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RISK ANALYSIS FOR MANAGEMENT OF THE TROPICAL TUNA FISHERY IN THE EASTERN PACIFIC OCEAN, 2020

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CONTENTS

The staff's work, including the new assessments of tropical tunas, has been severely disrupted and delayed by the coronavirus pandemic, and many documents for the meeting of the SAC are not yet finalized. However, it is important that the members of the SAC and observers be informed as soon as possible of the direction and extent of the work, and of the very substantial progress that has been made, so some of the most essential documents are being published in draft form, and may be modified after discussion at the virtual sessions of the Committee.

EXECUTIVE SUMMARY

The management advice for tropical tunas in the eastern Pacific Ocean (EPO) provided to the Commission by the IATTC scientific staff has traditionally been based on a 'best assessment' approach. In 2018 the staff

[1] Postponed to a later date to be determined.

concluded that the results of its stock assessment of bigeye in the EPO were not reliable enough to be used as a basis for management advice to the Commission, and in 2019 extended this conclusion to its assessment of yellowfin (IATTC-94-03). The assessment issues (SAC-09 INF B; SAC-10 INF-F) were addressed in the staff's workplan to improve the stock assessments for tropical tunas, which included external reviews of the assessments for bigeye and yellowfin, and has now been successfully completed.

New benchmark assessments are available for yellowfin and bigeye (SAC-11-07, SAC-11-06). These assessments represent a fundamental change from the staff's previous 'best assessment' approach: they are the basis for a 'risk analysis', in which a variety of reference models are used to represent plausible alternative hypotheses about the biology of the fish, the productivity of the stocks, and/or the operation of the fisheries, thus effectively incorporating uncertainty into the management advice as it is formulated. The risk analysis for yellowfin and bigeye was used to evaluate several management quantities related to the IATTC's harvest control rule (HCR) for tropical tunas. In this document, the results are presented separately for each species for the two components of the analysis, *Current stock status* and *Decision analysis*, the latter evaluating the risk of exceeding the target and limit reference points resulting from different durations of the temporal closure of the fishery.

This transition to risk analysis significantly advances stock assessment science and the formulation of management advice for tropical tunas at IATTC. First, the process resulted in the identification of a set of reference models (alternative hypotheses, or '*states of nature*') which describe the population dynamics of yellowfin (SAC-11-07) and bigeye SAC-11-06, as well as the main axes of uncertainty in the stock assessments for both species. Second, the approach provides a methodology for assigning relative weights to the plausibility of these alternative hypotheses that takes into consideration a range of factors (*e.g.* expert opinion, model fit, plausibility of results and parameter estimates, and diagnostics) (SAC-11 INF-F). Finally, the final product of the risk analysis are probability statements for exceeding the reference points established in the HCR.

For **yellowfin**, considering the relative weights of the different models and their combined distributions for the management parameters, there is only a 12% probability that the stock is overfished ($P(S_{cur}<S_{MSY})$ = 12%), and a 9% probability that overfishing is taking place ($P(F_{cur}>F_{MSY})$ = 9%). There is zero probability that both *S* and *F* limit reference points have been exceeded ($P(S_{cur}<S_{LIMIT})$ = 0%; $P(F_{cur}>F_{LIMIT})$ = 0%).

For **bigeye**, there is a 53% probability that the stock is overfished ($P(S_{cur}<S_{MSY})$ = 53%), and a 50% probability that overfishing is taking place ($P(F_{cur}>F_{MSY})$ = 50%). There is a small probability that both *S* and *F* limit reference points have been exceeded ($P(S_{cur}<S_{LIMIT})$ = 6%; $P(F_{cur}>F_{LIMIT})$ = 5%).

The risk analysis unambiguously shows that the yellowfin stock in the EPO is healthy, but the results are less clear for bigeye. The bimodal nature of the probability distributions from the bigeye risk analysis for the management quantities of interest indicates that the stock is either well below or well above the levels corresponding to MSY (S_{MSY}). Clearly, optimal management, or even whether the bigeye stock size should be increased or decreased, cannot be determined from the risk analysis. However, the combined probability distribution for the pessimistic models shows only a 10% probability of exceeding F_{LIMIT} for the current closure duration (72 days), indicating that it is unlikely that this limit has been exceeded. Therefore, a *status quo* harvest strategy should be appropriate in the short term.

The bimodality of the bigeye probability distributions complicates the evaluation of the status of the bigeye stock and the evaluation of the potential outcomes of management actions. This issue needs to be addressed in the future to improve management advice. There are two avenues towards this goal: 1) continue to improve the stock assessment models, which also involves their data inputs, and 2) develop and evaluate management strategies that are shown to be robust to the main uncertainties, including the bimodality, using Management Strategy Evaluation (MSE), a process that is already ongoing at IATTC (MSE

Workplan and recent Workshops). Improving the stock assessment models and their input data should focus on investigating the time spans of the models, assumptions about stock structure, and estimation of growth. Improving estimates of natural mortality and of selectivity for fisheries assumed to have asymptotic selectivity should also be considered. MSE provides a framework for developing management strategies that incorporate, and are robust to, the different forms of unavoidable uncertainties involved in fishery management, thereby providing a formal approach to evaluate management actions designed to achieve fisheries objectives.

1. INTRODUCTION

1.1. Background

The management advice for tropical tunas in the eastern Pacific Ocean (EPO) provided to the Commission by the IATTC scientific staff has traditionally been based on a 'best assessment' approach. This consists of four steps: 1) **define the 'base case' stock assessment model**, with the most plausible assumptions about biology (*e.g*. natural mortality, growth, stock-recruitment relationship) and fisheries (*e.g*. catchability, selectivity); 2) **fit the base case model** to the best available data (*e.g*. standardized catch-per-unit-effort (CPUE) indices of abundance and length-composition data); 3) **estimate the base case model parameters** (*e.g.* recruitment in unfished conditions, selectivity parameters) and **quantities of interest** (*e.g*. depletion of the stock, *F* multiplier[2]), and 4) **formulate management advice** based on the quantities of interest.

The *F* multipliers estimated in the base case assessments of bigeye and yellowfin have been used as a basis for the staff's recommendations for management measures; specifically, to determine the duration of the seasonal closures, taking into consideration recent increases in fishing capacity.

In 2018 the staff concluded that the results of its stock assessment of bigeye in the EPO were not reliable enough to be used as a basis for management advice to the Commission, and in 2019 extended this conclusion to its assessment of yellowfin (IATTC-94-03). The main problem with both assessments was that their results became overly sensitive to the inclusion of new data, in particular recent observations for the indices of relative abundance from the longline fishery (SAC-09 INF B; SAC-10 INF-F). These and other issues were addressed in the staff's workplan to improve the stock assessments for tropical tunas, which included external reviews of the assessments for bigeye and yellowfin, and has now been completed.

For bigeye, a major issue was the apparent 'recruitment shift' ('*R* shift') in the mid-1990s, when the assessment estimated that the average recruitment doubled at the same time as the purse-seine catches of bigeye, mostly smaller fish, increased from 10,000 to nearly 50,000 metric tons (t) in three years with the rapid expansion of the fishery on fish-aggregating devices (FADs) in the equatorial EPO, and longline catches of large bigeye halved. Although it is possible that recruitment did in fact increase, this result appears anomalous, and various hypotheses have been proposed to explain it (see Aires-da-Silva *et al*. (2010) Valero *et al*. (2019) and Punt *et al*. (2019) for details). The external panel that reviewed the bigeye assessment in 2019 concluded that: *"… while it cannot be definitively rejected that an actual recruitment regime shift has occurred, the balance of evidence is that it is an artefact of some aspect of the model and/or the way it has been parameterized."* Another issue with the bigeye assessment that needed to be addressed, which may be related to the cause of the *R* shift, was the misfit to the length-composition data for the longline fishery with assumed asymptotic selectivity. Although the panel did not identify a particular replacement for the current base case model, it suggested a range of alternatives for the staff

[2] *F* multiplier = F_{MSY} (the fishing mortality that will produce the maximum sustainable yield) divided by F_{cur} (the average fishing mortality for the three most recent years). An *F* multiplier of less than 1 indicates that fishing mortality is above the MSY level.

to consider, including different natural mortality schedules, growth models, and estimation procedures.

For the yellowfin stock assessment, the problems were inconsistencies between the indices of relative abundance based on longline data and those based on purse-seine data, the recent increase in the average size of fish in some fisheries, a systematic lack of fit to length-composition data for the fishery with asymptotic selectivity, and the possibility of spatial structure of yellowfin in the EPO. As with bigeye, the yellowfin review panel did not single out a particular model configuration as a replacement for the current base case model, but suggested a variety of alternatives for the staff to consider.

1.2. Uncertainty

The IATTC's **harvest control rule** (HCR) for tropical tunas establishes that "*if the probability that fishing mortality (F) will exceed the limit reference point (F_{LIMIT}) is greater than 10%, as soon as is practical management measures shall be established that have a probability of at least 50% of reducing F to the target level (F_{MSY}) or less, and a probability of less than 10% that F will exceed F_{LIMIT}*"(Resolution C-16-02). This requires, firstly, an estimate of fishing mortality, but also a way of quantifying the probability that a management action will have the desired effect. This uncertainty is addressed in the base case assessment with confidence intervals for the quantities of interest and sensitivity analyses which compare the results with those from other models, but these analyses are typically used only to give context to the point estimates and associated management advice.

Two categories of uncertainty are addressed here: *parameter* uncertainty and *structural (model) uncertainty,* and these are described below.

Parameter uncertainty estimates are used to quantify the precision of the stock assessment parameters (*e.g*. virgin recruitment) and derived quantities (*e.g*. recruitment and biomass). In the EPO tropical tuna stock assessments, the staff has relied on a simple normal approximation method to obtain confidence intervals for model parameters, derived quantities, and projections. These are plotted on a Kobe plot to portray the uncertainty of the stock status in terms of the fishing mortality and spawning biomass relative to the target and limit reference points for the base case and a more conservative model that assumes a moderate stock-recruitment relationship[3]. The confidence intervals have also been used to estimate the probability of exceeding the limit reference points for these two models.

Structural (model) uncertainty reflects the possibility that there may be alternative models that provide a reasonable representation of the processes under study (*e.g*. different shapes of the growth curve or stock-recruitment relationship; asymptotic versus dome-shaped selectivity). Sensitivity analyses have been used in the EPO tropical tuna assessments in an attempt to capture model uncertainty, to show the impact of alternative model assumptions on model fit and management quantities (by reporting the management quantities of interest for both the base case and sensitivity analyses, and by plotting each model on the Kobe plot). Although the sensitivity analyses help to put the base case results and associated management advice in context, the staff's management advice has relied exclusively on the base case results and has not explicitly accounted for model uncertainty and its implications for the potential outcomes of alternative management decisions.

The staff is using two related approaches to address these shortcomings: risk analysis, discussed here, and management strategy evaluation (MSE), discussed in the proposed MSE Workplan and recent Workshops (see for example Valero and Aires-da-Silva 2020). The staff is putting forward a proposal to fund the

[3] Expressed as steepness (*h*; see Maunder and Deriso 2014), a measure of the degree to which the biomass of a spawning stock and recruitment to that stock are interdependent. A steepness of 1 (h = 1) means recruitment is independent of stock biomass; the lower the value of *h*, the closer the relationship. For most tropical tunas there is little or no evidence of such a relationship, so a conservative value of h = 0.75 is used.

continuation of its MSE workplan during 2021-2023.

1.3. Risk analysis: a new approach to stock assessment and management advice at IATTC

Risk analysis, of which there are many types, takes uncertainty into account quantitatively in its management advice. It has a long history in fisheries: for example, decision tables that predict the outcomes of a range of management actions under different sets of assumptions (called '*states of nature*'), and their associated probabilities, have been used for decision-making in several fisheries (Punt and Hilborn 1997). More recently, probability statements have been integrated directly into **harvest control rules** (HCRs), under which specified combinations of stock and fisheries status and trends trigger predefined management actions, and explicit estimates of uncertainty are used to evaluate the probability statements. HCRs are often based on target, limit, and/or threshold reference points, as for example the IATTC's HCR for tropical tunas cited above.

The staff has successfully completed the workplan to improve the tropical tuna stock assessments, and new benchmark assessments are available for bigeye and yellowfin (SAC-11-06, SAC-11-07). These assessments represent a fundamental change from the staff's previous 'best assessment' approach: they are the basis for a 'risk analysis', in which a variety of reference models are used to represent plausible alternative assumptions about the biology of the fish, the productivity of the stocks, and/or the operation of the fisheries, thus effectively incorporating uncertainty into the management advice as it is formulated.

This change represents a paradigm shift at IATTC, both for the staff's work and for the Commission's decision-making regarding the conservation of tropical tunas. The new assessment framework offers the following advantages: 1) it explicitly incorporates the results of all reference models (*model uncertainty*) and the precision of each model's parameter estimates (*parameter uncertainty*); 2) it allows a probabilistic evaluation of whether the target and limit reference points specified in the IATTC harvest control rule for tropical tunas (C-16-02) have been exceeded; 3) it can be integrated into the Management Strategy Evaluation (MSE) framework under development at IATTC as a basis for developing operating models.

This new approach to formulating management advice for tropical tunas includes:

- Two **stock assessment reports**, for bigeye (SAC-11-06) and yellowfin (SAC-11-07), presenting the results from all reference models for each species (model fits, diagnostics, derived quantities and estimated parameters that define stock status);
- A **risk analysis** (results summarized in this document) using the methods described in SAC-11 INF-F, specific for tropical tunas, which assesses current stock status and the probability (risk) of exceeding target and limit reference points specified in the IATTC harvest control rule, as well as the expected consequences of alternative management measures in terms of closure days;
- **Stock status indicators** (SAC-11-05) for all three tropical tuna species (bigeye, skipjack, yellowfin); and
- The **staff's recommendations** (SAC-11-15) for the conservation of tropical tunas, based on the above.

2. METHODS

2.1. Objectives of risk analysis for EPO tropical tunas

Following FAO (1995b), the staff defines risk as "*the probability of something undesirable happening*". In this case, the undesirable event is exceeding the target and limit reference points specified in the IATTC harvest control rule.

The broad goal of risk analysis for the management of tropical tunas in the EPO is to use information from all available sources (stock assessment model results, population dynamics theory, auxiliary information, and expert knowledge) to estimate the current status of the stocks of yellowfin and bigeye tunas in terms of fishing mortality (*F*), spawning biomass (*S*), and the associated target (F_{MSY}, S_{MSY}) and limit (F_{LIMIT}, S_{LIMIT}) reference points established in Resolution C-16-02. Unlike in the 'best assessment' approach, which uses point estimates, in the risk analysis the uncertainty in quantities of interest for management is represented as a probability distribution.

The specific objectives of the risk analysis are:

1. At current levels of *F*, estimate the probability (*P*) (risk) of exceeding the target and limit reference points for *F* and *S* specified in the harvest control rule in C-16-02, thus:
    a. $P(F>F_{MSY})$, $P(F>F_{LIMIT})$
    b. $P(S<S_{MSY})$, $P(S<S_{LIMIT})$
2. Under alternative levels of input control management measures (duration of the purse-seine closure), estimate the probability of exceeding the target and limit reference points for *F* and *S* specified in the harvest control rule in C-16-02, thus:
    a. $P(F(\text{closure days})>F_{MSY})$, $P(F(\text{closure days})>F_{LIMIT})$
    b. $P(S(\text{closure days})<S_{MSY})$, $P(S(\text{closure days})<S_{LIMIT})$

where *F*(closure days) and *S*(closure days) are the fishing mortality and spawning biomass corresponding to the closure days, respectively.

2.2. A pragmatic risk analysis approach

The pragmatic risk analysis approach taken by the IATTC staff to implement harvest control rules, which considers multiple models and uses EPO bigeye as a case study, is described in detail in Maunder *et al*. 2020 (SAC-11 INF-F). This approach is a compromise between computational demands, complexity, and statistical rigor. It acknowledges the need to weight models based on information in the available data, but does so in a context where the complexity of fisheries stock assessment models prevents strict adherence to statistical rigor.

The approach consists of four main steps:

1. **Identify alternative hypotheses** ('*states of nature*') about the population dynamics of the stock that address the main issues in the stock assessments. The complete collection of hypotheses is arranged in a flow chart that shows dependencies among hypotheses and facilitates model development. For further information on the hypotheses, see SAC-11 INF-J for yellowfin and SAC-11 INF-F for bigeye.

2. **Translate the alternative hypotheses into stock assessment models**. For EPO yellowfin, 12 models were required to represent the various states of nature (SAC-11-07; SAC-11 INF-J), and for bigeye, 14 models (SAC-11-06; SAC-11 INF-F). Each model was run with four values for the steepness (*h*) of the stock-recruitment relationship.

3. **Determine the relative weight of the supporting evidence for each hypothesis (model),** expressed as *relative probability*, to avoid potential biases caused by giving all hypotheses equal weight in the risk analysis. The weight represents the reliability of the model, and is determined using a mix of metrics based on several factors (expert opinion, model fit, plausibility of parameter estimates and results, model diagnostics, *etc*.). The weights are rescaled to obtain a relative probability for each model.

4. **Combine the model relative probabilities with probability distributions of the quantities of interest estimated for each model**. The probability distributions represent the **uncertainty** in the estimates of the current status of the stock relative to the reference points, and are used to

calculate the **probability** that the target and limit reference points specified in C-16-02 will be exceeded.

2.3. Evaluation of current stock status and decision analysis

The risk analysis, carried out separately for yellowfin and bigeye, is divided into: (1) an assessment of the current status of the stock; and, (2) an evaluation of the consequences of alternative management actions, specifically modifying the duration of the temporal closure of the purse-seine fishery, currently 72 days (Resolution C-17-02)

Current status relative to a reference point was calculated as a weighted average of the point estimates of the ratio from each of the alternative stock assessment models, with weights equal to the relative model probabilities (equal to the expected value under the normal distribution assumption made for each model). The probability of exceeding a reference point was calculated using the cumulative distribution functions (CDFs) for the ratios of F_{cur} and S_{cur} relative to the reference points for each of the alternative models, which are then combined using the model probabilities.

To evaluate the consequences of modifying the duration of the purse-seine closure, the risk analysis was used to determine the probability of exceeding the fishing mortality reference points for bigeye under six different closures:

BET	Days	
1	0	No closure
2	36	50% of current closure
3	70	Closure required for 50% probability that F is below the MSY level ($P(F_{cur}<F_{MSY}) = 0.5$)
4	72	Current closure
5	88	Closure required to achieve F_{MSY} based on the expected value ($E(x)$) of F_{cur}/F_{MSY} for bigeye
6	100	≈150% of current closure

For these calculations, the fishing mortality is assumed to be proportional to the number of days the fishery is open, adjusted by the spatial closure in October (the '*corralito*') and changes in the carrying capacity of the purse-seine fleet. No projections were conducted, so the spawning biomass reference points (S_{MSY}, S_{LIMIT}) could not be evaluated at this stage; this will be done in future developments of the risk analysis.

3. RESULTS AND DISCUSSION

The risk analysis for yellowfin and bigeye was used to evaluate several management quantities related to the IATTC HCR. The results are presented separately below for each species for the two components of the analysis, *Current stock status* and *Decision analysis*, which evaluates the risk of exceeding the reference points resulting from different durations of the temporal closure.

3.1. Current stock status

3.1.1. Yellowfin

There were 12 final model configurations considered for yellowfin in the risk analysis (see SAC-11 INF-J for all model configurations initially considered). The 12 configurations, which correspond to 48 models because there are four steepness (h) values associated with each configuration, are summarized in **Table A** to facilitate interpretation of the of the results of the risk analysis. The *Density dependence*, *Time block middle*, and *Time block end* models were developed to address issues with the index of abundance, and the *Estimate growth* and *Dome-shape selectivity* models were developed to address the misfit to the composition data for the fishery with asymptotic selectivity.

TABLE A. Model configurations (hypotheses) used for yellowfin tuna in the EPO	
Model	**Description**
A. Proportional	
Base-A	Index of abundance proportional to abundance. Growth fixed; selectivity of all fleets and survey time-invariant; F19 selectivity asymptotic; index catchability (*q*, the proportionality constant between the index and biomass) time-invariant.
EstGro-A	As Base-A, but fitted to otolith data, growth estimated.
EstSel-A	As Base-A, but assumes dome-shaped F19 selectivity, with parameters estimated.
B. Density dependence	
Base-B	As Base-A, but assumes index of abundance is non-linearly related to biomass, with parameters estimated.
EstGro-B	As Base-B, but growth estimated.
EstSel-B	As Base-B, but assumes dome-shaped F19 selectivity, with parameters estimated.
C. Time block middle	
Base-C	As Base-A, but assumes a time block during 2001-2003 for the index catchability (*q*) (to accommodate a large increase in the index) and a time block for selectivity during 2002-2007 for the index, and F18 and F19 fisheries. F19 selectivity assumed dome-shaped during 2002-2007, otherwise asymptotic.
EstGro-C	As Base-C, but growth estimated.
EstSel-C	As Base-C, but assumes dome-shaped F19 selectivity, with parameters estimated.
D. Time block end	
Base-D	As Base-A, but assumes a time block beginning in 2015 for the index (both catchability and selectivity) and for F19 selectivity (to accommodate increase in size in the index and fishery with asymptotic selectivity).
EstGro-D	As Base-D, but growth estimated.
EstSel-D	As Base-D, but assumes dome-shaped F19 selectivity, with parameters estimated.

The yellowfin management quantities are shown in **Table 1**. The estimates of fishing mortality (*F*) and spawning stock (*S*) relative to levels corresponding to the MSY-related target and limit reference points are described below. For an explanation of the model configurations referred to in the column headings, see Table A.

TABLE 1. Management quantities for yellowfin tuna in the EPO.
E(x) is the expected value. P=0.5 is median of the distributions of P(S_{cur}/S_{MSY}) and P(F_{cur}/F_{MSY})

	A. Proportional			B. Density dependence			C. Time block middle			D. Time block end			Combined	
	Base-A	EstGro-A	EstSel-A	Base-B	EstGro-B	EstSel-B	Base-C	EstGro-C	EstSel-C	Base-D	EstGro-D	EstSel-D	E(x)	*P*=0.5
P (Model)	0.01	0.05	0.06	0.03	0.13	0.09	0.05	0.10	0.24	0.03	0.06	0.14	1.00	
Fishing mortality (*F*)														
F_{cur}/F_{MSY}	1.24	0.95	0.69	1.01	0.65	0.55	0.93	0.72	0.47	0.79	0.72	0.73	0.67	0.65
$P(F_{cur}>F_{MSY})$	0.88	0.37	0.05	0.46	0.03	0.01	0.32	0.07	0.00	0.13	0.08	0.09	0.09	
F_{cur}/F_{LIMIT}	0.46	0.45	0.31	0.38	0.32	0.25	0.38	0.35	0.22	0.33	0.33	0.31	0.30	
$P(F_{cur}>F_{LIMIT})$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Spawning biomass (*S*)														
S_{cur}/S_{MSY_d}	0.78	1.07	1.48	1.01	1.60	1.74	1.09	1.48	2.02	1.31	1.48	1.40	1.57	1.58
$P(S_{cur}<S_{MSY})$	0.93	0.41	0.07	0.48	0.04	0.08	0.34	0.06	0.03	0.15	0.09	0.11	0.12	
S_{cur}/S_{LIMIT}	1.87	1.96	2.60	2.62	3.24	3.70	2.33	2.53	3.25	2.99	2.94	3.08	2.98	
$P(S_{cur}<S_{LIMIT})$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

a. Fishing mortality (*F*)

F_{cur}/F_{MSY}

The combined distribution of F_{cur}/F_{MSY} is unimodal (**Figure 1a**), and only a small amount of the combined distribution is above 1, indicating a low probability of F_{cur} being above F_{MSY} (9%, **Table 1; Figure 5a**). The models used for dealing with the issues related to the index of abundance had an impact on the distribution of F_{cur}/F_{MSY}. The EstSel-C models are most optimistic ($F_{cur}<F_{MSY}$) and also received the highest weights, while those that assume the index is proportional to abundance are the most pessimistic and were assigned the lowest weights (**Figure 1b**). The hypotheses to explain the misfit to the composition data also have a large impact on the probability distribution of F_{cur}/F_{MSY}. The EstGro and EstSel models are more optimistic, and also were assigned the highest weights (**Figure 1c**). The *h* parameter also influences the distributions of F_{cur}/F_{MSY}, with higher steepness being more optimistic, as expected.

F_{cur}/F_{LIMIT}

The combined distribution of F_{cur}/F_{LIMIT} is also unimodal and similar to the distribution for F_{cur}/F_{MSY}, but shifted to the left (**Figure 2a**). There is no probability above 1, indicating that the probability of F_{cur} being above F_{LIMIT} is zero (**Table 1; Figure 5b**). The composition of the model distributions is similar to the distributions for F_{cur}/F_{MSY}, as expected (**Figure 2b-d)**.

b. Spawning biomass (*S*)

S_{cur}/S_{MSY_d}

The combined distribution of S_{cur}/S_{MSY_d} is unimodal (**Figure 3**). The composition of the distribution is similar to that for *F*, but reversed on the x-axis. Only a small amount of the distribution is below 1, indicating that the probability of the spawning biomass being below S_{MSY} is low (12%, **Table 1; Figure 6a**).

S_{cur}/S_{LIMIT}

The probability distribution for S_{cur}/S_{LIMIT} is unimodal and similar to the distribution for S_{cur}/S_{MSY_d}, but shifted to the right (**Figure 4**). The composition of the distribution is similar to that for S_{cur}/S_{MSY_d}. There are no model distributions below 1, indicating that the probability of exceeding S_{LIMIT} is zero (**Table 1; Figure 6b**).

c. Kobe plot

To capture the uncertainty about the population dynamics of yellowfin in the EPO, the 48 **reference models** (12 models x 4 steepness values), each reflecting a different hypothesis, are considered when evaluating the status of the stock. The results of each model is shown on a Kobe plot in **Figure A**. The majority of the results are optimistic ($F<F_{MSY}$, $S_{cur}>S_{MSY\_d}$), but some are pessimistic ($F>F_{MSY}$, $S_{cur}<S_{MSY\_d}$).

Historically, the status of the stocks was determined by the best estimate of the ratio of the current status to the reference point. This approach could be updated to include the alternative models by using the expected value or a weighted average of the best estimates from each model, weighted by the model probabilities. However, the uncertainty estimated in the risk analysis should be explicitly presented in the status determinations. Considering the relative weights of the different models and their combined distributions for the management parameters, there is only a 12% probability that the stock is overfished ($P(S_{cur}<S_{MSY})$ = 12%, **Table 1**) and a 9% probability that overfishing is taking place ($P(F_{cur}>F_{MSY})$ = 9%, **Table 1**). There is zero probability that both *S* and *F* limit reference points have been exceeded ($P(S_{cur}<S_{LIMIT})$ = 0%; $P(F_{cur}>F_{LIMIT})$ = 0%; **Table 1**). To be consistent with the probabilistic nature of the risk analysis and the HCR, the black dot on the Kobe plot representing the combined models is based on $P(S_{cur}/S_{MSY}<x)$ = 0.5 and $P(F_{cur}/F_{MSY}>x)$ = 0.5.

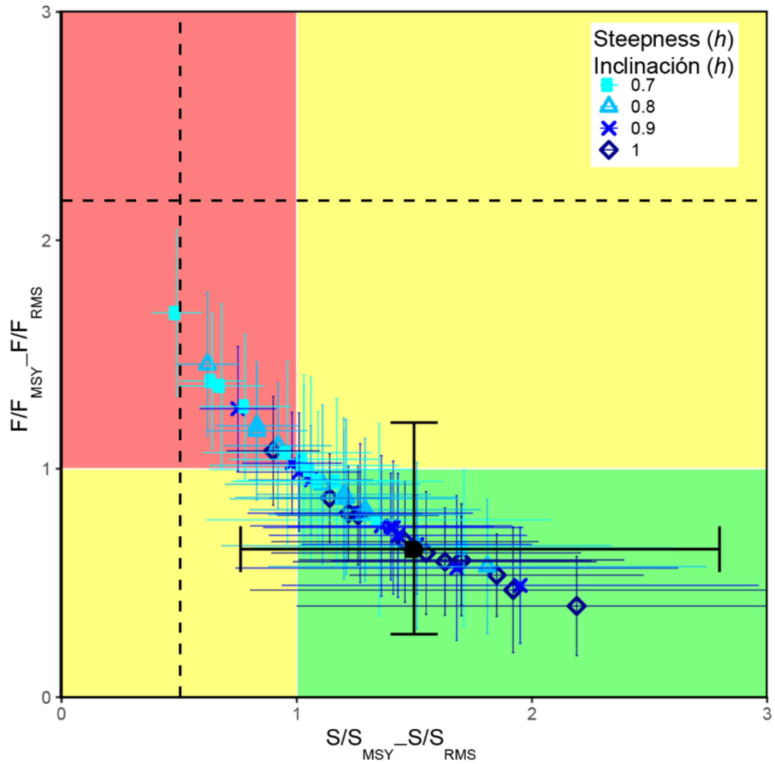

Figure YFT. Kobe (phase) plot of the time series of estimates of spawning stock size (*S*) and fishing mortality (*F*) of yellowfin tuna relative to their MSY reference points. The colored panels are separated by the target reference points (S_{MSY} and F_{MSY}). Limit reference points (dashed lines), which correspond to a 50% reduction in recruitment from its average unexploited level, based on a conservative steepness (*h*) of 0.75 for the Beverton-Holt stock-recruitment relationship, are merely indicative, since they vary by model and are based on all models combined. The center point for each model indicates the current stock status, based on the average fishing mortality (*F*) over the last three years; The solid black circle represents all models combined; to be consistent with the probabilistic nature of the risk analysis and the HCR, it is based on $P(S_{cur}/S_{LIMIT}<x) = 0.5$ and $P(F_{cur}/F_{MSY}>x) = 0.5$. The lines around each estimate represent its approximate 95% confidence interval.

3.1.2. Bigeye

After model weighting, which eliminated several models due to lack of convergence (see SAC-11 INF F for details), 12 model configurations were retained, corresponding to only 44 models because four models did not converge, with which current status and effects of management decisions were evaluated.

In the following, these model configurations, combined with specific modifications, are referred to by the acronyms in **Table B**. Models B-F (*Short-term*, *Pre-adult movement*, *Estimate growth*, *Dome-selectivity*, and A*dult mortality*) were developed to address the *R* shift, and D-F (*Estimate growth*, *Dome-selectivity*, and *Adult mortality*) were also developed to address the misfit to the composition data for the fishery with asymptotic selectivity.

TABLE B. Model configurations (hypotheses) used for bigeye tuna in the EPO

Model	Description
BASE	Not used in the risk analysis. However, this model is the basis for all other models. The selectivity for one of the longline fisheries is asymptotic. This model is similar to the base case

TABLE B. Model configurations (hypotheses) used for bigeye tuna in the EPO	
Model	**Description**
	model used in previous assessments except that the weighting for the composition data uses the Francis method. Growth and natural mortality are fixed.
A. Environment	
Env	This model assumes that the regime shift is real and is caused by a change in the environment. The selectivity for one of the longline fisheries is asymptotic. This model is similar to the base case model used in previous assessments except that the weighting for the composition data uses the Francis method and it estimates a parameter representing the change in recruitment.
Env-Fix	Environment, Fixed (don't estimate growth or natural mortality, asymptotic selectivity)
Env-Gro	Environment, estimate growth
Env-Sel	Environment, dome-shape selectivity
Env-Mrt	Environment, estimate adult natural mortality
B. Short-term	
Srt	This hypothesis is evaluated using only the data from 2000 – 2019 (other models use data from 1975-2019). It is assumed that the regime shift in recruitment is due to some unknown model misspecification in the early period (prior to 2000) that cannot be identified/resolved with available data, and thus, is not addressed by the other models.
Srt-Fix	Short-term, Fixed (don't estimate growth or natural mortality, asymptotic selectivity)
Srt-Gro	Short-term, estimate growth
Srt-Sel	Short-term, dome-shape selectivity
Srt-Mrt	Short-term, estimate adult natural mortality
C. Pre-adult movement	
Mov	This model approximates movement of fish into or out of the EPO from the CPO by applying natural mortality to fish starting at an age that is between those selected by the floating-object fishery and those selected by the longline fishery. Higher natural mortality represents fish moving out of the EPO and lower natural mortality represents fish moving into the EPO. This modified mortality schedule also could capture actual differences in age-specific natural mortality driven by a variety of processes.
D. Estimate growth	
Gro	Estimating growth allows for a larger biomass and therefore reduces the regime shift in recruitment. The length composition data for the fishery with asymptotic selectivity has few fish around the asymptotic length and therefore the model estimates a high fishing mortality, and corresponding low biomass, to reduce the number of large fish and fit the length composition data. Estimating growth produces a low asymptotic length, reducing the predicted number of large fish and fits the length composition data without increasing fishing mortality, which allows for a larger biomass. All four parameters of the Richards growth curve and the two parameters representing the variation of length at age are estimated. The model is fit to the otolith age conditioned on length data. This model can also address the misfit to the length composition data.
E. Dome selectivity	
Sel	A dome-shape selectivity for the longline fishery allows for a larger biomass and therefore reduces the regime shift in recruitment. The length composition data for the fishery with asymptotic selectivity has few fish around the asymptotic length and therefore the model estimates a high fishing mortality, and corresponding low biomass, to reduce the number of large fish and fit the length composition data. Estimating a dome-shape selectivity reduces the predicted number of large fish caught allowing the model to fit the observed length

TABLE B. Model configurations (hypotheses) used for bigeye tuna in the EPO	
Model	**Description**
	composition data, but also produces a "cryptic biomass" increasing the biomass estimate. A double normal selectivity curve is used. This model can also address the misfit to the length composition data.
F. Adult mortality	
Mrt	Estimating adult natural mortality allows for a larger biomass and therefore reduces the regime shift in recruitment. An increased value of natural mortality reduces the fishing mortality that is needed to fit the length composition data and therefore increases the biomass for a given level of catch. This model can also address the misfit to the length composition data.

The bigeye stock management quantities are shown in **Table 2**. The results of fishing mortality (*F*) and spawning stock (*S*) relative to the MSY related target and limit reference points are described below. For an explanation of the model configurations referred to in the column headings, see **Table B**.

TABLE 2. Management quantities for bigeye tuna in the EPO. E(x) is the expected value. *P*=0.5: median of the distributions of $P(S_{cur}/S_{MSY})$ and $P(F_{cur}/F_{MSY})$

	Env-Fix	Env-Gro	Env-Sel	Env-Mrt	Srt-Fix	Srt-Gro	Srt-Sel	Srt-Mrt	Mov	Gro	Sel	Mrt	Combined	
P(Model)	0.01	0.13	0.05	0.02	0.04	0.22	0.11	0.07	0.01	0.24	0.09	0.02	*E*(x)	*P*=0.5
Fishing mortality (*F*)														
F_{cur}/F_{MSY}	1.82	0.82	0.99	1.25	1.84	1.42	1.36	1.57	0.81	0.59	0.73	0.89	1.07	1.00
$P(F_{cur}>F_{MSY})$	1.00	0.18	0.44	0.84	1.00	0.97	0.92	0.99	0.15	0.01	0.07	0.25	0.50	
F_{cur}/F_{LIMIT}	0.96	0.47	0.58	0.69	0.97	0.78	0.77	0.84	0.47	0.34	0.43	0.50	0.60	
$P(F_{cur}>F_{LIMIT})$	0.33	0.00	0.00	0.01	0.38	0.07	0.06	0.14	0.00	0.00	0.00	0.00	0.05	
Spawning biomass (*S*)														
S_{cur}/S_{MSY_d}	0.34	1.32	1.02	0.69	0.32	0.56	0.59	0.45	1.31	1.85	1.53	1.16	1.09	0.92
$P(S_{cur}<S_{MSY})$	1.00	0.19	0.49	0.96	1.00	1.00	1.00	1.00	0.16	0.03	0.07	0.27	0.53	
S_{cur}/S_{LIMIT}	0.97	3.61	2.67	2.04	0.97	1.65	1.65	1.38	3.84	5.24	4.21	3.63	3.07	
$P(S_{cur}<S_{LIMIT})$	0.59	0.00	0.00	0.02	0.50	0.06	0.09	0.19	0.00	0.00	0.00	0.00	0.06	

a. Fishing mortality (*F*)

F_{cur}/F_{MSY}

For the combined distribution, F_{cur} is 7% above F_{MSY} (**Table 2**). This distribution is bimodal (**Figure 7a**), due to the substantial differences in the estimates between the *Short-term* models, which are more pessimistic (F_{cur}/F_{MSY} mostly above 1; **Figure 7b**), and the "medium-term" models (**Figure 7b**) that do not assume the *R* shift is real (*Gro*, *Sel*, *Mrt*, *Mov*), which are more optimistic (F_{cur}/F_{MSY} mostly below 1). The remaining model, *Environment*, which assumes that the *R* shift is real, falls between these two groups, but with most of its probability density on the optimistic side (F_{cur}/F_{MSY} mostly below 1; **Figure 7b**); it was assigned a lower weight. The hypotheses to explain the misfit to the longline composition data (*Gro*, *Sel*, *Mrt*) also have a large impact on the probability distribution, with *Gro* and *Sel* being more optimistic and also were assigned the greatest weights (**Figure 1c**). The *h* parameter also influences the distributions of F_{cur}/F_{MSY}, with greater steepness being more optimistic, as expected (**Figure 7d**). A substantial amount of the combined distribution is above 1, indicating that the probability of $F_{cur} > F_{MSY}$ is not negligible.

The probability of exceeding the reference points are calculated using cumulative distribution functions (CDFs) (**Figure 11a**). The CDF for F_{cur}/F_{MSY} generally reflects two groups of models (with high and low probabilities, respectively, of being below F_{MSY}) corresponding to the modes in the probability distribution and their composition, as noted above (**Figure 7**). The combined distribution has a 50% probability of exceeding F_{MSY} (**Table 2**).

F_{cur}/F_{LIMIT}

F_{cur} is below F_{LIMIT} for all reference models (F_{cur}/F_{LIMIT}<1; **Table 2**). For the combined distribution, F_{cur} is at about 60% of F_{LIMIT}. The combined distribution of F_{cur}/F_{LIMIT} is also bimodal and similar to the distribution of F_{cur}/F_{MSY}, but shifted to the left (**Figure 8a**). The composition of the model distributions is similar to the distributions for F_{cur}/F_{MSY} (**Figure 7**), as expected. There is little probability above 1, indicating that the probability of exceeding F_{LIMIT} is low (5%; **Table 2** and **Figure 11b**).

b. Spawning biomass (*S*)

S_{cur}/S_{MSY_d}

For all models combined, S_{cur} is 9% above S_{MSY_d} (**Table 2**). The probability distribution for S_{cur}/S_{MSY_d} is generally bimodal, but also has some smaller modes (**Figure 9**). The composition of the distribution is similar to that for *F*, but reversed on the X axis. A substantial amount of the combined distribution is <1, indicating that the probability of being below the S_{MSY_d} is not negligible (53%; **Figure 12a)**.

S_{cur}/S_{LIMIT}

S_{cur} is well above S_{LIMIT} (S_{cur}/S_{LIMIT}>1; **Table 2**). The probability distribution for S_{cur}/S_{LIMIT} is bimodal and similar to the distribution for S_{cur}/S_{MSY_d}, but without the smaller modes and shifted to the right (**Figure 10**). The composition of the distribution is similar to that for S_{cur}/S_{MSY_d}. There is little of the overall model distribution below 1, indicating that the probability of exceeding S_{LIMIT} is low (6%; **Figure 12b**).

c. Kobe plot

To capture the uncertainty about the population dynamics of bigeye in the EPO, 44 **reference models** (12 models x 4 steepness values; 4 did not converge), each reflecting a different hypothesis, are considered when evaluating the status of the stock. The results of each model are shown on a Kobe plot in **Figure B**. The numbers of models producing optimistic ($F<F_{MSY}$, $S_{cur}>S_{MSY\_d}$) and pessimistic ($F>F_{MSY}$, $S_{cur}<S_{MSY\_d}$) results are about the same.

Historically, the status of the stock was determined by the best estimates of the ratio of the current status to the reference point. This approach could be updated to include the alternative models by using the expected value or a weighted average of the best estimates from each model, weighted by the model probabilities. However, the uncertainty estimated in the risk analysis should be explicitly presented in the status determinations. Considering the relative weights of the different models and their combined distributions for the management parameters, there is only a 53% probability that the stock is overfished ($P(S_{cur}<S_{MSY})$ = 53%, **Table 2**) and a 50% probability that overfishing is taking place ($P(F_{cur}>F_{MSY})$ = 50%, **Table 1**). There is a small probability that both *S* and *F* limit reference points have been exceeded ($P(S_{cur}<S_{LIMIT})$ = 6%; $P(F_{cur}>F_{LIMIT})$ = 5%; **Table 2**). To be consistent with the probabilistic nature of the risk analysis and the HCR, the point on the Kobe plot representing the combined models is based on $P(S_{cur}/S_{MSY}<x)$ = 0.5 and $P(F_{cur}/F_{MSY}>x)$ = 0.5.

As noted above, the distribution of the management quantities for bigeye is bimodal, not unimodal. Therefore, some important management implications should be considered (see section 3.2).

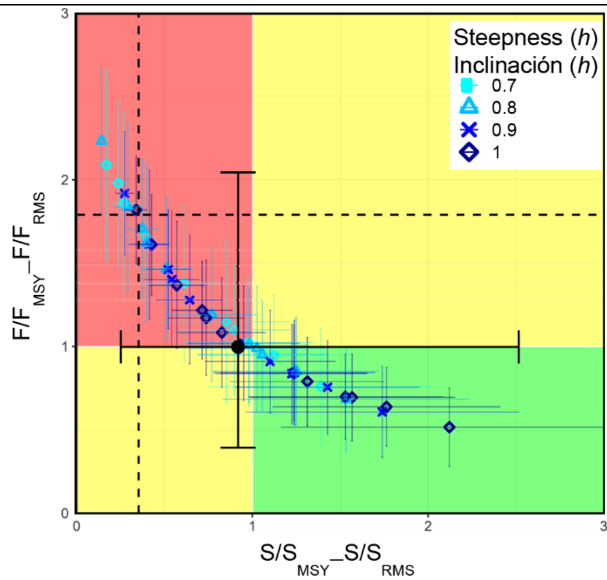

FIGURE BET. Kobe (phase) plot of the time series of estimates of spawning stock size (*S*) and fishing mortality (*F*) of bigeye tuna relative to their MSY reference points. The colored panels are separated by the target reference points (S_{MSY} and F_{MSY}). Limit reference points (dashed lines), which correspond to a 50% reduction in recruitment from its average unexploited level based on a conservative steepness value (*h* = 0.75) for the Beverton-Holt stock-recruitment relationship, are only indicative since they vary by model and are based on all models combined. The center point for each model indicates the current stock status, based on the average fishing mortality (*F*) over the last three years; The solid black circle represents all models combined, and to be consistent with the probabilistic nature of the risk analysis and the HCR, it is based on $P(S_{cur}/S_{LIMIT}<x) = 0.5$ and $P(F_{cur}/F_{MSY}>x) = 0.5$. The lines around each estimate represent its approximate 95% confidence interval.

3.2. Decision analysis on alternative management measures

The decision analysis evaluates the consequences, in terms of exceeding the reference points specified in the harvest control rule, of alternative management actions: specifically, six different durations of the temporal closure of the purse-seine fishery (Section 2.6). The results of the decision analysis for the two species (**Tables 3** and **4**) are presented, in the decision table format specified in Punt and Hilborn (1997), for the *F*-based reference points only.

The decision table has four elements: in the two header rows, the 12 alternative hypotheses (*states of nature*) about the population dynamics, and the relative weight of each (expressed as a probability, *P*); in the 'Closure days' column, six alternative management actions (days of closure; see section 2.6) including the current closure; and in the remaining columns, the consequences of each action if a particular hypothesis is true, expressed as a performance measure: the probability (risk; *P*) of *F* exceeding the target ($P(F>F_{MSY})$) and limit ($P(F>F_{LIMIT})$) reference points.

3.2.1. Yellowfin

For yellowfin, the combined expected risk of *F* exceeding F_{MSY} is below 50% for all six closure durations (**Table 3; Figure 13a**), varying from 26% (no closure) to 5% (100 days), with a low risk (9%) for the current closure (72 days). One model (Base-A) produced a pessimistic result (a risk above 50% of exceeding F_{MSY} for all scenarios (**Table 3)**), but this model has a very low relative weight (0.01).

Across all models, there is no risk (0%) of *F* exceeding F_{LIMIT} for all closures (**Table 3; Figure 13a**), regardless of which model is chosen to be true.

TABLE 3. Decision table for yellowfin tuna in the EPO													
Closure days	A. Proportional			B. Density dependence			C. Time block middle			D. Time block end			Comb
	Base-A	EstGro-A	EstSel-A	Base-B	EstGro-B	EstSel-B	Base-C	EstGro-C	EstSel-C	Base-D	EstGro-D	EstSel-D	
***P*(*F*>*F*MSY)**											Probability	≤50%	>50%
0	0.99	0.74	0.23	0.88	0.17	0.09	0.74	0.29	0.02	0.43	0.30	0.32	0.26
36	0.97	0.56	0.12	0.70	0.08	0.04	0.53	0.17	0.01	0.27	0.17	0.19	0.17
70	0.88	0.37	0.05	0.46	0.03	0.01	0.32	0.07	0.00	0.13	0.08	0.09	0.09
72	0.87	0.36	0.05	0.44	0.03	0.01	0.31	0.07	0.00	0.13	0.08	0.08	0.09
88	0.77	0.28	0.03	0.33	0.01	0.01	0.22	0.04	0.00	0.08	0.05	0.05	0.06
100	0.68	0.22	0.01	0.26	0.01	0.00	0.16	0.02	0.00	0.06	0.03	0.03	0.05
***P*(*F*>*F*LIMIT)**											Probability	≤10%	>10%
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

3.2.2. Bigeye

For bigeye, the combined expected risk of F exceeding F_{MSY} ranges between 62% and 43% (**Table 4; Figure 13b**). A 50% risk of F exceeding F_{MSY} is reached at 70 days of closure, two days less than the current closure, which has a 49% risk.

The expected risk values describe the combined distribution of F_{cur}/F_{MSY} across models. However, as described in section 3.1.2.a, the distribution of F_{cur}/F_{MSY} (along with other quantities of interest) is bimodal for bigeye, due to the substantial differences in estimates between two groups of models and states of nature, one more pessimistic and the other more optimistic (**Figures 7 to 10**). The combined values fall between these two states, and it is important to understand the risks of relying solely on the combined value or on one group of models over another when the latter is closer to the true state of nature.

Relying only on results of the pessimistic models to formulate management advice implies high risks of exceeding F_{MSY} within the range of closure days analyzed (0-100 days) (**Figure 14**). A longer closure would be necessary to reduce this risk to an acceptable level, but there is no specification on what that acceptable level is in C-16-02. Instead, the harvest control rule is only specific about the probability level to exceed the limit reference points (10%). If the pessimistic models are assumed to be closer to the *true state of nature*, the risk of exceeding F_{LIMIT} under the current closure at 72 days is 10% (weighted average of the combined pessimistic models; **Figure 15b**). Therefore, any reduction of the 72-day closure will exceed the limit under the combined pessimistic models.

If, instead, management is driven by the results of the optimistic models, reducing the current temporal closure has a probability of less than 50% and 10% of exceeding F_{MSY} and F_{LIMIT}, respectively (**Figures 14 and 15**). Obviously, if the optimistic models are used, but the pessimistic models are closer to the *true state of nature,* the risk of exceeding F_{LIMIT} will be substantially higher than 10% (**Figure 15**).

In summary, results from the bigeye risk analysis essentially fall in between two possible states (optimistic and pessimistic, relative to reference points) that cannot be discerned based on data, model valuation, or other criteria currently available. The resulting bimodality of the combined distributions of management quantities limits the utility of the risk analysis to evaluate probability statements about the status of the stock relative to reference points. Caution should be taken when interpreting these probability distributions for management purposes, and averages or the use of simple probability statements such as

P(F_{cur}>F_{MSY}) should be avoided. Instead, the whole probability distributions should be considered. The consequences of making management actions (closure duration) should neither focus on the average nor solely assuming a state of nature is correct (either optimistic or pessimistic) without consideration of the risks associated to the assumed state of nature being wrong.

Probability	≤50%	>50%

TABLE 4. Decision table for bigeye tuna in the EPO

Closure days	Env-Fix	Env-Gro	Env-Sel	Env-Mrt	Srt-Fix	Srt-Gro	Srt-Sel	Srt-Mrt	Mov	Gro	Sel	Mrt	Comb
***P*(*F*>*F*$_{MSY}$)**											Probability	≤50%	>50%
0	1.00	0.48	0.78	0.98	1.00	1.00	0.99	1.00	0.47	0.09	0.31	0.65	0.62
36	1.00	0.32	0.63	0.93	1.00	0.99	0.97	1.00	0.30	0.03	0.17	0.45	0.56
70	1.00	0.19	0.44	0.84	1.00	0.97	0.92	0.99	0.15	0.01	0.07	0.25	0.50
72	1.00	0.18	0.43	0.83	1.00	0.96	0.91	0.98	0.14	0.01	0.06	0.24	0.49
88	1.00	0.13	0.35	0.75	1.00	0.93	0.87	0.97	0.09	0.00	0.04	0.17	0.46
100	1.00	0.09	0.28	0.67	1.00	0.88	0.81	0.95	0.06	0.00	0.02	0.11	0.43
											Probability	≤10%	>10%
0	0.97	0.00	0.04	0.17	0.89	0.39	0.37	0.57	0.00	0.00	0.00	0.00	0.21
36	0.79	0.00	0.01	0.06	0.67	0.19	0.18	0.33	0.00	0.00	0.00	0.00	0.12
70	0.33	0.00	0.00	0.01	0.38	0.07	0.06	0.14	0.00	0.00	0.00	0.00	0.05
72	0.30	0.00	0.00	0.01	0.36	0.06	0.06	0.13	0.00	0.00	0.00	0.00	0.05
88	0.11	0.00	0.00	0.00	0.25	0.03	0.03	0.08	0.00	0.00	0.00	0.00	0.03
100	0.04	0.00	0.00	0.00	0.17	0.02	0.02	0.04	0.00	0.00	0.00	0.00	0.02

4. CONCLUSIONS

This transition to risk analysis significantly advances stock assessment science and the formulation of management advice for tropical tunas at IATTC. First, the process resulted in the identification of a set of reference models (alternative hypotheses, or 'states of nature') which describe the population dynamics of yellowfin and bigeye, as well as the main axes of uncertainty in the stock assessments for both species. Second, the approach provides a methodology for assigning relative weights to the plausibility of these alternative hypotheses that takes into consideration a range of factors (*e.g.* expert opinion, model fit, plausibility of results and parameter estimates, and diagnostics). Finally, the final product of the risk analysis are probability statements for exceeding the reference points established in the HCR.

The risk analysis unambiguously shows that the yellowfin stock in the EPO is healthy, but the results are less clear for bigeye. The bimodal nature of the probability distributions from the bigeye risk analysis for the management quantities of interest indicates that the stock is either well below or well above the levels corresponding to MSY (S_{MSY}). Clearly, optimal management, or even whether the bigeye stock size should be increased or decreased, cannot be determined from the risk analysis. However, the combined probability distribution for the pessimistic models shows only a 10% probability of exceeding F_{LIMIT} for the current closure duration (72 days), indicating that it is unlikely that this limit has been exceeded. Therefore, a *status quo* harvest strategy should be appropriate in the short term.

The bimodality of the bigeye probability distributions complicates the evaluation of the status of the bigeye stock and the evaluation of the potential outcomes of management actions. This issue needs to be addressed in the future to improve management advice. There are two avenues towards this goal: 1) continue to improve the stock assessment models, which also involves their data inputs, and 2) develop and evaluate management strategies that are shown to be robust to the main uncertainties, including the bimodality, using MSE.

4.1. Improving the stock assessments

The risk analysis can be used to identify areas of research to improve the assessment by looking at the hypotheses that caused the bimodality and by focusing on hypotheses that received high weights. The bimodality for bigeye tuna is mainly caused by differences in the time span of the model, and further work investigating these differences should be conducted. The hypotheses that estimated growth received 58% of the weight, indicating that improving the estimates of growth should be a priority. Improving estimates of natural mortality and of selectivity for the fishery that assumes asymptotic selectivity should also be considered.

The risk analysis for yellowfin tuna was limited to assessments that assume a single stock in the EPO because evaluating all possible models initially considered would not be practical. Preliminary models suggest that stock structure might be present within the EPO, and these models should be further investigated.

4.2. MSE

While work on resolving issues related to model misspecificiation should be continued, the staff acknowledges that there may always be unresolved issues in knowledge, their impact on taking appropriate management action, and the inherent limits of modelling complex and changing natural systems and their fisheries. The risk analysis work is a first step towards the explicit incorporation of uncertainty in the stock assessment and formulation of management advice for the tropical tunas in the EPO. The risk analysis focused on two sources of uncertainty: uncertainty related to which models were used to assess the stock (*model uncertainty*) and the uncertainty associated with the estimation properties of each model (*parameter uncertainty*). There are other sources of uncertainty (implementation, *etc*.) and elements of the current strategy, along with alternatives (types and estimation of reference points, specificity of the current HCR, performance metrics, *etc*.), that are important for evaluating the robustness of the management advice and what strategies are more likely to achieve desired management objectives. The models and their weighting developed in the risk analysis could be used to inform the development of operating (simulation) models for MSE. The MSE process could be used to evaluate setting management actions based on simpler models or empirical HCRs that rely on trends in data (rather than complex models). This process could be either an alternative or complementary approach to the recent (best-assessment) or current (risk analysis) approaches, while both data and stock assessments are improved. An MSE Workplan is already ongoing at IATTC, and should be continued (see recent Workshops).

Given the substantial uncertainty in stock assessments in general, and in those for tropical tunas in particular, management decisions should not be based on point estimates from a single base-case model or even point estimates derived from an average from multiple models. Management should take into consideration the uncertainty in the estimates, in the model structure and in other components of the system (imperfect implementation of strategies, interplay between scientific advice and management action, *etc.*). MSE provides a framework for developing management strategies that incorporate, and are robust to, the different forms of unavoidable uncertainties involved in fishery management, thereby providing a formal approach to evaluate management actions designed to achieve fisheries objectives.

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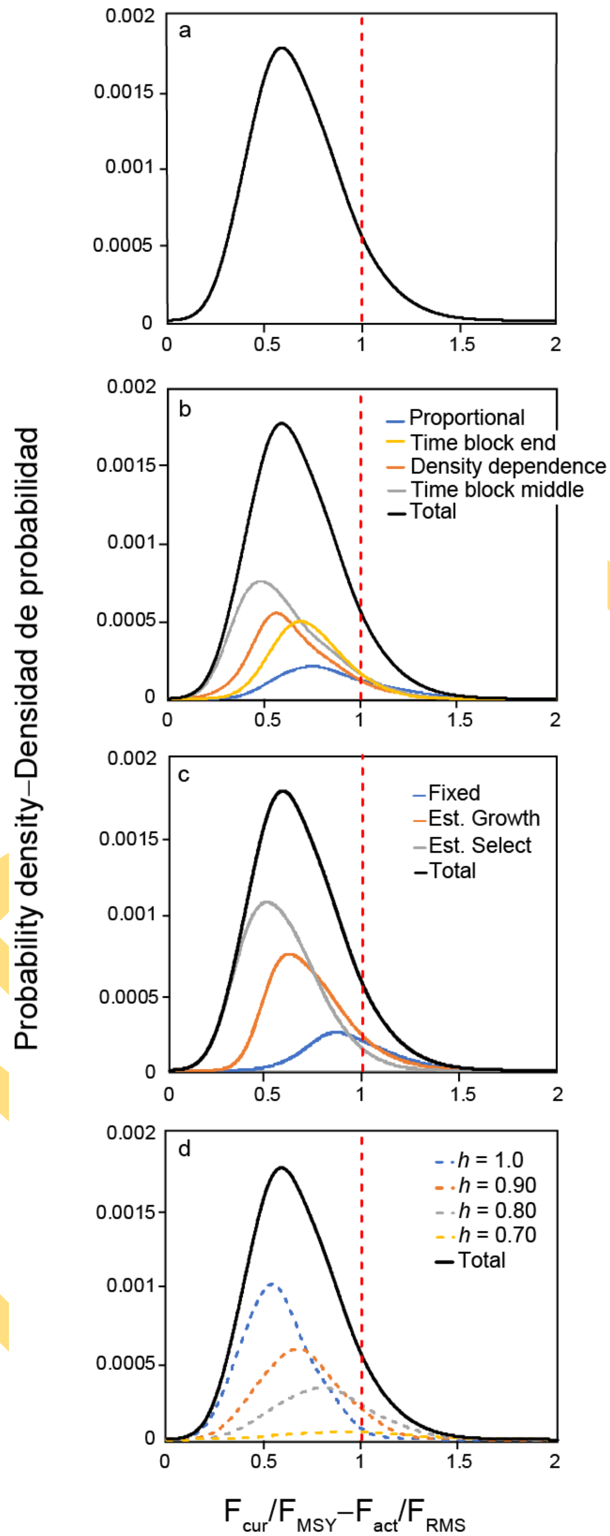

FIGURE 1. Yellowfin probability density functions for F_{cur}/F_{MSY} broken down into different components.
FIGURA 1. Funciones de densidad de probabilidad para F_{act}/F_{RMS} de aleta amarilla divididas en diferentes componentes.

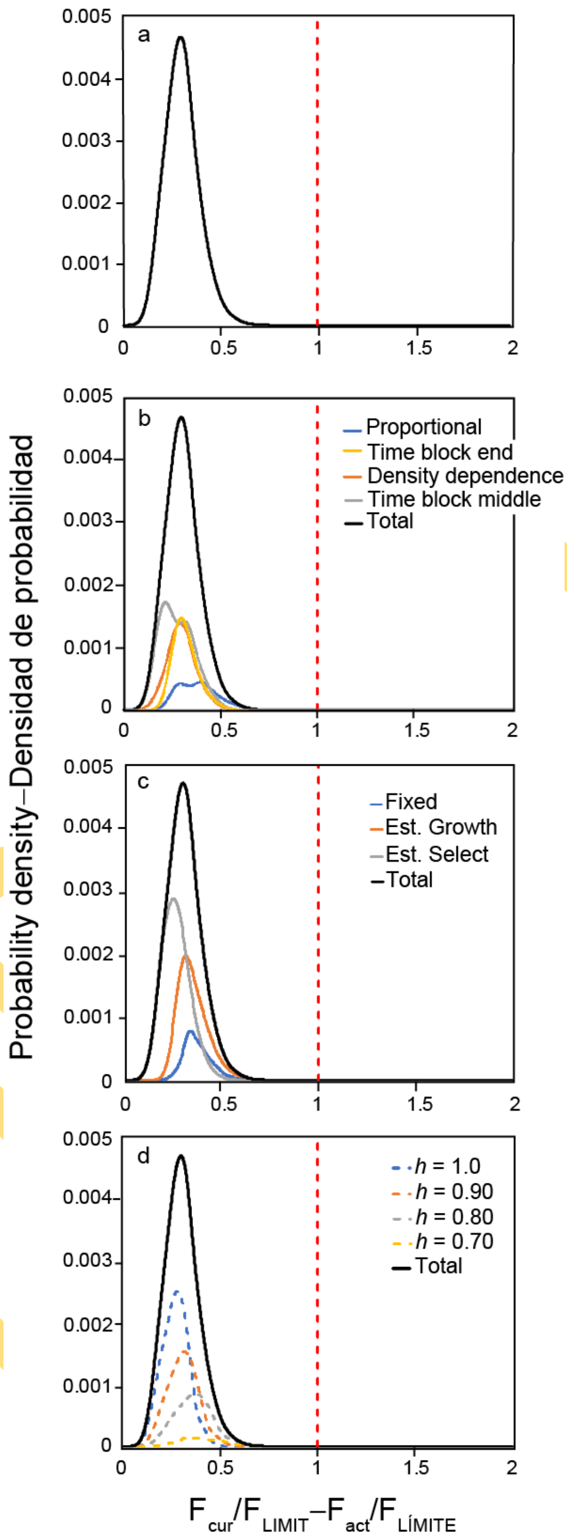

FIGURE 2. Yellowfin probability density functions for F_{cur}/F_{LIMIT} broken down into different components.
FIGURA 2. Funciones de densidad de probabilidad para $F_{act}/F_{LÍMITE}$ de aleta amarilla divididas en diferentes componentes.

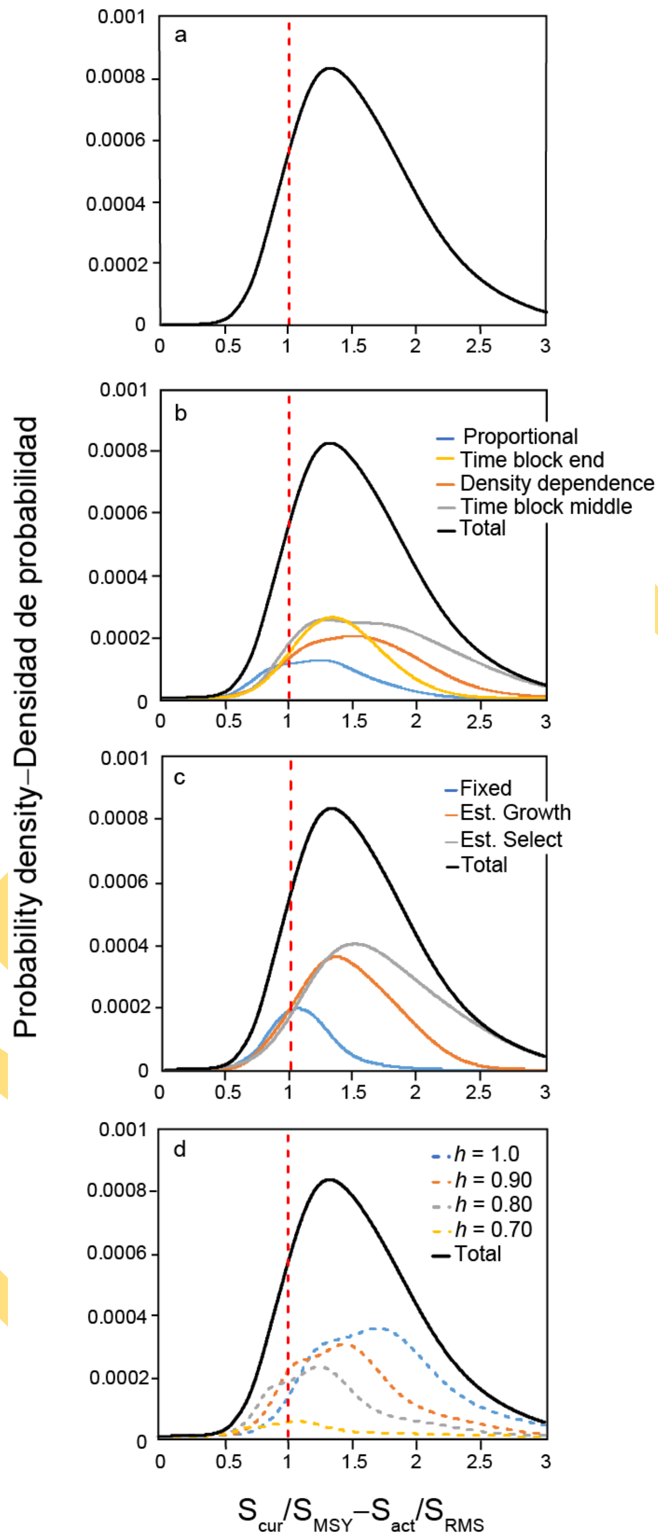

FIGURE 3. Yellowfin probability density functions for S_{cur}/S_{MSY} broken down into different components.
FIGURA 3. Funciones de densidad de probabilidad para S_{act}/S_{RMS} de aleta amarilla divididas en diferentes componentes.

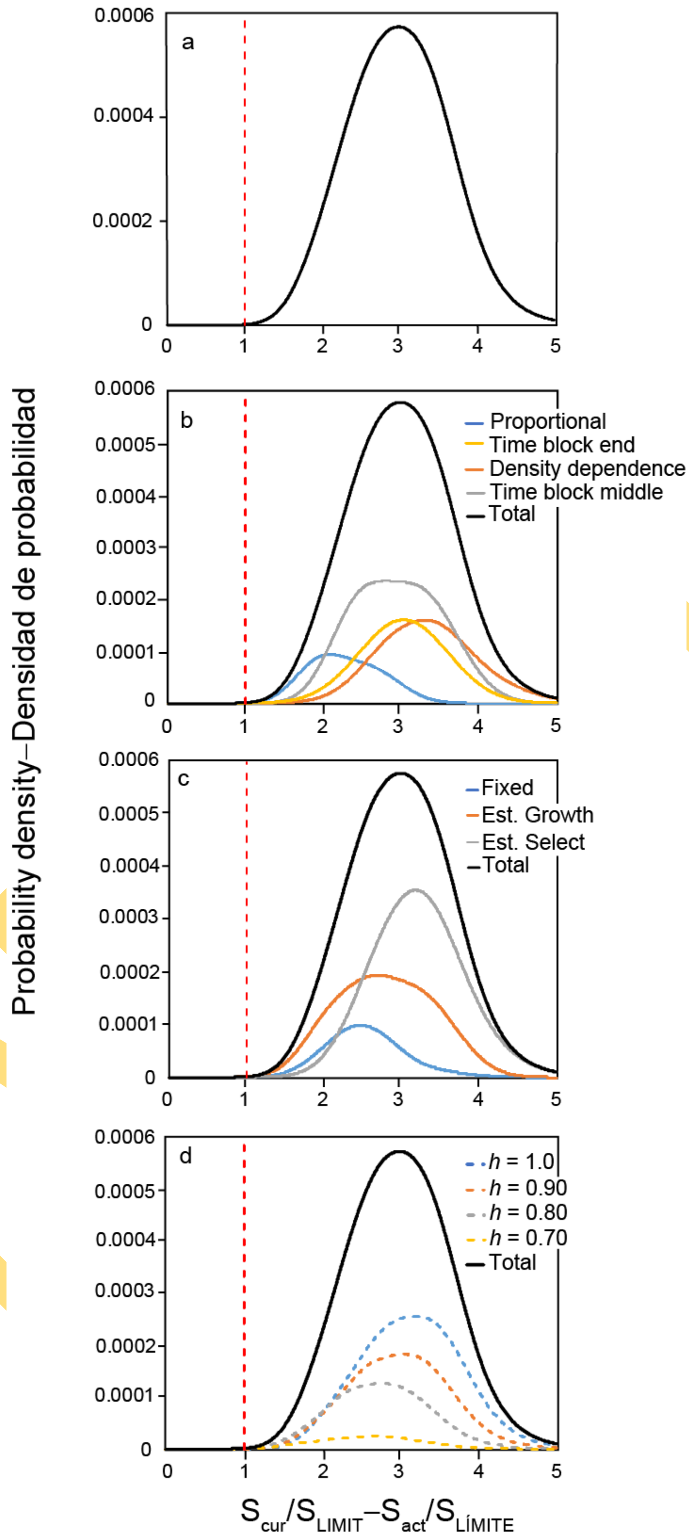

FIGURE 4. Yellowfin probability density functions for S_{cur}/S_{LIMIT} broken down into different components.
FIGURA 4. Funciones de densidad de probabilidad para $S_{act}/S_{LÍMITE}$ de aleta amarilla divididas en diferentes componentes.

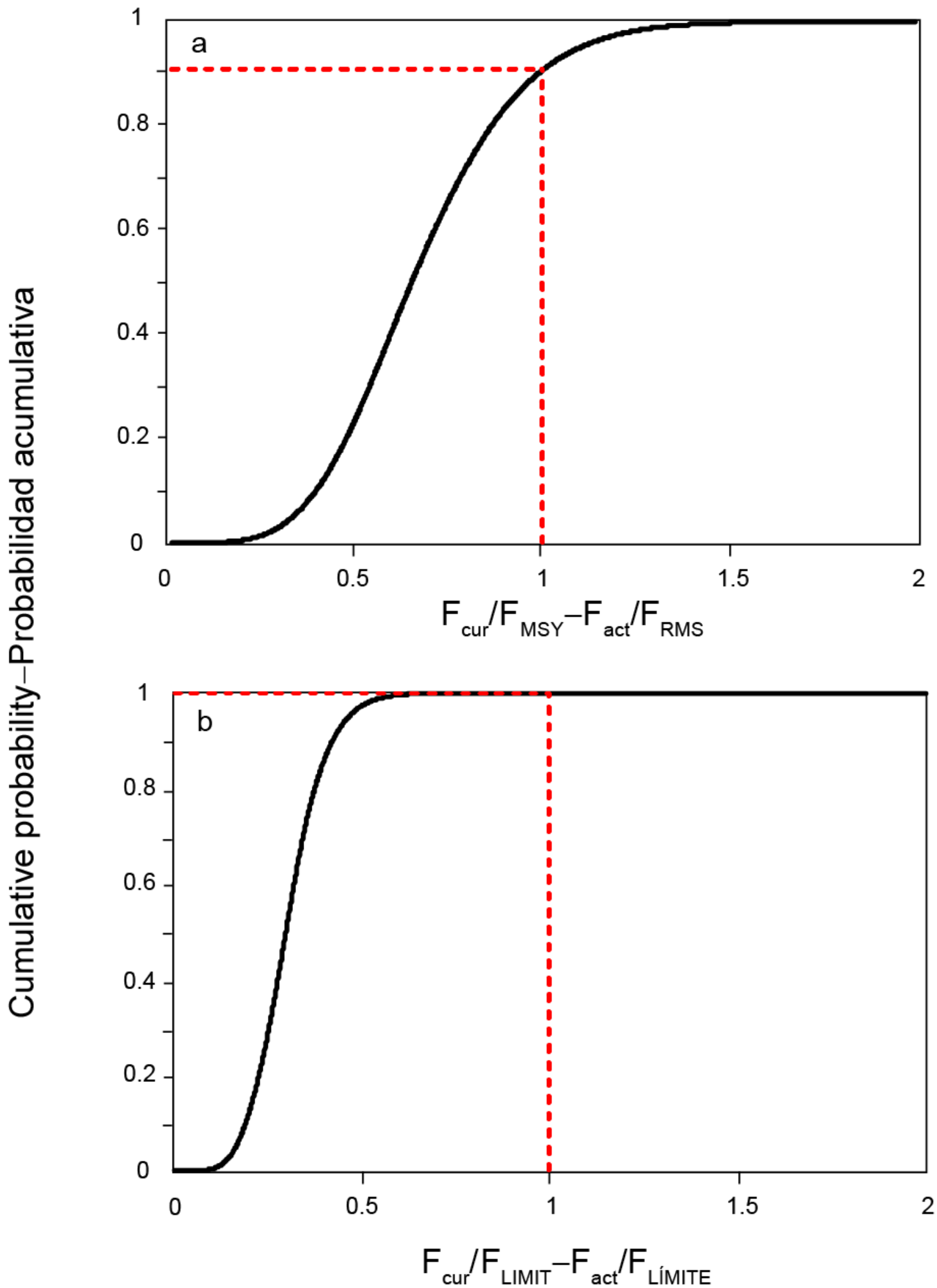

FIGURE 5. Yellowfin cumulative distribution functions (CDFs) for: a) F_{cur}/F_{MSY}; b) F_{cur} /F_{LIMIT}. **FIGURA 5.** Funciones de distribución acumulativa (FDA) de aleta amarilla para: a) F_{act}/F_{RMS}; b) F_{act} /$F_{LÍMITE}$.

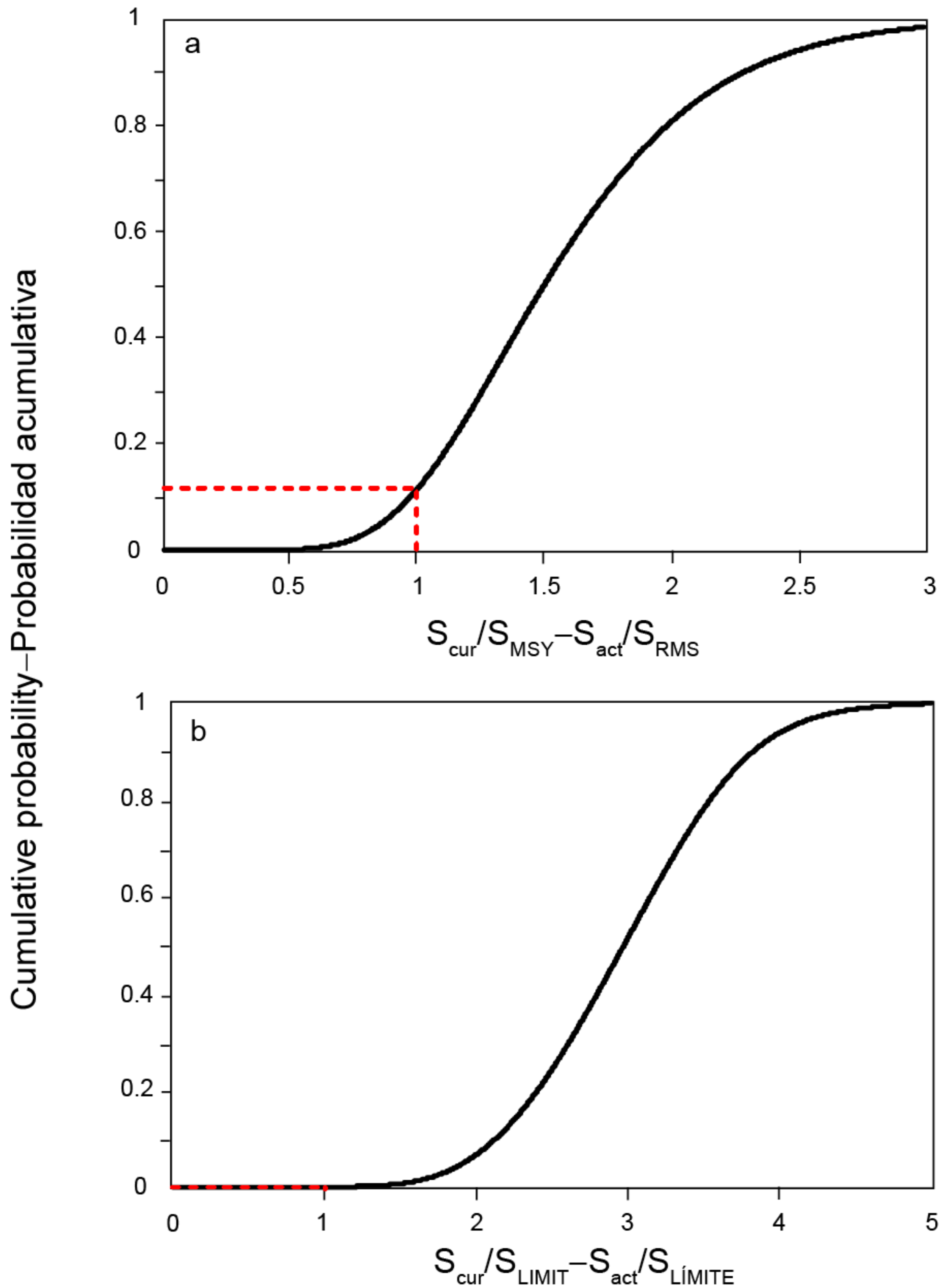

FIGURE 6. Yellowfin cumulative distribution functions (CDFs) for: a) S_{cur}/S_{MSY}; b) S_{cur} /S_{LIMIT}.
FIGURA 6. Funciones de distribución acumulativa (FDA) de aleta amarilla para: a) S_{act}/S_{RMS}; b) S_{act} /$S_{LÍMITE}$.

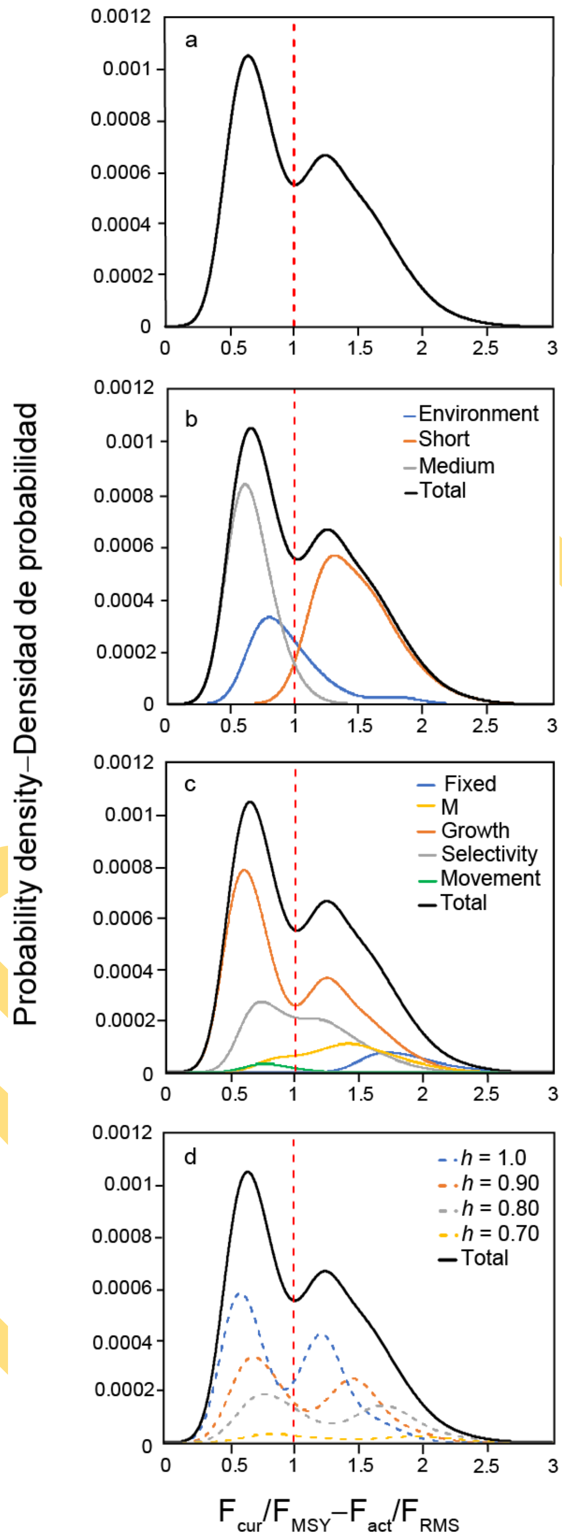

FIGURE 7. Bigeye probability density functions for F_{cur}/F_{MSY} for broken down into different components.
FIGURA 7. Funciones de densidad de probabilidad para F_{act}/F_{RMS} de patudo divididas en diferentes componentes.

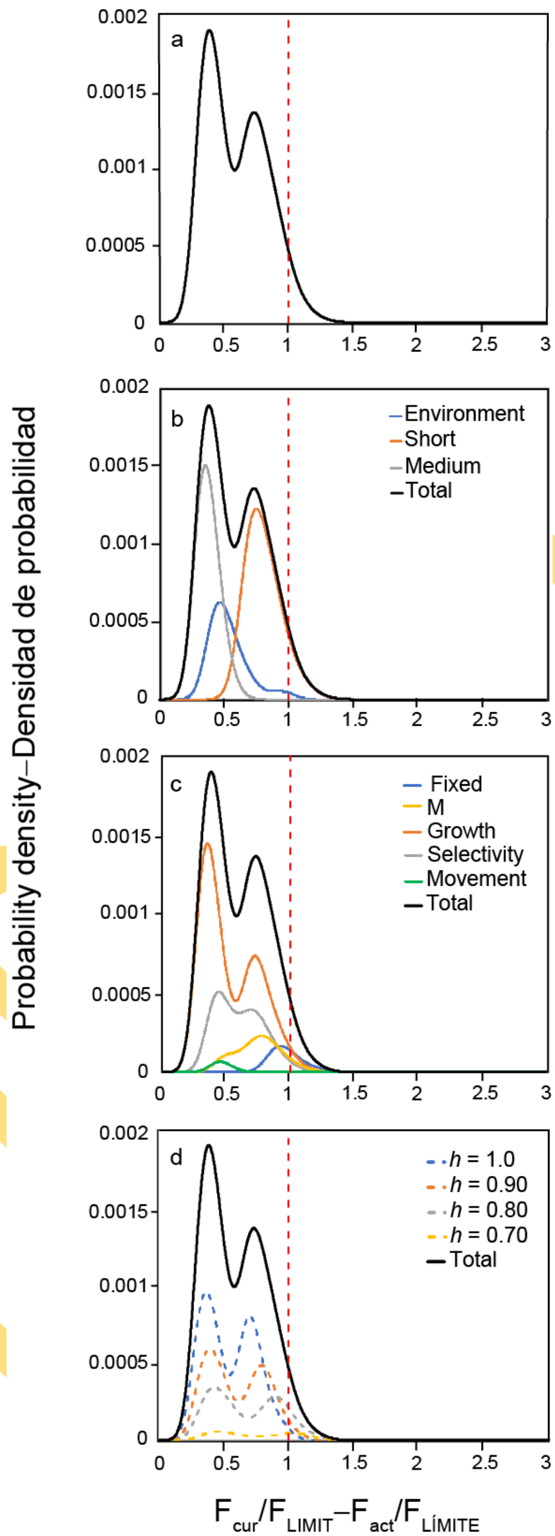

FIGURE 8. Bigeye probability density functions for F_{cur}/F_{limit} broken down into different components.
FIGURA 8. Funciones de densidad de probabilidad para $F_{act}/F_{LÍMITE}$ de patudo divididas en diferentes componentes.

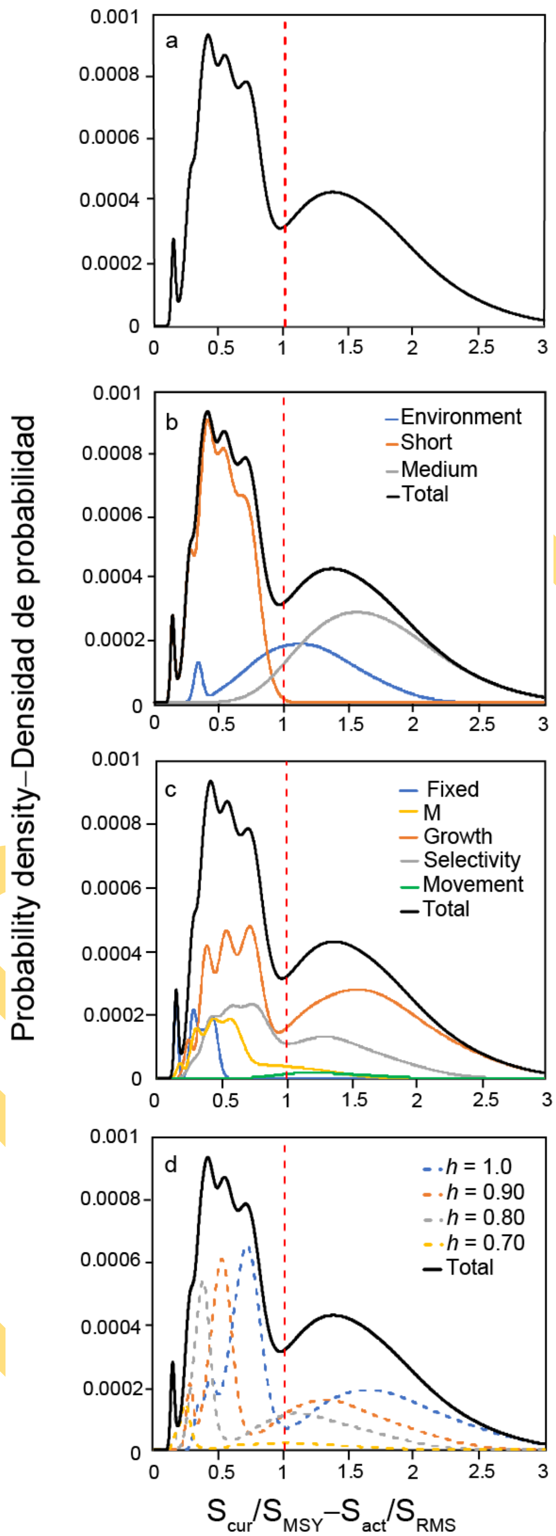

FIGURE 9. Bigeye probability density functions for S_{cur}/S_{MSY} broken down into different components. **FIGURA 9.** Funciones de densidad de probabilidad para S_{act}/S_{RMS} de patudo divididas en diferentes componentes.

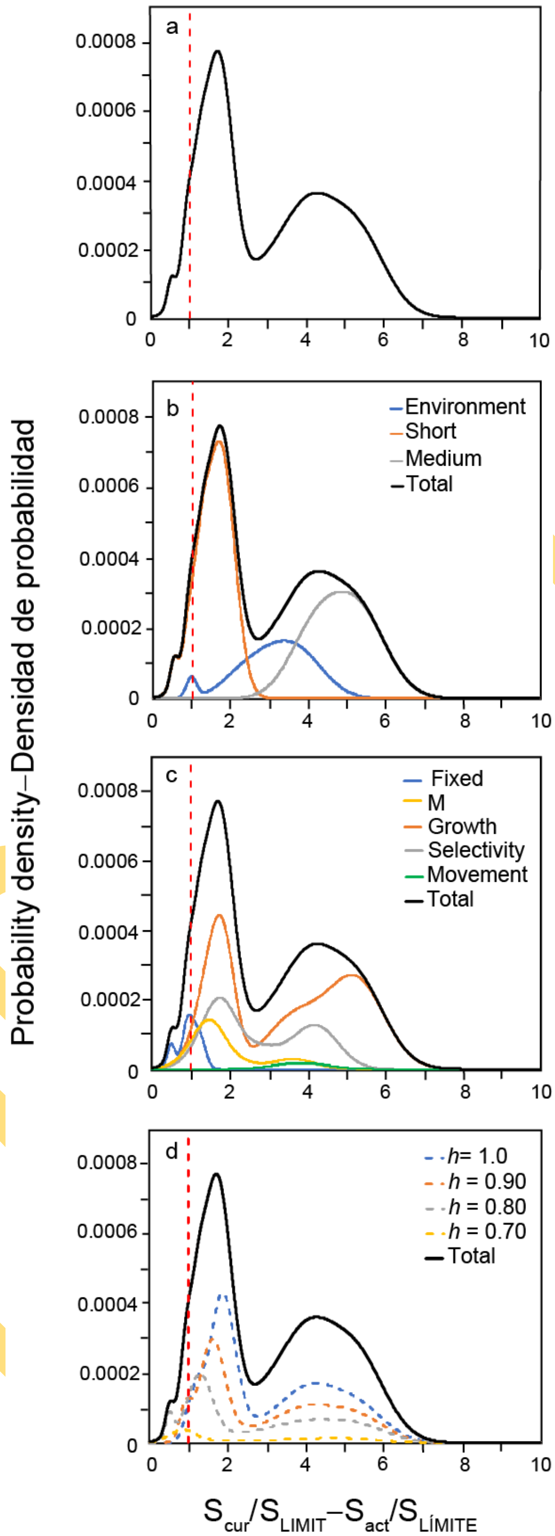

FIGURE 10. Bigeye probability density functions for S_{cur}/S_{limit} broken down into different components.
FIGURA 10. Funciones de densidad de probabilidad para $S_{act}/S_{LÍMITE}$ de patudo divididas en diferentes componentes.

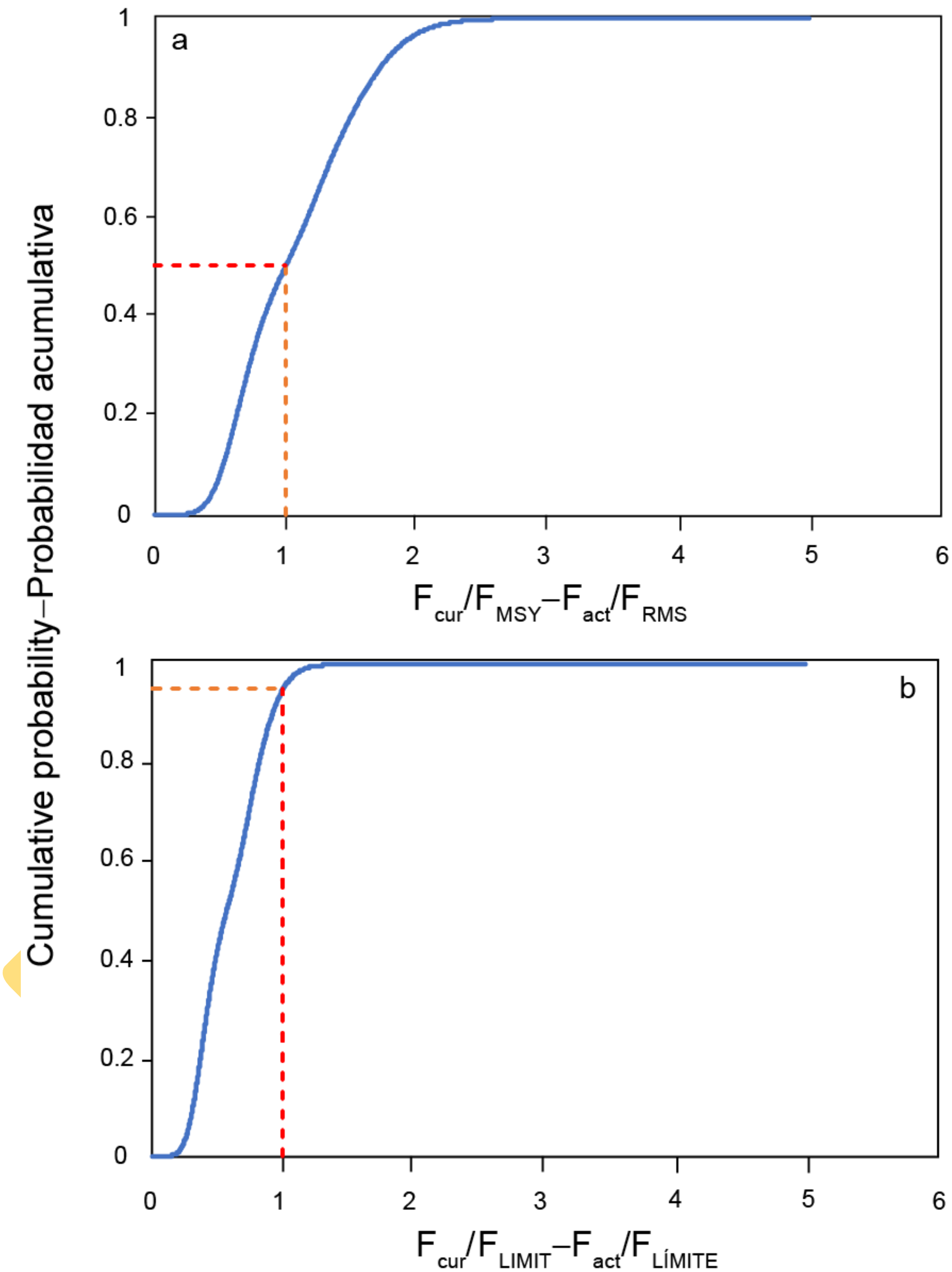

FIGURE 11. Bigeye cumulative distribution functions (CDFs) for: a) F_{cur}/F_{MSY}; b) F_{cu}/F_{LIMIT}.
FIGURA 11. Funciones de distribución acumulativa (FDA) de patudo para: a) F_{act}/F_{RMS}; b) F_{act} /$F_{LÍMITE}$.

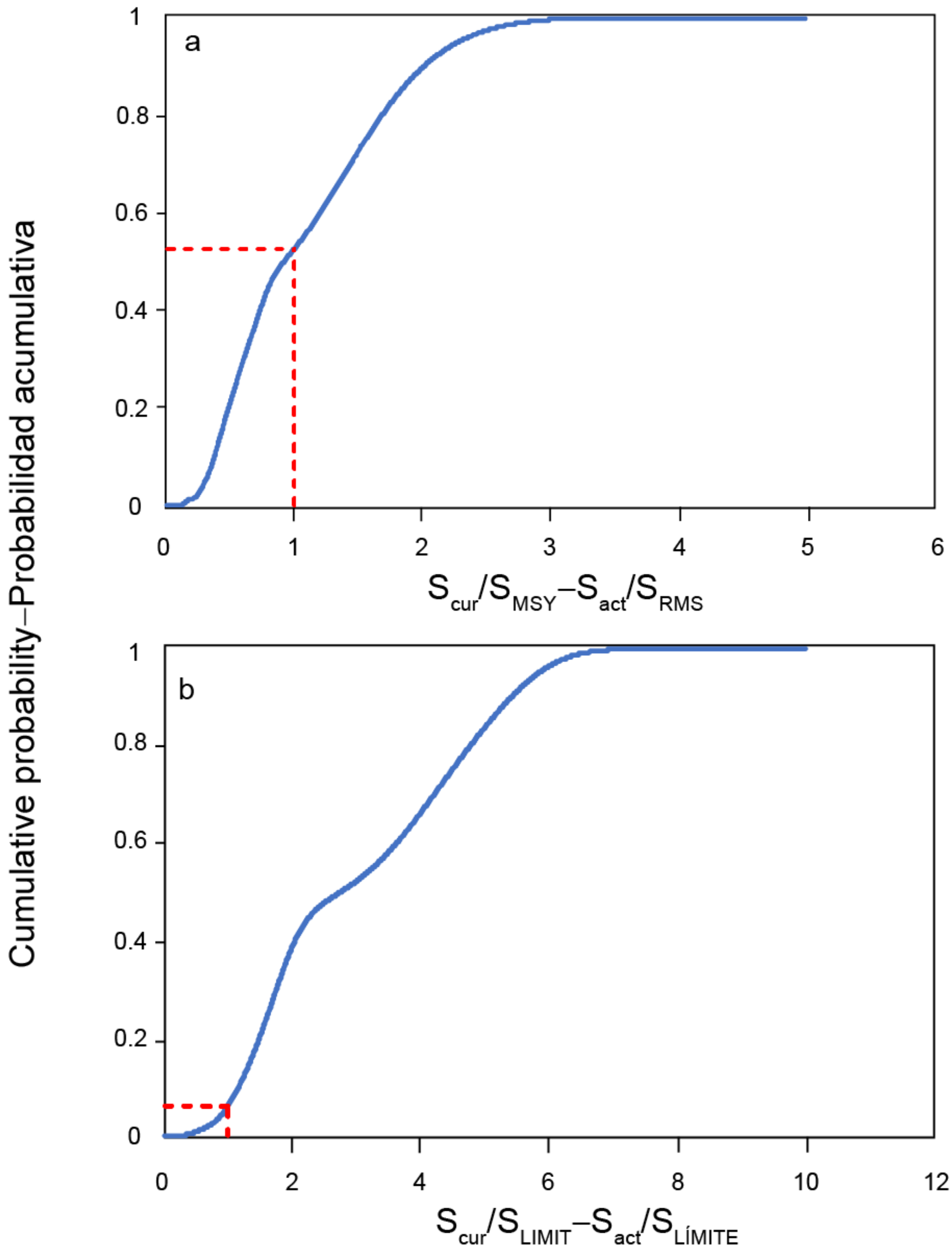

FIGURE 12. Bigeye cumulative distribution functions (CDFs) for: a) S_{cur}/S_{MSY}; b) S_{cur} /S_{LIMIT}.
FIGURA 12. Funciones de distribución acumulativa (FDA) de patudo para: a) S_{act}/S_{RMS}; b) S_{act} /$S_{LÍMITE}$.

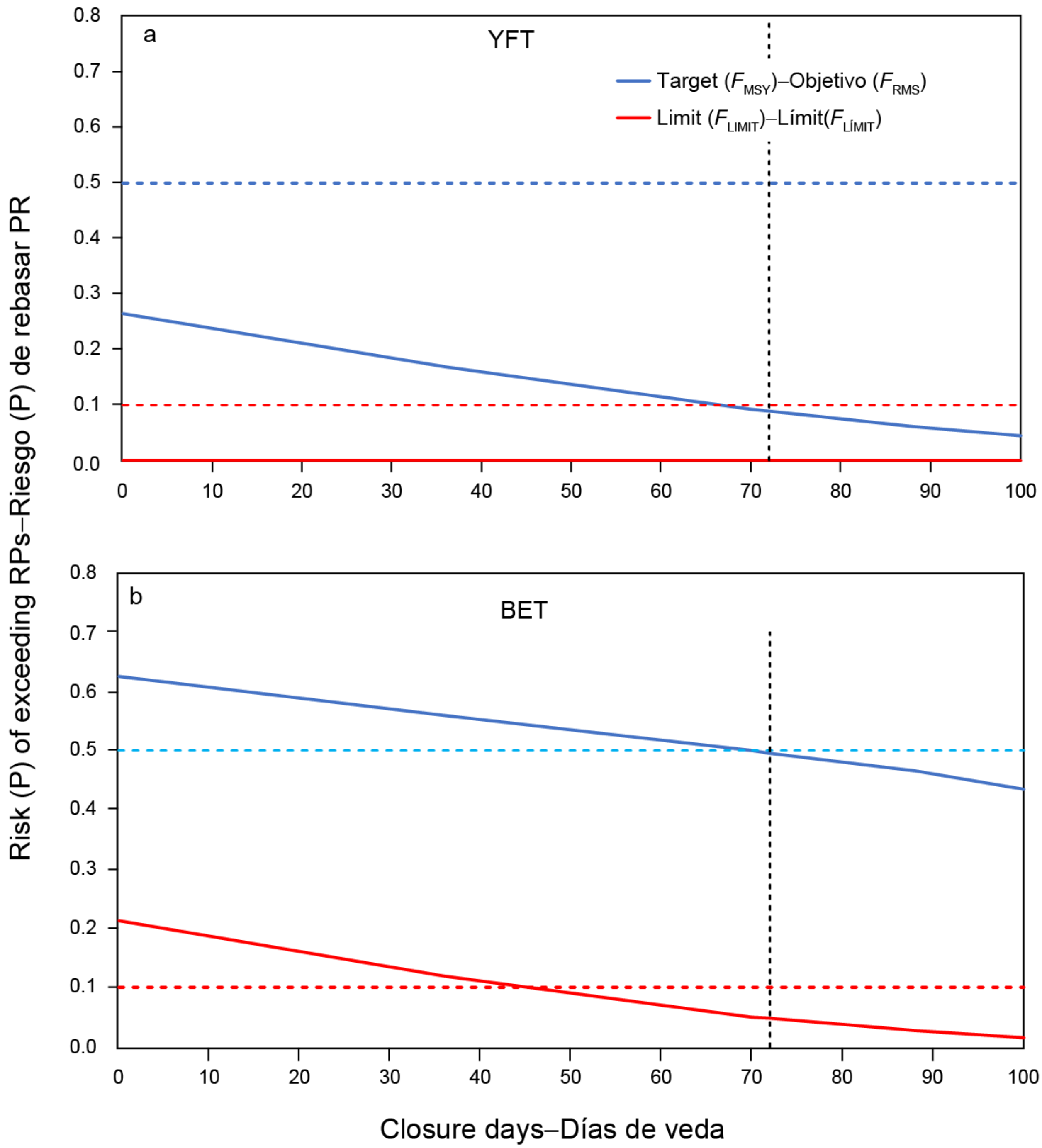

FIGURE 13. Risk curves showing the probability of exceeding the target and limit reference points (RPs) for different durations of the temporal closure. a) yellowfin and b) bigeye.

FIGURA 13. Curvas de riesgo que señalan la probabilidad de rebasar los puntos de referencia objetivo y límite de con diferentes duraciones de la veda temporal. a) aleta amarilla; b) patudo.

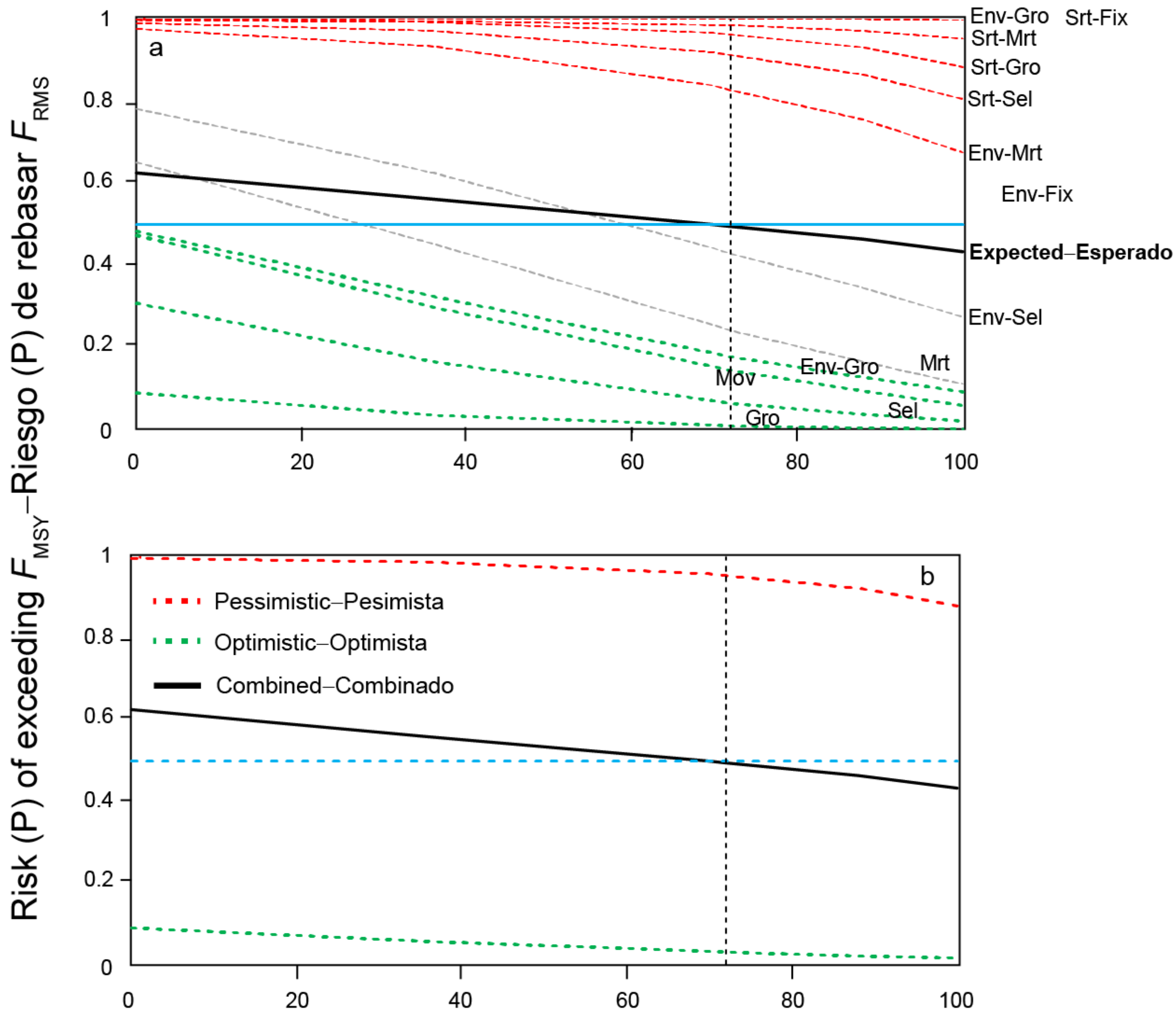

FIGURE 14. Bigeye risk curves showing the probability of exceeding the target RP for different durations of the temporal closure. a) individual models and b) combined by pessimistic and optimistic models resulting from the bimodal combined distribution for all models.

FIGURA 14. Curvas de riesgo para el patudo que señalan la probabilidad de rebasar el punto de referencia objetivo con diferentes duraciones de la veda temporal. a) modelos individuales; b) combinados por modelos pesimistas y optimistas que resultan de la distribución combinada bimodal de todos los modelos.

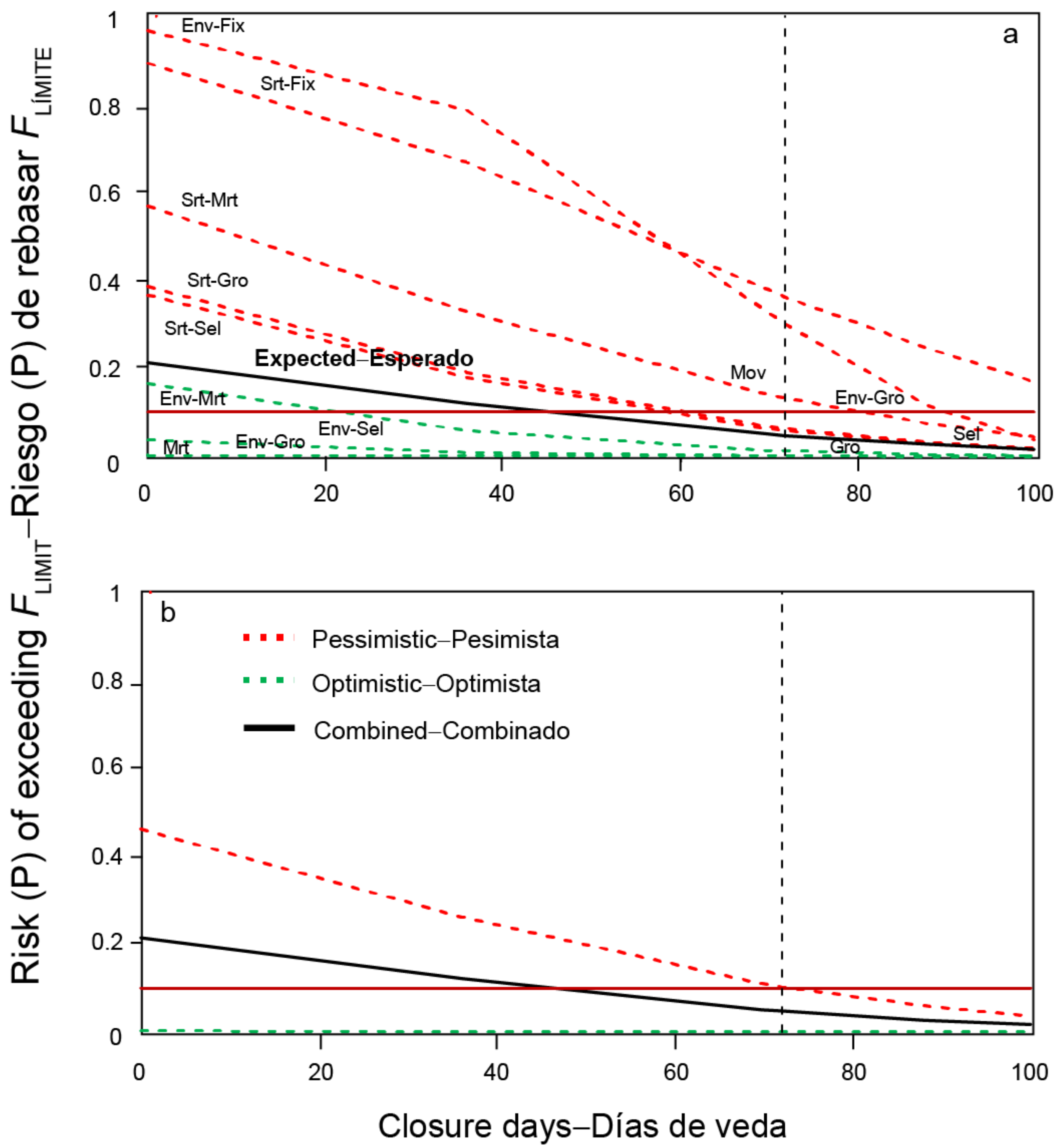

FIGURE 15. Bigeye risk curves showing the probability of exceeding the limit RP for different durations of the temporal closure. a) individual models and b) combined by pessimistic and optimistic models resulting from the bimodal combined distribution for all models.

FIGURA 15. Curvas de riesgo para el patudo que señalan la probabilidad de rebasar el punto de referencia límite con diferentes duraciones de la veda temporal. a) modelos individuales; b) combinados por modelos pesimistas y optimistas que resultan de la distribución combinada bimodal de todos los modelos.