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Identification of candidate limit reference points for the key target species in the WCPFC

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Ann Preece[1], Rich Hillary[1] and Campbell Davies[1]

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[1] CSIRO Marine and Atmospheric Research, P O Box 1538, Hobart, Tasmania 7001 Australia

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Enquiries should be addressed to:

Ann Preece
CSIRO Marine and Atmospheric Research,
P O Box 1538, Hobart, Tasmania 7001 Australia.
ann.preece@csiro.au

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1. EXECUTIVE SUMMARY

The aim of this commissioned project is to provide the Western and Central Pacific Fisheries Commission (WCPFC) and Scientific Committee with a set of candidate limit reference points for the key target species in the WCPFC, and to review steepness and depletion levels used across the tuna Regional Fisheries Management Organisations (RFMOs). Three categories of limit reference points, with varying data requirements and strengths and weaknesses, are examined: Maximum Sustainable Yield (MSY), spawning potential-per-recruit (SPR) and depletion based limit reference points.

A simulation model of tuna-like species has been developed to evaluate the consistency and robustness of reference points for specific target species of tuna in the Western and Central Pacific Ocean (WCPO). It's parameterised to represent yellowfin/bigeye and skipjack tuna type populations.

One of the key parameters in fisheries stock assessments is "steepness", which is a measure of the productivity of the stock at low stock size. A review of the stock assessments of tunas and tuna like species across the tuna RFMOs highlights the difficulty in estimating or assuming a value for steepness for the majority of tuna stocks. There is commonly insufficient data on recruitment at low stock size and recovery from depletion to enable steepness to be reliably estimated in the tuna stock assessments. Some reference points are sensitive to the value for steepness. Providing stock status and management advice that is robust to the uncertainty in steepness is essential for effective management, and is often understated.

We recommend a three-level hierarchical approach to selecting and setting limit reference points for fishing mortality (F) and Spawning Stock Biomass (SSB) based on decreasing levels of available information. The first level uses F_{MSY} and SSB_{MSY} but only in the case where a reliable and precise estimate of steepness is available. The second level uses F_{SPR} and 20% of SSB_0 for cases in which uncertainty in steepness is high, but the key biological (natural mortality, maturity) and fishery (selectivity) variables are reasonably well estimated. The third level does not include an F-based limit reference point if the key biological and fishery variables are not well estimated, but simply uses a SSB limit of 20% of SSB_0.

As noted in Harley et al (2009) and others, the usefulness of limit reference points is in their implementation through management actions to be taken when pre-specified indicators show that the fishery is reaching or breaching a specified limit reference point. Formal decision rules (or harvest control rules) have been demonstrated to be an important component of effective management in that they define the agreed management action required when a given limit reference point is approached or breached. We recommend that decision rules be formally evaluated via simulation modelling using a Management Strategy Evaluation (MSE) framework. This allows for exploration of differences in species-specific responses to exploitation and other uncertainties associated with implementation of management strategies.

2. INTRODUCTION

This report builds upon work on reference points and the Management Strategy Evaluation (MSE) framework already provided to the Commission and Scientific Committee (SC) meetings (Campbell, 2010; Harley at al, 2009; Norris, 2009; Davies and Basson, 2008; Davies and Polacheck, 2007). The aim of this work is to provide the Commission and Scientific Committee with a set of candidate limit reference points for the key target species in the Western and Central Pacific Fisheries Commission (WCPFC). The scope of this project is restricted to discussion of limit reference points and does not cover candidate target reference points. When target reference points are considered, they will need to be developed to ensure that they are compatible with and have a suitable buffer from limit reference points. Limit reference points are intended to mark the limit below which the stock biomass should not fall, and to avoid high fishing mortality that represents overfishing. There should be a small chance of breaching limit reference points (Davies and Basson, 2008); "Fishery management strategies shall ensure that the risk of exceeding limit reference points is very low" (Annex II UN Fish Stocks Agreement, 1995).

A range of potential limit reference points have already been summarised in the previous documents to the Commission. This report discusses the strengths and weaknesses of candidate limit reference points in three categories considered most appropriate in the current context of the WCPFC and tuna RFMOs more generally. These are: Maximum Sustainable Yield (MSY), spawning potential-per-recruit (SPR) and depletion based limit reference points. Steepness is a key uncertainty that affects some reference point calculations more than others and a review of steepness across the tuna and tuna-like stock assessments from the tuna Regional Fishery Management Organisations (RFMOs) is discussed. The level of depletion that constitutes the limit at which risks to the stock become unacceptably high for the stock is also briefly reviewed. A simulation model of tuna-like species has been developed to evaluate the consistency and robustness to uncertainty in steepness of reference points for specific key target species in the Western and Central Pacific Ocean (WCPO). A small set of limit reference points is recommended for consideration by the Commission. Related candidate indicators are also discussed.

3. OBJECTIVE AND DEFINITIONS

This project addresses items 1 and 4 of project 57 defined in the scientific work plan for the WCPFC. The details of project 57 are in appendix A. The aims of this project are to identify limit reference points for the key target species in the WCPFC, and to summarise their strengths, weaknesses, the information needed to calculate them and the information that they provide. In addition, the project aims to review "steepness" which is a key uncertainty in the calculation of many types of reference points and indicators, and to review the levels of depletion that may be used for limit reference points. Items 2 and 3 from project 57 will be addressed by the scientists in the Secretariat of the Pacific Community - Oceanic Fisheries Program, (SPC-OFP), and are not part of this report.

Several terms require definition:

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).

Limit reference points are measured by "**indicators"** of the stock status, such as the stock assessment estimate of the current spawning stock biomass (SBB_{curr}) compared with the spawning stock biomass at Maximum Sustainable Yield (i.e. SSB_{curr}/SSB_{MSY}).

The limit reference points measure performance relative to the **management objectives** of the WCPFC, which are inferred from the WCPFC convention as; to ensure the conservation of the key target species biomass and to avoid overfishing. Biomass limit reference points are used for the former and F-based limit reference points for the latter. The setting of WCPFC objectives for use in a management strategy framework is described in Davies and Polacheck, 2007.

We interpret "the **key target species** in the WCPFC fisheries" to mean the four main target tuna species (Bigeye, Yellowfin, Albacore, Skipjack), and to a lesser extent the two billfish species (Swordfish and Striped Marlin).

Depending upon the management objectives of the Commission (to be discussed in a management workshop in 2011 or 2012), additional limit reference points may also need to be developed to address objectives that are not only related to the key target species. These may include objectives for by-catch species, ecosystem considerations, other conservation objectives and economic and social objectives.

Further definitions, including steepness and depletion are provided in the relevant sections below.

4. BACKGROUND

Default and candidate limit reference points for the WCPFC have been discussed in detail in previous documents to the commission (Norris, 2009; Harley et al, 2009; Davies and Basson, 2008; Davies and Polacheck, 2007) and we attempt to further build upon this work. As noted in Davies and Basson (2008) and Sainsbury (2008), limit reference points are often set in pairs to ensure against overfishing (breaching the fishing mortality limit reference point) and to avoid overfished stocks (breaching the biomass limit reference point). Overfishing is where the harvest rate in the fishery is too high relative to the fishing mortality at MSY, and has a high likelihood of reducing the biomass of the stock to below its acceptable level. Overfished is where the biomass is below an acceptable level.

Norris (2009) provides a useful summary of indicators and their related reference point types, including a brief summary of the theory behind them, and we refer the reader to this for further information. Davies and Basson (2008) conclude, in the context of the WCPFC, the use of MSY-based limit-reference points are reasonable default limit reference points. Norris (2009) in reviewing the legal background in the use of reference points by the Commission, notes that the selection of reference points does not have to be restricted to MSY-based limit reference points. Davies and Basson (2008) and Harley et al (2009) further review the legal background to setting reference points. In addition to relevant sections in UN Fish Stocks Agreement (UNFSA, 1995), UN Convention on the Law Of the Sea (UNCLOS, 1982) and the WCPFC convention, there exist criteria in other fora (IUCN red listing (IUCN, 2001) and CITES listing (CITES, 2007)). These additional two sets of criteria have also been considered in this work (in the section on depletion), since avoiding the consequences of listing may be of interest to the Commission and stakeholders in the fishery.

As noted in Harley et al (2009), Davies and Basson (2008) and Davies and Polacheck (2007) the usefulness of limit reference points is in their implementation through management actions to be taken when pre-specified indicators show that the fishery is reaching or breaching a specified limit reference point. It’s important to recall that for limit reference points management actions should be taken before the stock approaches the limit reference point. Sainsbury (2008) points out that a limit reference point is not a threshold at which risks to the stock change abruptly, it’s more likely that the changes are “steady and smooth” along a continuum. Not knowing the exact value at which further decline in the population will occur is not essential if there is a well designed and tested harvest strategy in place and that timely action is taken when needed. Factors, such as current state of the stock, recent recruitment history, differences in life-history characteristics, and potential shifts in selectivity, can be tested in simulation models to aid design of management actions that are likely to be robust to these uncertainties.

The specification of the probability of an indicator exceeding the reference point also needs to be defined and evaluated in a MSE framework. The combination of the probability level and the actual level of the limit reference point is often referred to as the “risk” to the conservation and future productivity of the stock. Below the limit reference point future recruitment is expected to decline, if fishing mortality is too high, and this increases the likelihood of environmental or other external effects negatively impacting on the stock, which will, in turn, lead to further declines in the spawning stock in the future. The decision on the level of risk (combination of the level of limit reference point and associated probability) should be decided by managers when setting objectives and associated reference points in the context of a formally specified management strategy that can be simulation tested and refined through MSE and dedicated consultation with stakeholders (Davies and Basson, 2008). Quantifying the probability that an indicator has breached a reference point is difficult, and the means to address this is discussed briefly in the section *Issues relating to uncertainty* below.

5. LIMIT REFERENCE POINTS AND CANDIDATE INDICATORS

There are many different variants of limit reference points, but to allow for a concise discussion on strengths and weaknesses, information provided and data requirements, we discuss these using three main categories – 1) MSY based, 2) SPR based and 3) Depletion based estimates.

Each of these three types of limit reference points have been introduced in the previous work presented to the SC and Commission. Variants in the indicators used to measure performance relative to the reference points also have strengths and weaknesses, which we identify in the following sections.

5.1 Maximum Sustainable Yield

Maximum sustainable yield (MSY) is the maximum catch that can be sustained by the fishery at equilibrium. MSY is most often calculated by finding the deterministic equilibrium dynamics of the stock in question, using the current selectivity for each fishery. The fishing mortality rate is adjusted to modify the catches taken, until the maximum yield that can be indefinitely taken from the stock is found. The WCPFC stock assessments conducted by OFP-SPC provide all the inputs required to calculate deterministic MSY.

MSY based reference points are built into much of the legal framework for governance of highly migratory fisheries (e.g. UNCLOS, 1982; UNFSA, 1995; and the WCPFC convention) and the specification and attributes of the associated limit reference points are well documented. Davies and Basson (2008) conclude that MSY based reference points are reasonable default limit reference points for target species of the WCPFC ("default" meaning until fully evaluated in conjunction with decision rules using a management strategy evaluation framework). Historically, MSY reference points were used as target reference points, but these have been recognised for sometime now as limits reference points for fishing mortality and biomass (Mace, 2001; Punt and Smith 2002).

There are several ways to define limit reference points based on MSY, including the spawning biomass or total biomass at MSY (SSB_{MSY} or B_{MSY}), and the fishing mortality rate at MSY (F_{MSY}). Indicators, or the measures used to estimate if the stock status is near, or has breached, the biomass and fishing mortality limit reference points include $SSB_{current}/SSB_{MSY}$ and $F_{current}/F_{MSY}$, respectively. The WCPFC is already familiar with MSY based reference points, because stock status advice currently provided to the WCPFC includes the candidate indicators $B_{current}/B_{MSY}$ and. $F_{current}/F_{MSY.}$

Spawning Stock Biomass is preferable to total biomass in candidate indicators, because recent recruitment is less well estimated than older age classes in the last few years of the stock assessment (Harley et al, 2009). $SSB_{current}$ can be defined as the most recent few years (e.g. four is used in WCPFC stock assessments), and excludes the estimate from the last year in the stock assessment, whereas SSB_{latest} uses only the most recent estimate from the last year of the stock assessment. SSB_{latest} is preferred over $SSB_{current}$ (Harley et al, 2009).

For fishing mortality (F) reference points, the indicator $F_{current}/F_{MSY}$ uses the F from recent years, excluding the last year (current), in preference to F_{latest} (most recent estimate) because the estimates in last year tend to be high, and then drop when the next year of data is added, as identified by retrospective analyses (Harley et al, 2009). Catch and effort data are often incomplete in the last year, making the most recent estimates uncertain (Langley et al, 2010). Using the most recent few years, and excluding the most recent years estimate of F or SSB creates a lag between stock status advice and implementation of management action. These lags, and the related alternative indicators, can be investigated for their importance in the effectiveness of a harvest strategy through simulations testing using management strategy evaluation (e.g. Kolody et al, 2010a).

The information required to estimate MSY and associated reference points is available from the stock assessment outputs available to the WCPFC. Selectivity by fishery and estimates of the spawner-recruit relationship, natural mortality (M) and maturity from the stock assessment are used to estimate MSY. Hence, while the estimation of MSY and associated indicators does not use the stock assessment model, some form of stock assessment is required to estimate the required inputs parameters. In general, the stock assessments themselves, such as MULTIFAN-CL require large data inputs.

F_{MSY} indicators provide information on whether overfishing is occurring, and B_{MSY} indicators provide information on whether the stock is below the level at which MSY can be taken.

MSY based reference points are sensitive to uncertainties in steepness and selectivity. Stock assessments in the WCPFC, IOTC, IATTC and others show that for various levels of steepness there is a wide range of values for MSY, and there is a wide range of values for the indicators of current status in biomass and fishing mortality relative to MSY (e.g. Hoyle et al, 2010; Langley et al, 2010; Harley et al, 2010). Another key issue relating to potential problems with deterministic MSY is system stochasticity, such as variation recruitment and catchability. In the context of deterministic MSY, fishing at F_{MSY} will eventually lead to a constant yield of C_{MSY} and, once attained, fixing the catch at C_{MSY} will always result in a fishing mortality of F_{MSY}. There is no such simple relationship in the context of stochastic systems (which is the reality for tuna and tuna like species): in this context, in the long-term an F_{MSY} management strategy (based on deterministic MSY) will almost surely lead to an average yield lower than C_{MSY}, and such a fixed catch level imposed on the population can often have a high probability of causing substantial and permanent depletion of the spawning stock, even when starting from the unfished state.

This fundamental disparity between deterministic MSY and the stochastic dynamics of the stock is explored in more detail further on. For assessments of the kind undertaken in the WCPFC, where many implicitly random effects are estimated, this issue warrants serious consideration when considering any MSY-based limit reference points.

5.2 Spawning Potential per Recruit

Spawning-potential-per-recruit (SPR) is the potential contribution to SSB over the lifetime of a single recruit. It is calculated at the unfished level (SPR_0) and the relevant fishing mortality value which reaches the target reduction of the unfished level (e.g. *x*% of SPR_0) is estimated and used as a limit reference point (Mace, 1994). Davies and Basson (2008) and Gabriel and Mace (1999) recommend that the fishing mortality limit reference point be calculated for a 40% reduction in SPR_0 ($F_{40\%SPR}$) if the stock-recruitment relationship is not known (see Basson and Dowling 2008 for further details). Brodziak (2002) recommends a limit at $F_{35\%SPR}$ as a conservation target, but this is considered too low for less resilient stocks, where fishing mortality $F_{35\%SPR}$ may be too high to result in the desired level of SSB.

The information required to calculate fishing mortality reference points using SPR are natural mortality (M), maturity, and selectivity, which are available from the WCPFC stock assessments. A stock-recruitment relationship, and therefore steepness, is not required.

These F based limit reference points provide a measure of the fishing mortality rate at which the spawning potential is reduced to 40% (or 35% or 30% etc), and whether the current fishing mortality is too high, indicating overfishing. $F_{\%SPR}$ reference points are sensitive to changes in selectivity.

Candidate indicators for use with $F_{\%SPR}$ fishing mortality limit reference points are $F_{current}/F_{40\%SPR}$. For the reasons described above (i.e. most recent estimate being less reliable), $F_{current}$ is preferable over F_{latest}. Performance of these two candidate indicators as components of formal harvest strategies can be evaluated in MSE testing.

5.3 Depletion based reference points

Depletion based limit reference points are based on the depletion level of the total, or spawning, biomass and provide biomass-based limit reference points (e.g. *x*% of SSB). Most common depletion limit reference points are defined as a % of the initial unfished spawning stock biomass (SSB_0). Appropriate levels of depletion for different situations are discussed in the next section.

An advantage of depletion-based reference points that use the candidate indicators ($SSBcurrent/ SSB_0$), is that they are relatively stable from assessment to assessment (despite changes in those assessments), and in many of the tuna and tuna-like stock assessments have provided the least variation in the range of results across a range of steepness values used (e.g. Kolody et al, 2010b, Anon, 2010a).

In some of the WCPFC stock assessments, possible changes in the productivity of the stock for various time periods in the stock assessment have been identified. These changes are often attributed to environmental shifts and could be of concern in the WCPFC in the future because of climate change. It is also possible that the productivity changes are an artifact of the models. Depletion can be calculated using the current estimate of the stock that would have occurred in the absence of fishing ($SSB_{t,unfished}$) given the current recruitment "level" (which may be some representative back-average). However, where the stock recruitment relationship is uncertain, as with these species, we have used the equilibrium estimates of the initial spawning stock biomass (SSB_0). If recruitment has no link to the mature stock biomass, and is purely environmentally driven, this approach makes conceptual sense. If, however, there is some (potentially unknown) stock-recruit relationship, then current observed recruitment is then partly driven by the mature stock biomass that is almost surely not in an unfished state. Inferring the unfished SSB for example from this recruitment level would then be inconsistent with the stock dynamics and could underestimate the level of depletion in the stock.

As noted above, for candidate indicators and the limit reference points, SSB is preferable over total biomass (TB), because the most recent recruitment estimates included in current total biomass are the least reliable, and there are more data in the stock assessment model to estimate SSB.

Data requirements: Depletion levels can be calculated from stock assessment model output (e.g. the Multifan-CL output produced from the SPC assessments). They require an estimate of the initial or reference time SSB and last year, or years, of the stock assessment SSB. The stock assessments themselves require a considerable amount of data (e.g. Harley et al, 2010).

Depletion estimates provide information on how much the spawning stock biomass has been reduced since fishing began, or since the reference time period, and therefore how much SSB remains, and the estimated impact on historic, current and future recruitment and yield.

6. LEVELS OF DEPLETION THAT MAY SERVE AS APPROPRIATE LIMIT REFERENCE POINTS

The International Whaling Commission (IWC), Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Australian harvest strategy policy, and NZ fisheries use depletion limit reference points of 20% of SSB_0 (sometimes as proxy's for other reference points) in formal management strategies. $20\%SSB_0$ is the formal rebuilding target for SBT because the stock is less than $20\%SSB_0$ and in a depleted state.

$25\%B_0$ has been used as a limit reference point in US west coast groundfish management. Sainsbury (2008) recommends $30\%SSB_0$ as the best practice biomass depletion limit reference point, allowing for stocks with low productivity. $20\%SSB_0$ is considered a threshold for recruitment overfishing for productive stocks (Myers, 1994), but is too low for low productivity stocks, may have genetic and ecosystem implications, slower rebuilding rates, and potential for increased risks to fisheries from effects of climate change (Sainsbury, 2008). Beddington and Cooke (1983) introduced $20\%SSB_0$ as a “lower limit where recruitment declines might be expected to be observable”. Beddington and Cooke also introduced the risk level that is commonly used in a management strategy framework, where the probability of the stock falling below $20\%SSB_0$ should be less than 10%, and that this be measured over a 20 year timeframe. That is, there should be a high probability (90%) that management will avoid the SSB falling below 20% of it's unfished level. 20% of the virgin biomass has become a default level at which it is considered that serious management action should be taken to rebuild the stock.

In addition to limit reference points used in other international and national fisheries management fora, CITES and the IUCN red list are increasingly being engaged by some fishery stakeholders. The criteria for listing under both bodies are based on historical extent of decline i.e. depletion. The range of critical depletion varies under the CITES criteria from 5% to 20% depending on the known or likely productivity of the population, based on life history characteristics. For IUCN red listing the criteria for listing as critically endangered include reversible declines of >80% (i.e. depletion <20%). These depletion estimates are related to the concept of a “minimum safe biological level” for a stock. The safe level will be dependent upon the relative productivity of the population, which can be described, in part, by relevant life-history characteristics.

The life-history characteristics for the key target species in the WCPFC range from skipjack (fast growing, short lived, early maturity), in a continuum through yellowfin, albacore, bigeye to swordfish and striped marlin (longer lived, later age at maturity slower growing) (Robert Campbell, pers. comm). The fast growing, early maturity, species such as skipjack are assumed to be more resilient to fishing than the slower growing species.

Davies and Basson (2008) note that for short lived species where current harvesting is predominantly on juveniles, the aim of any management action would be to ensure that enough survive to mature and spawn, and therefore the relevant reference points would be spawning stock biomass. For the longer lived, later maturing species the aim of fisheries management is to maintain the spawning stock and because of differential productivity with age, to maintain sufficient age classes in the spawning stock. Hence, both the total SSB and its age composition is of interest.

7. STEEPNESS: A KEY UNCERTAINTY IN STOCK ASSESSMENTS AND REFERENCE POINTS INDICATORS

Steepness is a measure of the productivity of a stock, and can be interpreted as a measure of the resilience of the stock to fishing pressure. It ranges in value from 0.2 to 1.0, for the most commonly used Beverton-Holt model, with higher values equating to more productive and resilient stocks. At the lowest end of this range, 0.2 indicates that at a spawning stock biomass level of 20% of its unfished state (SSB_0), recruitment would be 20% of its virgin unfished level. That is, essentially a linear relationship between recruitment and spawning biomass. For a steepness of 0.7, if the spawning stock is reduced to 20% of SSB_0, recruitment should still be on average 70% of its unfished level.

A review of the stock assessments of tunas and tuna like species across the tuna RFMOs highlights the difficulty stock assessment scientists have in estimating or assuming a value for steepness. A variety of techniques are used: estimating steepness (e.g. Harley et al, 2010), using informative or uniform priors, fixing steepness at a single value, fixing it at several values to provide sensitivity analyses (e.g. Hoyle et al, 2010; Harley et al, 2010; Langley et al, 2010; Kolody, 2010), and assuming there is no-stock recruitment relationship by setting steepness =1 (e.g. Maunder et al, 2010) in some IATTC stock assessments). The RFMO's scientists producing the primary stock assessments that are used for management advice acknowledge that, in the majority of cases, if not all, there is not enough information on steepness in the available data, and that the stock-recruitment relationship is weak. This is common across the various tuna and billfish species.

In, addition to the stock assessment work for tunas, theoretical research on steepness and its importance to stock status indicators is ongoing, providing useful reviews of the techniques for handling steepness in stock assessments. According to work by Mangel et al (2010), steepness can be calculated if the demographics of the population are known and there is detailed information on the key dynamics (growth, mortality implicitly assumed to be measured at zero population size) of the larval stage of the fish. This means that if natural mortality, detailed larval dynamics, and growth (and the uncertainty in them) are known, then an estimate of the distribution of plausible values for steepness can be made. Unfortunately these quantities are usually not known and stock assessments often use a variety of fixed values for natural mortality at age etc. Mangel et al (2010) also note that because of the relationship between steepness and the "demographics of the population", that when using several fixed values of steepness, other parameters in the model should also be adjusted for these different steepness values to remain internally consistent. This is not something that has been explored in the RFMO stock assessments as far as we know, but sometimes the cross combination effects of various natural mortality and steepness values are explored, but the intention driving this is not consistency. In such stock assessments, strong correlation often appears between the steepness and other parameters such as growth and natural mortality. While this is principally more of an indicator of a lack of unambiguous information in the data on the key parameters, it also reaffirms the logical linkage between the various key life-history processes and parameters.

Maunder et al (2010) attempt to handle the weak relationship between spawning stock and recruitment by using steepness set equal to 1, to infer that there is “no stock recruitment relationship”. However Mangel et al (2010) argue that in this case it would be better to assume that “any value of steepness could be possible” and that an (almost) uniform prior on all values for steepness would be a better implementation. Where steepness is estimated (e.g. Aires da Silva and Maunder, 2010), steepness is estimated to be almost equal to 1. Note that in this assessment they also produce results and stock status advice for a variety of values for steepness. In other stocks (eg Harley et al, 2010) high values of steepness can also be estimated, but the estimates are very high and the authors express little confidence in these (e.g. Harley et al, 2009). Conn et al, 2010 notes that in simulation studies, steepness estimates tend to be close to the upperbound (1.0) even though true steepness is much less than 1.0.

Rosenberg and Restrepo (1996) argue from a precautionary approach that if steepness is not known, then recruitment proportional to SSB should be assumed, i.e. that there is no compensation in the stock recruitment relationship.

Conn et al (2010) show that where there is contrast in spawning stock biomass estimates (for example from a “2-way trip”- depletion and then rebuilding of a stock), that it may be possible to estimate steepness. Harley et al (2009) state that for the WCPO tuna stocks “it is extremely doubtful that steepness can be estimated within our individual stock assessment models”, because there is little information for recruitment at low stock size. Tuna stocks that have been depleted but have not yet recovered (e.g. SBT) also have difficulty estimating steepness, and show high variability in recruitment, indicating some resilience to low stock sizes. Tunas are generally assumed to be in the mid to high, but not low, range of steepness values, because of the ability to persist given high variability in recruitment and seemingly high estimates of mortality. The general life-history characteristics of tuna-like species indicate medium to high resilience that varies by species. The contributing factors are high fecundity, longevity (for some species), growth rate and age of maturity. The Myers (1999) meta-analyses of steepness showed that an average of 0.7 or higher was common across the species examined including some tunas and billfish. Because of this perception of at least medium resilience, and the Myers (1999) meta-analyses results for steepness, a reduced range of steepness values has been used in many of the tuna RFMOs stock assessments, at the middle to upper end of the range for steepness (Table 1).

Table 1: Steepness values used in stock assessments across the tuna RFMOs

RFMO	Species	Authors	Fixed steepness values	Estimate of steepness
IOTC	Yellowfin	Langley et al, 2010	0.6, 0.7, 0.8, (0.9)	
	Bigeye	Kolody et al, 2010$_b$	0.55, 0.75, 0.95	
	Swordfish	Kolody, 2010	0.7 and 0.9	0.61, 0.68. 0.98
	Swordfish	Martel, 2010	-	
	Swordfish	Wang & Nishida 2010	0.6, 0.8, 0.9, 0.95	
CCSBT	SBT	Anon, 2010b	0.385, 0.55, 0.64, 0.73 and 0.82	
IATTC	Bigeye	Aires-da-Silva and Maunder, 2010	1.0 and 0.75	
	Striped marlin	Hinton et al, 2010	1.0 and 0.75	0.98
WCPFC	Skipjack	Hoyle et al, 2010	0.65, 0.75, 0.85, 0.95	
	Bigeye	Harley et al, 2010	0.55, 0.75, 0.95	0.98
	Yellowfin	Langley et al, 2009	0.55,0.65,0.75,0.85,0.95	
	Albacore	Hoyle & Davies 2009	0.55 – 0.95	
	Swordfish	Kolody et al 2008, and Davies et al, 2008	0.65 and 0.95	

Harley et al (2009), Kolody et al, (2010a), ISSF (Anon, 2011) and others have noted that using a single value for steepness for providing stock status advice does not characterise the uncertainty in the advice provided. Several ways for including a broad range of structural assumptions and combinations of structural assumptions (e.g. a cross of fixed values for steepness and natural mortality) has been described and used in the WCPFC and other RFMOs (Harley et al, 2009; Kolody et al, 2008; Kolody, 2010a; Langley et al, 2010; Anon, 2010b; Hoyle et al, 2010). In several stock assessments across RFMOs, the practice now is to use a range of values for steepness to provide stock status advice. In some cases attempts have been made to combine the results by weighting alternative hypotheses or by sampling from a grid of the alternative hypotheses (e.g. Langley et al, 2010; Kolody, 2010; Harley et al, 2009; Hoyle et al, 2010; Anon, 2010b). The uncertainty in the limit reference point and the indicator of stock status relative to that limit reference point will need to be taken into account by fishery managers in determining the risk level that is acceptable for various limit reference points and, where they exist, their corresponding decision rules. Uncertainties in steepness are unlikely to be resolved in the near term. Langley et al (2010) and others suggest that consideration should be given to adopting reference points that are less dependent on stock recruitment relationship parameters such as steepness.

8. CANDIDATE LIMIT REFERENCE POINTS

8.1 Tuna-like operating model

We developed a simple yet representative age-structured operating models for exploring the most appropriate limit reference points for the various species. The models are parameterised to be largely consistent with the type of models currently used to assess the key species (in terms of both fishery and biological structure) but are used only to explore the relative utility (or otherwise) of the relevant reference points, not to provide specific values. The latter should be done through formal MSE of both the reference points and decisions rules for each of the target species.

Two models are developed: one yellowfin/bigeye tuna-like, and the other skipjack tuna-like, given there is enough similarity between yellowfin and bigeye but enough difference between both of these species and skipjack to justify the split. Key biological parameters (natural mortality, maturity, growth, weight etc.) are taken directly from the most recent yellowfin (Langley et al, 2009) and skipjack (Hoyle et al, 2010) assessments. For the yellowfin model, two generic purse-seine and long-line fleets are included, with a 75% dominance of the purse-seine fleet; for the skipjack model a generic pole and line/purse seine and long-line fleet with a 90% dominance of the pole and line/purse seine fishery is used. In both cases, selectivities of each fleet are parameterised loosely based on the estimates of selectivity from the key fleets, as per the relevant current assessments.

8.1.1 Generic model

For both examples the underlying model is age structured, with the usual survival equation from one age-class to the next:

$$(1) \qquad N_{t,a} = N_{t-1,a-1} \exp\left(-M_a - \sum_f F_{t,f} s_{f,a} \right),$$

where *N* are the numbers at age *a* and time *t*, *M* is the age-specific rate of natural mortality, *F* is the fishery-specific rate of fishing mortality, and *s* is the fishery-specific selectivity-at-age ogive. For the youngest age-class a Beverton-Holt stock-recruit relationship is assumed:

$$(2) \qquad \begin{aligned} N_{t,1} &= \frac{\alpha SSB_{t-1}}{1+\beta SSB_{t-1}}, \\ SSB_t &= \sum_{a=1}^{A} N_{t,a} w_a m_a, \end{aligned}$$

and *w* and *m* are the weight and maturity-at-age, respectively, with the parameters α and β parameterised in terms of the steepness, *h*, and the unfished spawning stock biomass and recruitment levels, B_0 and R_0, respectively:

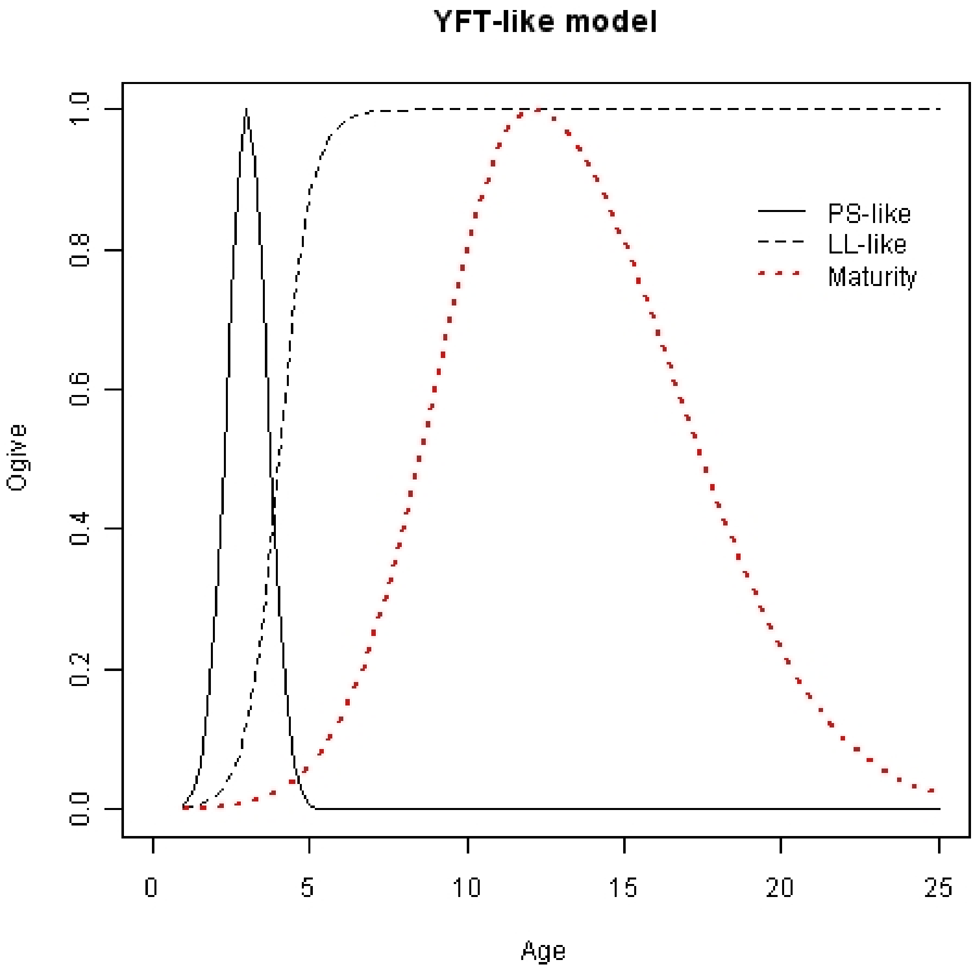
$$\begin{aligned} \alpha &= \frac{4R_0 h}{B_0(1-h)}, \\ \beta &= \frac{5h}{B_0(1-h)}. \end{aligned} \tag{3}$$

When calculating the per-recruit reference points the stock-recruit relationship is obviously omitted and $N_{t,1} = 1$ and it is assumed that $B_0 = 1$ at all times, so the analyses are relative and all biomass levels are reported relative to this unit B_0.

8.1.2 Specifics of the “yellowfin” model

The yellowfin-like model (which is also roughly intended to function as a bigeye-like model) as already mentioned has two fleets (one purse-seine the other long-line with a 75%:25% effort split assumed) and Figure 1 shows the selectivity ogives in relation to maturity and ages are represented in quarters as per the current assessment. In terms of growth, weight-at-age and natural mortality all are assumed to be the same as those used in the latest assessment.

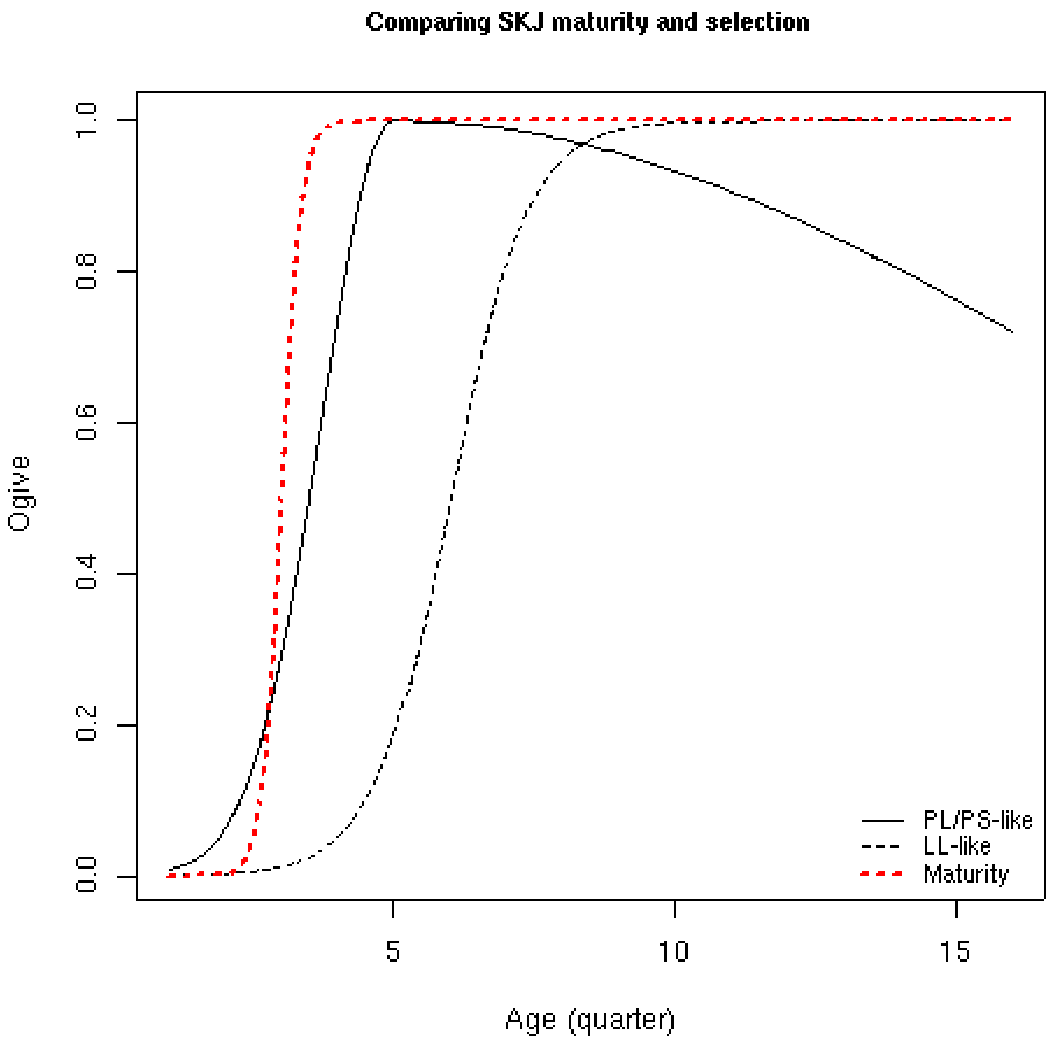
Figure 1: Summary of the yellowfin-like model in terms of the selectivity-at-age of the two fisheries, purse-seine (PS) and long-line (LL), and how they compare to the current maturity-at-age ogive. Ages are shown in quarters not years.



8.1.3 Specifics of the “skipjack” model

For the skipjack model there are also two fisheries (a pole-and-line/purse-seine fishery and a long-line fishery with a 90%:10% effort split assumed). Maturity-at-age for skipjack was modelled via a logistic function and as a default full maturity was assumed to be reached above 1 year old and 50% maturity (*am50*) assumed to be at 9 months old. Growth, natural mortality and weight-at-age were all modelled as per the assumptions made in the most recent assessment and a summary of the default model (in terms of selectivity and maturity) can be found in Figure 2.

Figure 2: Summary of the skipjack-like model in terms of the selectivity-at-age of the two fisheries and how they compare to the current maturity-at-age ogive. Ages are shown in quarters not years.



8.2 Fishing mortality and spawning biomass limit reference points

We explore several options for both fishing mortality and spawning biomass-based limit reference points with a strong emphasis on consistency between reference points, and their plausibility in relation to probably the key unknown (with any real precision) parameter: steepness. There has been suggestion that MSY form the basis for these F and spawning biomass related reference points, and that when MSY is not available that biomass depletion and per-recruit F-based reference points (such as the spawner-per-recruit reduction ratio $F_{SPRx\%}$) be used instead (Mace, 1994; Mace 2001; Sainsbury, 2008).

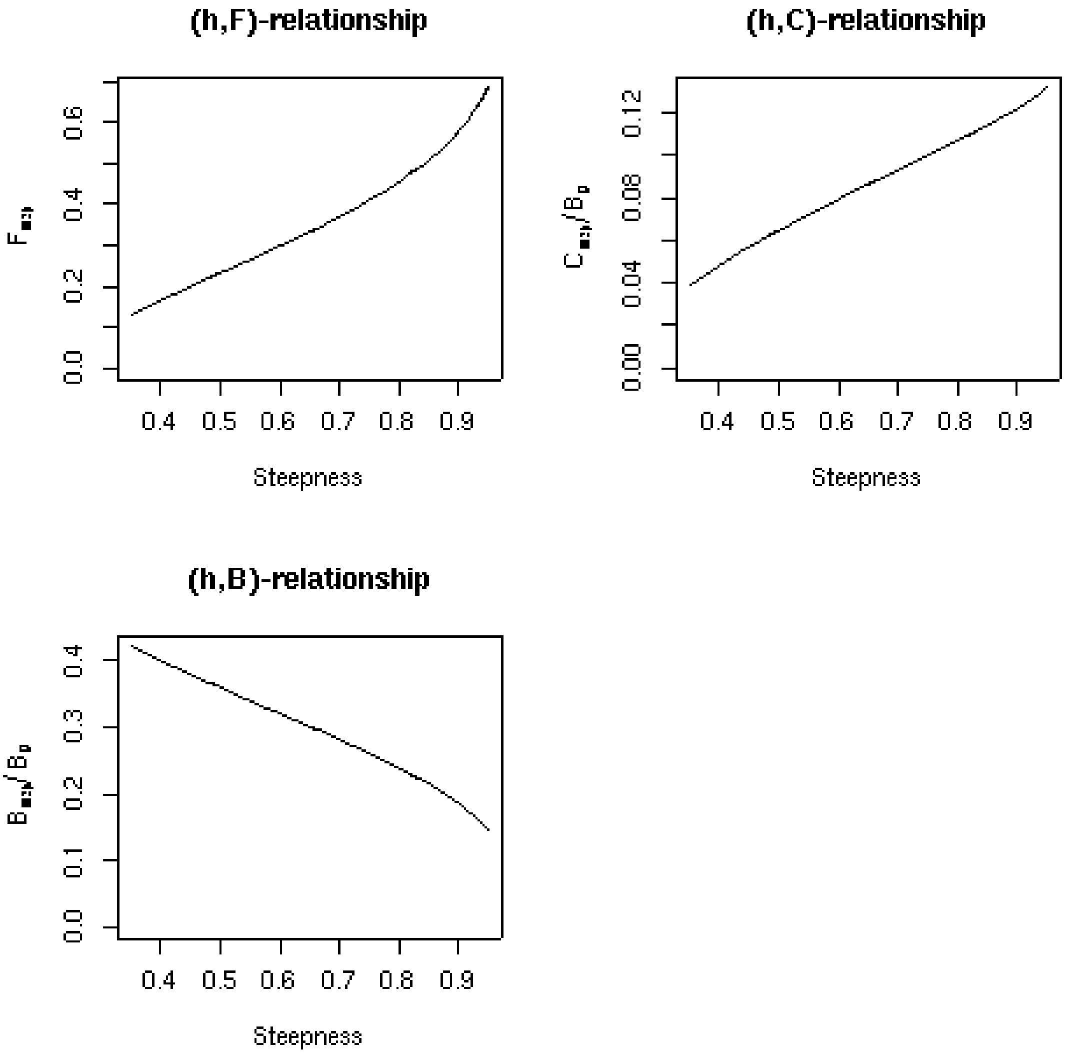
Using the yellowfin-like model, Figure 3 shows how the key (deterministic) MSY quantities (F_{MSY} and B_{MSY}/C_{MSY} relative to B_0) vary with the steepness parameter, for a range of values from 0.35-0.95. A clear conclusion from Figure 3, and a fact that is familiar to many assessment scientists, is that if one does not have a good understanding of the steepness parameter then one cannot provide a robust estimate of MSY, even with reliable estimates of all the other key life-history and fishery parameters. As an example: for a range of steepness values from 0.7-0.9, a plausible range across many tuna stocks and assessments (e.g. Kolody et al, 2010b; Harley et al, 2010), F_{MSY} ranges from 0.37 to 0.59 and the SSB depletion (i.e. relative to SSB_0) at which MSY is achieved ranges from 0.28 to 0.18 – a more than 50% change in both key quantities at their extrema.

Truly informative data on steepness generally arises when a population has experienced a (strong) decline followed by a subsequent recovery, ideally more than once. In the case of both yellowfin and bigeye in the WCPO, they exhibit classical 'one-way trip' dynamics, in that there has been a general continuous decline in abundance from the onset of industrial fishing to the present. Currently, the data do not appear to provide unambiguous, nor precise, information on the steepness and without this information we are not in a position to estimate MSY (see Figure 3) with any confidence.

In light of these results and the review of previous work, we recommend a three-level hierarchical approach to selecting appropriate limit reference points for WCPO tuna stocks:

1. **If** the steepness is well estimated, then F_{MSY} and B_{MSY} are appropriate limit reference points
2. **If** the steepness is not well estimated (and essentially unknown) and **if** the relevant life-history and fishery information (natural mortality, selectivity, maturity) are both available and reliably estimated then $F_{SPRx\%}$ and γSSB_0 are appropriate candidate F and SSB limit reference points, respectively (with an appropriately justified rationale for the selection of the fractions x and γ)
3. **If** the relevant life-history and fishery information are not reliably estimated then only use the SSB-based limit reference point, γSSB_0.

Figure 3: Summary of the influence of steepness on the key MSY quantities (fishing mortality, top left; yield relative to B_0, topright; SSB relative to B_0, bottomleft) for the yellowfin-like model.



The second level of the approach is proposed as, even though one would have already performed an assessment for a given assumed level of steepness, the assessment quantities of interest (depletion and selectivity, for example) are usually robust to a range of steepness values. This is a somewhat useful “by-product” of the overall lack of information on steepness from our perspective: we have what we need to robustly estimate the reference points and assess the status of the stock relative to them. The rationale behind the third level in the hierarchy will become apparent when we address the skipjack modelling results.

In terms of fishing mortality we use the concept of the fractional reduction (relative to unfished conditions) in per-recruit spawning biomass. Given an unfished level of spawning-potential-per-recruit, SPR_0, and a target reduction fraction of this level under exploited equilibrium conditions, δ, we estimate the level of fishing mortality, F, which solves the following equation:

$$(4) \qquad SPR(F) = \delta \times SPR_0 .$$

Various levels of the target reduction level, *δ*, have been proposed, ranging from 0.3 to 0.6, depending on the life-history and fishery characteristics of the stock in question (Gabriel and Mace, 1999; Sainsbury, 2008).

For the relevant level of SSB depletion, *γ*, we choose the value of 0.2 – the limit SSB reference point is 20% of the level seen in the absence of fishing, SSB_0. This level forms the basis of the limit reference points for significant regional fisheries management organisations and for many national fisheries management policies (Sainsbury, 2008) as well as being a central theme in both the IUCN red list (IUCN, 2001) and trade fora like CITES (CITES, 2007). The value of $\gamma = 0.2$, when steepness is essentially unknown, can help to avoid recruitment over-fishing in medium to strongly productive species (Sainsbury, 2008), is based on a stock status quantity (SSB depletion) that is generally robust to the key biological inputs (including steepness), and is consistent with a variety of metrics of the risk to a population's persistence used at the international and many domestic levels.

8.2.1 Yellowfin and bigeye tuna

As shown with the yellowfin-like model in Figure 3, the robust estimation of MSY-based reference points (*F*, yield, and SSB) is not feasible without reliable and precise information on steepness. Given the 'one-way trip' nature of the key relative abundance information and the associated estimates in the biomass trends over time for both yellowfin and bigeye tuna, it is unlikely that current, or assessments in the near-future, will be able to reliably and precisely estimate steepness for either of these stocks. Given our suggested hierarchical structure, we recommend that the second-level is most applicable for both yellowfin and bigeye tuna as we generally have well estimated biological and fishery parameters, but no reliable estimate of steepness.

We have already recommended that a default SSB limit reference point of 20% of SSB_0 is likely to be appropriate, so we now focus on identifying an appropriate level of SPR reduction, *δ*, that would form the basis of the *F*-based limit reference points. Given that most historical work (Mace, 1994; Gabriel and Mace, 1999; Mace, 2001) has suggested values that range from 0.3 to 0.4 for reasonably to highly productive species we explore these values as two candidates for *δ*. We look at two consistency factors:

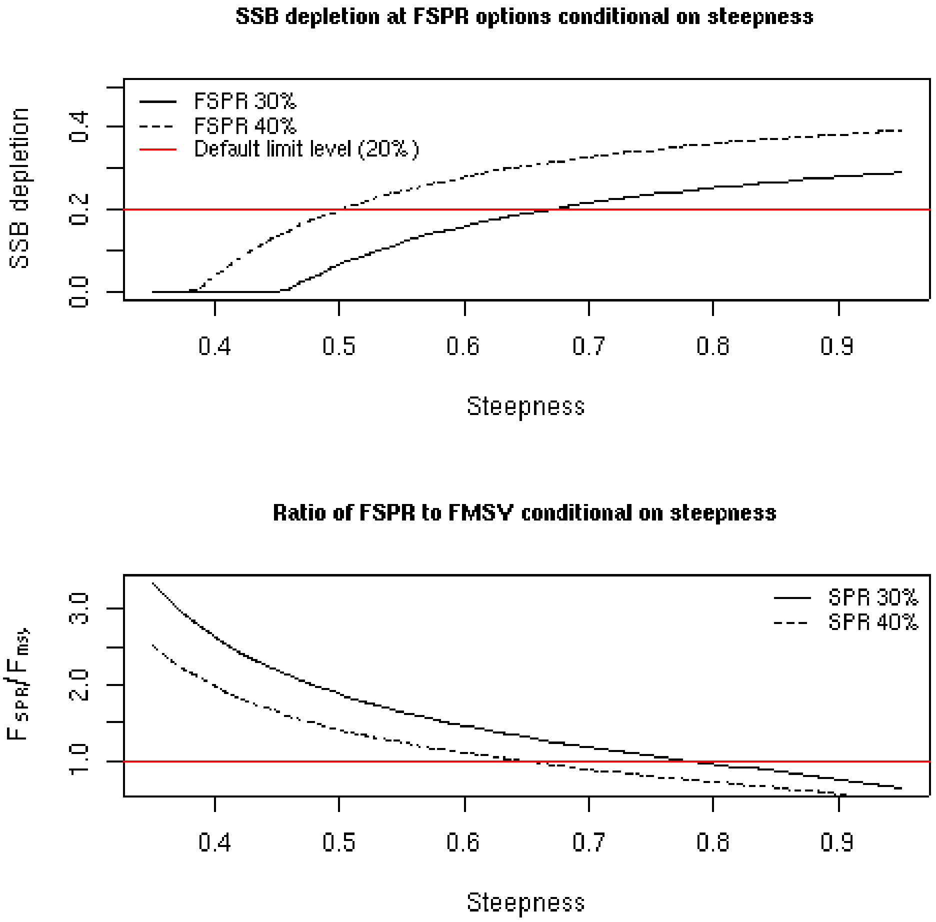
1. The consistency of the SSB depletion level at F_{SPR} and the assumed default limit level of 20%, across a range of steepness values.
2. The consistency of the estimates of F_{SPR} and F_{MSY} across a range of steepness values.

While we may not know the steepness, we can assess the internal consistency of the two reference points (the first factor, given there is an implied equilibrium SSB depletion level at F_{SPR}), as well as the consistency between F_{SPR} and F_{MSY} (the second factor, given F_{MSY} is the "true" limit reference point).

Figure 4 looks at these two consistency issues for the $\delta = 0.3/0.4$ scenarios. In relation to consistency between the SSB depletion level of 0.2 and the implied depletion level at F_{SPR}, the 30%/40% options ($\delta = 0.3/0.4$) are less conservative than the *20% SSB* depletion level at steepness levels below around 0.67/0.5 and exceeds F_{crash} below steepness levels of around 0.45/0.38. For more productive stocks with steepness levels above 0.6 to around 0.95 the 30% option is much closer to the 20% depletion level than the 40% option (the implied depletion is some 50-100% larger for $\delta = 0.4$, while varying between -20 to 50% for $\delta = 0.3$). In terms of the two SPR target levels and how F_{SPR} relates to F_{MSY}, for $\delta = 0.3$ we see that F_{SPR} exceeds F_{MSY} for steepness levels below 0.78, but for $\delta = 0.4$ this occurs at steepness levels below 0.65.

One would generally prefer a reasonable level of consistency between the limit reference points over a range of plausible true steepness values as differences between the *F* and SSB-related reference points are likely to result in unintended outcomes when making decisions, which are likely to result in poor management performance. On the other hand, to be consistent with the intent of their use, we would prefer limit reference points to be precautionary and, as such, have a high likelihood of minimising the risk to the stock in the case that the more pessimistic hypotheses about the stock's resilience and productivity is in fact true. It is worth noting that in relation to maximising yield, levels of F_{SPR} above or below F_{MSY} can be expected to lead to lower long term yields, but levels above it also lead to lower levels of SSB depletion and lower potential risk to the stock for lower steepness levels. For $\delta = 0.3$ we do see more consistency between the two limit reference points in terms of SSB depletion, but this is associated with levels of fishing mortality that exceed F_{MSY} over a much wider range of steepness levels than $\delta = 0.4$ (see bottom of Figure 4).

Figure 4: consistency of the estimates of F_{SPR} ($\delta = 0.3/0.4$) in relation to (top) the implied SSB depletion at F_{SPR} for a range of steepness values (with our default SSB depletion value of 0.2 shown in red), and (bottom) the ratio of F_{SPR} to F_{MSY} for a range of steepness values.



8.2.2 Skipjack tuna

For skipjack we performed only the per-recruit analyses, as there appeared to be issues relating to the knowledge about the maturity-at-age relationship that make even the sensible and robust estimation of the SPR-type reference points difficult. For all fisheries where non-uniform selectivity occurs across the age classes the interaction of selectivity and maturity is a key process that can significantly affect estimation of sustainable mortality rates and overall yield. Even for a given level of steepness, higher/lower levels of mortality can be sustained if the population is selected after/before the onset of sexual maturity. In contrast to Skipjack, yellowfin tuna tend to be targeted well before the onset of sexual maturity (see Fig1 and the recent assessment). This makes them less able to sustain higher levels of mortality than if they were selected after the age at first spawning (or 50% maturity for example) but it does induce a degree of stability in the estimation of our key reference points, in that they are affected by but generally robust to small changes in the assumptions about maturity and selectivity.

In contrast to yellowfin, where the maturity-at-age information is very detailed, there appears to be much less information available for skipjack, apart from that they are generally mature at about 1 year old (Hoyle et al, 2010). Assuming a logistic curve for maturity and a 9 month age at 50% maturity we see in Figure 2 that there is a lot of similarity between the generic pole-and-line/purse-seine selectivity and the maturity-at-age relationship, with only minimal selection prior to the onset of maturity. This results in considerable sensitivity of the estimates of F_{SPR} for skipjack for both the $\delta = 0.3$ and 0.4 scenarios.

Figure 5: sensitivity of the estimates of skipjack F_{SPR} to the target reduction ratio, δ.

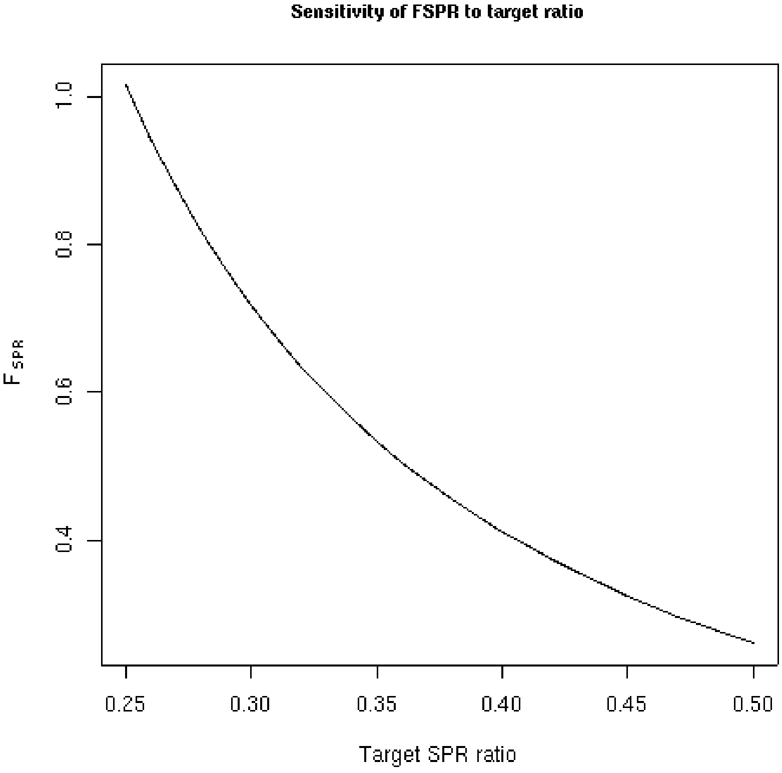


Figure 6: sensitivity of the estimates of skipjack F_{SPR} to the age (in quarters) at 50% maturity (am50), for a target reduction ratio of $\delta = 0.4$ and assuming the age at full maturity to be fixed at 4 quarters (1 year old).

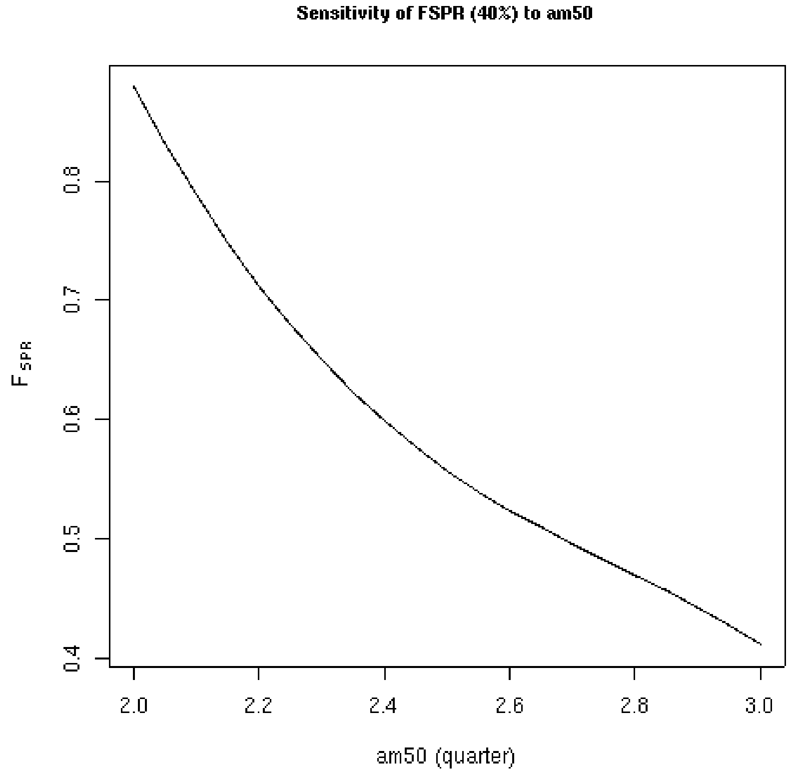


Figure 5 shows the sensitivity of the estimates to the target reduction level, δ. The estimate of F_{SPR} for $\delta = 0.3$ is almost twice what it is at $\delta = 0.4$ – from Figure 4 the difference between the estimates for the yellowfin model was never more than 50% and often smaller than this. Figure 6 shows the sensitivity of the estimates to the age at 50% maturity (in terms of quarters of a year) for the $\delta = 0.4$ option. Even for a change of 3 months (from 6 to 9 months) in the age at 50% maturity the estimates of F_{SPR} decrease by more than a factor or 2. This is a relatively simple model but already it exhibits very considerable sensitivity to the structural and parametric assumptions made about selectivity and maturity. For the real example, which has more fisheries with similar but varying selectivities, one would imagine a similar sensitivity is almost inevitable and may quite possibly be amplified.

8.2.3 Albacore and billfish

Given the uncertainties in some of the key life-history and fishery variables required for either level 1 or level 2 in our suggested hierarchical approach, we recommend that a similar approach to skipjack be used and that level 3 (the default SSB depletion option) be used for albacore and billfish, in general, except where a thorough exploration of model sensitivity and, or, formal MSE results are available.

9. ISSUES RELATING TO UNCERTAINTY

In this work we have addressed the issue of uncertainty in population parameters only in relation to the age-at-maturity for skipjack using a sensitivity analysis approach. Obviously, if one has a reasonable understanding of the uncertainty in the key quantities required to estimate the reference points then this should be included, and any resultant sensitivity addressed. Also, to be consistent with the precautionary approach, it is important to not only have limit reference points, but specific probabilities that specify the extent to which these limits may be approached or "exceeded" and when and what form of management action must be taken. The use of point estimates to estimate whether a stock is above or below the reference point, does not account for the precision, or lack of, of the estimate of the relevant indicator (usually derived from the assessment) (see Davies and Polacheck 2007 for further discussion of this issue). Ideally the combination of the reference point and associated probability and decision rules will be specified and agreed in advance of the need for serious management action.

It is a matter for the relevant body to decide on the probability associated with particular limit reference points. Davies and Basson (2008) and others, note that limit reference points are by definition to be avoided and therefore the probability of having exceeded the LRF "should be a very low percentage – say 5% or 10% at the most; the exact choice is one the Commission needs to make on the basis of the level of risk they (stakeholders, managers, society) are prepared to take". In the absence of an agreed percentage, 10% could be used as a candidate interim value, if required by the SPC-OFP scientists for their work on the additional 2 parts of this project (see appendix A). Davies and Polacheck (2007) and Davies and Harley (2010) note that there is an interaction between the limit reference point, the precisions of the estimate and the structural and other uncertainties that are incorporated into the estimation, and therefore all these factors must be considered (and usually evaluated by simulation testing to ensure they are precautionary) before adopting a particular value.

In addition, it is recommended that there should be a suitable methodology in place with which one can actually compute these probabilities, given the relevant limit reference points and the current stock assessment. In relation to the assessments used in the WCPO it seems likely that the most pragmatic approach is to use approximations (such as the delta-method) or likelihood profiles to assess these probabilities given that the estimation of these "true" probabilities (via some kind of Bayesian MCMC-type analysis) is not yet feasible with the current stock assessment methods.

A second issue we would discuss is stochasticity and the calculation and subsequent use of deterministic (MSY, FSPR etc.) reference points. Some work has already been undertaken (Davies and Harley, 2010) to explore stochastic projections (via recruitment uncertainty) for key WCPO stocks. Taking MSY as an example: the value of F_{MSY} from a deterministic calculation will **not** be the same as F_{MSY} calculated using stochastic approaches, such as maximum average yield (MAY; Francis, 1992). More simply, if one used deterministic estimates of F_{MSY} to manage a stock (even when starting from unfished conditions) which in reality has at least one source of stochastic process, such as recruitment variability, the true (stochastic) equilibrium yield and SSB depletion would both be lower than those expected estimated using deterministic MSY. In the case of the Beverton-Holt stock recruitment model and any level of steepness below 1, a weak year-class (say *x%* below the average) in any given year will always have a stronger negative impact on the future mean recruitment levels (via decreased SSB) than a strong year class (that is also *x%* above the average) and its positive impact on the future SSB and mean recruitment. This is hard-wired into the Beverton-Holt model: the directional derivative for decreasing SSB is negative and larger in magnitude than the (positive) derivative in the direction of increasing SSB. The strength of this effect is driven largely by an interaction between the strength of the level of stochasticity (not just recruitment driven) and the steepness itself – the higher the variation and/or the lower the steepness the stronger this disparity between deterministic and stochastic becomes. Given the assessments of tuna species using Multifan-CL have several (implicit) random effects embedded within them (recruitment, growth, effort etc.) it is perhaps worth considering how to deal with deterministic estimates of say MSY derived from within this model, and the potential disparity these may have when using stochastic projections also using the underlying assessment model.

10. CONCLUSIONS ON CANDIDATE LIMIT REFERENCE POINTS

In general, we recommend a three-level hierarchical approach to setting limit reference points for fishing mortality and SSB. The first level uses F_{MSY} and B_{MSY} but only where a reliable and precise estimate of steepness is available. The second level uses F_{SPR} and 20% of SSB_0 assuming that steepness is not known well, if at all, but that the key biological (natural mortality, maturity) and fishery (selectivity) variables are reasonably well estimated. The third level does not provide an F-based limit reference point if the key biological and fishery variables are not well estimated or understood, but simply suggests that the SSB limit of 20% of SSB_0 be used.

In terms of strengths and weaknesses in such an approach, we take each level in turn. For level 1 (MSY essentially) the obvious strength is that it covers productivity directly, maximising yields while maintaining the population level at a safe and productive level. The key weakness of this approach is the difficulty in robustly estimating it, and that such information is not available for the key species of interest. In terms of level 2, a key strength is that it does not require an estimate of steepness and can be done with the information currently available from a reasonably robust assessment (e.g. The current yellowfin and bigeye assessments). Two major weaknesses are that: (i) if there is significant uncertainty in the key life-history and fishery variables (M, selectivity etc.), and (ii) depending on the true steepness level and the choice of target SPR depletion level, there can be significant inconsistency between the F and SSB-based reference points. For level 3, the key strength is that it is probably the most robust of the three approaches (SSB depletion tends to be one of the most robust status indicators in assessments of this type), but its key weakness is that it does not use information on mortality, which means that it is an effective proxy for a stock being overfished, but not for whether over-fishing is occurring.

For yellowfin and bigeye we recommend using the second level. We suggest that the default level of SPR reduction (the δ parameter) to use should be 0.4 (i.e. a 40% reduction in the per-recruit spawning potential expected for unfished conditions). The reason for this is because, while a value of $\delta = 0.3$ is more consistent (in terms of the implied SSB depletion across a range of steepness values) with the SSB limit of 20% of SSB_0 (see Figure 4), this value can lead to levels of F_{SPR} that exceeded F_{MSY} for steepness values lower than about 0.8 (still fairly high) which could lead to both reduced yields and a higher risk to the stock for less productive populations (i.e. for lower steepness levels).

For skipjack, given the strong sensitivity of the estimates of F_{SPR} to the specifics of the maturity-at-age relationship, we recommend a level-three approach. At present, there is an indication that the uncertainty in the nature of the maturity-at-age relationship may prevent the robust estimation of F_{SPR}. If this relationship becomes better understood then perhaps a tier-two approach may be appropriate, but for now it is perhaps best to simply use the recommended SSB limit reference point only.

11. SUMMARY

In this commissioned report we provide a review of steepness and depletion drawing particularly from the work in the tuna RFMOs, and recommend a three-level hierarchical approach for setting limit reference points. Maximum Sustainable Yield, Spawner Potential per Recruit and Depletion based limit reference points have been reviewed in terms of their strengths, weakness and data requirements, and information they provide for use in a management framework.

Steepness is a measure of the productivity of the stock at low stock size. It is difficult for the current stock assessments to estimate steepness, and a range of values should be used to provide management advice. Steepness for the tuna and tuna-like species is likely to be in the mid to high range of values.

Depletion based limit reference points measure the level of depletion of the total or spawning stock biomass (e.g. *x*% of the initial unfished spawning stock biomass (SSB_0). *20% of* SSB_0 is considered a threshold for recruitment overfishing for productive stocks (Myers, 1994), and is commonly used as a limit reference point in other RFMOs and fisheries management and conservation organisations. Since the key target species in the WCPFC are considered to be reasonably productive stocks (mid to high steepness), *20% of* SSB_0 is considered as a default value for the depletion based limit reference points.

A three-level hierarchical approach to setting limit reference points for fishing mortality and SSB is recommended. Only 1 set of limit reference points, from 1 level of the hierarchy, is used, depending on the understanding of key parameters in the stock assessment models. The first level uses F_{MSY} and B_{MSY} but only when a reliable and precise estimate of steepness is available. The second level uses F_{SPR} and 20% of SSB_0 assuming that steepness is not known well, but that natural mortality, maturity and fishery selectivity variables are reasonably well estimated. The third level does not provide an F-based limit reference point if the key biological and fishery variables are not well estimated or understood, but simply suggests that the SSB limit of 20% of SSB_0 be used.

An age-structured operating model was developed to explore the most appropriate limit reference points for each of the target species. It was parameterised as a yellowfin/bigeye type and a skipjack type population.

For yellowfin and bigeye we recommend using the second level of the hierarchy of reference points. We suggest that the default level of SPR reduction (the δ parameter) to use should be 0.4 (i.e. a 40% reduction in the per-recruit spawning potential expected for unfished conditions).

For skipjack, we recommend the third level of the hierarchy because of the sensitivity of the estimates of F_{SPR} to the maturity-at-age relationship.

For Albacore and the billfish species, we recommend the third level of the hierarchy be used because of the uncertainties in some of the key life-history and fishery variables required for level 1 or level 2

12. ACKNOWLEDGMENTS

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APPENDIX A – DEFINITION OF PROJECT 57 FROM THE WCPFC SCIENTIFIC WORKPLAN

Note: This report covers items 1 and 2 below. Items 3 and 4 will be undertaken by SPC-OFP scientists.

1. Identify candidate indicators (e.g. Bcurrent/B0, SB/SBMSY) and related limit reference points (LRPs) (e.g. Bcurrent/B0=X, SB/SBMSY =Y), the specific information needs they meet, the data and information required to estimate them, the associated uncertainty of these estimates, and the relative strengths and weaknesses of using each type within a management framework.

2. Using past assessments, evaluate the probabilities that related performance indictors exceed the values associated with candidate reference points.

3. Evaluation of the consequences of adopting particular LRPs based on stochastic projections using the stock assessment models.

4. Undertake a literature review and meta-analyses to provide insights into levels of depletion that may serve as appropriate LRPs and other uncertain assessment parameters (e.g. steepness).

Contact Us

Phone: 1300 363 400
+61 3 9545 2176

Email: enquiries@csiro.au

Web: www.csiro.au

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