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A review of candidate biological reference points for northern stocks of highly migratory species in the North Pacific Ocean

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A REVIEW OF CANDIDATE BIOLOGICAL REFERENCE POINTS FOR NORTHERN STOCKS OF HIGHLY MIGRATORY SPECIES IN THE NORTH PACIFIC OCEAN[1]

ISC

July 2010

[1] Information prepared by ISC working groups with full discussion contained in ISC10 report, Annexes 6 and 9 for albacore tuna, 5 and 8 for billfishes, and 7 for Pacific bluefin tuna.

A REVIEW OF CANDIDATE BIOLOGICAL REFERENCE POINTS FOR NORTHERN STOCKS OF HIGHLY MIGRATORY SPECIES IN THE NORTH PACIFIC OCEAN

Introduction

Biological reference points (BRPs) are part of a precautionary approach to fisheries management and seek to avoid serious harm to a stock while permitting maximum sustained yield or other catch scenario. Limit reference points attempt to constrain harvesting within safe biological limits for a stock. Recruitment overfishing (fishing mortality above which the recruitment to the exploitable stock becomes significantly reduced) and growth overfishing (fishing mortality at which the losses in weight from total mortality exceed the gain in weight due to growth) are often considered to be the major biological risks to the resiliency and productivity of a stock, with recruitment overfishing considered to have the more serious and potentially harmful impacts. Limit reference points (LRP) are fishing mortality rates or biomass levels which must not be exceeded and are frequently implemented to avoid recruitment overfishing because when a stock falls below the threshold level associated with a LRP, there is a high probability that the resiliency and productivity of the stock will be so impaired that serious harm to the stock will occur. Target reference points (TRP) are fishing mortality rates or biomass levels which permit long-term sustainable exploitation of a stock and are determined by productivity objectives for the stock, broader biological considerations, and socio-economic objectives. Typically, the biological consequences of exceeding a TRP are not as severe as those incurred if a LRP is exceeded.

History of ISC BRP discussion in ISC

In 2005, ISC reviewed biological reference points important to the management of albacore fisheries of the North Pacific Ocean (ISC5 report section 6a and ISC5 Plenary document 7). It reviewed preliminary simulation analysis that focused on determination of future fishing mortality rates (F) that result in levels of stock biomass (B) and spawning stock biomass (SSB) observed historically (1975-04). At the time, ISC agreed that biological reference points will be needed to guide future fishery management discussions, particularly about North Pacific albacore.

In 2006, ISC reviewed background information on BRPs (see ISC6 Report, section 6.6 and Plenary document 6) including overfished and overfishing reference points and BRPs that are commonly used. The ISC acknowledged that dialogue with management bodies will need to take place to complete the adoption of appropriate BRPs.

In 2009, ISC convened a seminar on Reference Points for Highly Migratory Species Fisheries Management (see ISC9, Annex 13). The seminar included seven presentations on the theory and application of biological reference points and socioeconomic indicators for fisheries management with special consideration of highly migratory species. The presentations focused on objective measures of sustainability, resource management in tuna RFMOs, and associated yield-based reference points, modern spawning potential reference points, and reference points for ecosystem-based fishery management.

In 2009, the ISC was tasked with identifying potential BRPs for northern stocks of highly migratory species in the Pacific Ocean at the 5th regular session of the Northern Committee (NC) in Nagasaki, Japan, and asked to report its findings at the 6th session of the NC in September 2010.

ISC working groups worked on this request during regular intercessional meetings in 2009 and 2010 and developed the following tables for: albacore tuna, Pacific bluefin tuna, and billfish focusing on the "generic" BRPs typically used in stock status evaluations of the species, noted the pros and cons of using each BRP and listed the estimated value of each BRP.

Albacore – Table 1

The albacore working group (WG) was reminded that their focus has been on limit and precautionary reference points. The WG needs to know management goals for a stock in order to recommend a suitable reference point. The present request from the Northern Committee is not specific with respect to management objectives and as a result the WG has presented information on a variety of reference points in previous stock assessments. The group discussed the ISC Chair's request for species specific reference points and noted that an interim objective to maintain the spawning stock biomass (SSB) above the average level of its ten historically lowest points (ATHL) with a probability greater than 50% has been established for north Pacific albacore and that the associated F-based reference point, FSSB-ATHL, will be estimated in future stock assessments. The F_{SSB} reference point concept was first discussed by the WG in 2005 (Conser et al. 2005; ISC-ALBWG/05/06) to ensure that SSB in future years remains within the range of the historically 'observed' SSB that supported productive, large-scale fisheries in the North Pacific for many years. At that time, the WG examined the minimum observed SSB and the lower 10^{th} and 25^{th} percentiles as potential limit reference points and concluded that the minimum would not be suitable, but did not make a recommendation on either the 10^{th} or 25^{th} percentile. The threshold level of ATHL is with a few hundred tonnes of the lower 10^{th} percentile of spawning biomass. However, the WG notes that the 10^{th} or 25^{th} percentile thresholds are more robust statistically than ATHL. The WG will also present the F_{SSB} reference point framework (Ichinokawa et al. 2010; ISC/10-1/ALBWG/10) because it illustrates the tradeoffs between SSB thresholds, equilibrium and non-equilibrium dynamics, and the level of certainty in not exceeding a threshold on the associated F_{SSB} reference point. The framework is also a useful tool for eliciting feedback from the Northern Committee that the WG needs to make further progress on reference points, namely the SSB threshold, the level of certainty required (50% vs. 95%), and the projection period that should be used (Reference ISC10, Annex 9, pages 15-21).

Table 1. Albacore tuna candidate biological reference points.

BRPs	Recent Estimate (Year)		Description	Data Needs	Model
	50% Prob.	95% Prob.			
F_{MSY}			Fishing mortality rate associated with maximum sustainable yield	Catch, CPUE, life history parameters	Age structured & dynamic-pool models
F_{MED}			Fishing mortality rate corresponding to the median observed recruit/SSB ratio	Catch, CPUE, life history parameters	Age structured & dynamic-pool models
$F_{40\%}$	0.32 (2006)		F that reduces SSB/R to 40% of unfished state	Life history parameters (length-weight, M, size at age, sex ratio)	Age structured model
$F_{35\%}$	0.38 (2006)		F that reduces SSB/R to 35% of unfished state		
$F_{30\%}$	0.45 (2006)		F that reduces SSB/R to 30% of unfished state		
$F_{20\%}$	0.65 (2006)		F that reduces SSB/R to 20% of unfished state		
$F_{0.1}$	0.45 (2006)		F at which slope of Y/R is 10% of value at origin	Life history parameters (length-weight, M, size at age, sex ratio)	Age structured & dynamic-pool models
F_{MAX}	2.07 (2006)		F corresponding to maximum yield per recruit	Life history parameters (length-weight, M, size at age, sex ratio)	Age structured & dynamic-pool models
F_{loss} [A]			Fishing mortality rate expected to keep biomass at Bloss	Catch, CPUE, life history parameters	Age structured model
B_{loss} [A]			Minimum observed biomass (or SSB)	Catch, CPUE, life history parameters	Age structured model
B_{MSY}			Stock biomass associated with maximum sustainable yield	Catch, CPUE, life history parameters	Age structured & dynamic-pool models
SSB_{MSY}			Spawning stock biomass associated with maximum sustainable yield	Catch, CPUE, life history parameters	Age structured & dynamic-pool models

Table 1. Albacore (continued).

BRPs	Recent Estimate (Year)		Description	Data Needs	Model
	50% Prob.	95% Prob.			
F_{SSB}			Fishing mortality rate that ensures future spawning stock biomass (SSB) remains above a specified threshold level with a certain probability.	Configuration of stock assessment model and projection software requires discussion with managers	Age structured & dynamic-pool models
$F_{SSB-10\%}$	0.70 (2006)	0.55 (2006)	Fishing mortality rate that prevents the SSB from declining below the 10th percentile of observed SSB		
$F_{SSB-25\%}$	0.66 (2006)	0.51 (2006)	Fishing mortality rate that prevents the SSB from declining below the 25th percentile of observed SSB		
$F_{SSB-50\%}$	0.56 (2006)	0.39 (2006)	Fishing mortality rate that prevents the SSB from declining below the median (50th percentile) of observed SSB		
$F_{SSB-ATHL}$	0.75 (2009)		Fishing mortality rate that prevents the SSB from declining below the average of the ten historically lowest observed SSB		
$F_{SSB-min}$	0.81 (2006)	0.64 (2006)	Fishing mortality rate that prevents the SSB from declining below the minimum observed SSB		

Table 1. Albacore (continued).

BRPs	USE (target/limit)	Pros	Cons	Robustness to M[B]	NPALB Comments
F_{MSY}	target or limit	Considers both S/R and OY concepts; consistent with goals of many management bodies	Difficult to estimate; sensitive to S/R steepness and other structural assumptions; risk of recruitment overfishing; productivity changes (e.g., regime shifts) may have unpredictable effects		$F_{MSY} = F_{MAX}$ based on previous stock assessment because steepness of S/R relationship = 1 was used.
F_{med}	target		Assumes S/R; may not be robust if number of recruits estimated from narrow range of SSB	Estimates relatively sensitive to M assumption	
$F_{40\%}$	target or limit	Proxies for FMSY; Knowledge of S/R relationship is not required	Difficult to specify which %SPR is an appropriate proxy; advice in literature based on assumptions about stock productivity; not robust to changes in selectivity; does not consider impacts of environmental change on productivity	Estimates relatively sensitive to M assumption	Life history parameter estimates for albacore are old and need updating; may affect estimates of Fx%; difficult to estimate unfished biomass, especially for NPALB exploited historically
$F_{35\%}$					
$F_{30\%}$					
$F_{20\%}$					
$F_{0.1}$		Proxy for F_{MSY}; Knowledge of S/R relationship is not required; Can be estimated if Y/R curve asymptotic in contrast to F_{MAX}; Accounts for changes in life history parameters over time and selectivity patterns.	Not useful for recruitment overfishing	Estimates highly sensitive to changes in M	Life history parameter estimates for albacore are old and need updating; may affect estimates

Table 1. Albacore (continued).

BRPs	USE (target/limit)	Pros	Cons	Robustness to M^B	NPALB Comments
F_{MAX}	limit	Estimated from Y/R so S/R relationship doesn't need to be known; F > FMAX considered growth overfishing	Difficult to estimate if Y/R curve is asymptotic; not useful for recruitment overfishing	Estimates highly sensitive to changes in M	Life history parameter estimates for albacore are old and need updating; may affect estimates
F_{loss} [A]	limit	Ease of calculation relative to F_{SSB}; easy to understand the concept as a limit	Assume equilibrium dynamics which may not be realistic	Estimates relatively sensitive to M assumption	B_{loss} occurred at beginning of time series when backward simulation models do not estimate well. Robustness of estimate based on previous stock assessment questioned; may not be an issue with implementation of SS3 for upcoming stock assessment but requires further research
B_{loss} [A]	limit	Ease of calculation relative to Fssb; easy to understand the concept as a limit	Assume equilibrium dynamics which may not be realistic	Estimates relatively sensitive to M assumption	B_{loss} occurred at beginning of time series when backward simulation models do not estimate well. Robustness of estimate based on previous stock assessment questioned; may not be an issue with implementation of SS3 for upcoming stock assessment but requires further research

Table 1. Albacore (continued).

BRPs	USE (target/limit)	Pros	Cons	Robustness to M^B	NPALB Comments
B_{MSY}	target or limit	Considers both S/R and OY concepts; consistent with goals of many management bodies (straightforward); Accounts for changes in life history parameters over time and selectivity patterns.	Difficult to estimate; sensitive to S/R steepness and other structural assumptions; not robust to change in selectivity; productivity changes (e.g., regime shifts) may have unpredictable effects		
SSB_{MSY}	target or limit	Considers both S/R and OY concepts; consistent with goals of many management bodies (straightforward); Accounts for changes in life history parameters over time and selectivity patterns.	Productivity changes (e.g., regime shifts) may have unpredictable effects		
F_{SSB}	target or limit	Flexibility in way it's calculated; flexible based on management goals; increases need to determine risk strategy of management; Based on concept of avoiding recruitment overfishing Simulation-based; takes into account uncertainties as buffers by quantifying non-equilibrium dynamics,	Flexibility in way it's calculated; increases need to determine risk strategy of management; computer intensive; Requires specification of: (1) threshold SSB level, (2) probability that stock remains above threshold, and (3) length of projection period. Sensitive to projection period used in simulation, e.g., 5- vs 25-yr.	$F_{SSB-10\%}$: insensitive, $F_{SSB-25\%}$: insensitive, Sensitivity for $F_{SSB-50\%}$ was not tested.	Flexibility in way it's calculated; increases need to determine risk strategy of management; computer intensive; Requires specification of: (1) threshold SSB level, (2) probability that stock remains above threshold, and (3) length of projection period. Based on concept of Avoiding recruitment overfishing
$F_{SSB-10\%}$	Limit/Precautionary				
$F_{SSB-25\%}$	Limit/Precautionary				
$F_{SSB-50\%}$	Target				

Table 1. Albacore (continued).

BRPs	USE (target/limit)	Pros	Cons	Robustness to M^B	NPALB Comments
F_{SSB}	target or limit	estimates of historical SSB, and parameter estimates in the terminal years.	Occurs at beginning of time series when VPA does not estimate old fish well; this may not be true with new SS3 model;	$F_{SSB-10\%}$: insensitive, $F_{SSB-25\%}$: insensitive, Sensitivity for $F_{SSB-50\%}$ was not tested.	Flexibility in way it's calculated; increases need to determine risk strategy of management; computer intensive; Requires specification of: (1) threshold SSB level, (2) probability that stock remains above threshold, and (3) length of projection period. Based on concept of Avoiding recruitment overfishing
$F_{SSB-10\%}$	Limit/Precautionary				
$F_{SSB-25\%}$	Limit/Precautionary				
$F_{SSB-50\%}$	Target				
$F_{SSB-ATHL}$	Limit/Precautionary			Estimates insensitive to M assumption	Consistent with interim objective for NP ALB;
$F_{SSB-min}$	Limit/Precautionary			Estimates relatively sensitive to M assumption	Occurs at beginning of time series when VPA does not estimate old fish well; this may not be true with new SS3 model;

A – see Kai 2010 - ISC/10-1/ALBWG/09.
B – see Kiyofuji et al. 2010 - ISC/10-1/ALBWG/11.

Pacific bluefin tuna – Tables 2A and 2B.

The ISC was tasked with identifying potential biological reference points (BRPs) for all northern stocks of highly migratory species in the Pacific Ocean at the 5th regular session of the Northern Committee (NC) in Nagasaki, Japan, and asked to report its findings at the 6th session of the NC in September 2010. To complete this assignment, the Pacific bluefin tuna WG created two tables to compile information on a list of potential reference points for PBF. Table 1 follows the format suggested by ISC chair, describes and characterizes a suite of potential reference points, including comments on their strengths and weaknesses, PBF-specific comments. Table 2 includes additional technical details on sensitivity, data needs and model structures. In creating the tables, there were different opinions with respect to the utility of the sensitivity of reference points as a criterion for choosing a suitable reference points. Since similar discussions have already done for the ISC/10-1/PBFWG/04, (reference Annex 7, pages 9 and 11 for details). The WG did not identify specific target or limit reference points in this list, but where WG members had such knowledge, it has been noted how the reference points in the table have been used by other RFMOs and science-advisory bodies.

Table 2A. Pacific bluefin tuna candidate biological reference points.

BRPs	**Recent Estimate (Year)** **BRP/F_{04-06}**	**Range of RP by M***	**Description**	**USE (target/ Limit)**	**Pros**	**Cons**	**PBF comments**
F_{msy}			Fishing mortality rate associated with maximum sustainable yield	either	Consider both recruitment and growth overfishing; Concept of optimal yield (OY)	Difficult to estimate; Sensitive to S/R steepness and other structural assumptions	$F_{msy}=F_{max}$ based on preliminary stock assessment because steepness of S/R is estimated to be 1
F_{max}	2	0.76-3.58	F corresponding to maximum yield per recruit	limit	Consider growth overfishing; Concept of maximum yield	Does not consider recruitment overfishing; Difficult to estimate if Y/R curve is asymptotically flat topped	
$F_{0.1}$	2.86	1.14-5.08	F at which slope of Y/R is 10% of value at origin	either	Consider growth overfishing; Conservative measure in contrast to the F_{max} ;Possible to estimate even if Y/R curve is flat topped.	Does not consider recruitment overfishing.	
$F_{\%SPR}$	1.33($F_{10\%}$) 1.93($F_{20\%}$) 2.60($F_{30\%}$) 3.44($F_{40\%}$)	0.64-1.97 ($F_{10\%}$) 0.92-2.91 ($F_{20\%}$) 1.24-3.97 ($F_{30\%}$) 1.63-5.30 ($F_{40\%}$)	F that reduces SSB/R to a certain % of unfished state	either	Consider recruitment overfishing.	Does not consider growth overfishing nor optimal yield.	

Table 2A. Pacific bluefin tuna (continued).

BRPs	**Recent Estimate (Year) BRP/$F_{04\text{-}06}$**	**Range of RP by M***	**Description**	**USE (target/ Limit)**	**Pros**	**Cons**	**PBF comments**
F_{med}	1.24	1.24-1.55	Fishing mortality rate corresponding to observed 1/SPR	target	Consider recruitment overfishing; Based on the historical time series of *S*/*R*	Assumes *S*/*R*; may not be robust if number of recruits estimated from narrow range of *S* and the relationship is negative correlation, does not consider growth overfishing	*1. It theoretically assume that there is a stock recruitment relationship, which is inconsistent with h=1 in the present assessment.
F_{loss}	0.919	0.66-1.02	Fishing mortality rate expected to keep biomass at Bloss	limit	Consider recruitment overfishing; Based on the historical time series of *S*/*R*;Ease of calculation relative to F_{SSB}; Easy to understand the concept as a limit.	Assumes S/R; may not be robust if number of recruits estimated from narrow range of S and the relationship is negative correlation, does not consider growth overfishing. Does not have any cushion so relatively risky (not precautionary) compared to Fssb	
Adjusted Floss			Floss multiplied by a value (0<x<1) e.g. 0.5xFloss might be a target. Value can also be based on algorithm such as described in ISC/10-1/PBFWG/4	Target/precautionary depending on choice of multiplier	Converts Floss to a corresponding target value that may be useful for management. Easy to understand the concept as a target related to risk at Floss. Consider recruitment overfishing.	Same as above. Except there is a cushion due to multiplier.	The optimal value of the adjustment could benefit from more research, but existing PBFWG analyses provide a useful basis.

Table 2A. Pacific bluefin tuna (continued).

BRPs	**Recent Estimate (Year) BRP/$F_{04\text{-}06}$**	**Range of RP by M***	**Description**	**USE (target/ Limit)**	**Pros**	**Cons**	**PBF comments**
F_{SSB}	1.06 ($F_{SSB\text{-min-}5\%}$) 1.11 ($F_{SSB\text{-ATHL-}5\%}$) 1.32 ($F_{SSB\text{-}25\%lower\text{-}5\%}$) 0.88 ($F_{SSB\text{-min-}50\%}$) 0.93 ($F_{SSB\text{-ATHL-}50\%}$) 1.09 ($F_{SSB\text{-}25\%lower\text{-}0.5}$)	0.92-1.14 ($F_{SSB\text{-min-}5\%}$) 0.98-1.20 ($F_{SSB\text{-ATHL-}5\%}$) 1.20-1.43 ($F_{SSB\text{-}25\%lower\text{-}5\%}$) 0.69-1.00 ($F_{SSB\text{-min-}50\%}$) 0.75-1.05 ($F_{SSB\text{-ATHL-}50\%}$) 0.91-1.19 ($F_{SSB\text{-}25\%lower\text{-}0.5}$)	Fishing mortality rate that ensures future spawning stock biomass (SSB) remains above a specified threshold level with a certain probability.	Either, and precautionary depending on the choice of threshold.	Flexibility in way it's calculated; flexible based on management goals; increases need to determine risk strategy of management Consider recruitment overfishing. Simulation based; takes into account uncertainties as buffers by quantifying non-equilibrium dynamics, estimates of historical SSB, and parameter estimates in the terminal years.	Flexibility in way it's calculated; increases need to determine risk strategy of management; computer intensive; Requires specifications of: (1) threshold SSB level, (2) probability that stock remains above threshold, and (3) length of projection period. Sensitive to projection period used in simulation, e.g., 5 - vs 25- yr. Does not consider growth overfishing	
B_{loss}			Minimum observed stock biomass (or SSB)	limit	Ease of calculation relative to F_{SSB}; Easy to understand the concept as a limit. Consider recruitment overfishing	Uncertainty around *SSB*. Does not consider growth overfishing. Lack of cushion so relatively risky.	Wide range of *SSB* over the stock assessment period
B_{msy}			Stock biomass associated with maximum sustainable yield	either	Consider both recruitment and growth overfishing; Concept of optimal yield (OY)	Difficult to estimate; Sensitive to *SSB*/*R* steepness and other structural assumptions	

*The ranges of BRPs are shown when changing M larger than age 1 fish from 0.19 to 0.31.

*1. There were different opinions for interpretations of importance of steepness assumption.

Table 2B. Pacific bluefin tuna candidate biological reference points – sensitivity characteristics and technical data needs of each. Boxes filled with gray indicate that the relevant information is not available currently.

BRPs	Sensitivity to M [*1*2]	Sensitivity to others[*1*2]	Data Needs
F_{msy}			Catch, CPUE, life history parameters
F_{max}	High	High	life history parameters (length-weight, M, size at age, sex ratio)
$F_{0.1}$	High	High	life history parameters (length-weight, M, size at age, sex ratio)
$F_{\%SPR}$	High	Medium for $F_{10\%}$, high for $F_{20\%}$, $F_{30\%}$ and $F_{40\%}$	life history parameters (length-weight, M, size at age, sex ratio)
F_{med}	Low	Low	Catch, CPUE, life history parameters
F_{loss}	Medium	Medium	Catch, CPUE, life history parameters
Adjusted Floss			Same as Floss, and other data is depending on how including buffers
F_{SSB}	Medium		Configuration of stock assessment model and projection software requires discussion with managers
B_{loss}			Catch, CPUE, life history parameters
B_{msy}			Catch, CPUE, life history parameters

[*1]: Most (high), some (medium) and a few (low) of runs changed the estimates of reference points largely (based on Table 1 in ISC/10-1/PBFWG/04 for F_{ssb}, and Fig. 3-5 in ISC/10-1/PBFWG/02 for others).
[*2]: There were different opinions for interpretations of sensitivity with respect to BRP's. Some members considered insensitivity was preferable, while others considered it was an undesirable property. See discussion part for ISC/10-1/PBFWG/02.

Billfish – Table 3

The following BRP table for billfish was completed at the April 2010 IC BILLWG workshop. The table includes 17 BRPs that are commonly used for stock assessment of highly migratory species, and were characterized using attributes including: the definition and management purpose, model structure, data needs, limit or target reference point, type of overfishing, pros/cons, and special comments (Reference ISC10, Annex 8).

Table 3. Billfish candidate biological reference points.

Biological Reference Point	Definition and Management Purpose	Model Structure[1]	Data Needs[2]	Limit or Target Reference Point	Type of overfishing	Pros/Cons and Special Comments
F based Reference Points						
FMSY	Fishing mortality that maximizes yield under existing environmental conditions.	Age-structured or size-structured model for one or two sexes	Fishery catch, fishery catch per unit effort or other relative abundance indices, life history parameters	Has been used as limit and target reference point in various RFMOs	Recruitment and growth	FMSY is difficult to estimate if stock-recruitment relationship is not known. This BRP may be easy to implement but also entails high risk of recruitment overfishing. Can be estimated with biomass dynamics modeling.
F_{MAX}	Fishing mortality that maximizes yield per recruit under existing environmental conditions	Age-structured yield per recruit model	Life history parameters	Has been used as a limit and a target BRP	growth	F_{MAX} may be appropriate if recruitment is relatively constant over a range of fishing effort. This BRP may be very risky for some rapidly-growing species because it may cause recruitment overfishing
$F_{0.1}$	The fishing mortality rate corresponding to 10% of the slope of the Y/R curve at the origin.	Age-structured yield per recruit model	Life history parameters	Has been used as a limit and a target BRP	growth	A more precautionary exploitation level relative to F_{MAX}. Often thought to reduce potential recruitment overfishing without a substantial loss in yield.
F_{MED}	The fishing mortality rate to produce replacement recruitment often taken to the median of the R/S distribution. Fishing mortality to maintain recruitment at replacement level observed during specified period.	Estimates of Spawners and Recruits	Estimates of Spawners and Recruits. Typically drawn from an age structured assessment model.	Target or Limit	Recruitment	[3]Value dependent on the range of SSB used in the calculations. Not informative if estimates of recruitment taken from a narrow range of spawning biomass. No assumptions about recruitment process. Risky with the specification of BH h=1.0.

Table 3. Billfish (continued).

Biological Reference Point	Definition and Management Purpose	Model Structure[1]	Data Needs[2]	Limit or Target Reference Point	Type of overfishing	Pros/Cons and Special Comments
F based Reference Points						
F_T (F_{crash})	Fishing mortality rate corresponding to the slope of the S/R function at the origin. Theoretical upper bound of sustainable rates.	A S/R curve and a relationship of SSB/R and F	Estimates of Spawner and Recruits. Typically drawn from an age structured assessment model.	Limit	Recruitment	Fishing at F_T leads to extinction. Can only be interpreted as a Limit. Upper limit. Does not account for dispensatory effects.
$F_{X\%SPR}$	Fishing mortality rate that produces X% of the unfished spawning potential under equilibrium conditions. Sometimes used for a proxy for other BRP's.	Age-structured Spawner per recruit model	Life history parameters	Has been used as a limit and a target BRP	Recruitment	Although a recruitment based BRP, it is a per-recruit calculation and thus does not depend on estimating the S/R relation. The appropriate level (X%) can be difficult to determine.
F_{SSB}	Fishing mortality rate that produces no more than a specified probability of SSB falling below a defined level of SSB during a given projection period.	Age or length structured assessment	Fishery catch, fishery catch per unit effort or other relative abundance indices. May use additional data such as, life history parameters, biological samples etc.	Target or Limit	Recruitment	Assumes that specified level of spawning biomass is sufficient to insure recruitment success. Flexible which is both a pro and a con. Requires lots of specifications.
F_{lim}	Fishing mortality if maintained will drive the stock to the biomass limit (B_{lim}).	The same as typically associated with an age structured model.	Estimates of spawners and recruits.	Limit	Recruitment	Specified B_{lim}.

Table 3. Billfish (continued).

Biological Reference Point	Definition and Management Purpose	Model Structure[1]	Data Needs[2]	Limit or Target Reference Point	Type of overfishing	Pros/Cons and Special Comments
F based Reference Points						
F_{pa}	Fishing mortality if maintained drives stock to precautionary biomass limit (B_{pa})	The same as typically associated with an age structured model.	Estimates of spawners and recruits. Need information on accuracy of assessment and risk to be accepted.	Limit	Recruitment	Specified B_{pa}. More precautionary version of F_{lim}.
F_{loss}	Fishing mortality if maintained drives a stock to the lowest observed spawning stock.	Age-structured or size-structured model for one or two sexes.	Fishery catch, fishery catch per unit effort or other relative abundance indices, life history parameters.	Limit	Recruitment.	Usually used as a proxy of F_{lim} when data is limited.

Table 3. Billfish (continued).

Biological Reference Point	Definition and Management Purpose	Model Structure[1]	Data Needs[2]	Limit or Target Reference Point	Type of overfishing	Pros/Cons and Special Comments
Biomass based reference points						
B_{MSY}	The average biomass resulting from fishing at F_{MSY}	Age-structured or size-structured model for one or two sexes.	Fishery catch, fishery catch per unit effort or other relative abundance indices, life history parameters.	Has been used as limit and target reference point in various RFMOs	Recruitment	B_{MSY} is difficult to estimate if stock-recruitment relationship is not known. Can be estimated with biomass dynamics modeling. This BRP may be easy to implement but also entails high risk of recruitment overfishing
B_{MAX}	The average biomass resulting from a fishing mortality that maximizes yield per recruit	Age-structured yield per recruit model	Life history parameters	Has been used as a limit and a target BRP	[4]Associated value	B_{MAX} may be appropriate if recruitment is relatively constant over a range of fishing effort. Seldom used for management but included because F_{MAX} is defined.
$B_{0.1}$	The average biomass level associated with fishing at $F_{0.1}$	Age-structured or size-structured model for one or two sexes	Fishery catch, fishery catch per unit effort or other relative abundance indices, life history parameters	Has been used as limit and target reference	[4]Associated value	Seldom used for management but included because $F_{0.1}$ is defined.
$B_{X\%}$ (depletion)	A biomass level that is some specified fraction of the estimated unfished biomass level	Biomass dynamic or age structured model.	Fishery catch, fishery catch per unit effort or other relative abundance indices.	Has been used as limit and target reference	Recruitment	Must use additional analysis to determine the appropriate depletion level. Usually a proxy for BMSY. Depletion is typically calculated relative to unfished level, however substantial uncertainty exists in the calculation of unfished state.
B_{lim}	Set on basis of historical data. Biomass below B_{lim} entails high risk that recruitment might be reduced.	The same as typically drawn from an age structured model.	Estimates of spawners and recruits.	Limit	Recruitment	Needs long time series of data (multiple generations). Easy to understand and based on observed values.
B_{pa}	Precautionary buffer against natural variability and uncertainty associated with B_{lim}. (Note that $B_{pa}>B_{lim}$)	The same as typically drawn from an age structured model.	Estimates of spawners and recruits. Need information on accuracy of assessment and risk to be accepted.	Limit	Recruitment	Needs long time series of data (multiple generations). Easy to understand and based on observed values.
B_{loss}	The lowest observed spawning biomass.	Age structured model.	Fishery catch, fishery catch per unit effort or other relative abundance indices, life history parameters.	Limit	Recruitment.	Used as a proxy for B_{lim}. Needs long time series of data (multiple generations). Easy to understand and based on observed values.

[1]Model structure applies to calculation of reference point only. Additional model complexity may be needed to calculated observed metric (F, SSB etc) for comparison.

[2]Data needs applies to calculation of reference point only. Additional data may be needed to calculated observed metric (F, SSB etc) for comparison.

[3] There was no consensus that F_{med} was risky when steepness was specified as 1.0.

[4] Associated values are often reported along with their F complement, but may not be used for management.