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LIMIT REFERENCE POINTS IN MARINE RESOURCE MANAGEMENT AND THEIR APPLICATION FOR TUNA AND BILLFISH STOCKS

Juan L. Valero, Mark N. Maunder, Alexandre M. Aires-da-Silva, Carolina Minte-Vera, Jiangfeng Zhu

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SUMMARY

In this manuscript we review reference points for fishery management available in the literature, and their application for tuna and billfish stocks. Reference points are benchmarks used to determine the status of fishing stocks relative to desirable (Target Reference Points) and undesirable (Limit Reference Points) states. Both Target and Limit Reference Points can be operationalized by using Harvest Control Rules that specify management actions depending on the state of the stock relative to them. Reference points can be based on biomass, fishing mortality, or empirical data. Biomass and fishing mortality reference points are the most commonly used, they can be based on model estimates or using proxies. Although Empirical Reference Points are relatively easier to compute and communicate, they have not been as commonly used and they need to be thoroughly tested to evaluate robustness to biological and fisheries uncertainty and variability. There has been a general shift in considering F_{MSY} as a limit rather than a target, although F_{MSY} and B_{MSY} are used as targets in some cases (*e.g.* tropical tunas, IATTC, IOTC).

Target reference points are intended to reflect the explicit or implicit economic, social or political objectives of the fishery. Therefore, managers and stakeholders typically have a role in interpreting and identifying candidate target reference points related to management objectives. Limit reference points are intended to reflect the biological limits to sustainable exploitation. Therefore, it is a role of scientists to identify and provide objective advice on candidate limits reference points, taking into account undesirable processes such as impaired recruitment and depensation (disproportionally large negative impacts on stocks at low abundance). However, in most situations relationships between spawning biomass and recruitment have been difficult to be described properly and consistently in a manner that would allow formally deriving limit reference points from them that are void of some degree of arbitrariness. In addition, several studies have found little if any support for depensation across a range of stocks, although depensation cannot be ruled out based on the limited availability of data and research to date. There is a variety of reference points and harvest control rules that have been proposed in the literature and that have been applied to stocks worldwide. Approach, rational, and stage of implementation in the development of reference points and harvest control rules have varied greatly among tuna RFMOs. Main differences are in the treatment of MSY reference points as a limit or target and level of implementation of harvest control rules. On the other hand, a common feature is that tuna and billfish RFMO managed stocks have not been estimated to have been below their respective limit reference points, so most of these limits are not necessarily based on biological information on the respective species. The selection of reference points, particularly limit reference points, should take into consideration the action implemented when the reference point is exceeded. It is important to consider rebuilding targets for depleted stocks, with consideration of the levels chosen, evaluation of recovery timeline and subsequent actions after recovery, for example redefinition of target and limit reference points. Reference points and harvest control rules cannot be sensibly evaluated without considering them as part of a fishery management strategy and management system, or without including uncertainty, risk, robustness and tradeoffs between all elements of each fishery. Simulation testing work such as Management Strategy Evaluation can be an effective evaluation approach.

1. INTRODUCTION

The Precautionary Approach to fisheries management provides a basis for sustainable management of natural resources, motivating the development of reference points (RP) and harvest control rules (HCR) by fisheries management institutions (UN, 1995; FAO, 1995). Their implementation allows for the determination of the state a fish stocks relative to desirable states, or target reference points, as well as relative to non-desirable states, or limit reference points (LRP), where the sustainability of the stock may be compromised. There are other intermediate reference points, often called threshold or trigger reference points, corresponding to a state of the stock intermediate between target and limit reference points (Garcia, 1996) that may result in additional management action. Reference points are also instrumental in determining the status of stocks relative to two common undesirable states: being overfished and/or undergoing overfishing. The definitions and determination of overfished and overfishing may differ by legal framework or management system. In this report we will follow the definitions available in Sainsbury (2008):

“Overfished: The condition that results from persistent overfishing. The population is below the limit reference point or some other expression of unacceptable impact, usually related to some combination of reduced long-term yield, reduced resilience or ability to recover, and unacceptable impacts on associated or dependent species.”

“Overfishing: A rate or pattern of fishing that if continued would result the population becoming overfished. The population may or may not be overfished while overfishing is taking place.”

The intent of the Precautionary Approach to fishery management is to protect fish stocks from fishing practices that could risk their long-term sustainability, and to accomplish so even in the face of biological, fisheries or scientific uncertainty (Garcia, 1996). HCRs describe how harvest is intended to be controlled by management in relation to the state of some indicator of stock status (Berger, 2012; Anonymous, 2015). Harvest control rules may have associated reference points (for example HCRs specifying different levels of fishing mortality or catch limits depending on the estimated state of the stock relative to reference points) or not (for example specifying different levels of fishing mortality or catch limits depending on trends of stock indicators). In both cases, harvest control rules can be used to provide advice about the potential outcomes of management alternatives. In this manuscript we review reference points for fishery management available in the literature, and their application for tuna and billfish stocks.

2. CATEGORIES OF REFERENCE POINTS

There is a large variety of reference points that can be divided into several categories depending on their metric (*e.g.* Biomass, Fishing mortality, empirical), derivation (*e.g.* Estimated by models, Proxies) and other factors. We will cover some of these categories in this report.

2.1. Biomass reference points

Biomass reference points can be used as a benchmark to evaluate if stocks are overfished. Furthermore, population (*e.g.* reproduction) and ecological processes (*e.g.* ecosystem role, energy flows) are related to stock biomass. Although different biomass quantities can be estimated for a stock (*e.g.* total, mature, vulnerable, spawning including both sexes, female spawning biomass), typically female or total spawning biomass is the metric that is used for reference points. The justification is that spawning biomass relates more directly to recruitment. Since management actions do not directly control biomass, stock biomass relative to biomass reference points is typically used to trigger management actions that affect catch limits, fishing effort or mortality (Sainsbury, 2008). There is a variety of alternative biomass mortality reference points (See Table 1) and their use has varied around the world.

2.2. Fishing mortality reference points

Although the biological processes relevant to stock productivity and sustainability are more related to stock biomass (and its relationship to abundance and density), fishing mortality (and its relationship with catch or fishing effort limits) is more directly under management control than biomass. In addition, fishing mortality is generally more immediately impacted by management, while the effect on biomass accumulates over time. Biomass may also fluctuate in part due to factors beyond management control, such as environmental influences on processes such as recruitment, natural mortality, and growth. There is a variety of alternative fishing mortality reference points (See Table 2) and their use has varied around the world, some of which are outlined below.

In the US, national level requirements for fisheries management and assessment are operationally interpreted and applied in each fishery management plan. The US National Standards requires that fishing mortality for each stock must not exceed F_{MSY}, which is a limit reference point. A range of proxies can be used if F_{MSY} or MSY cannot be reliably estimated. An Optimum Yield (OY) is determined based on a MSY that must prevent overfishing, and that can be reduced from the MSY limit to take into account social, economic and precautionary considerations. The fishing mortality target reference points are related to the OY, which must be risk averse. Tiered systems with different methods and approaches to identify appropriate limit and target reference points exist for the Gulf of Alaska (NPFMC, 2016), West Coast and coastal California (Kaufman *et al.*, 2004). ICES sets limit reference points for fishing mortality by selecting a precautionary limit reference point (F_{pa}) that is expected to result in a very low probability to exceed the intended fishing mortality limit (F_{lim}) when taking into account estimation uncertainty

(ICES, 2003).

2.3. Empirical reference points

Although biomass and fishing mortality based reference points can have formal rationales relating them to population and fishery processes, they remain quantities that are not measured directly and depend on models for their estimation. Stock assessment models can be misspecified and biased (Maunder and Piner, 2015) potentially having impacts on the estimation and reliability of estimated reference points (Hilborn 2002). Empirical reference points focus on quantities that can be more or less directly measured such as catch, fishing effort, catch rate, fishing season length, individual size (*e.g.* average fish length or percentile), spatial range of the stock or habitat use (*e.g.* spawning locations), and sex ratio are examples of empirical indicators (Sainsbury 2008, Clarke and Hoyle 2014). The potential appeal of empirical reference points is not only that are derived more direct observations/estimation than those based on fishing mortality or biomass, but also in that they are easily understood and communicated, and are at least in theory logistically simpler to implement. However, empirical reference points have not been commonly used, in part because is still not clear if they are robust to fisheries and biological variability and uncertainty.

On issue with using empirical based reference points is the rational for their construction. Intuitively, limit reference points based on historical quantiles (*e.g.* the lowest estimated biomass or the 5% percentile of estimated biomass levels) might be reasonable, if the stock recovered from those levels. However, since the impact of fishing mortality is cumulative and the highest fishing mortality may have only been in a few years, this rationale might not be appropriate. Similarly, targets might be based on biomass or fishing mortality levels estimated historically when the state of the fishery was considered good. Social, economic or other factors could also be used. For example, a limit reference point could be based on catch rates that are unprofitable, or a target based on catch rates that maximize profits.

2.3.1. Catch per unit of effort (CPUE)

Catch rate is a commonly used and basic indicator in fishery management, typically as an index of stock abundance within a stock assessment model. However, there are cases where it has been used as the basis for empirical reference point. Reference points have been based on commercial catch rates for New Zealand rock lobsters (Starr *et al*., 1997) and Australian toothfish (Tuck *et al*. 2001) while survey catch rates at fixed locations during a historical period considered sustainable have been the basis for abalone reference points (Worthington *et al*. 2002). Punt *et al*. (2001) evaluated alternative empirical reference points for Australian swordfish, including catch rates, and found that they not perform well, either by being too insensitive or not sensitive enough to changes in stock. An alternative decision rule for the same swordfish stock (Davies *et al*. 2007) was shown to be robust when incorporating a hierarchical decision approach to identify management actions given processes behind the change in the empirical indicators (*i.e.* growth, recruitment or fisheries dynamics). Another example from Australia (Dowling *et al*. 2008) used catch rate thresholds to trigger management actions for low-value or data-poor stocks. The IATTC proposed to use standardized catch rates on floating object purse seine sets to assess and manage silky sharks (Aires-da-Silva *et al*. 2014), as well as other indicators of stock status for skipjack tuna (Maunder, 2017) this could be a first step if some of these indicators were to inform the development of LRPs.

2.3.2. Fish size

Punt *et al*. (2001) evaluated alternative empirical reference points for Australian swordfish, including catch rates, percentiles of the distribution of fish length in the catch, and percentiles of the distribution of fish weights in the catch.

Critical weight has been presented by the IATTC as part of its Stock Assessment Reports, it is the weight corresponding to critical age, is compared to the average weight in the total catch and the average weight in each fishery, as predicted by the stock assessment model (Maunder, 2003). The critical age is a theoretical concept that maximizes the yield from a cohort by removing all the individuals at a single age. The weight corresponding to the critical age may provide information on the status of the stock and the efficiency of the different fishing methods with respect to maximizing yields. Maunder (2003) tested the appropriateness of critical weight as a reference point for fisheries management. Analyses for different values of the steepness of the stock-recruitment relationship, natural mortality, growth rate, and age at maturity showed that the ratio of average weight in the catch at maximum sustainable yield (MSY) to critical weight was relatively insensitive and around 0.8. However, this ratio is very sensitive to the selectivity curve. Fishing at a level that produces an average weight that is 80% of the critical weight, gives yields close to MSY and is relatively insensitive to the selectivity (age at first vulnerability in knife-edge selectivity) and is robust to small misspecification in natural mortality or the growth rate. Critical weight does not appear to be a good indicator of stock status. Eighty percent of critical weight may be a useful reference point for low-information species. Calculation of critical weight requires only estimates of natural mortality and growth rate by age. Evaluation of the stock based on critical weight requires only the measurement of average weight. There are several possible problems with using critical weight as a reference point, including difficulty in estimating the natural mortality rate, and sensitivity of average weight to recruitment fluctuations (Maunder, 2003). Stock indicators based on the fish size caught relative to size at maturity, optimum size for maximizing yield, and conservation of large individuals (Cope and Punt, 2009) has been used for Atlantic skipjack tuna (ICCAT, 2014)

3. BENCHMARKS FOR MANAGEMENT

Reference points are benchmarks used to determine the status of fishing stocks relative to desirable (Target Reference Points) and undesirable (Limit Reference Points) states, intermediate states that may require additional management action are often called threshold or trigger reference points. It is important to consider rebuilding targets for depleted stocks, with consideration of the levels chosen, evaluation of recovery timeline and subsequent actions after recovery, for example redefinition of target and limit reference points.

3.1. Target reference points

Target reference points reflect the explicit or implicit economic, social or political objectives of the fishery. Therefore, managers and stakeholders typically have a role in interpreting and identifying candidate target reference points related to management objectives.

Tuna RFMO management objectives are based on "optimal utilization" or "long term conservation and sustainable use" (Anonymous, 2015). As a result, TRPs adopted or being discussed are around fishing mortality levels that achieve high yields or high catch rates, while avoiding LRPs. At the 2013 ISSF Workshop (Anonymous, 2013), there was considerable discussion on whether F_{MSY} should be viewed as a target or a limit. Where there was little or no quantitative analysis of uncertainty, the workshop's opinion was that F_{MSY} should be used as a limit, although F_{MSY} and B_{MSY} are used as target in some cases (*e.g.* tropical tunas, IATTC, IOTC). It has been argued that in cases where there was good knowledge of uncertainty, the use of F_{MSY} as a target has potential, with appropriate considerations of risk. However, in cases where there is little or no quantitative analysis of uncertainty or their incorporation in HCRs, or where F_{MSY} is determined assuming perfect knowledge, F_{MSY} should be used as a limit reference point as suggested in the UNFSA Annex II Guidelines (Anonymous, 2015). Following this rationale, a precautionary buffer should be considered between F_{MSY} and F target. On the other hand, the use of F_{MSY} as a limit in most situations is expected to be very cautious because F_{MSY} is not usually associated with being beyond biologically safe limits. Given recruitment variability and steepness assumptions, a potentially large range of biomass levels could be expected at F_{MSY}, so treating F_{MSY} as a limit or target should probably be considered case by case (Anonymous, 2015).

One important consideration of target reference points is how they relate to the limit reference point and the action taken when the limit is exceeded. If drastic action is taken when the limit reference point is exceeded (*e.g.* the fishery is closed or drastically diminished) then the target reference point needs to be set at levels to ensure that there is a low probability that the limit reference point is exceeded to avoid social and economic problems. Therefore, the target reference point should be set in the context of the limit reference point, the action taken when the limit reference point is exceeded, the overall harvest control rule, and the uncertainty in the method (*e.g.* the stock assessment) used to evaluate if a limit has been exceeded.

3.2. Limit Reference Points

Limit reference points are intended to reflect the biological limits to sustainable exploitation. Therefore, it is a role of scientists to identify and provide objective advice on candidate limit reference points, taking into account undesirable processes such as impaired recruitment and depensation (disproportionally large negative impacts on stocks at low abundance). However, in some cases the limit reference could also be set based on socio-economic factors such as catch rates that are unprofitable.

Limit reference points are typically developed in pairs to identify and initiate alternative management actions to avoid overfishing and the stock being in an overfished status. Fishing mortality-based LRPs have the advantage to be related more easily to fishing effort, which is important for example for international stocks where catch quotas may be logistically impractical. Fishing effort (and therefore fishing mortality) can be more directly controlled by fisheries managers. Although biomass-based LRPs more closely reflect the actual biological status of the population (Sainsbury 2008), they involve an estimation of stock biomass. Having a pair of LRPs that represent fishing intensity and stock status, respectively, permits alternative management actions depending on the stocks estimated to be experiencing overfishing or estimated to be overfished. Management should be precautionary given that uncertainty is an unavoidable component in the design and choosing of LRP, as well as in the estimation of stock trend and status relative to LRPs. A way forward could be by incorporating intermediate reference points that would activate management action before reaching the LRP or by incorporating managers preferred risk level into the LRP itself. Ideally, stocks should be managed so that there is a very low (but not zero) probability the LRP will be reached (Clarke and Hoyle, 2014). Risks associated with, and management actions associated with approaching or reaching a LRP should be recognized, discussed and agreed even if a LRP has not been reached.

Most tuna stocks managed by RFMOs have been considered to be in healthy states (Anonymous, 2015; Pons *et al*., 2017). On the other hand, a recent review (Jorda *et al*., 2011) identified four tuna stocks as overfished and experiencing overfishing: East and West Atlantic bluefin tunas, Southern bluefin tuna, and North Atlantic albacore tuna. Pacific bluefin tuna is also overfished, but it is unclear if overfishing is occurring because recent implemented management has not been evaluated and reference points have not yet be set. Interim LRPs have been implemented by IOTC, IATTC and ICCAT; LRPs have been adopted by WCPFC; whereas CCSBT does not currently have LRPs. For WCPFC, limits are based on a proportion of estimated unfished total or adult stock biomass, while the rebuilding target of CCSBT is expressed in similar terms of unfished total biomass. Different methods have been used to estimate the unexploited biomass level (in WCPFC, the value represents the average unexploited adult biomass level calculated over a recent 10-year period). For IOTC and ICCAT, limits are expressed relative to B_{MSY}. MSY is a function of selectivity (reflecting the overall mix of gears/fisheries), and assumed steepness value, and hence will change over time. For IATTC, limits are expressed relative to the virgin (unexploited) recruitment (R_0). Given that the adopted limits are often expressed in different units which can be difficult to compare, they are converted to the ratio to unfished spawning biomass level (LRP/B_0) and to the ratio to recruitment expected under unfished conditions R_{LRP}/R_0 (Table 3).

Myers *et al*. (1994) evaluated alternative spawning biomass limit reference points for 71 stocks and defined recruitment overfishing as seriously reduced recruitment. They recommended a biomass limit reference point associated to 50% of the maximum predicted average recruitment ($R_{\max}$) while warning that no method performed well in all circumstances so generalization was difficult. The 50%$R_{\max}$ often corresponds to very low limit spawning biomass levels, in the range of 10% to less than 5%B_0 for a broad range of life histories (Myers *et al*. 1994). For BET and YFT in the EPO it corresponds to 7.7%B_0 (assuming a stock-recruitment steepness of 0.75; Maunder and Deriso, 2014). Sainsbury (2008) argued that although the spawning biomass related to 50%$R_{\max}$ is understandably a limit to be avoided (*e.g.* FAO definition of a recruitment overfished stock showing a significantly reduced average recruitment), this would set the limit reference point at a level where the stock impact has already occurred. Other management bodies (*e.g.* ICES 2003) have taken a more conservative approach by defining a spawning biomass limit reference point such that average recruitment is not reduced, instead of 50% reduced as in 50%$R_{\max}$ (Sainsbury, 2008).

The origin of 20%B_0 as a commonly used LRP to define overfished stocks can be traced to the 1980s and 1990s (Beddington and Cooke 1983; Francis 1992). The rationale behind it was to avoid driving stocks to levels low enough that bad, perhaps irreversible, damage to biological processes that would risk stock long term sustainability. Myers *et al*. (1994) analyzed 20%B_0 as a limit reference point and found it a reasonable limit for recruitment overfishing under the definitions used by ICES (2000) and Cooke (1984) given that there is little reduction in recruitment at the 20%B_0 limit. Myers *et al*. (1994) mostly used productive stocks for his work, latter work found that a more appropriate limit for less productive stocks is 30%B_0 (Musick, 1999; Mace *et al*., 2002). The study by Preece *et al*. (2011) was the basis for the WCPFC implementation of LRPs of 20%B_0 limit, which refers to the work by Beddington and Cooke (1993) and Myers *et al*. (1994).

In New Zealand, the use of 20% B0 as a limit affects the definition of $\mathrm{B}_{\mathrm{MSY}}$, requiring that stocks not fall below 20%B0 more than 10% of the time under a MSY harvest strategy (Sullivan *et al*. 2005). This results in a larger target biomass reference point than calculated from yield curves alone. The primary concern about being below 20%B_0 is reduced recruitment. However, except for stocks with lowest steepness values there is not expected to be significant lost yield at that level. That is, 20%B_0 seems to be at a level that produces very close to the maximum sustainable yield for most fish stocks. For example Thorson *et al*. (2011) found that B_{MSY} ranged from 26–46%B_0 for a range of 147 stocks, with Clupeiformes and Perciformes having lower and Gadiformes and Scorpaeniformes having higher SB_{MSY}/SB_0 values. For tuna stocks assessed by the IATTC, SB_{MSY}/SB_0 is in the order of 0.21 (bigeye tuna) and 0.27 (yellowfin tuna). The second possible concern about lower stock sizes is depensation.

The collapse of the northern cod fishery in Atlantic Canada during the early 1990s (Hutchings and Myers, 1994) and subsequent lack of recovery after reduced fishing pressure (Rice, 2006) brought to attention to potential negative effects of driving populations to very low abundance or density. Potential detrimental effects could be in the form of recruitment declines, distributional changes or ecological shifts. Some of the more serious potential effects can be depensatory if stocks are driven to low enough abundances where survival and/or recruitment are affected in a manner that is not proportional to the reduction in abundance or density, for example by interfering the chances of finding mates (Allee effect, see Liermann and Hilborn, 2001), increased predatory effects on offspring given the same level of predation pressure (Liermann and Hilborn, 2001; Roemer *et al*., 2002), or niche invasion by other species (Utne-Palm *et al*, 2010, Roux *et al*. 2013).

Several works have explored the evidence for depensatory mechanisms in recruitment across a wide range of stocks. Earlier works by Myers *et al*. (1995) and Liermann and Hilborn (1997) used a large spawner-recruit database assembled by Myers and found little evidence for depensatory recruitment processes. More recent works (Keith and Hutchings, 2012; Hilborn *et al*. 2014) based on an expanded and updated database found little evidence of depensation in the recruitment process. Hilborn *et al*. (2014) focused only on stocks that were estimated to have been reduced to below 20% of maximum biomass. They reported that only four (North Sea herring, Atlantic cod, Atlantic menhaden, and sea scallops) out of a total of 113 stocks showed some support for depensation in the spawner-recruit relationship, and that this was less than what is expected by chance alone. They also found that stocks at low abundance almost always recovered when fishing pressure is reduced, as predicted by non-depensatory models. There is also evidence that stock productivity is commonly impacted by changes in environmental regimes (Vertpre *et al*. 2013). Although there is evidence that some stocks can rebound after recovery from very low abundances (less than 1% of B_0) such as Pacific bluefin tuna (ISC, 2016) there are not enough populations for which data are available to be included in depensation studies, so depensation at such low stock sizes cannot be ruled out (Hilborn *et al*, 2014).

3.3. Threshold reference points

Limit reference points can be defined from such considerations so as to recognize and maintain the stock within biologically safe limits by having a low probability of reaching the LRP despite uncertainties in assessing current status (ICES, 2003). Several management organizations and national settings use two limit reference points, one for when precautionary management action occurs, typically called soft limits, and one when severe management action occurs (*e.g.* closure of the fishery), often called hard limits. For example, in New Zealand soft limit reference points are 0.5 B_{MSY} while hard limits are 0.25 B_{MSY} (Anonymous, 2008).

3.4. Rebuilding targets

Is important to consider rebuilding targets for depleted stocks, for example southern Bluefin tuna, where the identified interim target is to rebuild the stock to $0.2B_0$ by 2035 (Hillary *et al*., 2015). In WCPFC, the target is to reduce fishing mortality on the bigeye tuna stock to F_{MSY} levels through 2017; while ICCAT has identified B_{MSY} as a rebuilding target for bluefin, albacore, marlins and swordfish stocks, with different timelines (Anonymous, 2015). The WCPFC set an initial rebuilding target (WCPFC, 2015) of rebuilding pacific Bluefin tuna to the historical median spawning stock biomass (around $7\%B_0$), although discussions are still ongoing with different proposed targets. The USA proposed rebuilding the stock to $20\%B_0$ and then setting the LRP at $15\%B_0$, while the PEW Charitable Trusts proposed $24\%B_0$ as an LRP for Pacific bluefin tuna (Nakatsuka *et al*., 2017).

4. HARVEST CONTROL RULES

Harvest control rules specify a pre-agreed course of management action as a function of identified stock status and other economic, societal or environmental conditions, relative to agreed reference points (Berger *et al*. 2012). HCRs may have associated reference points, for example specifying different levels of fishing mortality depending on the estimated state of the stock relative to reference points (*e.g.* Restrepo and Powers, 1998) or not, for example specifying different levels of fishing mortality depending on trends of stock indicators (*e.g.* southern bluefin tuna Hillary *et al*., 2015).

Tuna RFMOs have had limited formal implementation of HCRs, with the exception of the empirical HCR of the Management Procedure for CCSBT (Hilary *et al*., 2015), although they have been in development and different stages of implementation for individual fisheries (Anonymous, 2015). However, there are no explicit statements on how to operationalize targets and limits, which might indicate implicit harvest control rules. An example of flexible implementation of HCR is ICCAT recommendation to maintain with high probability stocks in the green quadrant of the Kobe plot (F≤FMSY and B≥BMSY), and that management action should be taken to move the stock back to the green zone if the stock is determined to be in the red or yellow zone of the Kobe plot. In turn, the potential for the Kobe II strategy matrix to be considered as a form of HCR was discussed, given that ICCAT uses this to guide subsequent harvest levels. Simulation testing of Kobe-based rules is not straightforward, although testing of the implicit management procedure has been performed for ICCAT (Kell *et al*., 2000). However, constant catch projections are often tested alongside, and compared with, more complicated feedback-based HCRs in MSE, in part to demonstrate the benefits of feedback (*e.g.* CCSBT). It has been argued that wide stakeholder involvement during the development, evaluation and implementation of HCRs is paramount for their success (Clarke and Hoyle, 2014; Hilborn *et al*., 2014), with successful examples from CCSBT (Hillary *et al*., 2015) and outside tuna RFMOs demonstrating wide stakeholder engagement.

The decision about which Limit Reference Points are appropriate should be made in the context of the management action to be applied if the limit is exceeded. For example, limit reference points can be treated as “soft” or “hard” in relationship to the management action associated to a stock falling, or being at risk of falling, below such reference point (Anonymous, 2008). Punt and Smith (2001) outline the appropriate use of LRPs in managing fish stocks. Reaching or falling below a LRP should not mean that the species has a high risk of biological extinction: an appropriate response would be a reduction in fishing mortality rather than the closure of the whole fishery. If an LRP is appropriately set, the probability of triggering it should be low, but not zero. A well-managed fish stock or fishery with an appropriate harvest control rule is expected to approach or fluctuate around a TRP, and to have a very low probability (*e.g.* less than 10%) of exceeding an LRP (Sainsbury 2008).

5. REFERENCE POINTS AND HARVEST CONTROL RULES FOR TUNA SPECIES

The development and implementation of limit reference points for tuna species has been recently reviewed by Nakatsuka *et al*. (2017). There are five tuna RFMOs that manage the tuna and billfish stocks worldwide: the Western and Central Pacific Fisheries Commission (WCPFC) covers the western and central Pacific Ocean; the Inter-American Tropical Tuna Commission (IATTC) covers the eastern Pacific Ocean; the International Commission for the Conservation of Atlantic Tunas (ICCAT) covers the Atlantic Ocean; the Indian Ocean Tuna Commission (IOTC) covers the Indian Ocean; and the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) covers Southern bluefin tuna. Approaches and rationales in developing reference points and harvest control rules have varied greatly among tuna RFMOs (Table 4). Although IATTC, ICCAT, IOTC and WCPFC have adopted limit reference points, CCSBT has not. However, CCSBT (2010) specifies that the spawning stock biomass of southern bluefin tuna should not be allowed to fall below the 2010 biomass (around 5%B_0), which might be considered an operational LRP. The adopted limit reference points of the remaining tuna RFMOs correspond to a range of 7.7%B_0 for the IATTC to 20%B_0 for ICCAT and WCPFC (Table 3). In the IATTC, the rational for the limit reference is the spawning biomass that results in a reduction of 50% in recruitment relative to the expected level in unfished conditions (R_{MAX}) using a conservative assumption of the steepness (h = 0.75) of the stock recruitment relationship (Maunder and Deriso, 2014). This value of steepness was chosen to contrast with the assumption of no identifiable stock-recruitment relationship (h = 1) in IATTC’s bigeye and yellowfin stock assessments. The estimated, or more often assumed, steepness value has a large impact on the relationship between the ratios of limit reference points to their respective metrics in an unfished state, than they do on estimates of MSY related quantities. Steepness values for tuna and billfish stocks from the other tuna RFMOs range from 0.8 to 0.9 (Table 3). Tuna RFMOs also differ in their use of B_{MSY} and F_{MSY} as a target (IATTC, IOTC, ICCAT, CCSBT) or limit (WCPFC). Given the sensitivity of MSY quantities to model assumptions, the WCPFC uses instead a B_{MSY} proxy of 20%B_0 based on a review by Preece *et al*. (2011) and the work by Beddington and Cooke (1993) and Myers *et al*. (1994). However, none of those works indicated undesirable outcomes, such as an irreversible decline in recruitment of 20%B_0 based on specific biological information for tuna life histories. Since most of the tuna and billfish stocks listed in Table 3 have not been estimated to have been below their respective limit reference points it can be inferred that most of these limits are not necessarily based on biological information on the respective species. Pacific Bluefin tuna has a longer history of exploitation and a contrasting history of paired estimates of spawning biomass and recruitment. Nakatsuka *et al*. (2017) proposed an empirical method to determine a species-specific limit reference point based on this paired estimates by formally identifying the biomass level that would prevent recruitment overfishing. They identified 5%B_0 as an appropriate limit, which compares to a similar ratio for implied CCSBT limit and slightly lower than the IATTC's 7.7%B_0.

Tuna RFMOs have limited formal implementation of HCRs with the exception of the empirical HCR of the Management Procedure for CCSBT (Hilary *et al*., 2015) and the HCR for tropical tunas (yellowfin, bigeye and skipjack) recently adopted by the IATTC (2016). A recent review of global tuna stocks relative to Marine Stewardship Council criteria, found that only three (IATTC yellowfin, bigeye, and skipjack tuna) of the 19 stocks of tropical and temperate tunas have implemented well-defined harvest control rules (Powers and Medley, 2016). In spite of this, HCRs have been in development and are at different stages of implementation for individual fisheries across the other RFMOs (Anonymous, 2015; Powers and Medley, 2016). However, there are no explicit statements on how to operationalize targets and limits (Table 4), although there seems to be implicit, simple harvest control rules such as for example the adjustment of fishing mortality to F_{MSY} if it exceeds this value in the IATTC management system (Maunder and Deriso, 2013) or the use of the Kobe plot in ICCAT (Kell *et al*., 2000). A preliminary evaluation of the IATTC interim reference points under a proposed harvest control rule was conducted by Maunder *et al*. (2015), which found a lower than 10% chance of dropping below the LRP over a 9-year management period, misspecification of the assumed steepness of the stock recruitment relationship and natural mortality lead to increased risk, work on this is ongoing.

6. DISCUSSION

Sensible development, evaluation and implementation of reference points do no happen in a vacuum, but as part of a management strategy in a management system. Three phases have been described (Davies and Basson, 2009; Clarke and Hoyle, 2014) in the development of reference points: 1) Selecting appropriate types of reference points, 2) Defining specific values for selected reference points, and 3) Operationalizing the selected reference types and values within the management system. In order for each element of the process and associated tradeoffs to be understood and accepted it is expected that stakeholders are included in the discussions during each phase (Clarke and Hoyle, 2014). Some potential issues in management systems based on reference points have been highlighted by Hilborn (2002) including (1) uncertainties in current stock biomass and virgin stock biomass as applied in reference point formula, (2) inappropriateness of using reference points to stocks for which they were not derived, (3) the tendency of reference-point use to produce an environment in which stock-assessment scientists rarely evaluate alternative management policies, and (4) overemphasis on reference points to the detriment of more pressing issues in fisheries management. It has been argued that at least some of these issues could be mitigated by relying on more data-based approaches and there are several examples from a variety of life history and management systems for example from the New Zealand rock-lobster fishery (Starr *et al*., 1997) to the southern Bluefin tuna (Hillary *et al*., 2015). In addition to the potential merits and issues with reference points, there has been an increased consideration of their application in stocks worldwide in part driven by Marine Stewardship Council (MSC) certification conditions (see for example Powers and Medley, 2016).

Reference points and harvest control rules are typically developed in a single species context, however most fisheries around the world are multiple-specific. This complicates the interpretation and implementation of reference points and harvest control rules since they may differ among species depending on each species status, productivity, and vulnerability. There are also considerations for the applicability and discussion of best practices for reference points based on the management context they are used such as target, by-catch, threatened, endangered or protected species as well as habitats and food web considerations (see Sainsbury *et al*., 2008).

7. CONCLUSION

There is a variety of reference points and harvest control rules that have been proposed in the literature and that have been applied to stocks worldwide. Approach, rational, and stage of implementation in the development of reference points and harvest control rules have varied greatly among tuna RFMOs. Main differences are in the treatment of MSY reference points as a limit or target and level of implementation of harvest control rules. A common feature is that most tuna and billfish RFMO managed stocks have not been estimated to have been below their respective limit reference points, so most of these limits are not necessarily based on biological information on the respective species. The selection of reference points, particularly limit reference points, should take into consideration the action implemented when the reference point is exceeded. It is important to consider rebuilding targets for depleted stocks, with consideration of the levels chosen, evaluation of recovery timeline and subsequent actions after recovery, for example redefinition of target and limit reference points. Tuna RFMOs have limited formal implementation of HCRs, with the exception of the empirical HCR of the Management Procedure for CCSBT (Hilary *et al*., 2015) and the HCR for tropical tunas (Yellowfin, bigeye and skipjack) recently adopted by the IATTC (2016). In spite of this, HCRs have been in development and are at different stages of implementation for individual fisheries across the other RFMOs. Reference points and harvest control rules cannot be sensibly evaluated without considering them as part of a fishery management strategy and management system, or without including uncertainty, risk, robustness and tradeoffs between all elements of each fishery. Simulation testing work such as Management Strategy Evaluation can be an effective evaluation approach.

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TABLE 1. Common biomass reference points

Reference Point	Description	Pros	Cons	Target / limit
XB_{MSY}, $XSSB_{MSY}$	Ratio of Biomass, or spawning stock biomass (SSB), needed to produce MSY	Considers recruitment and growth overfishing	Difficult to estimate, sensitive to recruitment and selectivity	Either
XB_0 or $XSB_{current,F=0}$	Ratio of biomass stock relative to unfished, or spawning biomass expected in the absence of fishing.	Can be used for data poor stocks; measures relative abundance in cases where absolute abundance is difficult to estimate.	Unfished biomass estimates depend on assumptions, may be unreliable.	Either
B_{XR0} or B_{XRMAX}	Biomass expected to produce X fraction of virgin/maximum recruitment.	Considers recruitment overfishing	Depends on current and historical recruitment estimates	Limit
B_{MAX}	Biomass or spawning biomass produced when F=FMAX in equilibrium	Considers growth overfishing	Difficult to estimate when the yield curve is flat topped, sensitive to assumptions when curve is flat topped, Not consider recruitment overfishing;	Either
$B_{0.1}$	Biomass or spawning biomass produced when F=F0.1	Considers growth overfishing, adjusts for flat topped YPR curve	Difficult to estimate when the yield curve is flat topped Does not explicitly consider recruitment overfishing.	Either
B_{loss}	Minimum biomass (or SSB)	Considers recruitment overfishing	Does not consider growth overfishing. No cushion, risky	Limit

TABLE 2. Common fishing mortality reference points

Reference Point	Description	Pros	Cons	Target / limit
F_{MSY}	Fishing mortality rate that results in B_{MSY} on average	Considers recruitment and growth overfishing	Sensitive to recruitment variability and assessment assumptions	Either
F_{MAX}	Fishing mortality rate producing the maximum yield per recruit.	Considers growth overfishing; easy to calculate.	Does not consider recruitment overfishing; Difficult to estimate if yield curve is flat topped, sensitive to assumptions when curve is flat topped	Limit
$F_{0.1}$	F at which slope of Y/R is 10% of value at origin	Consider growth overfishing; more conservative than F_{MAX}; estimatable even if yield curve is flat topped.	Does not explicitly consider recruitment overfishing.	Either
$F_{X\%}$, $F_{X\%SPR}$	F that reduces SSB/R to a certain % of unfished	Considers recruitment overfishing.	Does not consider growth overfishing	Either
F_{MED}	F that can be supported by estimated survival rates from spawning to recruitment in50% of years.	For recruitment overfishing; based on the historicaltime series of recruitment.	Does not consider growth overfishing; appropriateness dependent on the stock-recruitment relationship that applies in a particular case	Either
$F_{SSB\text{-}Min}$	F that prevents SSB from falling below the minimum observed SSB	Reference point for recruitment overfishing.	Risk-prone; sensitive to period for calculations No consideration of growth overfishing	Limit
F_{loss}	F expected to keep biomass at Bloss	Reference point for recruitment overfishing; relatively easy to calculate.	Risk-prone, it does not provide any cushion; no consideration of growth overfishing; assumes good understanding of the stock-recruitment	Limit
F_{crash}	Lowest F that would eventually drive the stock to extinction	Based on the stock-recruit relationship but easier to calculate	Risk-prone, allows the stock to be on path to extinction	Limit
F=X%M	F is set at a % of natural mortality	Can be used in data-poor situations	Uncertainty in estimation of M, possibly too high for longer-lived species.	Limit

TABLE 3. Limit reference points (LRPs) adopted by tuna regional fisheries management organizations (CCSBT, IATTC, ICCAT, IOTC, WCPFC) and other management bodies and their values as ratios of unfished biomass (B0), steepness (h) and reduction in recruitment at the LRP (R_{LRP}) respect to recruitment expected under unfished conditions (R_0).

	Group	Stocks	LRP	LRP/B_0	h	R_{LRP}/R_0
CCSBT	Tuna	SBT	None	N/A	N/A	N/A
IATTC	Tuna	BET	$B_{0.5R0}$	0.077	0.750	0.500
		YFT	$B_{0.5R0}$	0.077	0.750	0.500
ICCAT	Billfish	SWO-N	0.4 $_{BMSY}$	0.200	0.830	0.830
IOTC	Tuna	BET	0.5 $_{BMSY}$	0.140	0.800	0.723
		YFT	0.4 $_{BMSY}$	0.140	0.800	0.723
		SKJ	0.4 $_{BMSY}$	0.140	0.900	0.854
	Billfish	SWO	0.4 $_{BMSY}$	0.140	0.900	0.854
WCPFC	Tuna	BET	0.2 $_{B,F=0}$	0.200	0.800	0.800
		SKJ	0.2 $_{B,F=0}$	0.200	0.800	0.800
		YFT	0.2 $_{B,F=0}$	0.200	0.800	0.800
		ALB-S	0.2 $_{B,F=0}$	0.200	0.800	0.800
NOAA - WC	Groundfish, Tier 1,2	Sablefish	0.25 $_{B0}$	0.250	0.600	0.667
	Flatfish	Petrale	0.125 $_{B0}$	0.125	0.900	0.837
NOAA - AK	Groundfish, Tier 3	Atka Mackerel-BSAI	0.5 $_{BMSY}$	0.175	0.800	0.772
IPHC	Flatfish	Halibut	0.2 $_{B0}$	0.200		
Australia	Various	Various	0.5 $_{BMSY}$	0.200		
New Zealand (soft)	Various	Various	0.5 $_{BMSY}$	0.200		
New Zealand (hard)	Various	Various	0.25 $_{BMSY}$	0.100		
ICES	Medium/Long living	Various	Reduction in recruitment based on SRR	Varies		
NAFO	Various	Various	Various	Varies		

TABLE 4. Limit reference points (LRP), target reference points (TRP) and harvest control rules (HCR) that have been formally adopted by the five tuna RFMOs. Modified from Anonymous (2015).

Element	CCSBT	IATTC	ICCAT	IOTC	WCPFC
LRP	None	Tropical tunas: F0.5R0 and B0.5R0 evaluated assuming a steepness of 0.75. Relates to a depletion of 0.077B0. (interim limits)	N. Atlantic swordfish: 0.4 B_{MSY} (interim limit)	Tropical tunas: 0.4 B_{MSY} (0.5 B_{MSY} for BET) (interim limits)	Tropical tunas and S. Pacific albacore: 0.2 $SB_{F=0}$ (0.2B0) evaluated using recent recruitment levels
TRP	None	B_{MSY}/F_{MSY}	"Green" quadrant of the Kobe plot seems a target zone, but no specific target reference points adopted.	Tropical tunas, albacore and swordfish: B_{MSY} and F_{MSY}	Skipjack 0.5$B_{F=0}$
HCR	Empirical (Juvenile survey, CPUE)	Tropical tunas: Reduce *F* to F_{MSY} if it exceeds this value	None	None	None