, and if we note this to happen, then the chances of overfishing are probably high.

Note quantifying Type I and Type-II errors at each level would eventually show a profile shown in Figure 2. Thus, the chance of making a Type II error when you take AMA when the reference point is high normally lower than when the reference point for the stock is low. In contrast, the type I error, i.e. you take an unnecessary AMA when it wasn't required occurs when the reference point is high is higher than when it is low (Figure 2). These profiles are generated by running the models numerous times at different levels for reference points. In addition, the probability of a Type II error with a small drop in productivity is a lot higher than detecting a larger drop in productivity.

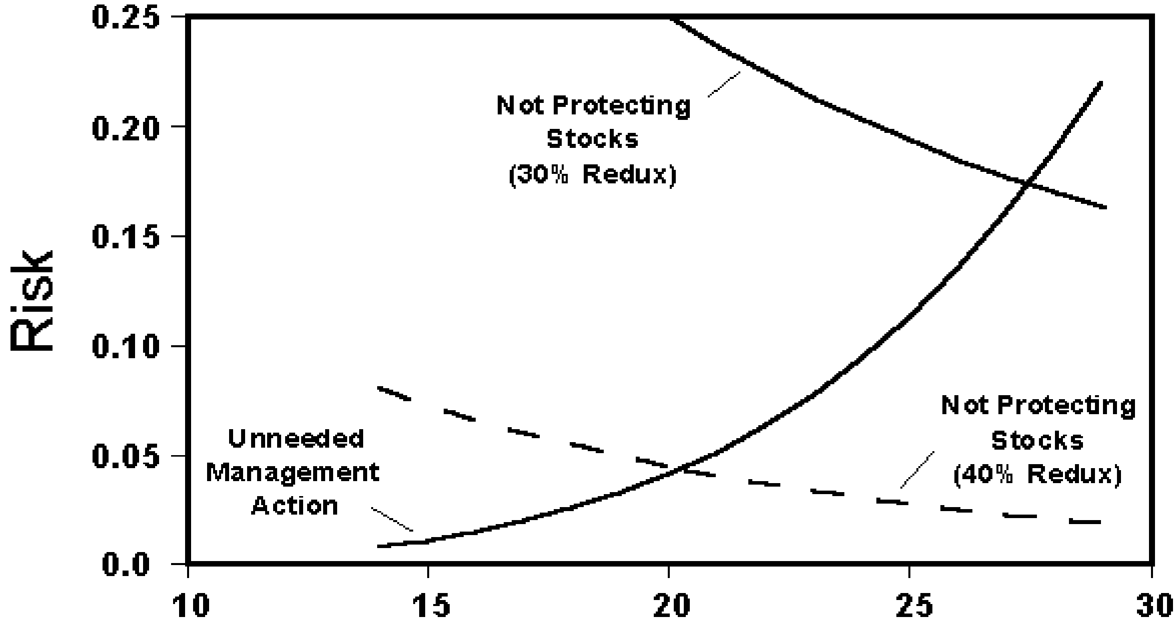


Figure 2: Type I and type II errors as a function of stock size for a theoretical population and estimated drops of 30 and 40% in productivity respectively

Simulation Model Used

A standard age structured model was used

$$N_{a+1,t+1} = N_{a,t}(1-u_t v_a)s_a \quad \text{for } a>1,\ a<n \qquad \text{eq. 6}$$

$$N_{n,t+1} = \left(N_{n,t} + N_{n-1,t}\right)(1-u_t v_n)s_n \quad \text{for } a=n \qquad \text{eq. 7}$$

$$E_t = \sum_a N_{a,t} f_a \qquad \text{eq. 8}$$

$$N_{1,t+1} = g(E_t) \qquad \text{eq. 9}$$

Where the functional forms are given in eq. 3 , 4 and 5 above. The only difference is that process error is used, and has some auto-correlation built in it, so equation 9 is modified to

$$N_{1,t+1} = g(E_t)e^{\varepsilon} \quad \text{where } \varepsilon \sim \sigma^2 N(0,1) \qquad \text{eq. 10}$$

Auto-correlation in the process error term is defined as

$$\varepsilon_t = \phi\varepsilon_{t-1} + (\sqrt{1-\phi^2})\varepsilon_t \quad \text{where } \varepsilon_t \sim \sigma^2 N(0,\sigma^2) \qquad \text{eq.11}$$

$$C_t = \sum_a u_t v_a N_{a,t} w_a \qquad \text{eq. 12}$$

Where

$N_{a,t}$ number of individuals age a time t

u_t fraction harvested time t

v_a vulnerability to fishing age a

n oldest age considered

s_a survival from natural mortality

E_t spawning biomass time t

f_a egg production age a

g recruitment function (B/H, Ricker etc)

C_t biomass of catch

w_a mass at age a

ϕ is the autocorrelation term, and can be between 0 and 1.

Albacore (Based on SS-III model presented in WPTmT 2012 by Kitikado et. al. 2012)

For an Albacore like Indian Ocean Tuna stock the following could be determined based on the following parameters shown in Table 1.

Table 1: Parameter values from the Albacore Assessment (IOTC 2012-WPtmT04-11 Rev_2).

Biological and ecological structures	
#Gender Group	1 (Sex ratio 1:1)
Age classes	0 - 10
Natural mortality	M=0.2207 (/year) constant over ages
Growth formula	L=147.5(1-exp(-0.126(t+1.89))) common to sex
Weight-length allometry	$W = aL^b$ with $a = 5.691 \times 10^{-5}$, $b = 2.7514$. common to sex.
Maturity	Age-specific (0 for Age <=3, 0.25 for Age=4, 0.5 for Age=5, 0.75 for Age=6 and 1 for Age>=7)
Fecundity	Proportional to the spawning biomass
Spawner-recruitment	B-H (fixed steepness at 0.8) and sigma_R=0.2

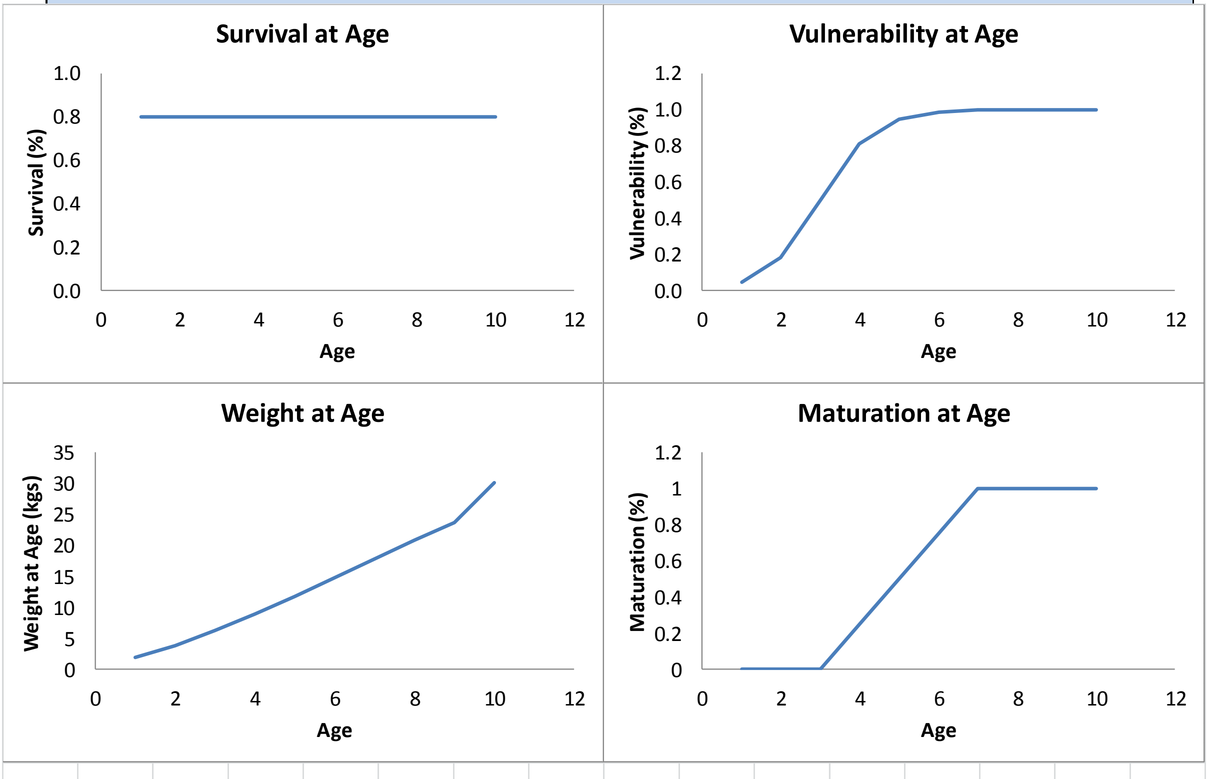


Figure 3: Graphical values of the key parameter values used in simulation

Based on these R0 and B0 as estimated from SS-III **(IOTC 2012-WPtmT04-11 Rev_2)** were 8866 ($e^{9.09}$) and 357351 t respectively using stable age distribution assumptions.

Assuming these parameters and the selectivity curve show above, and equilibrium conditions, u (optimal harvest) was estimated to be 0.42 (42%), S_{MSY} was estimated around 40348 t. Using a process error of 0.6, and average long-term yield levels were around 22kT 9Figure 7) though indicated that S_{MSY} = 108K t (Figure 7), with u=0.18 (F=0.19, Figure 7).

We chose to demonstrate the interim- threshold reference points (0.4*40,348), the threshold reference point is approximately 16,139 t based on stable equilibrium assumptions (or 43K t based on dynamic long-term yield assumptions). Based on the stable equilibrium assumptions (which may not be the most representative), we assess the risk to the population falling below this level as shown in Table 1 under different harvest rates and auto-correlation of process error shown below.

Table 2: Probability of falling below 0.4 S_{MSY} (estimated at 108K t from stable equilibrium assumptions) fishing at different rates and assuming different auto-correlation of the process error term (Note process error was assumed to be 0.6)

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
Auto-correlation	0.6	2%	36%	82%	99%	100%	100%
	0.65	1%	27%	72%	95%	100%	100%
	0.7	1%	20%	61%	89%	98%	100%
	0.75	0%	15%	52%	82%	96%	99%
	0.8	0%	11%	44%	74%	92%	98%
	0.85	0%	8%	36%	67%	87%	96%
	0.9	0%	6%	30%	60%	81%	92%
	0.95	0%	5%	26%	54%	75%	88%

Using the simulator and evaluating different management actions one can also evaluate the amount of time it takes (years) to get back to optimal spawning stock size given these assumptions, as well as other distributions as shown in Figure 4 and 5 below.

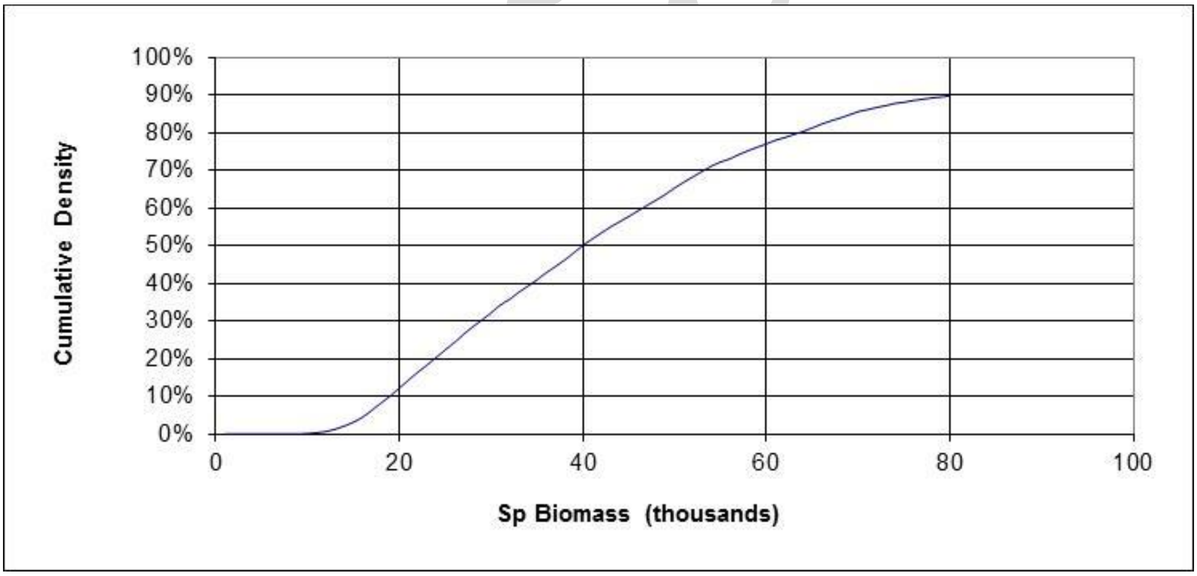


Figure 4: Assuming an auto-correlation, φ=0.33, a harvest rate, u=0.3, and a process error of 0.6, the cdf of the Spawning Biomass for an Indian Ocean Albacore like species indicates a less than 10% chance of ever going below 20K t, and a 3.7% chance it will go below the 0.4 SB_{MSY} threshold.

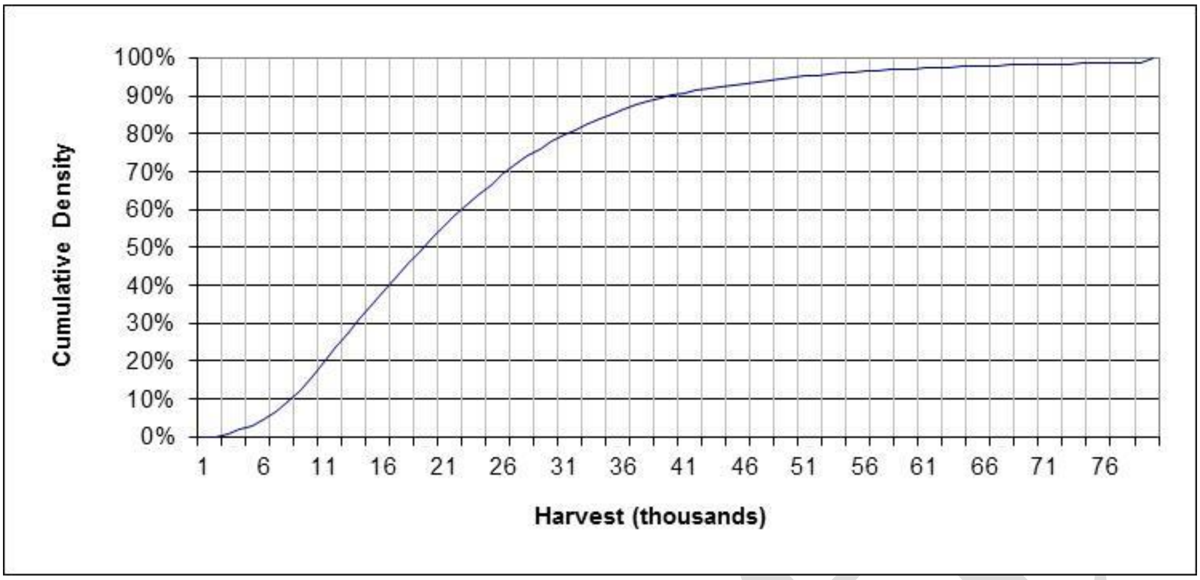


Figure 5: A cdf on the harvest estimates based on auto-correlation, φ=0.33, and a harvest rate, u=0.3. The average and median harvest estimates are ~24K and ~20K t respectively.

Table 2 above indicates that as long as auto-correlation, ϕ<0.5, there is fairly low probability <6% of going below the limit reference points and fishing at optimal rates (stable equilibrium rates indicate u=0.4, but the simulated rates show optimal u = 0.21). However, if there are clear decadal and regime changes in recruitment prevalent (ϕ>0.8), if we would like the p<0.05, the target harvest rate, 0.15<u<<0.2. Finer resolution values could be estimated with the simulator as needed, but this tool developed shows us how it could be used over the long run.

Finally, based on these values, we can assess the average rebuilding time if the population ever goes below these levels and we take a cut in harvest rates of 34% every time we go below the threshold limit reference point on Spawning Biomass to be above the threshold (Table 3), and above the target (Table 4). Note these values would be lower if the AMA goes to no fishing levels beyond those limits, i.e. a 100% cut in harvest rates when we exceed the limits.

Type I and Type II Errors for Albacore in relation to reference points.

For albacore, unless populations are dropped substantially below 30% of SMSY, the chances of making a Type II error are low. However, as we tend to manage more towards the target, then the Type I errors increase (Figure 6 below). For profiles here, the target exploitation rate was 0.3 (F=0.36) that is substantially higher than the estimated rate of F=0.19. If operated at those rate (F=0.19), the type I error is ~0. They Type II error is almost 1 at those rates, i.e. the chance of failing to detect a drop in productivity if fished at optimal rates is 1. However the risk to the fishery is low (0), as exploitation rates are extremely low for the population. In recent years, these rates are a lot higher and these are the rates (approximately) used to demonstrate the risk profiles shown in Figure 6.

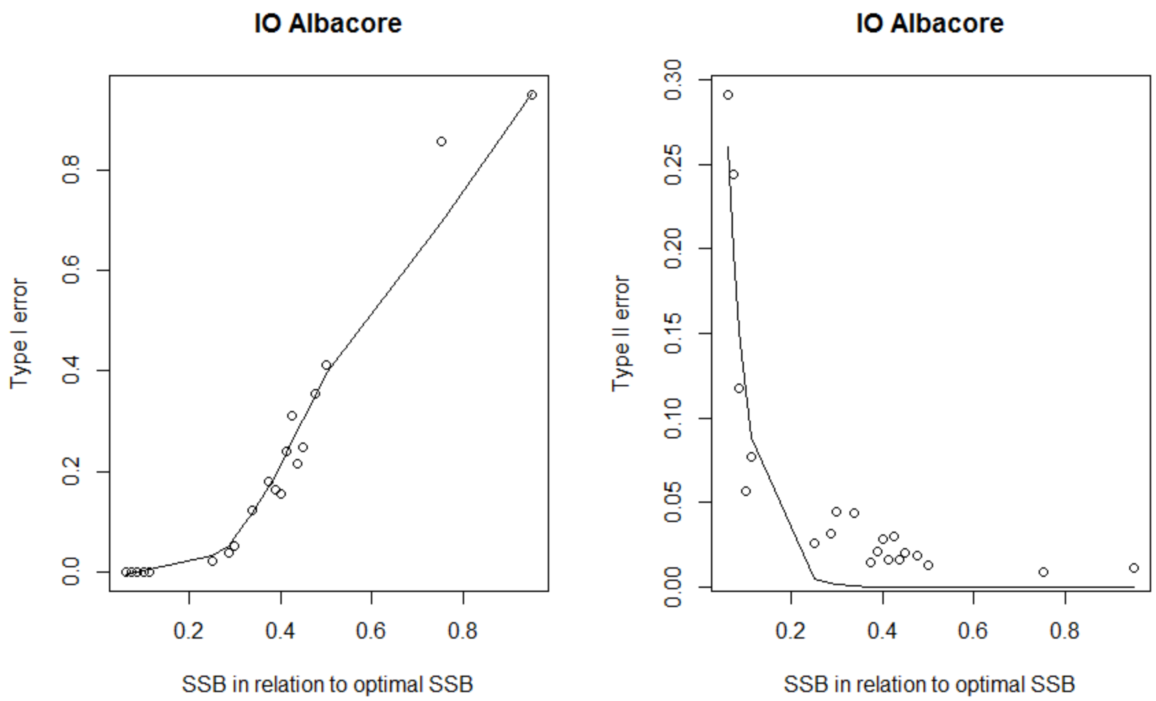


Figure 6: Type 1 and type II Errors simulated for an Albacore like stock in the IO with a 15% drop in productivity and fishing at u of 0.3 (F=0.36), with $\varphi=4$.

Table 3: The average number of years it would take the population to exceed the *limit* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.4 S_{MSY} (estimated at 108K t) and assuming different rates of fishing, and different auto-correlation of the process error term.

	Harvest Rate					
Auto-correlation	0.1	0.2	0.3	0.4	0.5	0.6
0.1	0	3	4	8	21	70
0.15	1	3	5	8	21	70
0.2	1	3	5	8	22	71
0.25	1	3	5	9	23	71
0.3	1	3	5	9	24	72
0.35	2	4	6	9	24	72
0.4	2	4	6	10	25	72
0.45	3	4	6	10	26	73
0.5	3	5	7	11	28	73
0.55	4	5	7	12	29	74
0.6	4	6	8	13	32	74
0.65	5	6	8	15	34	75
0.7	6	7	9	16	35	+76
0.75	7	8	10	18	36	+76
0.8	8	9	12	20	37	+76
0.85	9	10	15	23	38	+76
0.9	12	13	20	26	34	+76

Table 4: The average number of years it would take the population to exceed the *TARGET* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.4 S_{MSY} (estimated at 108K t from stable equilibrium estimation) and assuming different rates of fishing, and different auto-correlation of the process error term (Note 76 is the maximum limit set, so in reality the number of years would be more than 76 for each scenario shown).

	Harvest Rate					
Auto-correlation	0.1	0.2	0.3	0.4	0.5	0.6
0.1	4	8	20	66	+76	+76
0.15	5	8	20	64	+76	+76
0.2	5	8	21	63	+76	+76
0.25	5	9	21	62	+76	+76
0.3	5	9	22	62	+76	+76
0.35	6	10	23	63	+76	+76
0.4	6	10	24	63	+76	+76
0.45	7	11	25	65	+76	+76
0.5	7	11	26	67	+76	+76
0.55	8	12	28	70	+76	+76
0.6	8	13	29	75	+76	+76
0.65	9	14	30	75	+76	+76
0.7	10	15	32	76	+76	+76
0.75	11	17	33	+76	+76	+76
0.8	12	19	37	+76	+76	+76
0.85	15	24	37	+76	+76	+76
0.9	19	29	41	+76	+76	+76

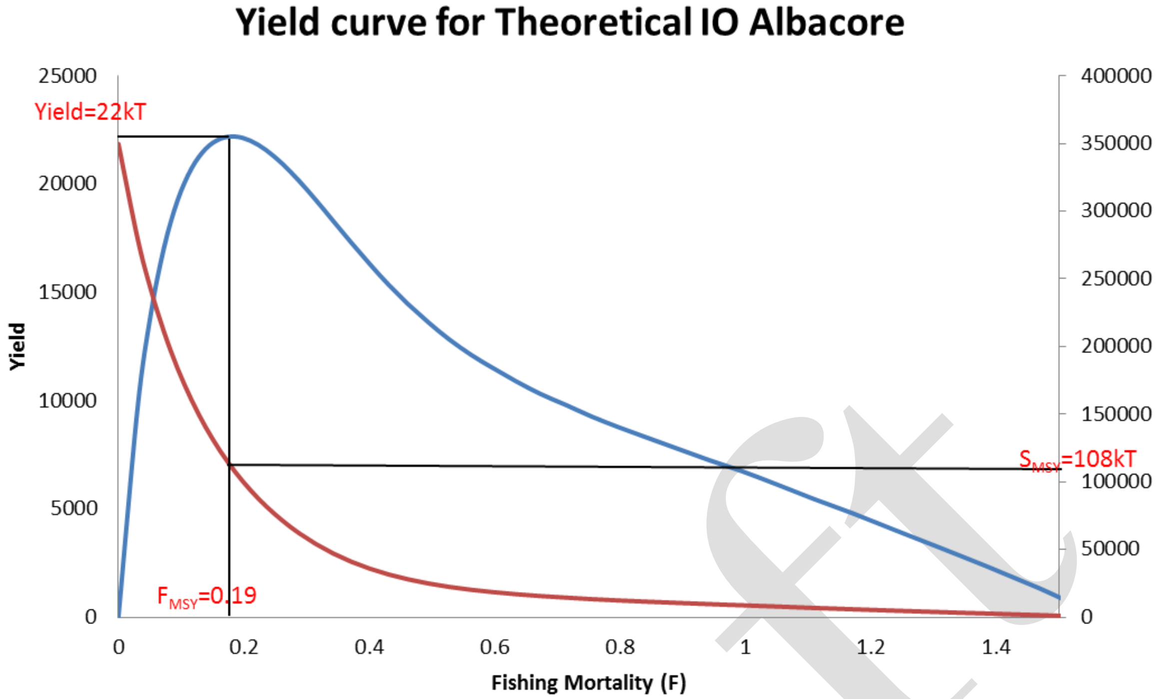


Figure 7: Based on the parameters, the theoretical yield curve for Albacore suggests a max yield of 22kT, F_{MSY} of 0.19 and S_{MSY} of 108kT.

The values displayed above differ from the ASPM model estimates presented in WPTmT. This is primarily because the more complicated models such as SS-3/ASPM were used in the assessment. ***This model uses only one area, and one fishery, whereas SS-3 has a lot more complex structure using numerous fisheries operating in the IO Region so the estimates are not to be relied upon. However, in non-dimensional units (i.e. F_{yr}/F_{MSY} or SB_{yr}/SB_{MSY}), it is useful for providing guidelines for a species or stock with similar life-history traits.***

Skipjack tuna (Based on model M12 Single area, fixed M, lower CV on CPUE higher eff N)

An age structured model on skipjack was also developed using similar biological parameters (Table 5, Figure 8) from the version used in the SS-III assessment.

Table 5: Biological Data for Skipjack Tuna

Parameter	Values
Gender group	1: Sex Ratio (1:1)
Age Class	0-8 (8 ages)
M at age	0.8/yr across all ages (survival=0.45/yr)
Growth	L(inf)=70, K=0.37, t(0)=0
Weight	α= 0.00000532, β = 3.35
Proportion Mature	0 to age 3, 0.25 (age 4), 0.5 (age 5), 0.75 (age 6), (age 7 and 8)
Fecundity	Proportional to Weight
Recruitment	h=0.8 (Sigma R= 0.55)

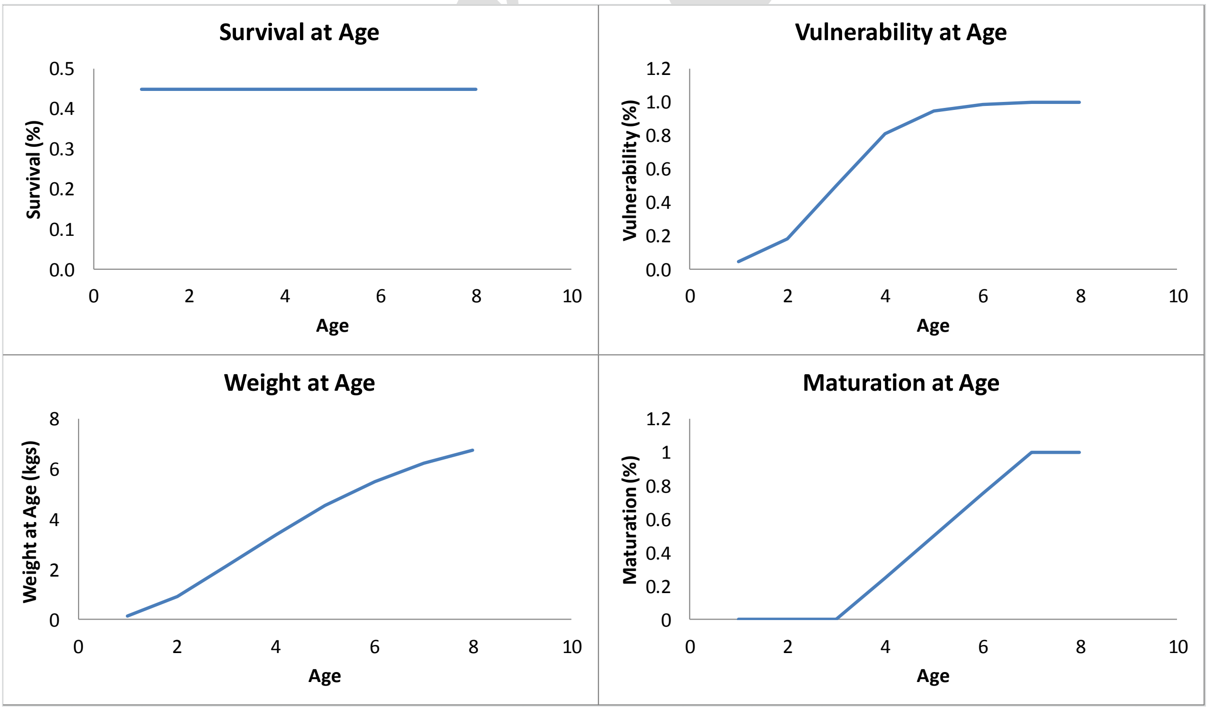


Figure 8: Key parameter values used for the skipjack simulation

Parameters derived from the simulation show that if the target reference point is around 650Kt (derived from SS-III), then the chances of taking an AMA at 250K tones is high (>45%, Figure 9) though yield targets remain high at these levels and is consistently around 400k T (Figure 10). However, using the parameters for the run developed here, the optimal spawning stock size is near 250K, or the 40% limit is closer to 100K t, and chances we go below that level is less than 1% when fishing at optimal rates. However, unlike Albacore, the chances of making a type II error on this population are extremely high at this level (Figure 11 and Figure 13). Hence, to be more conservative on Skipjack, one should manage the populations closer to the target rather than the limit. 60-75% of S_{MSY} from Figure 11 gives us a Type-II error that is less than 5%. But this is almost at the target level of SMSY in Figure 13 (derived from the selectivity curves and parameters used in this simulation).

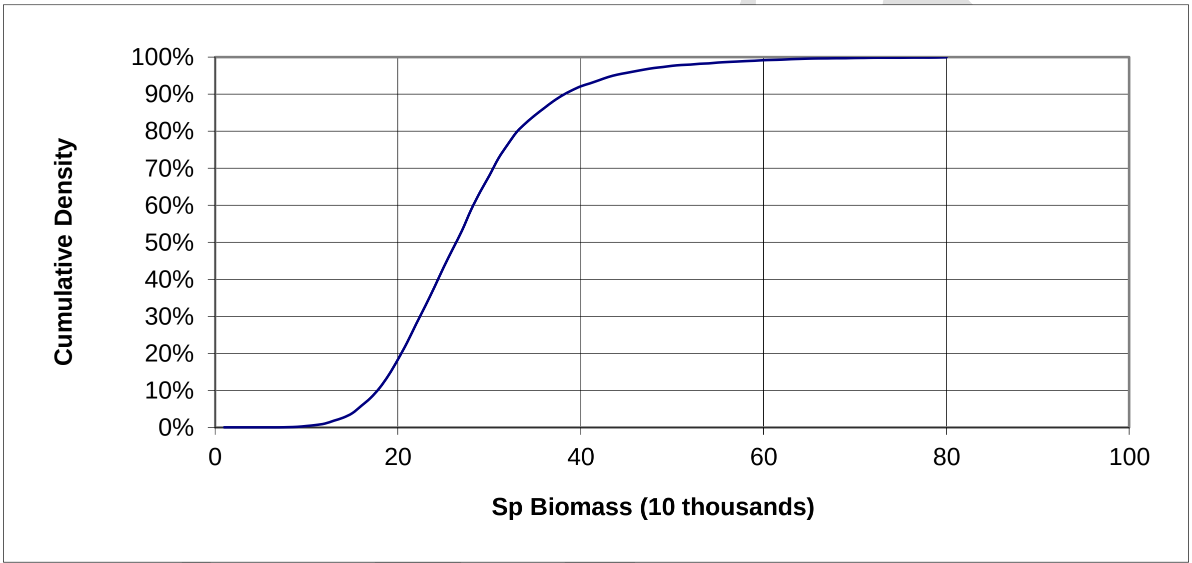


Figure 9***: Assuming an auto-correlation, φ=0.4, a harvest rate, u=0.4, the cdf of the Spawning Biomass for an Indian Ocean Skipjack like species indicates a less than 20% chance of ever going below 200K t, and less than 1% chance to be below 100kt.***

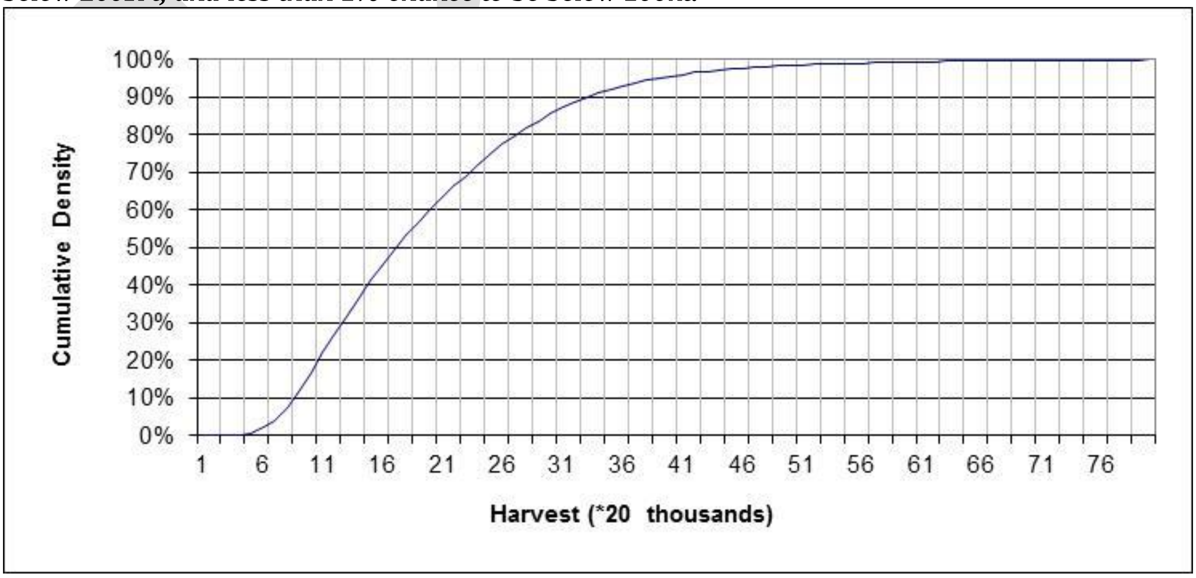


***Figure 10: A cdf on the harvest estimates based on auto-correlation, φ=0.4, and a harvest rate, u=0.4 (F=0.52). The average and median harvest estimates are ~409K and ~362K t respectively*.**

Type I and Type II Errors for Skipjack

Figure 11 illustrates that when the target reference point is the same as the limit reference point (i.e. SMSY), the chances of taking a decision to restrict the fishery when it isn't really needed is high. However, as we drop the limit to a lower value, the chances of taking a decision incorrectly diminishes significantly (left side of Figure 11). On the other hand, if we drop the limit reference point, and there is an adverse event that occurs dropping productivity, the probability of failing to detecting that drop is extremely high (right hand side of Figure 11), hence the limit should balance the risk of a type I versus Type II error.

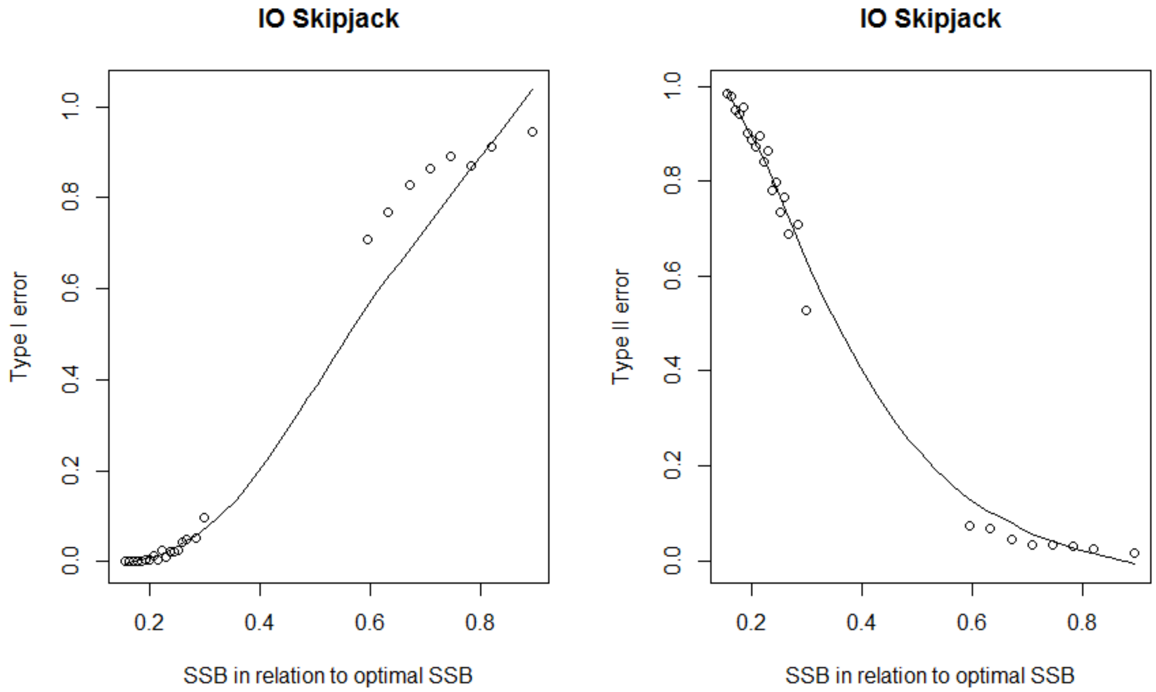


Figure 11: ***Assuming an auto-correlation, φ=0.4, a harvest rate, u=0.4, the type I Error (i.e. Taking a Management Action to restrict a fishery when it isn't needed, due to natural variation) and the type II error (failing to take a management action in a fishery when it was needed).***

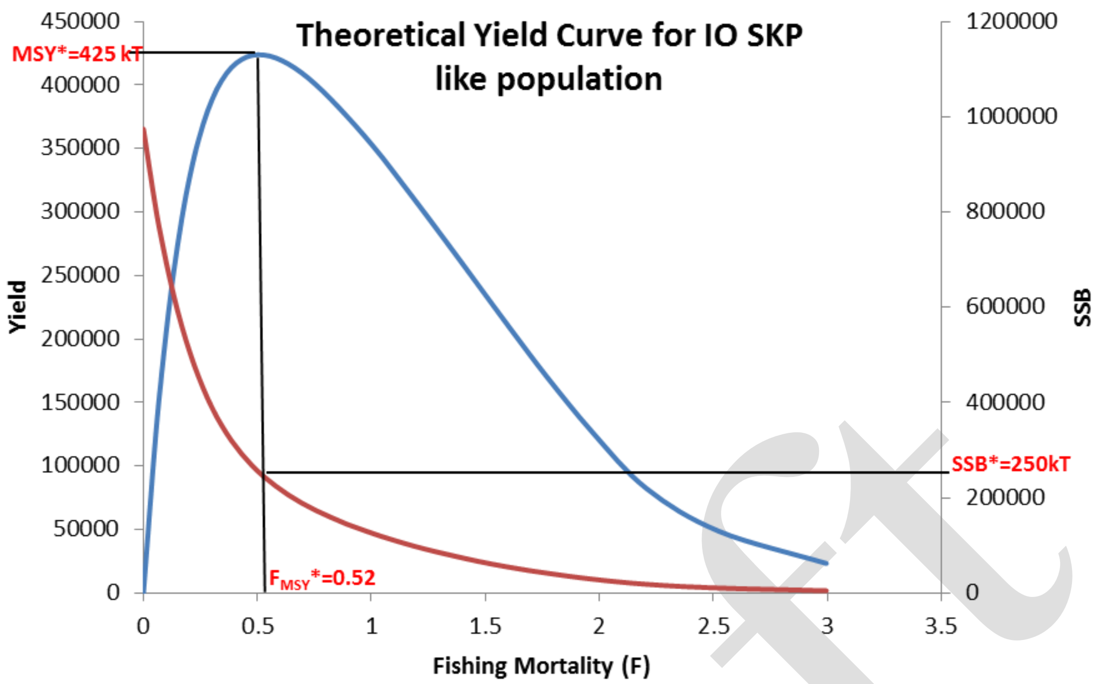


Figure 12: Yield vs F for Theoretical IO Skipjack population with 1 fishery and specified selectivity above

While evaluating the SS-III derived optimal SSB, one should not that the SSB based on the selectivity curve and yield curves for Skipjack (from parameters used in table 5) suggest a optimal SSB around 250kT (Figure 12 above). If we would use that as the derived reference point, then the Type 1 and Type II error curve, would change as shown in Figure 11 (scaled differently). **Note, these values will differ from the more complicated SS-3 assessment as this uses only one area, and one fishery, whereas SS-3 has a lot more complex structure using tagging data, and numerous fisheries operating in the IO Region.**

As was evident with Albacore (Tables 2, 3 and 4) as we increase the harvest rate (or fishing mortality, F), we tend to push the stock below the limit reference points for longer times. At lower harvest rates (u<0.4, F<0.51) the stock tends to bounce back fairly quickly from below the limit to above it (Table 6). However, it takes a substantially longer time to get to the target (Table 7), and unless fished substantially below the optimal rates, the stock will take a lot longer to rebound. In addition (Figure 11) indicate that the closer one fishes to the target, the lesser are the chances of making a Type II error (however this penalizes the fisheries), and some balancing of these two risks needs to occur. Finally (as indicated by Table 9) if the stock is more productive than the chances of going below the limits are lower though at higher harvest rates (u=0.6, F=0.92) the stock will still remain below the 40% of SMSY Threshold 252k T (when S_{MSY}=670.5KT), as is evident from Table 8 (Figure 13).

Table 6: The average number of years it would take the population to exceed the *limit* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.4 S_{MSY} (estimated at 250K t from this formulation) and assuming different rates of fishing, and different auto-correlation of the process error term.

	Harvest Rate					
Auto-correlation	0.1	0.2	0.3	0.4	0.5	0.6
0.1	0	0	0	1	1	3
0.15	0	0	0	1	1	3
0.2	0	0	0	1	1	3
0.25	0	0	0	1	2	3
0.3	0	0	1	1	2	3
0.35	0	0	1	1	2	3
0.4	0	0	1	1	2	3
0.45	0	0	1	1	2	4
0.5	0	0	1	1	2	4
0.55	0	1	1	2	3	4
0.6	0	1	2	2	3	4
0.65	0	1	2	2	3	5
0.7	0	1	2	2	3	+76
0.75	1	2	2	3	4	+76
0.8	3	3	3	3	4	+76
0.85	3	4	4	4	20	+76
0.9	4	5	4	6	64	+76

Table 7: The average number of years it would take the population to exceed the *TARGET* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.4 S_{MSY} (estimated at 250 Kt from SS-III) and assuming different rates of fishing, and different auto-correlation of the process error term (Note 76 is the maximum limit set, so in reality the number of years would be more than 76 for each scenario shown).

	Harvest Rate					
Auto-correlation	0.1	0.2	0.3	0.4	0.5	0.6
0.1	0	1	1	3	7	+76
0.15	0	1	2	3	7	+76
0.2	1	1	2	3	7	+76
0.25	1	1	2	3	7	+76
0.3	1	1	2	4	8	+76
0.35	1	1	2	4	8	+76
0.4	1	1	2	4	71	+76
0.45	1	2	3	4	73	+76
0.5	1	2	3	5	75	+76
0.55	2	2	3	5	+76	+76
0.6	2	2	3	5	+76	+76
0.65	2	3	4	6	+76	+76
0.7	3	3	4	6	+76	+76
0.75	3	4	5	17	+76	+76
0.8	4	4	6	21	+76	+76
0.85	5	6	10	41	+76	+76
0.9	6	7	18	+76	+76	+76

Table 8: Probability of dropping below the threshold (252Kt) when the harvest rates and steepness parameters vary

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
STEEPNESS	0.6	0%	1%	15%	57%	87%	99%
	0.65	0%	0%	9%	46%	80%	96%
	0.7	0%	0%	4%	32%	69%	90%
	0.75	0%	0%	2%	19%	54%	81%
	0.8	0%	0%	1%	8%	36%	67%
	0.85	0%	0%	0%	3%	19%	48%
	0.9	0%	0%	0%	1%	7%	26%
	0.95	0%	0%	0%	0%	2%	9%

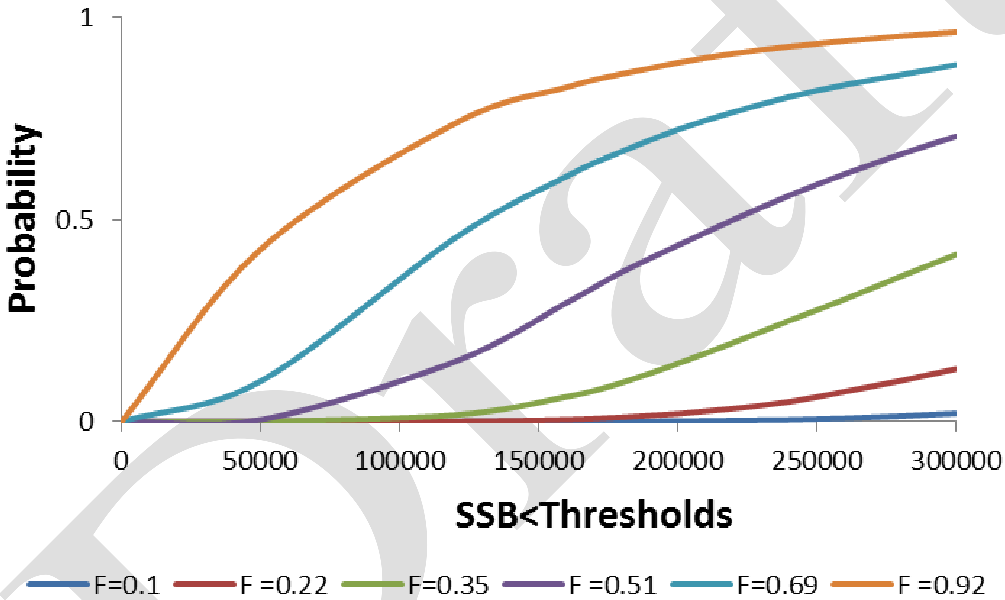


Figure 13: Probability of going below various thresholds at different levels of Fishing Mortality (F)

Bigeye Tuna

Bigeye Tuna analysis was based on the base run done in 2013 (Langley et. al. 2013).

Table 9: Biological Data for Bigeye Tuna

Parameter	Values
Gender group	**1: Sex Ratio (1:1)**
Age Class	**0-10 (10 ages)**
M at age	**M=0.8/age till age 2, 0.25/yr across all ages after that (survival=0.45/yr, and 0.78/yr pre and post 2 year olds respectively)**
Growth	**2 Stanza growth using VB log K curves (Eveson et. al. 2012) l_{inf}=150.9, k_1=0.15 k_2=0.51, α=3.4, β = 20, a=1.02, a_0=-1.2** $l(a) = L_\infty f(a - a_0; \theta)$ $f(a - a_0; \theta) = 1 - \exp(-k_2(a - a_0)) \left\{ \frac{1 + \exp(-\beta(a - a_0 - \alpha))}{1 + \exp(\alpha\beta)} \right\}^{-(k_2 - k_1)/\beta}$
Weight	**α= 0.00003661, β = 2.90**
Proportion Mature	**0 to age 3, 0.25 (age 4), 0.5 (age 5), 0.75 (age 6), 1(age 7-10+)**
Fecundity	**Proportional to Weight**
Recruitment	**h=0.8 (Sigma R= 0.55), R_0=29840 and E_0=904211 (from Langley et. al. 2013)**

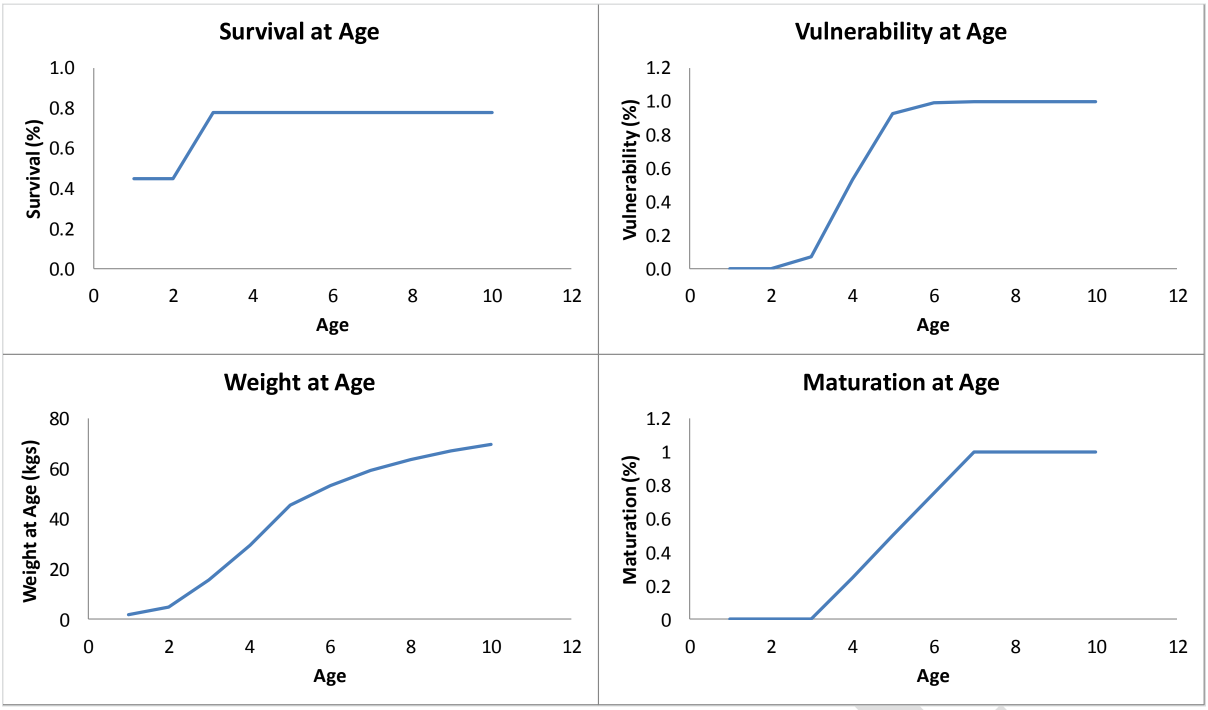


Figure 14: Key parameters on mortality, maturation selectivity and weight by age for BET

Based on this formulation (Figure 14, table 9), we ran a simulation again and evaluated the risk to the stock and the average catches (Figure 16) and spawning biomass (Figure 15) obtained by operating under optimal fishing conditions (F=0.22) and some natural variation. As with Albacore and Skipjack, we can quantify the probability of taking an AMA based on the parameters in Table 9, and the fishing rate (Figure 16). Thus based on this scenario, the chance of falling below 50% of S_{MSY} operating at optimum fishing levels is less than 1% (Figure 15).

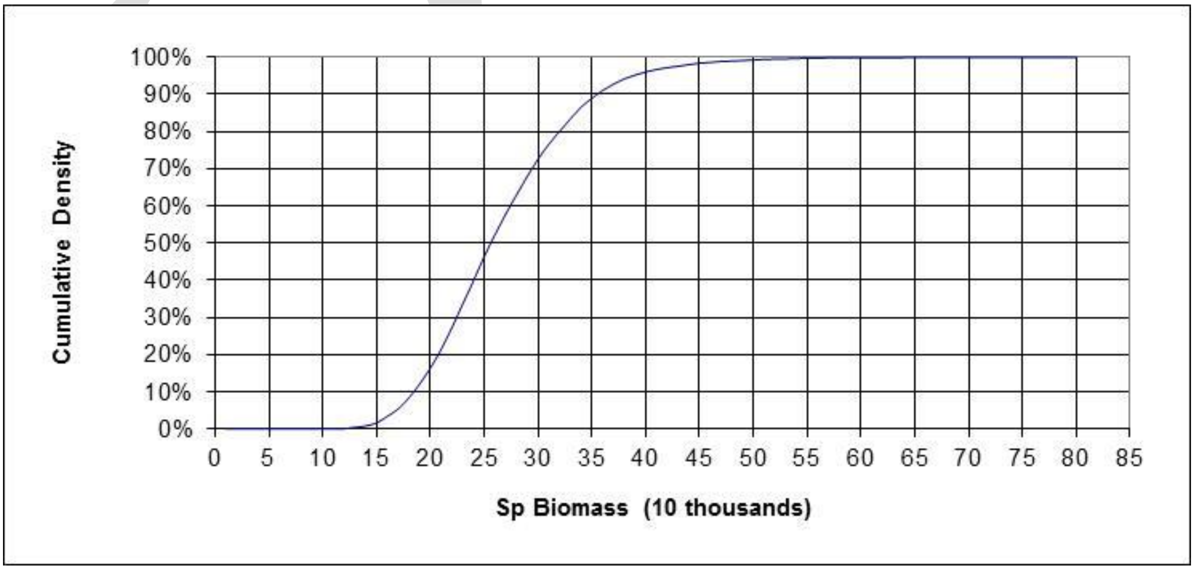


Figure 15: ***Assuming an auto-correlation, φ=0, a harvest rate, u=0.2 (F=0.22), the cdf of the Spawning Biomass for an Indian Ocean BET like species indicates a less than 20% chance of ever going below 200K t, and less than 1% chance to be below 125kt.***

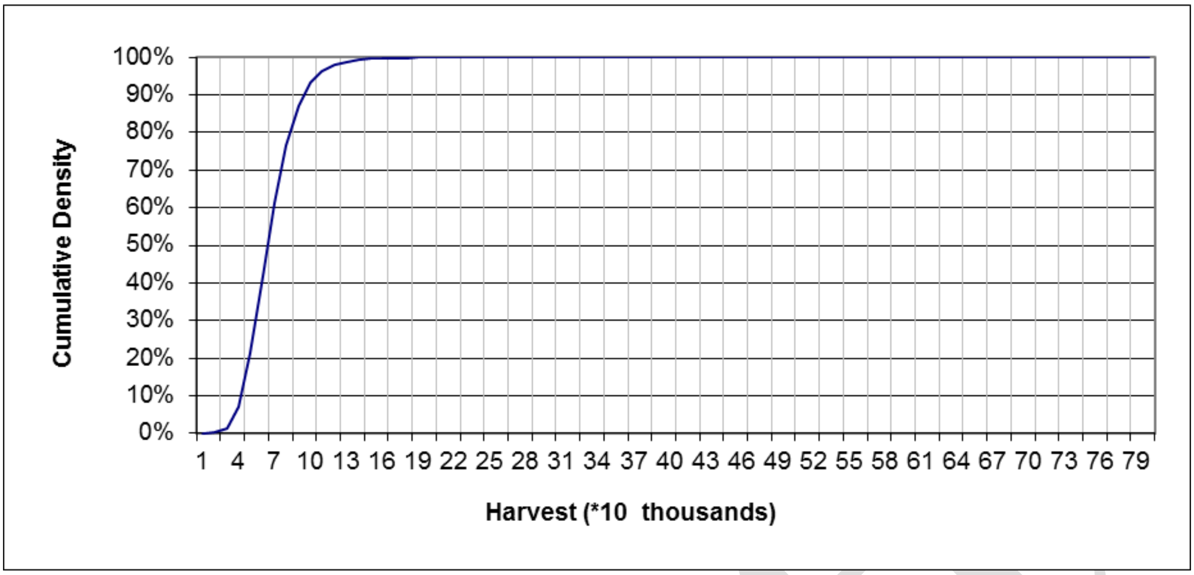


Figure 16: ***Assuming an auto-correlation, φ=0, a harvest rate, u=0.2 (F=0.22), the cdf of the catch for an Indian Ocean BET like species indicates the average and median harvest estimates are ~77K and ~74K t respectively***.

Type I and Type II errors for Bigeye

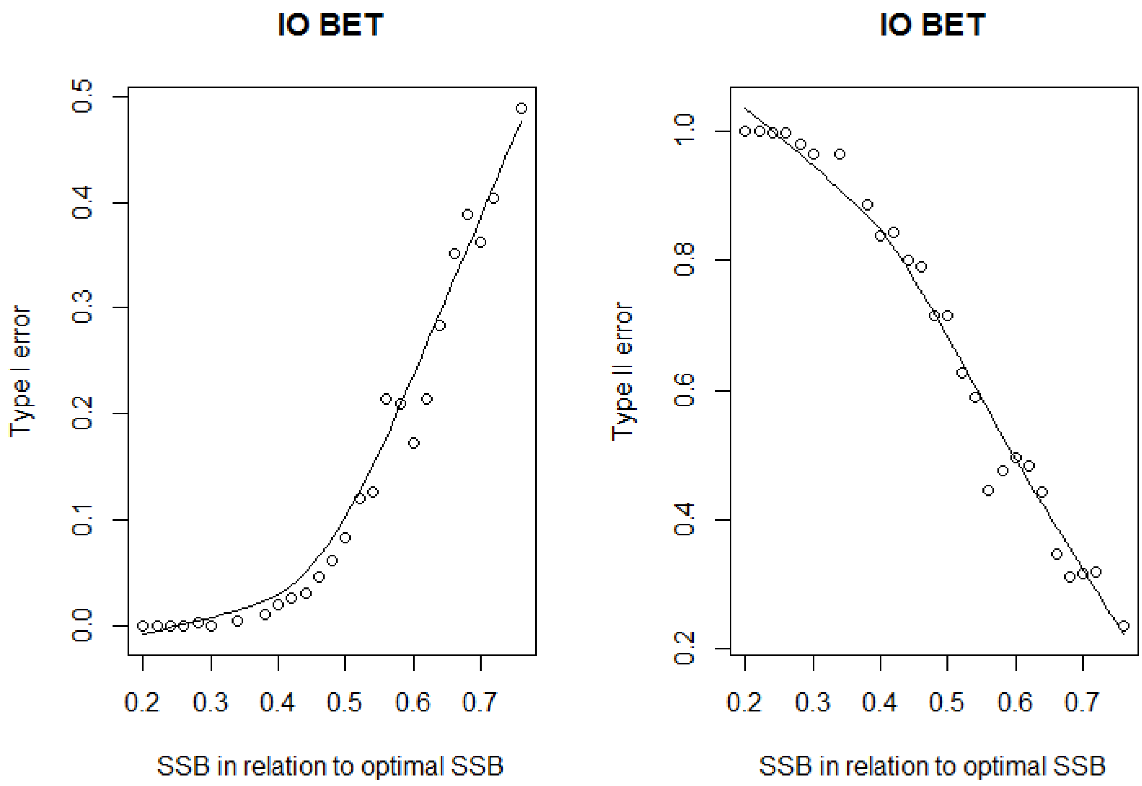


Figure 17: ***Assuming an auto-correlation, φ=0.4, a harvest rate, u=0.2 (F=0.22), the type I Error (i.e. Taking a Management Action to restrict a fishery when it isn't needed, due to natural variation) and the type II error (failing to take a management action in a fishery when it was needed). Note optimal SSB is taken from the scenario run here (250K is the target and 125K is the limit reference point based on 50% of the target). Note, for these simulations we use only one M across all ages (M=0.55)***

Operating at optimal harvest rates (F=0.22), and evaluating the limit (50% Target, I.e S_{MSY}) the probability of committing a type II error (i.e. failure to detect overfishing if there is a 15% drop in productivity) declines rapidly once the limit exceeds 60% the target. At 50% of the target, the chance of making a type 1 error is less than 10%; however the type II error is high at close to 60%. Only once we have a limit that exceeds 70% does the type II error drop (Figure 17). However, then the type I error increases to 50% (one of two time we will unnecessarily restrict a fishery). Based on balancing these two risks, a value of 60% maybe more appropriate.

Finally, risk to the IO BET like population and the time to reach limits and targets under different scenarios is shown in Table 10 and 11 respectively. As we exceed target FMSY (u=0.2), we see the recovery time increases significantly for these populations (Table 10 and 11 respectively). However, operating at optimal rates, and having simple control rules decreasing these rates keeps these populations conserved in the long run (Table 10 and 11 respectively). The effect of steepness and fishing mortality rates is shown in Table 12 (below).

Table 10: The average number of years it would take the population to exceed the *limit* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.5 S_{MSY} (estimated at 125K t from the model developed here) and assuming different rates of fishing, and different auto-correlation of the process error term. (Note 76 is the maximum limit set, so in reality the number of years would be more than 76 for each scenario shown). Once we exceed F_{MSY} by a factor of 2, the chances of coming back to the limit are very low if we have an auto-correlated process driving process error.

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
Auto-correlation	0.1	0	1	1	3	7	+76
	0.15	0	1	2	3	7	+76
	0.2	1	1	2	3	7	+76
	0.25	1	1	2	3	7	+76
	0.3	1	1	2	4	8	+76
	0.35	1	1	2	4	8	+76
	0.4	1	1	2	4	71	+76
	0.45	1	2	3	4	73	+76
	0.5	1	2	3	5	75	+76
	0.55	2	2	3	5	+76	+76
	0.6	2	2	3	5	+76	+76
	0.65	2	3	4	6	+76	+76
	0.7	3	3	4	6	+76	+76
	0.75	3	4	5	17	+76	+76
	0.8	4	4	6	21	+76	+76
	0.85	5	6	10	41	+76	+76
	0.9	6	7	18	+76	+76	+76

Table 11: The average number of years it would take the population to exceed the *TARGET* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.5 S_{MSY} (estimated at 250 Kt) and assuming different rates of fishing, and different auto-correlation of the

process error term (Note 76 is the maximum limit set, so in reality the number of years would be more than 76 for each scenario shown).

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
Auto-correlation	0.1	0	73	+76	+76	+76	+76
	0.15	0	73	+76	+76	+76	+76
	0.2	0	73	+76	+76	+76	+76
	0.25	0	73	+76	+76	+76	+76
	0.3	0	73	+76	+76	+76	+76
	0.35	0	74	+76	+76	+76	+76
	0.4	0	75	+76	+76	+76	+76
	0.45	0	75	+76	+76	+76	+76
	0.5	64	+76	+76	+76	+76	+76
	0.55	63	+76	+76	+76	+76	+76
	0.6	65	+76	+76	+76	+76	+76
	0.65	68	+76	+76	+76	+76	+76
	0.7	69	+76	+76	+76	+76	+76
	0.75	70	+76	+76	+76	+76	+76
	0.8	71	+76	+76	+76	+76	+76
	0.85	72	+76	+76	+76	+76	+76
	0.9	74	+76	+76	+76	+76	+76

Table 12: Probability of dropping below the threshold (125Kt) when the harvest rates and steepness parameters vary

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
STEEPNESS	0.6	0%	28%	91%	100%	100%	100%
	0.65	0%	16%	84%	100%	100%	100%
	0.7	0%	7%	72%	98%	100%	100%
	0.75	0%	2%	55%	92%	100%	100%
	0.8	0%	0%	33%	82%	98%	100%
	0.85	0%	0%	12%	64%	90%	99%
	0.9	0%	0%	2%	36%	75%	92%
	0.95	0%	0%	0%	10%	46%	75%

Finally, based on these assumptions and simulating the populations with the process error and no auto-correlation obtains a yield curve shown in Figure 18. Based on a simple fishery with logistic selectivity and the assumed maturation and weight at age, the target reference points for obtaining maximum yield are approximately 77k tons, and the optimal spawning Biomass is around 250kt. **Note, these values will differ from the more complicated SS-3 assessment as this uses only one area, and one fishery, whereas SS-3 has a lot more complex structure using spatial dynamics (movement), tagging data, and numerous fisheries operating in the IO Region.**

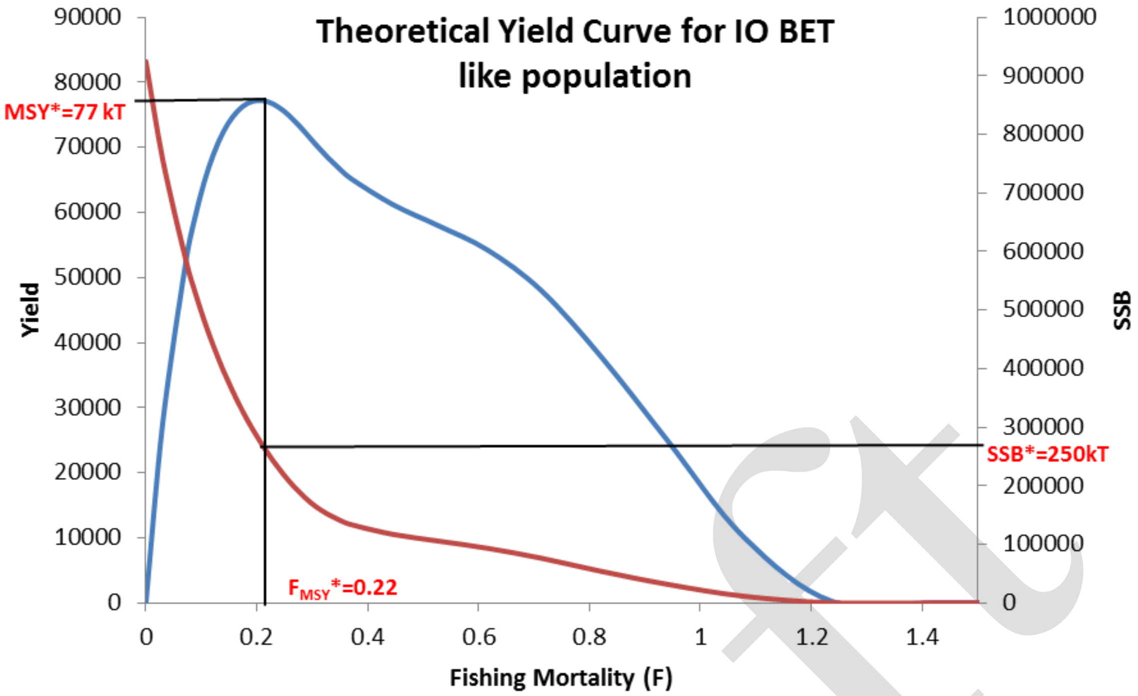


Figure 18: Based on the parameters, the theoretical yield curve for an IO Bigeye like stock suggests a max yield of 77kT, F_{MSY} of 0.22and S_{MSY} of 250kT.

Yellowfin Tuna

Yellowfin Tuna analysis was based on the base run done in 2012 (Langley et. al. 2012) for the biological data, and based on the other fishery parameters shown in Figure 19.

Table13: Biological Data for Bigeye Tuna

Parameter	Values
Gender group	**1: Sex Ratio (1:1)**
Age Class	**0-10 (10 ages)**
M at age	**M=0.8/age till age 2, 0.4/yr for age 4,5, and 0.3/yr across all other ages**
Growth	**2 Stanza growth using VB log K curves (Eveson et. al. 2012) l_{inf}=145, k_1=0.26 k_2=0.85, α=2.4, β = 20, a=0.67, a_0=-0.3** $l(a) = L_{\infty} f(a - a_0; \theta)$ $f(a-a_0;\theta) = 1 - \exp(-k_2(a-a_0)) \left\{ \frac{1+\exp(-\beta(a-a_0-\alpha))}{1+\exp(\alpha\beta)} \right\}^{-(k_2-k_1)/\beta}$
Weight	**α= 0.0000187, β = 3.02**
Proportion Mature	**0.03 age 1, 0.1 age 2, 0.15 age 3, 0.25 (age 4), 0.5 (age 5), 0.75 (age 6), 1(age 7-10+)**
Fecundity	**Proportional to Weight**
Recruitment	**h=0.8 (Sigma R= 0.55), R_0=35479 and E_0=1213971(from Langley et. al. 2012)**

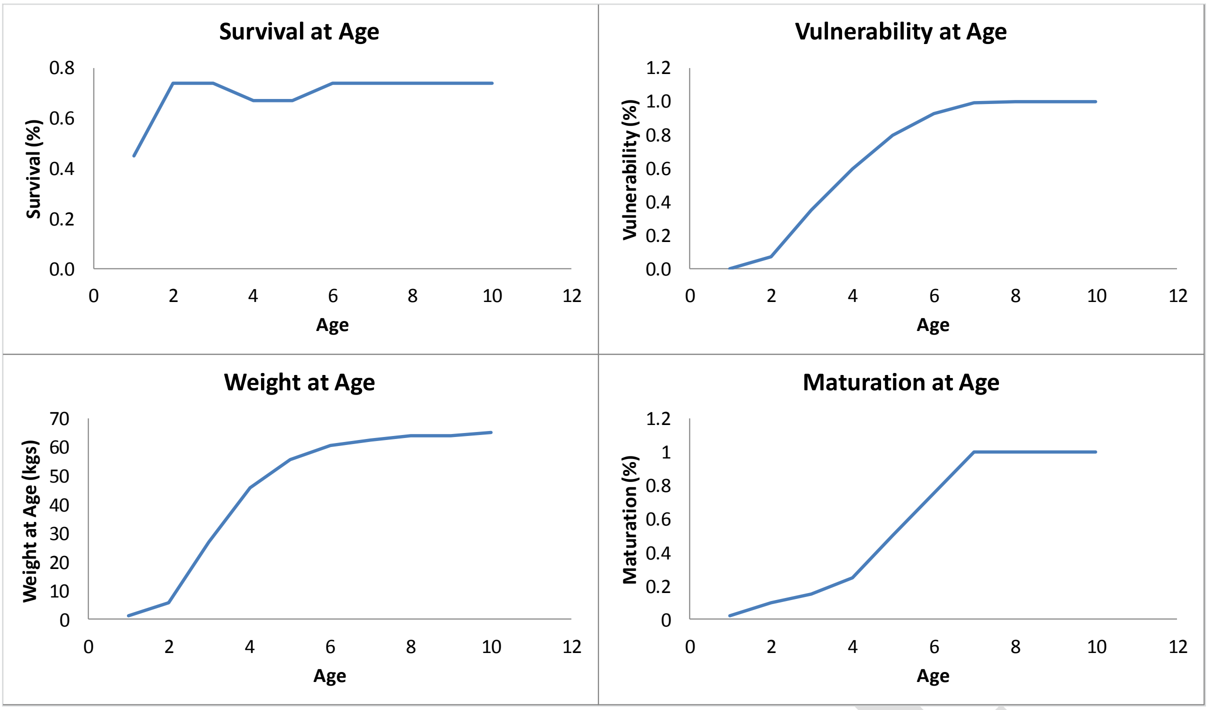


Figure 19: Survival , proportion vulnerable to a fishery, weight and proportion mature by age for YFT.

Similar profiles as to BET were generated for YFT. The chance of going below 140K t (40% of S_{MSY} estimated at 350K t, Figure 20) is very low (<1%). In addition catch profiles indicate a fairly healthy fishery reaching optimal yield targets as estimated from the simplified model (Figure 21).

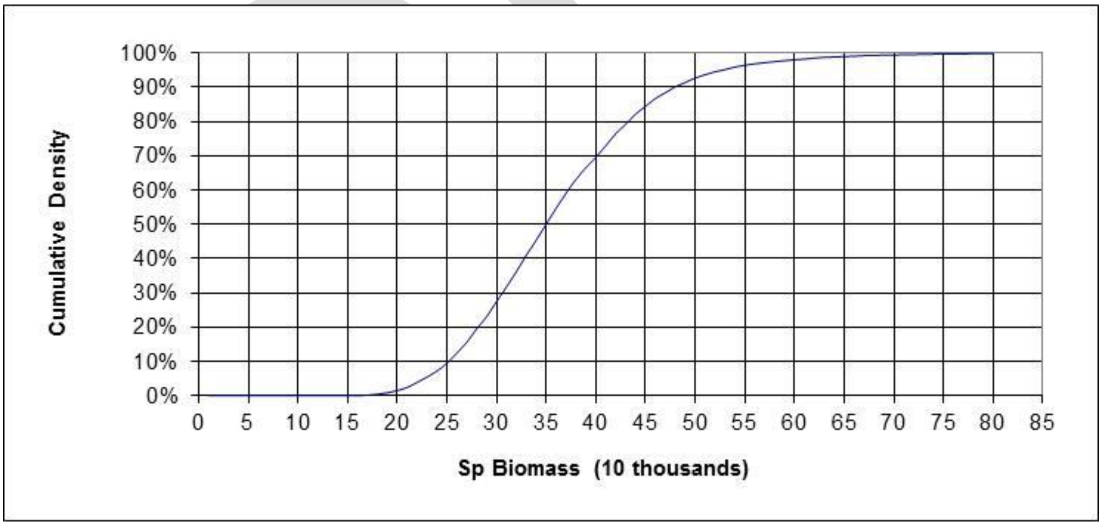


Figure 20: ***Assuming an auto-correlation, φ=0, a harvest rate, u=0.25 (F=0.29), the cdf of the Spawning Biomass for an Indian Ocean YFT like species indicates a less than 10% chance of ever going below 250K t, and less than 1% chance to be below 150kt.***

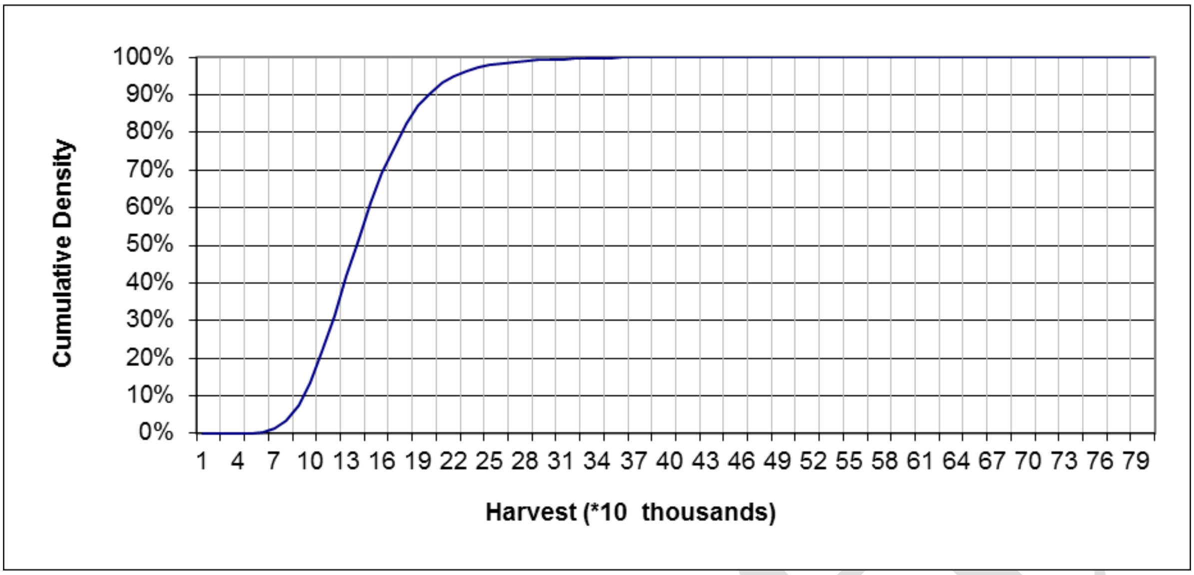


***Figure 21: Assuming an auto-correlation, φ=0, a harvest rate, u=0.25 (F=0.29), the cdf of the catch for an Indian Ocean BET like species indicates the average and median harvest estimates are ~153Kt and ~148K t respectively*.**

Type I and Type II Errors for Yellowfin Tuna

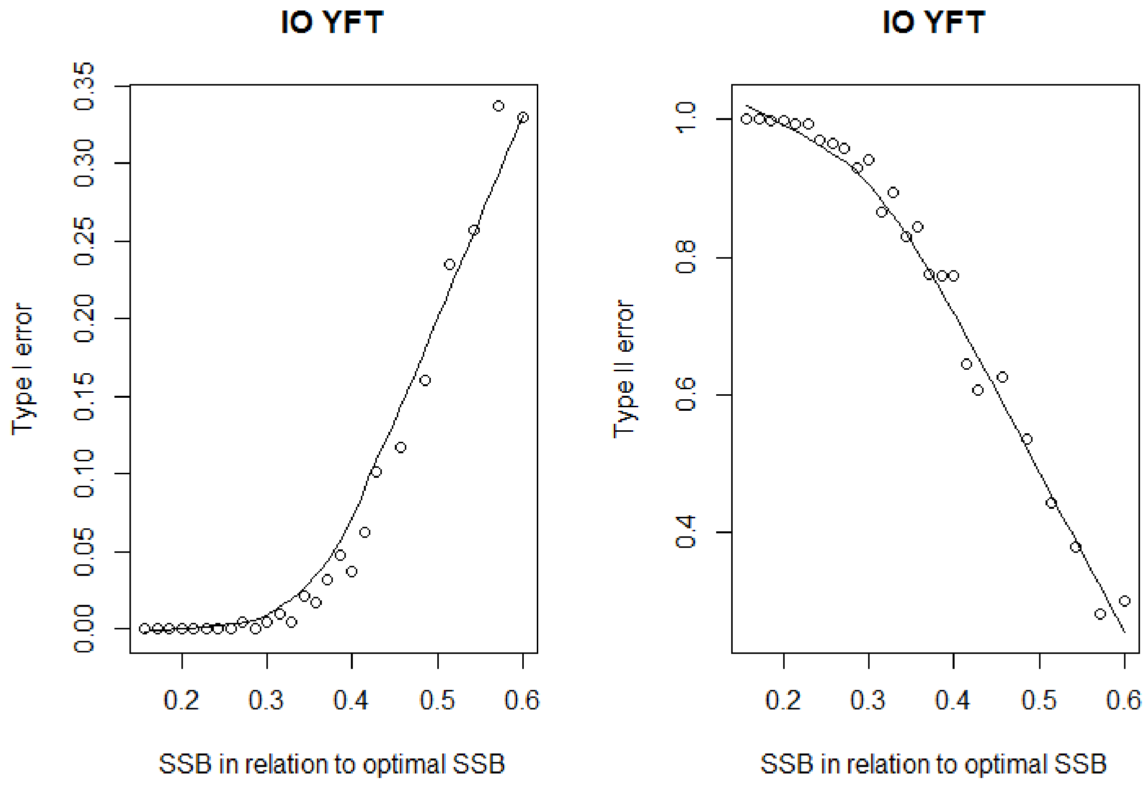


Figure 22: ***Assuming an auto-correlation, φ=0.4, a harvest rate, u=0.25 (F=0.29), the type I Error (i.e. Taking a Management Action to restrict a fishery when it isn't needed, due to natural variation) and the type II error (failing to take a management action in a fishery when it was needed). Note optimal SSB is taken from the scenario run here (350K is the target and 140K is the limit reference point based on 40% of the target). Note, for these simulations we use only one M across all ages (M=0.6)***

We estimated the time to recover to the limit and target reference points using the values estimated from the model (table 14 and 15). As long as the exploitation rate/harvest rate is below F=0.3, the stock appears to be rebound fairly quickly for the limit reference points (Table 14). However, for the target reference points, once we exceed the optimal rate (F=0.29), we have very low chances of ever achieving the target again (Table 15). Chances of going below thresholds go down as the productivity/steepness h increases (as before, Table 16).

Table 14: The average number of years it would take the population to exceed the *limit* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.4 S_{MSY} (estimated at 140K t from the model developed here) and assuming different rates of fishing, and different auto-correlation of the process error term. (Note 76 is the maximum limit set, so in reality the number of years would be more than 76 for each scenario shown). Once we exceed F_{MSY} by a factor of 2, the chances of coming back to the limit are very low if we have an auto-correlated process driving process error.

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
Auto-correlation	0.1	0	0	1	2	4	+76
	0.15	0	0	1	2	4	+76
	0.2	0	0	1	2	4	+76
	0.25	0	1	1	2	4	+76
	0.3	0	1	1	2	5	+76
	0.35	0	1	2	3	5	+76
	0.4	0	1	2	3	5	+76
	0.45	0	1	2	3	5	+76
	0.5	0	1	2	3	26	+76
	0.55	0	1	2	4	49	+76
	0.6	0	1	3	4	40	+76
	0.65	0	2	3	4	41	+76
	0.7	2	2	3	5	47	+76
	0.75	2	4	4	5	67	+76
	0.8	3	4	5	10	+76	+76
	0.85	3	5	5	18	+76	+76
	0.9	5	5	7	50	+76	+76

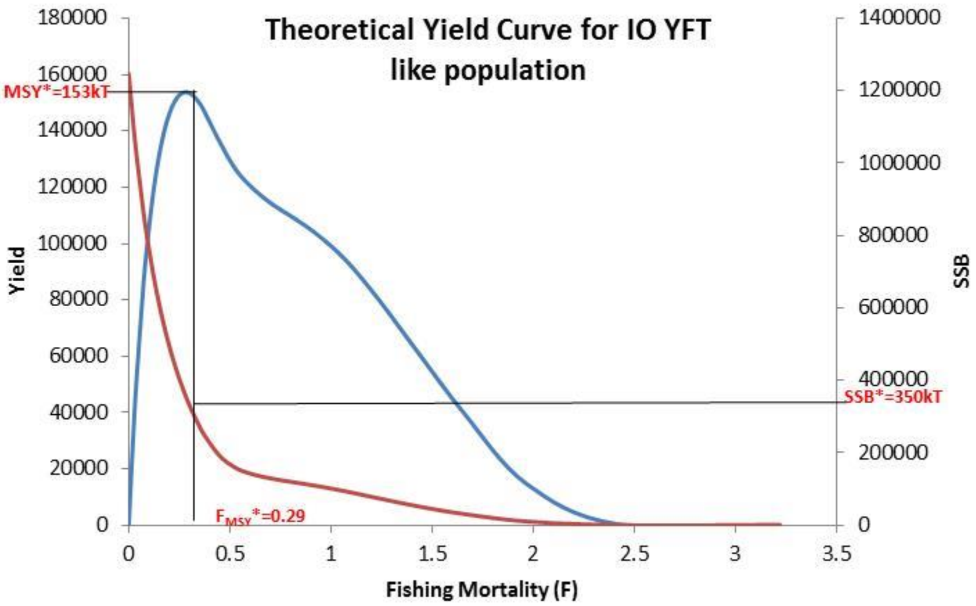
Table 15: The average number of years it would take the population to exceed the *target* reference point on Spawning Biomass using the HCR of 34% reduction in target rates if the stock fell below 0.4 S_{MSY} (estimated at 140K t from the model developed here) and assuming different rates of fishing, and different auto-correlation of the process error term. (Note 76 is the maximum limit set, so in reality the number of years would be more than 76 for each scenario shown). Once we exceed F_{MSY}, the chances of coming back to the target are very low if we have an auto-correlated process driving process error.

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
Auto-correlation	0.1	0	0	38	4	+76	+76
	0.15	0	0	38	14	+76	+76
	0.2	0	0	36	14	+76	+76
	0.25	0	6	36	14	+76	+76
	0.3	0	7	34	14	+76	+76
	0.35	0	8	31	18	+76	+76
	0.4	0	7	31	28	+76	+76
	0.45	0	8	34	28	+76	+76
	0.5	0	11	35	30	+76	+76
	0.55	0	13	33	33	+76	+76
	0.6	0	15	33	37	+76	+76
	0.65	0	17	32	36	+76	+76
	0.7	6	18	33	35	+76	+76
	0.75	7	19	34	36	+76	+76
	0.8	10	22	36	+76	+76	+76
	0.85	12	26	36	+76	+76	+76
	0.9	16	31	39	+76	+76	+76

Table 12: Probability of dropping below the threshold (140Kt) when the harvest rates and steepness parameters vary

		Harvest Rate					
		0.1	0.2	0.3	0.4	0.5	0.6
STEEPNESS	0.6	0%	1%	48%	91%	100%	100%
	0.65	0%	0%	33%	83%	99%	100%
	0.7	0%	0%	16%	70%	95%	100%
	0.75	0%	0%	5%	51%	86%	98%
	0.8	0%	0%	1%	27%	70%	91%
	0.85	0%	0%	0%	8%	45%	76%
	0.9	0%	0%	0%	1%	16%	50%
	0.95	0%	0%	0%	0%	2%	17%

Finally, based on these parameters, the theoretical yield curve for a Indian Ocean YFT like stock shows the limits for YFT for F_{MSY} to be around 0.29, the MSY target to be around 153K t, and the S_{MSY} target to be around 350K t. **Note, these values will differ from the more complicated Multifan assessment as it uses only one area, and one fishery, where Multifan has a lot more complex structure using spatial dynamics (movement), tagging data, and numerous fisheries operating in the IO Region.**



Discussion

While the approach is quite simple in principle, it helps us evaluate dimensionless reference points that we have for stocks in the IO Region. Even though the actual target rates and biomass levels will vary from the actual assessment, primarily as the assessments are a lot more complex in spatial and fishery structure, use different values of process error, have priors on numerous parameters, and in numerous cases also use tagging data.

In most cases the values that the simple model comes for target optimal yield levels are within the confidence bounds suggested for the stocks (other than for BET and YFT where they are off by a factor 1.5 to 2 respectively).

In all cases the reference points for fishing mortality suggest that when exceeded by a factor of 1.5 the stocks would never get back to optimal yield targets. This does not mean that the fishery is non-sustainable at those targets but that the yield will be much lesser than that at optimum yield levels. Thus if, one would like to maintain yield targets at levels that are optimal, the critical reference points should not exceed 1.2 F_{MSY} for any tuna stock managed in the Indian ocean if we would like to recover to optimal yield targets within 2-3 generations for the stocks being simulated. In addition, other than albacore, all Indian ocean stocks are susceptible to overfishing (based on the fishing at optimal rates) and managing to critical reference points. It is also recommended that the limit reference points for SSB should also be increased to 0.6-0.8 SB_{MSY} in order to avoid failing to detect a drop in productivity when fishing to optimal fishing levels. Conversely, if the fishing targets were reduced from optimal levels (0.8-0.9 F_{MSY}); the risk of overfishing would decline by a significant amount.

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References

Beverton, R.J.H. and Holt, S.J. 1957. On the dynamics of exploited fish populations. Fisheries Series 2, Vol. 19 U.K. Ministry of Agriculture and Fisheries, London.

Connell, J.H., and W.P. Sousa. 1983. On the evidence needed to judge ecological stability or persistence. American Naturalist 121(6):789-823.

Cadyma, E.L. 2003. Fish Stock Assessment Manual. FAO Fisheries Technical Paper 393. FAO, Rome.

DeAngelis, D.L., and J.C. Waterhouse. 1987. Equilibrium and nonequilibrium concepts in ecological models. Ecological Monographs 57(1):1-21.

Doak, D. F., D. Bigger, E. K. Harding, M. A. Marvier, R. E. O'Malley, and D. Thompson. 1998. The statistical inevitability of stability–diversity relationships in community ecology. *The American Naturalist* 151: 264–76.

Egerton, F.N. 1973. Changing concepts of the balance of nature. Quarterly Review of Biology 48:322-350.

Fieberg J. & Ellner S.P. 2000. When is it meaningful to estimate an extinction probability? *Ecology*, 81: 2040-2047.

Grimm, V. and C. Wissel. 1997. Babel, or the ecological stability discussions: an inventory and analysis of terminology and a guide for avoiding confusion. Oecologia 109: 323-334.

Kuhn, T. S. 1996. The structure of scientific revolution, 3rd edition. The University of Chicago Press, Illinois.

Mueller, L. D. and P. T. Huynh. 1994. Ecological determinants of stability in model populations. Ecology 75:430-437.

Mosqueira, I. and Kitakado, T. 2012. Working towards the evaluation of reference points and harvest control rules for IOTC stocks. IOTC–2012–WPM04–04.

Richards, L.J. and Maguire, J.J. 1998. Recent international agreements and the precautionary approach: new directions for fisheries management science. Can J Fish Aquat Sci 55:1545-1552.

Ricker. W.E.1975. Computation and Interpretation of Biological Statistics of Fish populations. Fisheries research Board of Canada, Bulletin No. 191.

Rodriguez, M. A. 1994. Succession, environmental fluctuations, and stability in experimentally manipulated microalgal communities. Oikos 70:107-120.

Tilman, D. 1996. Biodiversity: population versus ecosystem stability. Ecology 77:350-363