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PROPOSAL FOR BIOMASS AND FISHING MORTALITY LIMIT REFERENCE POINTS BASED ON REDUCTION IN RECRUITMENT

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1. INTRODUCTION

The implementation of the Antigua Convention and the commitment to the precautionary approach implies the formal use of reference points and decision rules by the Inter-American Tropical Tuna Commission (IATTC) for management of tuna and associated species in the eastern Pacific Ocean (EPO). Reference points are generally categorized by type (target or limit) and the quantity that they measure (usually biomass or fishing mortality). In general, limit reference points (LRPs) indicate states that management does not wish to exceed due to possible undesirable consequences, and target reference points (TRPs) indicate states that management wishes to obtain to maximize benefits from the fishery. LRPs are often associated with management action, perhaps as part of a harvest control rule, and in this context are often referred to as “trigger” reference points. The IATTC staff has historically based its conservation recommendations on an informal decision rule that is based on adjusting effort to the fishing mortality (F) corresponding to the maximum sustainable yield (MSY; F_{MSY}), implying that F_{MSY} is a TRP. The spawning biomass corresponding to MSY (S_{MSY}) has also been used by the IATTC as an informal reference point, but it is not clear whether as a target or a limit reference point. These informal reference points are based on the original IATTC Convention of 1949, which states that the goal of management is to maintain stocks at levels that support the MSY. Reference points, their use in harvest control rules, and their relationship to the Kobe plot and strategy matrix, in the context of the stocks managed by the IATTC, have been discussed in Maunder and Aires-da-Silva (2012), Maunder *et al*. (2012), Maunder (2013), Minte-Vera *et al*. (2013), and Maunder and Deriso (2013a).

F_{MSY}, which was traditionally treated as a management target, has been transformed into a precautionary limit reference point (LRP) (Mace 2001). By analogy (and since F_{MSY} and S_{MSY} are linked in equilibrium in such a way that, if F_{MSY} cannot be a target, neither can S_{MSY}), any biomass-based LRP should be at least S_{MSY}, and the TRP should be considerably higher than S_{MSY}. LRPs are generally considered to have a low probability of being exceeded if management is implemented to achieve the TRPs. This implies that, in general, fishing is carried out at a level (possibly substantially) below MSY, and that MSY can only be the management target if uncertainty is negligible. It also suggests that TRPs should be defined based on the assessment uncertainty, so that, as the assessment uncertainty diminishes, the TRP should get closer to the LRP. However, a stock can be managed sustainably below S_{MSY} and with fishing mortalities above F_{MSY}, and there have been many stocks that have a long sustainable history at these levels (*e.g*. North Pacific bluefin tuna). The catch levels may be lower than optimal because of suboptimal yield per recruit (YPR) or reduced recruitment, but they are still sustainable, although with a theoretically higher probability of collapse, and may satisfy other goals (*e.g*. high catches of other species, as in the case of skipjack harvested in sets on fish-aggregating devices (FADs) that also catch bigeye and yellowfin tuna).

This perplexing change, which is contrary to the traditional management objectives of most fisheries management organizations, has been embraced by many international agreements. The rationale for the change is confusing and vague, and the use of F_{MSY} as a LRP is unreasonable, particularly if the required probability of exceeding the LRP is very low. Certainly there is no disagreement with the goal stated by Sainsbury (2008): "Unacceptable outcomes are strongly based on avoiding irreversible, slowly reversible or long-term impacts of fishing (*e.g*. from UNCED 1992 and UNFSA 1995), and so there is an emphasis on avoiding recruitment overfishing, stock collapse and excessive depletion of very long-lived organisms", but F_{MSY} is not related to any of these. The use of F_{MSY} as a LRP should be re-evaluated in the terms of management objectives, overall consistency, stock assessment accuracy, and practicality.

Punt and Smith (2001) outline the appropriate use of LRPs in managing fish stocks. Triggering 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 clearly not zero. A fish stock or fishery 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). LRPs have been traditionally set on biological grounds to protect a stock from serious, slowly reversible, or irreversible fishing impacts, which include recruitment overfishing and genetic modification (Sainsbury 2008). In practical terms, this generally means determining the effect of exploitation on recruitment, typically through evaluating the stock-recruitment relationship.

The calculation of MSY and the associated reference points, and of other reference points, requires knowledge of several quantities, both biological (*e.g*. growth, natural mortality, maturity and fecundity, and the stock-recruitment relationship) and fishery-related (*e.g*. selectivity). For many stocks, some of these quantities are not available, and managers use proxy reference points (Clark 1991, 1993, 2002). In particular, the stock-recruitment relationship is difficult to estimate, and precautionary reference points based on spawner per recruit (SPR) are used. The estimates of these proxies are still based on uncertain quantities (*e.g*. natural mortality), and are therefore designed to work in a precautionary sense for a range of life histories, and do not require knowledge of the stock-recruitment relationship. For some stocks, the absolute level of the population size and fishing mortality is difficult to estimate, and standard reference points are not appropriate. In such cases, reference points based on historical biomass or fishing mortality levels may provide LRPs, using the concept that those levels occurred in the past and the population remained sustainable, but the outcome is unknown if they are exceeded. Tuna recruitment is highly variable, and several regime changes are apparent in the estimates of recruitment for the major EPO tuna stocks. It is possible that a moderately exploited stock could exceed biomass-based LRPs due to annual fluctuations in recruitment or a regime shift in recruitment. Estimates of absolute abundance for tuna stocks (and the associated depletion levels) are often uncertain due to the high productivity of tunas, their highly variable recruitment, the lack of detectable impact of catch on biomass and the lack of contrast in that impact, and the uncertainty in the growth estimates (which are needed to extract absolute abundance information from length-composition data). All these uncertainties need to be considered when developing LRPs, which would ideally be robust to the uncertainty.

Four main points should be kept in mind when developing LRPs:

1) Given that management is implemented to achieve the TRP, there should be a very low, but not zero, probability of exceeding the LRP;
2) The LRP should be based on biological grounds to protect a stock from serious, slowly reversible or irreversible fishing impacts;
3) The TRPs will often be at, or close to, MSY-related quantities; and
4) The decision about which LRPs are appropriate should be made in the context of the management action to be applied if the limit is exceeded.

We propose for consideration by the IATTC limit reference points based on the expected reduction in recruitment when a conservative (low) steepness value is used for the Beverton-Holt stock-recruitment relationship.

2. PROPOSED LIMIT REFERENCE POINTS

The LRPs should be based on biological grounds to protect a stock from serious, slowly reversible, or irreversible fishing impacts. In general, this is interpreted as ensuring that recruitment is not substantially impacted. Fishing impacts recruitment through the reduction of spawning biomass and the stock-recruitment relationship. Unfortunately, the stock-recruitment relationship is one of the most uncertain processes in stock assessment. One way to take this uncertainty into consideration when constructing the reference point is to create a probability distribution representing the uncertainty about the stock-recruitment relationship and and use that to determine the probability that recruitment will fall below a predetermined level. For example, the reference point could be a predetermined fraction of the recruitment (R) expected in unexploited conditions (x%R_0), where the recruitment is derived from a Beverton-Holt stock-recruitment relationship, $BH()$, that is a function of steepness (h, the fraction of virgin (unexploited) recruitment obtained when the spawning biomass (S) is reduced to 20% of its virgin level (S_0)) and the depletion level ($d = S/S_0$), which could both include uncertainty. The reference point is triggered when the probability of exceeding x%R_0 is greater than π.

$$P(BH(d,h) < x\%R_0) > \pi$$

Reference points are generally expressed as a single value for spawning biomass or fishing mortality. They can then be used in constructing the Kobe plot. These values can be determined by basing the reference points on a conservative value of h, to ensure that, if the reference point has been slightly exceeded, this relates to a small probability that the recruitment has been reduced to less than x%. The x%R_0 reference point ($r = R/R_0$) can then be converted into a biomass-based reference point based on the depletion level ($d = S/S_0$) by rearranging the Beverton-Holt stock-recruitment relationship (see Appendix):

$$d = \frac{0.2r(1-h)}{0.8h - r(h-0.2)}$$

An F-based reference point can be determined by finding the equilibrium fishing mortality corresponding to the depletion level.

The current depletion level (and associated equilibrium F) can be estimated by the stock assessment based on the best guess of steepness, but this value of steepness may differ from, and possibly be greater than, the value of steepness used when generating the LRP. Therefore, the current depletion may be underestimated in terms of the reference point assumptions, and thus it may be desirable to estimate an alternative value of depletion based on an assessment that uses the reference point steepness value.

The stock assessment estimate of the current depletion level will be dependent on the average recruitment used to estimate the virgin recruitment. Fish stocks often experience regime shifts in recruitment, presumably due to changes in the environment. One approach to dealing with these shifts is to use dynamic virgin biomass (*i.e.* simulate the population over time with the estimated recruitments, adjusted for the stock-recruitment relationship if necessary) in the estimate of current depletion.

3. APPLICATION TO TUNA STOCKS IN THE EPO

The proposed LRPs were applied to yellowfin and bigeye tuna in the eastern Pacific Ocean and bluefin tuna in the north Pacific. For each stock the reduction in recruitment, steepness of the stock-recruitment relationship, and probability of exceeding the LRP need to be determined. There is no guide to what reduction in recruitment is undesirable, but it is unlikely that a reduction of less than 50% would cause a stock collapse; so, 50% is a conservative value that is as good as any other, and we notate the corresponding LRPs as $F_{0.5R0}$ and $S_{0.5R0}$. If uncertainty is included in the depletion level or steepness, then the 10% probability of exceeding the LRP, as suggested in other studies, is probably reasonable.

However, to avoid complex calculations and produce single reference points for use in the Kobe plot, no uncertainty about the steepness of the stock-recruitment curve used in the LRP calculation is included in the analysis, so defining a probability level is not required. The current IATTC yellowfin and bigeye tuna assessments include a sensitivity analysis using a value of 0.75 for h, and this would be a reasonable candidate for the LRP steepness value. Since steepness is defined as the fraction of the virgin recruitment obtained when the spawning biomass is reduced to 20% of the virgin level, then a steepness of 0.75 would imply, without uncertainty in the depletion level or steepness, that the depletion level corresponding to the LRP would be somewhat less than 20%, and can be calculated simply from the Beverton-Holt stock-recruitment relationship (see Appendix), giving d = 0.077 (Figures 1 and 2). Estimating a consistent fishing mortality for inclusion in the Kobe plot is difficult because effort among fisheries changes over time, and there is no consistent age that has full selectivity to all fisheries. Therefore, F is calculated relative to F_{MSY} for yellowfin and bigeye tuna. The IATTC constructs the Kobe plot with both F and S as ratios of the MSY quantities, and that is how we present the LRPs in this analysis. A consistent measure for F was not available for Pacific bluefin tuna, so only the S-based LRP is evaluated.

The best estimates of depletion level and fishing mortality for both bigeye and yellowfin tuna are close to the MSY-based TRPs (Figures 3 and 4, respectively), and therefore do not exceed the LRPs. The approximate 95% confidence intervals also do not exceed the LRPs. In the case of bluefin, the spawning biomass exceeded the LRP throughout the 1970s and 1980s, and also since 2004. These results suggest that no management action based on the LRP is needed for bigeye and yellowfin tuna, but is needed for Pacific bluefin tuna.

4. DISCUSSION

There is a wide range of candidate reference points. Most of them are fairly arbitrary in their definition: even those based on the goals of LRPs to avoid something "detrimental" happening use an arbitrary definition of "detrimental". We considered possible reference points for the main IATTC tuna stocks based on several criteria, and in the process developed a new set of LRPs.

1. Given that management is implemented to achieve the TRP, there should be a very low, but not zero, probability of exceeding the LRP;
2. The LRP should be based on biological grounds to protect a stock from serious, slowly reversible or irreversible fishing impacts;
3. The TRPs will often be at, or close to, MSY-related quantities; and
4. The decision about which LRPs are appropriate should be made in the context of the management action to be applied if the limit is exceeded.

These criteria eliminate some reference points automatically. Standard MSY- and YPR-based reference points may be too close to the TRPs and do not address biological risk; extinction-based reference points are too extreme; and economic reference points are not based on biological risk. Other reference points, such as SPR and %S_0, are somewhat arbitrary, and those based on uncertainty in the estimates of MSY are not a measure of biological risk, or are more related to conservative targets rather than limits. Therefore, we developed a reference point based directly on declines in recruitment.

Due to natural fluctuations in abundance and the IATTC's use of effort limits to manage the fishery, we consider reference points based on fishing mortality more practical than those based on spawning biomass. However, the former do not directly address biological risk, whereas the latter do.

The reduction in recruitment-based LRP can be applied to other stock-recruitment relationships. We have applied it to the Beverton-Holt stock-recruitment relationship, which is used for many stocks and has a convenient algebraic solution for the S-based LRP based on a given value of steepness. The Ricker stock-recruitment relationship, which is also commonly used, has the complication that recruitment is also reduced at large stock sizes, but this should not be a concern for multi-cohort non-semelparous species. The hockey-stick model with a linear trend between zero spawning biomass and the average recruitment at the lowest observed spawning biomass could be used to determine the spawning biomass level at 50% of virgin (the average observed in this case) recruitment, but iterative updates would always ensure that the current spawning biomass produces recruitment above 50% of virgin recruitment. The hockey stick stock-recruitment model might be more appropriate if the bend in the hockey stick occurred somewhere above the lowest observed spawning biomass. We do not consider stock-recruitment models that use a constant ratio of recruits per spawning realistic for tunas, and so do not recommend their use. Maunder and Deriso's (2013) stock-recruitment model for highly-fecund species, based on temporal and spatial extent of spawning, may be more appropriate for tunas. However, the concept behind that model implies that the LRP should be based on the temporal and spatial extent of spawning rather than the spawning biomass level. The Maunder-Taylor-Methot stock-recruitment relationship for low-fecundity species (see Taylor *et al*. 2012) could be used to develop LRPs for sharks, but may not be amenable to algebraic solutions and requires the specification of two parameters.

The proposed LRP, in association with a harvest control rule, can best be evaluated within a framework of management strategy evaluation (MSE). MSE is a well-developed approach in fisheries science (Butterworth *et al*. 1997; De Oliveira *et al*. 1998; Butterworth and Punt 1999), but requires a significant amount of staff time and computational resources to carry out. There is a current project for MSE on tropical tunas encouraged by the Kobe 3 meeting in July 2012. MSE is only just starting to be developed for stocks managed by the IATTC (*e.g*. Maunder 2014). The proposed LRPs are for single-species management, and do not address ecosystem management concerns. The IATTC needs to define the action to be taken when the LRPs are exceeded.

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APPENDIX 1. The Beverton-Holt stock-recruitment relationship formulated in terms of steepness (h).

$$R = \frac{S}{\alpha + \beta S}$$

$$\alpha = \frac{S_0(1-h)}{4hR_0}$$

$$\beta = \frac{5h-1}{4hR_0}$$

where R is recruitment, S is spawning biomass, S_0 is the virgin (unexploited) spawning biomass, R_0 is the virgin (unexploited) recruitment, and h is steepness (the fraction of R_0 corresponding to $0.2S_0$).

Reparameterizing the equation in terms of $r = R/R_0$ and $d = S/S_0$ gives

$$r = \frac{1}{\frac{1-h}{4hd} + \frac{5h-1}{4h}}$$

So the S-based reference point as a fraction of virgin S (depletion) is

$$d = \frac{S}{S_0} = \frac{0.2r(1-h)}{0.8h - r(h-0.2)}$$

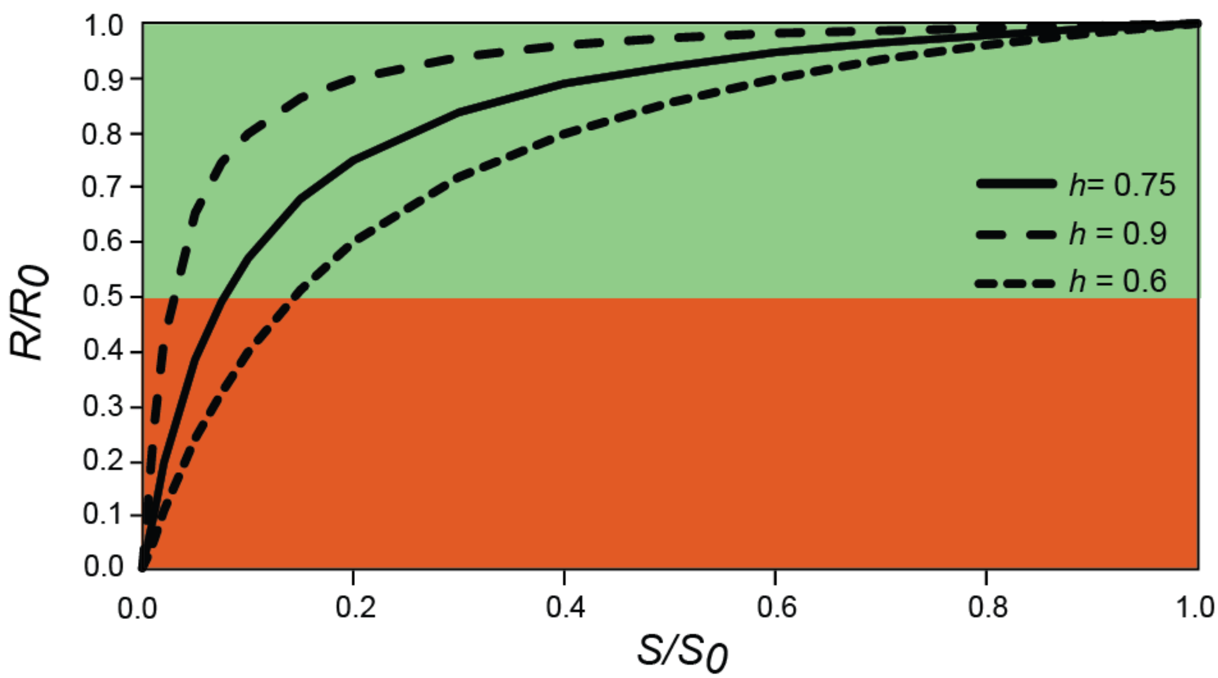

FIGURE 1. The Beverton-Holt stock-recruitment relationship with three different values for steepness (h). The orange area represents recruitment below the LRP definition of $0.5R_0$.

FIGURA 1. La relación población-reclutamiento de Beverton-Holt con tres valores diferentes de inclinación (h). La zona naranja representa reclutamiento inferior a la definición del PRL de $0.5R_0$.

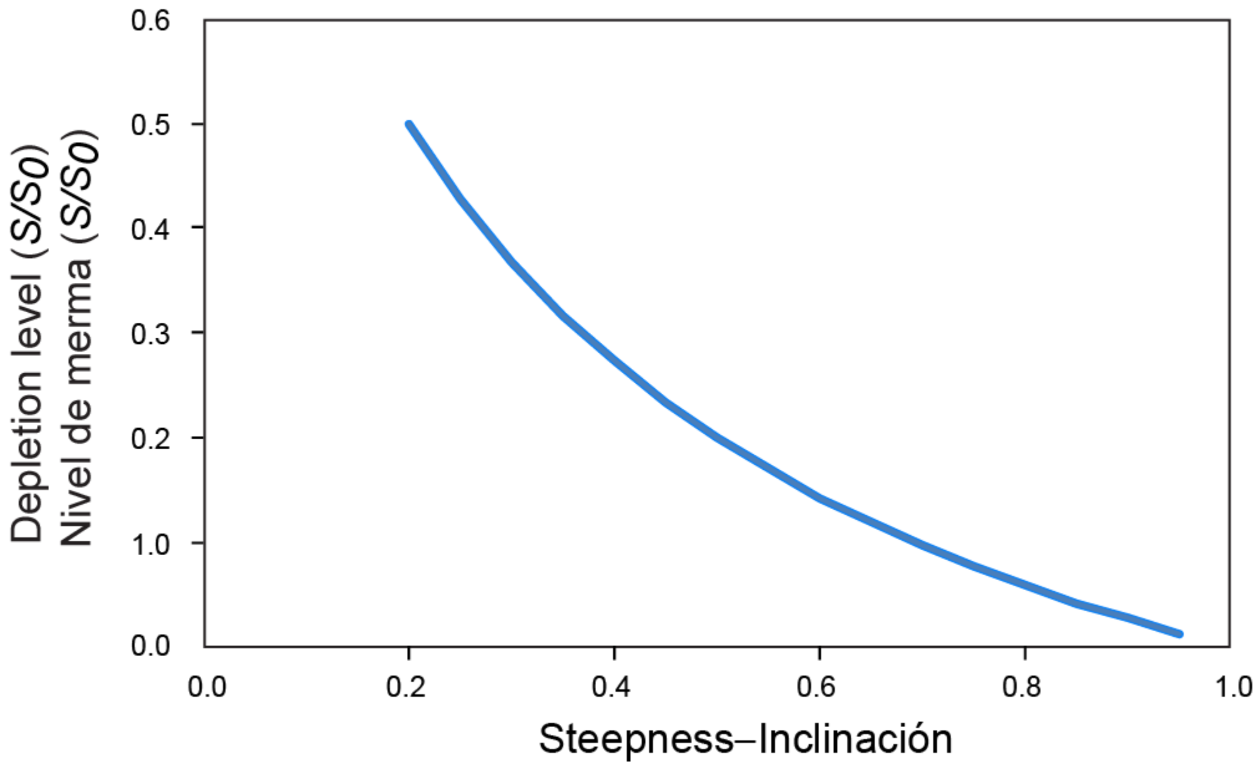

FIGURE 2. The depletion level required to make expected recruitment equal to $0.5R_0$ for different values of steepness.
FIGURA 2. Nivel de merma necesario para que el reclutamiento esperado equivalga a $0.5R_0$ con distintos valores de inclinación.

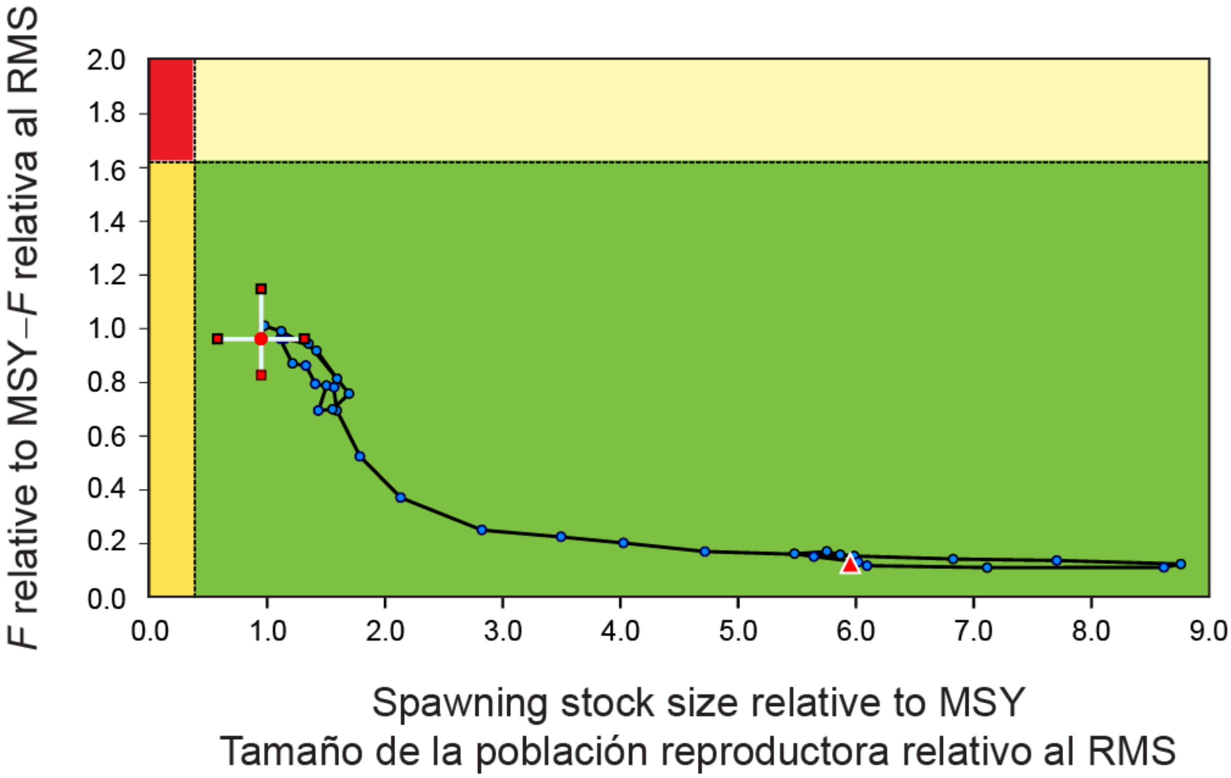

FIGURE 3. Kobe (phase) plot based on the proposed limit reference points for bigeye tuna. The triangle is the first year of the assessment (1975). The dot with the cross hairs is the last year of the assessment (2013) with approximate 95% confidence intervals.

FIGURA 3. Gráfica de Kobe (fase) basada en los puntos de referencia límite propuestos para el atún patudo. El triángulo es el primer año de la evaluación (1975); el punto (con su cruz de límites de confianza de 95% aproximados) es el último (2013).

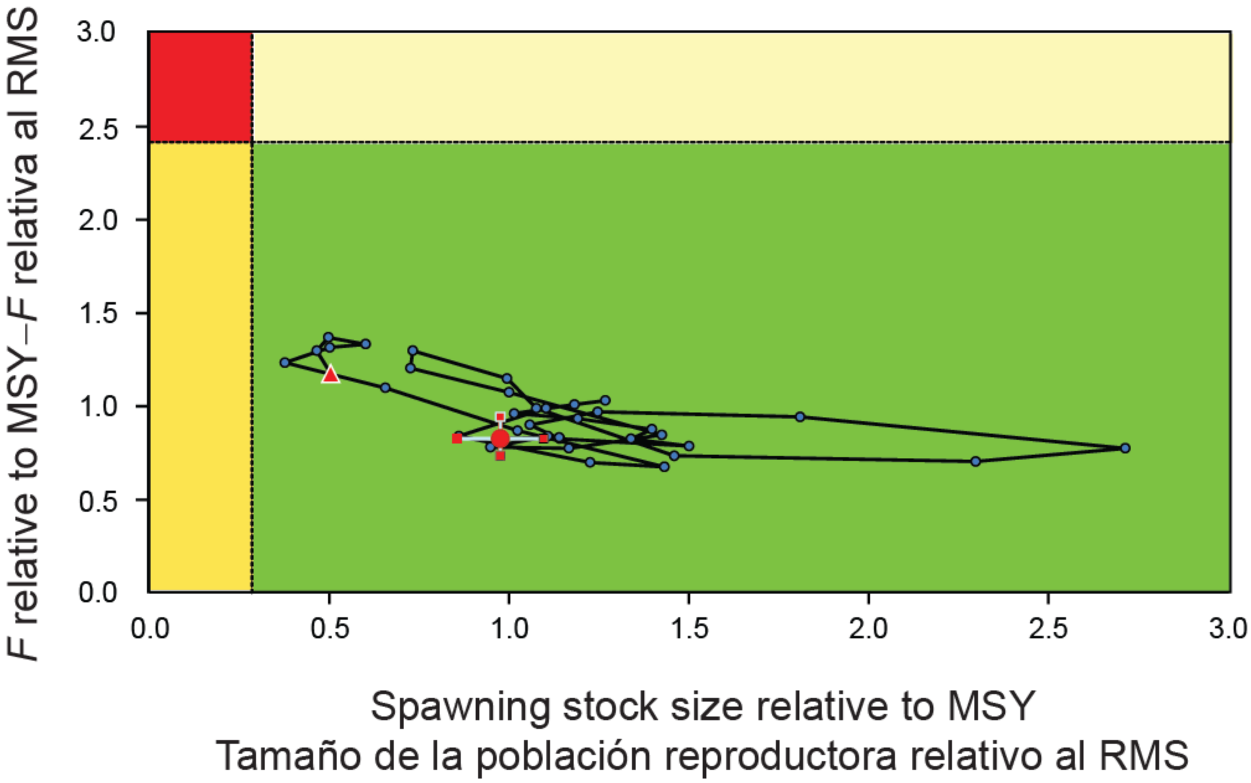

FIGURE 4. Kobe (phase) plot based on the proposed limit reference points for yellowfin tuna. The triangle is the first year of the assessment (1975). The dot with the cross hairs is the last year of the assessment (2013), with approximate 95% confidence intervals.

FIGURA 4. Gráfica de Kobe (fase) basada en los puntos de referencia límite propuestos para el atún aleta amarilla. El triángulo es el primer año de la evaluación (1975); el punto (con su cruz de límites de confianza de 95% aproximados) es el último (2013).

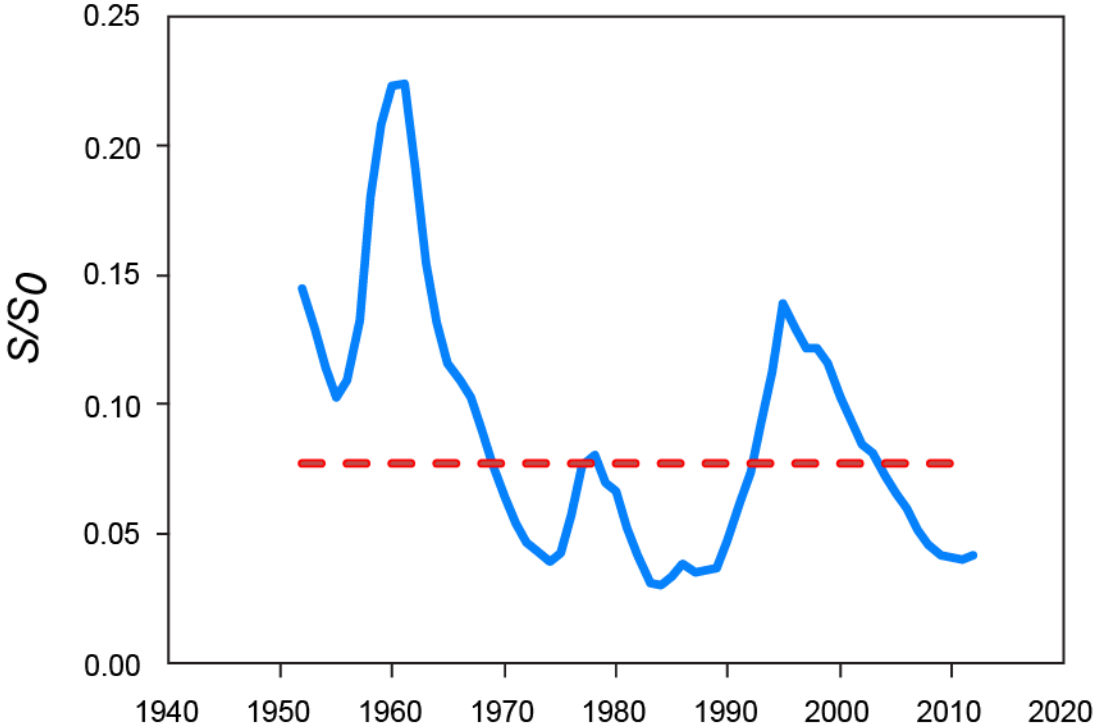

FIGURE 5. Ratio of spawning biomass to the average spawning biomass in an unexploited population compared to the spawning biomass limit reference point for Pacific bluefin tuna.
FIGURA 5. Razón de la biomasa reproductora y la biomasa reproductora media en una población no explotada comparada con el PRL basado en biomasa reproductora para el atún aleta azul del Pacífico.