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MOVING TOWARDS QUANTITATIVE ECOLOGICAL RISK ASSESSMENT FOR DATA-LIMITED TUNA FISHERY BYCATCH: APPLICATION OF "EASI-FISH" TO THE SPINETAIL DEVIL RAY (*MOBULA MOBULAR*) IN THE EASTERN PACIFIC OCEAN

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ABSTRACT

The IATTC staff recently developed a new spatially-explicit ecological risk assessment (ERA) approach—Ecological Assessment for the Sustainable Impacts of Fisheries (EASI-Fish)—to quantify the cumulative impacts of multiple fisheries on data-limited bycatch species in the EPO. The method is generally applied to a suite of impacted bycatch species, where a proxy of the instantaneous fishing mortality rate (*F*) is estimated for each species based on the 'volumetric overlap' of each fishery and each stock's distribution. *F* is then used in length-structured per-recruit models to assess the vulnerability of each species using conventional biological reference points (*e.g.* F_{MSY}, $SSB_{40\%}$). EASI-Fish is therefore, primarily used as a quantitative prioritization tool to allow fisheries managers to identify the most vulnerable species to which resources can be directed to either implement mitigation measures to remove the key risk(s) or subject the species to data collection programs to gather sufficient data to facilitate more traditional population assessments. However, EASI-Fish also has the capability of simulating hypothetical conservation and management measure (CMM) scenarios (e.g. spatial and/or temporal closures, gear modifications) that may mitigate fishery risks to a species, without incurring significant investment in costly data collection programs. This paper uses EASI-Fish to explore the changes in the vulnerability status of the spinetail devil ray (*Mobula mobular*)—a slow-growing species with low reproductive potential and a paucity of information on post-release mortality (PRM)—under 18 hypothetical CMM scenarios

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simulated for EPO purse-seine and longline tuna fisheries for 2016. CMMs involved various spatial and temporal closures of the EPO and 'hotspots', decreasing PRM, increasing the length at first capture and various combinations of these CMMs. The "status quo" scenario revealed that F_{2016} and the spawning stock biomass per recruit (SSB_{2016}) exceeded precautionary biological reference points ($F_{40\%}$ and $SSB_{40\%}$), classifying *M. mobular* as "most vulnerable". Increasing the duration and/or number of spatial closures significantly reduced the vulnerability of the species but was insufficient in changing its classification from "most vulnerable". Only 3 of the 18 scenarios resulted in the species being classified as "least vulnerable", which primarily involved reductions in PRM. This is fortuitous in that the development of best handling and release practices and the education of fishers is likely to be a far simpler, rapid and cost-effective CMM than the implementation of increased spatial and temporal closures and gear modifications that will likely result in substantial decreases in the catches of target species. However, given the current lack of reliable information on the PRM of *M. mobular*—and other mobulids—there is an urgent need for a tagging study to quantify the PRM of *M. mobular* from purse-seine and longline fisheries in the EPO.

INTRODUCTION

Over the past two decades there has been a significant shift in the fisheries management paradigm, from a focus on single species of economic importance, to ecosystem-based fisheries management (EBFM) that considers the broader ecological direct and indirect of fishing on non-target species, habitats, and the supporting ecosystem more broadly. The Inter-American Tropical Tuna Commission (IATTC) has formally adopted an ecosystem-based approach to the management of tuna fisheries in the eastern Pacific Ocean (EPO) through the Antigua Convention, in particular Article VII 1(f) "*adopt, as necessary, conservation and management measures and recommendations for species belonging to the same ecosystem and that are affected by fishing for, or dependent on or associated with, the fish stocks covered by this Convention…*".

Unfortunately, quantitatively demonstrating the fulfilment of ecological sustainability objectives is a significant challenge owing to the common paucity of reliable biological and catch information for the vast array of non-target species, especially those of little or no economic value. Therefore, assessing all impacted species using traditional stock assessment approaches is often both cost-prohibitive and impractical.

As many tuna fisheries establish or continue to develop bycatch monitoring programs to enable more formal population assessments of bycatch species to be undertaken in future, many of these fisheries have national and international obligations to report on their progress towards fulfilling various mandates. As a result, waiting several years for sufficient biological and catch data to be collected for bycatch species before beginning assessments may not be acceptable to some fishery stakeholders (Lack 2007) or the general public (Jacquet and Pauly 2007). There are several assessment frameworks that allow fisheries to assess ecological sustainability incrementally with increasingly sophisticated methods once required data become available. For example, the Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework developed by (Hobday *et al.* 2011) has been applied to all Australian Commonwealth fisheries, and more recently, other fisheries internationally.

The ERAEF approach assesses individual fisheries using a 3-tier system (Fig. 1). Level 1 is the starting point, especially for very data-poor fisheries, which involves simple qualitative methods based on 'expert' opinion, such as likelihood-consequence analysis (Fletcher 2005). Fisheries proceed to Level 2 where at least one taxon is found to be potentially vulnerable to overfishing, and the risk cannot be mitigated. Analyses undertaken at this level involve the use of semi-quantitative methods, such as the widely-used Productivity-Susceptibility Analysis (PSA) (Stobutzki *et al.* 2001). Again, if at least one taxon is found to be potentially vulnerable to overfishing, and the risk cannot be mitigated, the fishery is then subjected to a Level 3 assessment, which usually involves fully quantitative stock assessment. At Level 3, the species is generally subjected to similar conservation and management measures (CMMs) as might be developed for economically important target species, such as spatial and/or temporal closures or catch quotas.

In 2018, the IATTC developed a Strategic Science Plan (SSP) with an explicit goal to "*evaluate the ecological impacts of tuna fisheries"* and adopted the principles of the ERAEF framework by using best available evidence and methodologies to identify vulnerable species and prioritizing them for data collection, research and management. To attain this goal, in 2017 the IATTC staff fulfilled a second objective of the SSP to "*develop analytical tools to identify and prioritize species at risk*", by developing a flexible spatially-explicit quantitative ecological risk assessment approach—**E**cological **A**ssessment of **S**ustainable **I**mpacts of **Fish**eries (EASI-Fish)—specifically designed to quantify the cumulative impacts of multiple fisheries for data-limited bycatch species.

EPO tuna fisheries have been documented to interact with at least 117 taxa comprising teleosts, elasmobranchs, sea turtles, seabirds and marine mammals (Duffy *et al.* 2016). Some of these species are unavoidable bycatch and present significant conservation issues to be addressed by the IATTC, its Members, and CPCs. The mobulids (devil and manta rays) are a particularly vulnerable group of bycatch species in the EPO. Despite the low frequency of mobulid captures per set in the purse-seine fishery (Hall and Roman 2013; Lezama-Ochoa *et al.* 2019), their slow growth rates and low reproductive potential (Couturier *et al.* 2012; Dulvy *et al.* 2014) and lack of reliable information on their post-release mortality (PRM) presents a potentially significant conservation issue for mobulids in the EPO, where 31,328 sets were made in 2017 (IATTC, 2018). The species also faces similar threats by tuna fisheries throughout its worldwide distribution, including the western and central Pacific Ocean, and the Atlantic and Indian Oceans (Couturier *et al.* 2012).

Some international conservation instruments have been developed for mobulids, and particularly for purse-seine fisheries by some tuna Regional Fisheries Management Organizations (tRMFO). For example, in 2014 all mobulids were added to Appendices I and II of the Convention of Migratory Species (CMS) (CMS, 2015) and in 2016 all species of *Mobula* were listed under Appendix II of the Convention on International Trade in Endangered Species (CITES) (CITES, 2016). These measures were required to meet regional conservation goals as well as curb international trade of mobulid products (*e.g*. gill plates). In the EPO, IATTC Resolution C-15-04 entered into force in 2015, prohibiting the retention, transshipment, landing, storing, sell or offering the sale of any part or whole carcass of mobulid rays by all vessels, with the exception of small scale artisanal vessels. Additionally, the resolution stipulates improved handling practices to improve the probability of post-release survival through the prohibition of i) lifting the animals by the gill slits or spiracles, and ii) punching holes through their pectoral fins. This resolution has led to the development of new mitigation approaches aimed to enhance post-release survival of mobulids through gear modifications and handling and releasing practices (Poisson *et al.* 2014; Lawson *et al.* 2017). However, for some mobulids that can reach 310 cm disc width (DW) (Paulin *et al.* 1982) and have a dangerous tail spine, these mitigation approaches can be difficult for fishers to implement in practice.

The spinetail devil ray, *Mobula mobular* (Müller and Henle, 1841)—formerly *Mobula japanica* until being recently taxonomically reviewed (White *et al*. 2017)—is distributed circumglobally in tropical and subtropical waters and can be found in both coastal and oceanic pelagic waters (Croll *et al*., 2012; Francis and Jones, 2016). The species has a maximum recorded age (t_{max}) of 14 years (Cuevas-Zimbrón *et al.* 2013), exhibits low fecundity (1 pup every 2 years), and females reach maturity at 5–6 years of age (López 2009).

M. mobular is one of the most frequently caught mobulid species in the purse-seine fishery in the EPO (Hall and Roman 2013; Lezama-Ochoa *et al.* 2019). As a result of the species' low productivity and high susceptibility to capture in industrialized fisheries, it is listed as "Near Threatened" globally by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (www.iucnredlist.org).

Recent research by the IATTC staff in the EPO has described the spatial and temporal distribution of interactions and catch rates of bycatch species, including mobulids (Hall and Roman 2013; Lezama-Ochoa *et al.* 2017; Lezama-Ochoa *et al.* 2019), and modelling of their habitat specificity (Lezama-Ochoa *et al.* In Review). There have been three projects undertaken by IATTC staff assessing the relative vulnerability of tuna bycatch species—including mobulids—in the EPO using ecological risk assessment (ERA). Duffy *et al.* (In Review) and Griffiths *et al.* (2017) used PSA to assess the Class 6 purse-seine fishery and the 'industrial' longline fishery, respectively, while Griffiths *et al.* (2018) assessed the cumulative impacts of both aforementioned fisheries using EASI-Fish. These assessments determined that the EPO population of *M. mobular* is highly vulnerable to becoming unsustainable under the fishing conditions for the years assessed. However, there has been no attempt to use ERA to explore potential CMMs that may reduce the vulnerability of mobulids to fishing in the EPO.

Therefore, the aims of this paper were to explore the influence of various hypothetical CMMs on the vulnerability status of *M. mobular* as determined by the EASI-Fish approach. In particular, we sought to explore the impacts of: i) increasing the existing EPO-wide fishing closure, ii) decreasing post-release mortality (PRM) of captured rays, iii) increasing the length at first capture, iv) temporal closure of *M. mobular* 'hotspots', v) decreasing PRM on specific size classes of rays, and vi) using a combination of short temporal closures of 'hotspots' simultaneously with decreasing PRM due to improved handling practices. The overarching goal of the paper was to identify potentially effective management and/or handling strategies that may be rapidly, practically and cost-effectively implemented—individually or in unison—to improve the sustainability of the *M. mobular* population in the EPO, while minimizing the disruption of existing tuna fishing operations.

1. METHODS

1.1. Spatial extent of the assessment region and definition of included fisheries

The present assessment of *M. mobular* incorporated the entire EPO (defined as the region from the coast of the Americas to 150°W between 50°S and 50°N) for 2016 and includes the purse-seine fishery and the fishery by large-scale longline tuna fishing vessels (LSTLFVs) (herein called the "longline fishery").

The analyses presented in this paper draw upon data obtained from vessel logbooks or collected by on-board scientific observers, or submitted to the IATTC by its Members under Resolutions C-03-05 and C-11-08 and described in Document SAC-08-07b. Specifically, the longline fishery data were derived from vessels >24 m length overall (LOA) included in the IATTC Regional Vessel Register that are authorized to fish for tuna and tuna-like species, which provide monthly reports of catch and fishing effort at a resolution of at least 5°x5°, and from scientific observer programs that monitor at least 5% of the fishing effort by longline vessels over 20 m LOA under Resolution C-11-08.

The purse-seine fishery data were collected by the on-board observer program of the Agreement on the International Dolphin Conservation Program (AIDCP) between 2016, which covers 100% of the fishing effort by Class-6 (carrying capacity >363 t) purse-seine vessels. This fishery was disaggregated into three separate fisheries based on set type: i) sets associated with floating objects (OBJ), ii) sets associated with dolphins (DEL), and ii) sets on unassociated schools of tuna (NOA).

1.2. Assessing susceptibility as a proxy for instantaneous fishing mortality (*F*)

A quantitative evaluation of the vulnerability of *M. mobular* under various hypothetical management scenarios was made using the EASI-Fish ecological risk assessment approach detailed in Griffiths *et al.* (2018). In brief, EASI-Fish is comprised of separate susceptibility and productivity components. The susceptibility component in EASI-Fish is used to approximate the instantaneous fishing mortality rate (*F*) that is compared to biological reference points (BRPs) used in the productivity component, specifically length-structured yield and biomass per-recruit models.

EASI-Fish estimates the proportion of a length class (*j*) of a species' population that is susceptible to incurring mortality by fishery *x* (S_{xj}) in a given year, and is represented as:

$$S_{xj} = \frac{G_x}{G}\left(D_x A_{xj} N_{xj} C_{xj} P_{xj}\right) \quad \text{(Eq. 1)}$$

where *G* is the total number of grid cells occupied by *M. mobular* and G_x is the number of occupied grid cells containing at least one unit of fishing effort by fishery *x* during 2016.

In this study, *G* was estimated using relative environmental suitability (RES) models developed for *M. mobular* at 0.5° x 0.5° resolution based on presence-only data and environmental variables (depth, sea surface temperature, salinity, and primary productivity) using the method of Kaschner *et al.* (2006) (Fig. 2). Such maps are publicly available and free of charge (www.aquamaps.org), customizable, and the presence (source and predicted) and environmental data available for download should the user wish to use alternative habitat models (*e.g.,* generalized additive models, maximum entropy models). It should be noted that a range of habitat models are currently in development by Lezama-Ochoa *et al.* (In Review) for *M. mobular* in the EPO.

Although a knife-edge probability-of-occupancy (ψ) threshold (*e.g.,* 0.7) may be used for each cell to define distribution of each species, the predicted distribution can differ substantially depending on the threshold value used. Since the defined species distribution can influence the proportion of the population exposed to fishing, we accounted for this uncertainty by running the EASI-Fish model using distribution maps based on ψ values of 0.6-0.8 in 0.1 increments, with a preferred ψ value of 0.7 determined after modelled distributions were reviewed by experts and cross referenced with catch data (see Fig. 3).

Fishing effort for each fishery in 2016 was overlaid on the RES-derived habitat distribution map—for each ψ value— to calculate G_x. The percentage overlap of each fishery was calculated by dividing G_x by *G*. Effort data for purse-seine vessels were used at 0.5°x0.5° resolution. However, longline data were reported at 5°x5° resolution, so the longline grid conservatively assumes that there was at least one unit of effort in each occupied 0.5°x0.5° cell contained within a 5°x5° grid cell that contained effort.

The first four parameters in the parentheses of Equation 1 (D_x, A_{xj}, N_{xj}, and C_{xj}) comprise what is generically regarded as "selectivity" in fisheries stock assessments, which combines—often implicitly— "population availability" (the relative probability that a fish of length class *j* is located in the area and time where the fishery is operating) and "contact selectivity" (the relative probability that a fish of length class *j* will be retained once it comes in contact with the gear) (Millar and Fryer 1999). Because selectivity curves for each fishery were not available for *M. mobular*, it was considered important to disaggregate selectivity components as far as practicable and described hereafter.

Fishing season duration (D_x) is the proportion of the population that is available to fishery *x* given the proportion of a year when fishing is permitted, expressed as the number of fishing days divided by 365. In the EPO, Resolution C-13-01 mandated a 62-day closure of the purse-seine fishery in 2016.

Seasonal availability (A_{xj}) is the proportion of length class *j* that is available to capture by fishery *x*, given that some species undertake extensive intra-annual migrations outside the boundaries of the fishery, where they are unavailable for fishery interactions. Given the lack of tagging data for *M. mobular* to indicate seasonal movement outside of the fishery, a precautionary value of 1.0 was used for length class *j* in fishery *x*.

Encounterability (N_{xj}) is the proportion of length class *j* that may potentially encounter the gear used by fishery *x* based on the species' distribution in the water column relative to the normal fishing depth range of the gear. In the EPO, we defined the effective fishing depth range for all purse-seine set types as 0–200 m (Hall and Roman 2013) and 0–300 m for 'deep sets' by longlines (see Griffiths *et al.* 2017). Minimum, maximum, and preferred depths of each species were defined using the results of electronic tagging studies of *M. mobular* (Canese *et al.* 2011; Croll *et al.* 2012; Francis and Jones 2017).

Contact selectivity (C_{xj}) describes the proportion of length class *j* that is retained once it encounters the gear used by fishery *x*. In the absence of reliable gear selectivity curves for *M. mobular*, precautionary knife-edge selectivity (C_{xj}=1.0) was assumed from the age at birth, being 49.8 cm DW (White *et al.* 2006).

IATTC Resolution C-15-04 mandates the release of Mobulid rays in all fisheries, except those considered artisanal. Therefore, fishing mortality would be overestimated unless the component of the catch that survives mandatory release is accounted for. This is introduced in the model as post-release mortality (PRM) (P_{xj}), the proportion of length class *j* that is caught by fishery *x* and dies before, during, or soon after release. Post-release mortality data was not available for *M. mobular* in the EPO, so a precautionary value of 1.0 for fishery *x* was used as the status quo situation in 2016.

1.3. Productivity

Following the estimation of the overall susceptibility of length class *j* to incurring mortality from fishery *x* (S_{xj}), a proxy for the instantaneous fishing mortality rate in 2016 (F_{2016}) for *M. mobular* caught by all fisheries in 2016 was estimated as:

$$F_{2016} = -ln\left[1 - \sum_{x=1} q_x E_x \left(\frac{\sum_{j=1}^{n} S_{xj}}{n}\right)\right] \quad \text{(Eq. 2)}$$

Here, *n* is the number of length classes (in 5 cm increments) extending to the maximum recorded length (L_{max}) of *M. mobular*, fishing effort (E_x) is the total effort, scaled to a maximum of 1, of fishery *x* applied in area G_x in 2016, while the catchability coefficient (q_x) is the fraction of the stock that is caught by one unit of effort (E_x) in fishery *x*. In many data-limited fisheries *q* and *E* will not be known, so a precautionary approach is to assume both are equal to 1, all fish in a grid cell are caught where all other susceptibility parameters are fully realized.

F_{2016} was then compared with values for *F* for the selected BRPs derived from the per-recruit models (described below). However, it needs to be emphasized that, because of the assumptions and likely uncertainty in the parameters used in deriving the F_{2016} estimate, it should only be considered a proxy of *F* (and probably a conservatively high one). It is for this reason that the results from EASI-Fish should not be used to definitively define the status of a species' population, *sensu* a stock assessment. EASI-Fish was designed to be a quantitative prioritization tool to identify the most vulnerable species that should then be considered for data collection, further detailed analysis, research and management. In this study, the results provide a relative measure of the efficacy of the various management scenarios that were simulated.

1.4. Characterizing species productivity using per-recruit models

Y/R was used to characterise the biological dynamics of *M. mobular* using the generic Ricker (1975) model, which Chen and Gordon (1997) adapted for lengths as:

$$\frac{Y}{R} = \sum_{j=1}^{n} \frac{W_j b_j F}{b_j F + M}\left[1 - e^{-(b_j F + M)\Delta T_j}\right] e^{-\sum_{k=1}^{j-1}(b_k F + M)\Delta T_k} \quad \text{(Eq. 3)}$$

Here, new recruits and fully-recruited length classes are denoted by the subscripts *j* and *k*, respectively. W_j is the mean weight of a fish in length class *j*, while selectivity (b_j) is the proportion of the population in length class *j* that is caught across all fisheries, represented as:

$$b_j = \sum_{x=1}^{n} S_{xj} \quad \text{(Eq. 4)}$$

In the absence of age or length-specific estimates of the instantaneous natural mortality rate (*M*), *M* was assumed to be constant across all length classes. *F* was disaggregated into increments of 0.01, from zero to $L_{\max}$ (310 cm DW) (Paulin *et al.* 1982). The parameter Δ*T* represents the time taken for a fish to grow from one length class to the next, represented as:

$$\Delta T_j = \frac{1}{K} ln \frac{L_\infty - L_j}{L_\infty - L_j - d_j} \quad \text{(Eq. 5)}$$

where *K* and L_∞ are parameters from the von Bertalanffy growth function (Table 1), and *d* is the width of the length class, calculated as L_{j+1} - L_j.

The spawning stock biomass-per-recruit (SSB/R) model of (Quinn and Deriso 1999) is complementary to Y/R, and can be modified to suit the analysis of length rather than age classes and be represented as:

$$\frac{SSB}{R} = \sum_{j=1}^{n} W_j m_j \prod_{x=r}^{j-1} e^{-(b_j F + M)} \quad \text{(Eq. 6)}$$

where W_j is the mean weight of *M. mobular* in length class *j* (L_j) taken from the length-weight relationship (Table 5), m_j is the proportion of mature females at the mean length of length class *j*, and the product operator describes the number of fish surviving from the length at recruitment (L_r) to L_j. Because the number of spawners was not known, and the model estimates the relative SSB/R, the initial number of spawners was set to a value of one. The value for m_j was taken from a female maturity ogive for *M. mobular* caught in the Indo-Pacific region (White *et al.* 2006), represented in the logistic form:

$$m_j = \frac{1}{1 + e^{\left(-r\left(L_j - L_{50}\right)\right)}} \quad \text{(Eq. 7)}$$

where L_j is the mean length of a fish in length class *j*, L_{50} is the length at which 50% of the population is mature, and *r* is the curvature parameter.

1.5. Estimating natural mortality (*M*)

The instantaneous natural mortality rate (*M*) is difficult to estimate directly, and so it is commonplace to run stock assessment models using a range of *M* values derived from multiple estimators based on life history invariants. Therefore, *M* values were derived from five estimators recommended by Kenchington (2014) and Then *et al.* (2015) (Table 1). Priority was given to values estimated by $t_{\max}$-based estimators ($\text{Hoenig}_{\text{nls}}$ and $\text{Hoenig}_{t\max}$) as recommended for elasmobranchs by Kenchington (2014), followed by *K*-based estimators that rely on von Bertalanffy growth parameters (Jensen, $\text{Pauly}_{\text{nls}}$, and $\text{Pauly}_{\text{LKT}}$). A mean annual water temperature of 25˚C for the EPO (Fiedler and Talley 2006) was used for the relevant estimators (Table 1).

1.6. Biological Reference Points (BRP)

Depending on the life history of a species, various BRPs have been used in stock assessment models to assess the status of a population relative to an estimated *F* value for a particular period or year. EASI-Fish uses a similar approach, but it is important to reiterate that its BRPs are used to quantify the relative vulnerability of a population to decline, rather than to determine stock status.

Although the *F* value at which yield is maximized (F_{MAX}) is often used as the BRP in Y/R models, F_{MAX} can be overly optimistic, since the stock-recruitment relationship in Y/R models is assumed to be time-invariant and recruitment independent of stock size—equivalent to a steepness (*h*) value of 1 (Gabriel and Mace 1999). Species such as elasmobranchs and marine mammals often have a strong stock-recruitment relationship (*i.e*. h<1) due to their low reproductive capacity and slow growth rate. Unfortunately, the stock-recruitment relationship is difficult to estimate (Lee *et al.* 2012), and hence taxonomic group-based proxies are often used in stock assessments as a result. For example, the Pacific Management Council used $F_{40\%}$ as a proxy for *Sebastes* species, and $F_{35\%}$ for all other stocks (Ralston 2002).

In a comparison of BRPs used in EASI-Fish to assess bycatch species with diverse life histories, Griffiths *et al.* (In Press) suggested that $F_{40\%}$ is most precautionary for elasmobranchs and is therefore adopted here to assess *M. mobular* in the EPO. Explicitly, $F_{40\%}$ is the *F* value corresponding to 40% of the spawning potential ratio (SPR), which is the SSB/R at the F_{2016} value divided by the SSB/R if F=0. The corresponding $SSB_{40\%}$ BRP is the SSB/R value at $F_{40\%}$.

The vulnerability of *M. mobular* in each hypothetical management scenario was determined using F_{2016} and the corresponding SSB/R value (SSB_{2016}) relative to the $F_{40\%}$ and $SSB_{40\%}$ values and displayed on a 4-quadrant phase plot (Fig. 4). The vulnerability definitions of these quadrants are: i) “Least vulnerable” (green; $F_{2016}/F_{40\%}$ <1 and $SSB_{2016}/SSB_{40\%}$ >1), ii) “Increasingly vulnerable” (orange; $F_{2016}/F_{40\%}$ >1 and $SSB_{2016}/SSB_{40\%}$ >1), iii) “Most vulnerable” (red; $F_{2016}/F_{40\%}$ >1 and $SSB_{2016}/SSB_{40\%}$ <1), and iv) “Decreasingly vulnerable” (yellow; $F_{2016}/F_{40\%}$ <1 and $SSB_{2016}/SSB_{40\%}$ <1).

1.7. Implementation of the model

The model was built in Microsoft Excel, with add-ins to perform Monte Carlo simulations to generate uncertainty estimates for specific model parameters given specified prior distributions (*e.g*., normal, triangular, or uniform). Once the parameter distributions were defined, the Y/R and SBB/R models were run 10,000 times using Monte Carlo simulations, each time using a random sample from the distribution prior defined for each parameter. The mean, standard error (SE), and 95% confidence intervals (95% CI) were derived for the BRPs F_{2016}, $F_{40\%}$, SSB_{2016}, and $SSB_{40\%}$.

1.8. Qualitative scoring of parameter data source quality

Although parameter uncertainty is incorporated into the EASI-Fish model, this does not necessarily indicate the precision, reliability, or relevance of the value to the fishery in which it is applied. A parameter quality index developed by Griffiths *et al.* (2018) was used to score the relevance of the data to *M. mobular* for the EPO by using a matrix of data quality by ocean basin and taxonomic resolution (Table 2). The parameter quality scores are represented in a radar plot, aiding in the interpretation of relative data quality for each model parameter.

1.9. Definition of hypothetical scenarios aiming to reduce vulnerability status of *M. mobular*

The flexibility of EASI-Fish allows specific spatial and temporal CMMs for a species in the EPO to be explored—in isolation or in concert—as well as the inclusion of length-specific changes in parameters such as gear selectivity and PRM. A total of 18 hypothetical management scenarios (Table 2) were implemented under five CMM categories detailed below:

1) **EPO-wide temporal closure**—no closure, 62 days (2011–2016; Resolutions C-11-01 and C-13-01) and 72 days (2018-2020; Resolution C-17-01), or 100 days,
2) **Changes in handling practices of *M. mobular***—current and additional handling practices promoted by the IATTC and its Members and CPCs were assumed to result in post-release

mortality (PRM) of 100%, 90%, 50%, or 10%,

3) **Increase in the length at first capture (L_c)**—as a result of hypothetical changes in gear configuration and selectivity, it was assumed L_c would increase from the length at birth (50 cm DW) to 90 cm, or 150 cm,
4) **Temporary closure of 'hotspots'**—Three mobulid 'hotspots' were identified (see Fig. 3) and defined as: 1) an expansion of the existing "corralito" spatial closure (4°N–5°S, 96°–110°W) to 4°N-5°S, 92°-110°W, 2) the "Costa Rica Dome", 4°N-11°N, 86°-98°W, and 3) the "Humboldt Convergence Zone", 2°-10°S, 79°-84°W. Simultaneous closure of the three hotspots were implemented for periods of 0, 30, 60, 90, or 180 days,
5) **Size-specific differences in PRM**—the assumed—and precautionary—value of 100% for PRM of all length classes was decreased to 75% for fish <70 cm or 200 cm DW to account for the possibility of some handling practices having greater efficacy than other,
6) **A combination of a 30-day closure of the three identified 'hotspots' with PRM** of 100%, 90%, 50%, or 10%.

For each category, specific scenario values were compared to the "status quo" fishery situation for 2016, which was an EPO-wide closure of 62 days, a 30-day closure of the existing "corralito", a length at first capture of 50 cm DW (equal to the average length at birth; White *et al.* 2006), and an assumed PRM of 100%, given the absence of PRM estimates for *M. mobular* in the EPO.

2. RESULTS

2.1. Estimates of susceptibility and fishing mortality (*F*)

The value for each susceptibility parameter contributing to the overall susceptibility (S_{xj}) estimate in EASI-Fish and a description of its derivation is given in Table 4. For the status quo scenario, the horizontal overlap of the longline fishery with the distribution of *M. mobular* was low (12%), mainly due to the fishery operating further to the west and south of the main population distribution of the species (Fig. 2). With respect the purse-seine fishery, the proportion of population overlap was low for NOA (9%), but highest for OBJ (15%) and DEL (29%) sets.

The fishing season duration afforded no protection from the longline fishery that fishes year-round (D_x =1.0), but each purse-seine fishery fished for 83% of the year due to the 62-day EPO-wide closure and the 30-day closure of the "corralito" area, which coincides with one of the 'hotspots' for *M. mobular* catches (Fig. 3).

With a lack of reliable long term tagging data for *M. mobular* in the EPO, it was assumed that the species was available year-round (A_{xj}=1.0) in the areas where effort was recorded for each fishery.

Encounterability was high (E_{xj}=1.0) for all fisheries since they each fish from the surface to depths beyond the typical depths occupied by *M. mobular*, as determined from electronic tagging studies.

Contact selectivity was highest for the three purse-seine fisheries (C_{xj}=0.83) due to the surface orientation and the small mesh of the gear relative to the size of *M. mobular*. Selectivity was lowest for the longline fishery (0.33), which is both a result of the depth of hooks used in "deep sets", and the use of fish or squid baits that do not comprise a high proportion of the natural diets of mobulids (Notarbartolo-di-Sciara 1988; Sampson *et al.* 2010).

PRM was assumed to be 100% for all fisheries in the absence of reliable tagging data to quantify PRM.

Under the status quo scenario in 2016, DEL sets imposed the highest instantaneous fishing mortality (F=0.24 yr^{-1}) on *M. mobular*, with OBJ sets and the longline fishery contributing 0.12 and 0.11 yr^{-1}, respectively, whilst the lowest fishing mortality was from NOA sets (0.07 yr^{-1}).

2.2. Vulnerability status of *M. mobular* in the EPO

The biological parameter values (and their sources) used in empirical equations and the per-recruit models for *M. mobular* are shown Table 5, while EASI-Fish estimates for F_{2016} and SSB_{2016} and the $F_{40\%}$ and $SSB_{40\%}$ BRPs are provided in Table 6.

Under the status quo scenario characterizing the fishery in 2016, F_{2016} and SSB_{2016} exceeded the $F_{40\%}$ and $SSB_{40\%}$ BRPs, resulting in the classification of *M. mobular* as “most vulnerable” (Fig. 5; Table 6).

Scenarios involving EPO-wide closure of the purse-seine fishery showed that having no closure resulted in the highest vulnerability value of any of the 18 scenarios, indicating that some level of closure has a positive effect on the vulnerability status of *M. mobular*. Increasing the duration of the EPO closure to the 2019 level of 72 days and increasing to 100 days reduced the vulnerability of *M. mobular*, but not to the extent where the species’ classification would be changed from “most vulnerable” (Fig. 5a).

Changing handling practices to reduce PRM resulted in some of the largest improvements in vulnerability status compared to the status quo scenario. However, only the scenario where PRM was 10% resulted in a change in vulnerability status from “most vulnerable” to “least vulnerable” (Fig. 5b).

Increasing the length at first capture to 90 cm or 150 cm DW both resulted in decreased vulnerability, but the classification of *M. mobular* remained as “most vulnerable” for these two scenarios (Fig. 5c).

The category of scenarios involving a combination of CMMs—reducing PRM to 75% of fish <70 cm or >200 cm DW—showed the smallest reductions in vulnerability of all 18 scenarios, with the species remaining in the “most vulnerable” category (Fig. 5d).

The second category of scenarios that also involved a combination of CMMs—reducing PRM coupled with a 30-day closure of ‘hotspots’—resulted in large reductions in vulnerability. However, the only scenario where the species classification changed to “least vulnerable” was using a PRM of 10% combined with the 30-day hotspot closure (Fig. 5e).

Of the 18 hypothetical CMM scenarios, only three resulted in the species moving from being classified as “most vulnerable” to “least vulnerable” (Table 6).

The radar plot in Figure 6 shows that data used for *M. mobular* had reasonably high reliability scores of 6 or more for each parameter and can therefore be regarded as a legitimate “most vulnerable” species. The lowest data scores were for the length-weight relationship (6) (used to convert lengths to biomass in the Y/R models), reproductive parameters (8) and natural mortality (7). Together the uncertainty in these parameters may have overestimated the true vulnerability of this species, although the relative differences in vulnerability estimates between scenarios would have been unbiased.

3. DISCUSSION

Ecological risk assessment (ERA) has been widely used in fisheries as a rapid and cost-effective means by which fisheries managers can identify species most vulnerable to fishing impacts and take steps to mitigate identified risks, or collect further information to facilitate more formal stock assessment (Hobday *et al.* 2011). There have been at least three ERAs undertaken in the EPO (Griffiths *et al.* 2017; Griffiths *et al.* 2018; Duffy *et al.* In Review), each indicating that elasmobranchs, including *M. mobular*, are among the most vulnerable species in the diverse suite of bycatch impacted by tuna fisheries. However, this paper has provided a demonstration of the utility of the EASI-Fish approach to quantify the cumulative impacts of multiple tuna fisheries on a data-limited bycatch species under various hypothetical CMMs. The advantage of using the EASI-Fish approach over other ERA methods is that various measures—that can be implemented individually or in unison—may be considered for the EPO to mitigate the risk of tuna fishing activities on the long-term sustainability of *M. mobular*, rather than investing significant resources into species-specific programs in order to collect specific data to undertake a fully integrated stock assessment, which may not be required if more practical and effective measures can be found.

3.1. Spatial and temporal closures

There are various CMMs used in fisheries to reduce the fishing impacts on target species, depending on the status of the stock. For example, if a stock assessment for a species indicates that overfishing is occurring (i.e. growth overfishing), CMMs that may be reasonably simple to implement and enforce may be changing gear configurations to change selectivity patterns, such as increasing the mesh size of nets or hook size used on longlines to reduce the capture of smaller size—and presumably younger—classes of fish (King 2007). Spatial and/or temporal closures are also a common means by which fishing mortality can be reduced if particular areas and periods can be identified where small size classes of fish are abundant and susceptible to capture.

A good example of the use of such a CMM in the EPO is the annual 30-day closure of the "corralito" that was originally implemented as an attempt to reduce fishing mortality on juvenile bigeye tuna (*Thunnus obesus*) (see Resolution C-02-04), but now serves a concomitant purpose for reducing the mortality on the complex of small-sized tunas caught in the same region including yellowfin tuna (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*). Population model simulations of the EPO bigeye tuna stock by Harley and Suter (2007) showed that spatial-temporal closures of the "corralito" and other 'hotspots' reduced the annual bigeye catch by up to 24%.

However, it was concluded that these closures alone were insufficient for reducing the fishing mortality to levels that would ensure the biological sustainability of the stock. As a result, Harley and Suter (2007) recommended alternative or supplementary CMMs to reduce fishing mortality, such as increasing the area and duration of closures as well as gear modifications, including changes in mesh sizes and the potential development of other gear technologies such as escape panels and sorting grids that are commonly used in demersal trawl fisheries (Brewer *et al.* 2006; Milton *et al.* 2009). Additional to the present "corralito" closure, the IATTC has implemented an EPO-wide closure of purse-seine fishing for varying periods through the history of the fishery—depending on the status of the target stocks—from 31 days in 2002–2003 (Resolutions C-02-04 and C-03-03), 42 days in 2004–2007 (Resolutions C-03-12, C-04-09 and C-06-02), 59 days in 2009 (Resolution C-09-01), 62 days in 2011–2016 (Resolutions C-11-01 and C-13-01), and 72 days for 2018–2020 (Resolution C-17-01).

It is worth noting that there have also been recent spatial closures implemented within the Exclusive Economic Zones of IATTC Member countries that were not implemented in the current version of the EASI-Fish model—since they were implemented after the 2016 assessment period—that may reduce the vulnerability of *M. mobular* to tuna fisheries more than had been indicated in the hypothetical scenarios implemented in the present study. Some of these include the closure of 147,629 km^2 around the Revillagigedo Islands—a group of four volcanic archipelago off Mexico—by the Mexican government in 2017. In the same year, the Colombian government significantly expanded the Malpelo Fauna and Flora Sanctuary to 2677 km^2. Also in 2017, the Costa Rican Government implemented an 831 km^2 marine protected area—the Cabo Blanco Marine Management Area.

Similar to the IATTC, the WCPFC has also implemented a spatial-temporal CMM to reduce the fishing mortality on small sized-tunas—primarily bigeye tuna—in the western and central Pacific Ocean (CMM-2012-01; *Conservation and management measure for bigeye, yellowfin and skipjack tuna of tuna in the western and central Pacific Ocean*). However, additional to a 2-month spatial-temporal closure of purse-seine fishing in a much larger area (20°N–20°S) than the IATTC's "corralito", the measure prohibits the deployment of, interaction with, or setting on FADs, which are well known to attract small-sized bigeye tuna (Dagorn *et al.* 2013).

Given that there appears to be no single management measure that can fulfil conservation targets for all target species of tunas in Pacific Ocean tuna fisheries, it is not surprising that the potential management options simulated by EASI-Fish for data-limited bycatch species such as *M. mobular* in the EPO proved equally as complex. Our results from simulating various spatial-temporal closures complemented the results of Harley and Suter (2007) in that the duration of recent EPO-wide closures (i.e. 62 and 72 days) and the short-term closures of hotspots reduced the vulnerability of *M. mobular*, but were insufficient to reclassify the species' vulnerability status to "least vulnerable". However, extending closure periods as suggested by Harley and Suter (2007), the only single management scenarios where the species classification changed to "least vulnerable" was achieved by dramatically increasing the EPO-wide closure to 100 days and the hotspot closure to 180 days. This is unlikely to be a feasible management option given the significant reduction in catch of target species that is likely to occur as a consequence.

3.2. Reducing post-release mortality as a viable conservation and management measure

Of the 18 CMM scenarios conducted on *M. mobular* using EASI-Fish, the only feasible scenarios that reduced the vulnerability status of *M. mobular* to "least vulnerable" involved a significant reduction in PRM, that would be presumed to occur with improved handling practices, such as those suggested by Poisson *et al.* (2012), Poisson *et al.* (2014) and IATTC Resolution C-15-04. These include:

- Small rays being handled by 2–3 people and being carried by the side of the animal's wings,
- Avoidance of dragging or lifting the ray by its cephalic lobes, gill slits or spiracles,
- Large rays should be released directly from the brailer, or released as soon as possible after landing on the deck using a ramp connected to an opening on the side of the vessel,
- Use of a cargo net or canvas sling to lift the ray by crane and gently release overboard,
- Avoidance of the use of wire around or through the animal to tow or lift the ray,
- Prohibition of gaffing or punching of holes through the body (e.g. to pass cable for lifting).

In the absence of reliable data relating to PRM in the longline fishery and the three purse-seine set types, we needed to make the precautionary assumption that PRM was 100% for each fishery, in spite of some limited evidence suggesting there is some survival of released rays. For example, in a study conducted in a purse-seine fishery in New Zealand, Francis and Jones (2017) tagged nine *M. mobular* with pop-up satellite tags. Seven tags successfully reported data, of which four indicated the tagged rays had died within four days of release—a PRM rate of 57%—although all four rays had been enclosed in the bunt of the net with the rest of the tuna catch prior to release.

IATTC observers have been recording the catch of mobulids since 1993, but their release condition has only been recorded since 2017 after Resolution C-15-04 entered into force in late 2016. Therefore, it is difficult to glean any reliable indication of the extent of PRM from this short-term datas*et al*one, and delayed mortality cannot be estimated without tagging. This prompted a pilot study examining the PRM of *M. mobular* caught by purse-seine in the tropical EPO, where IATTC staff collaborated with researchers from a number of institutions to tag five specimens with pop-up satellite tags, of which three (60%) survived (Stewart *et al.* 2018).

There is some evidence to suggest that PRM may be reasonably low for longline fisheries. For example, in the Atlantic Ocean longline fishery the at-vessel mortality rate for mobulids has been estimated to range between 1.4% (Coelho *et al.* 2012) and 5.4% (Mas *et al.* 2015). Therefore, a recommendation from the present study would be to undertake electronic tagging studies for both the EPO purse-seine and longline fisheries to quantify at-vessel mortality and PRM rates for *M. mobular*. These studies would benefit by quantifying PRM using handling practices, such as release directly from the purse-seine, compared to release from the brailer, or from the deck. The experimental design could be further stratified by animal size and handling time to release to better understand the efficacy of each release procedure.

It may be fortuitous that PRM has the potential to significantly reduce the mortality of *M. mobular* in EPO tuna fisheries, which are already subjected to a range of spatial and temporal closures as a means of managing catch rates of target tuna species. Handling and release practices that allow a significant proportion of captured fish to survive the sub-lethal effects of capture and release are much simpler and cost-effective to implement—if fishers maintain a high level of care in the recommended release procedures—than small-scale spatial and temporal closures to reduce the capture of *M. mobular*.

4. DIRECTIONS FOR FUTURE WORK

4.1. Species Distribution Models

An important component of the EASI-Fish approach is the species habitat 'base map', which is critical for defining the boundary of the species' distribution where it can be exposed to fishing. Given the limited data that is often available for bycatch species, a simple RES model was used in the present study to predict the probability-of-occupancy (ψ) of *M. mobular* in each 0.5°x0.5° grid cell in the EPO using 68,087 presence records from fishery data and covariates from remotely sensed environmental data (for a full description of the method see Kaschner *et al.* 2006). However, the spatial extent of the distribution is dependent upon value of ψ used, which can influence the proportion of the population exposed to fishing, and therefore the *F* value and the subsequent vulnerability classification. Although we accounted for uncertainty in our species distribution boundaries by running the EASI-Fish model using a range of ψ values, there is scope for improving the vulnerability assessment by using other more sophisticated Species Distribution Models (SDMs) that are capable of making use of presence and absence data and environmental data, where available (Elith and Leathwick 2009).

Models such as Generalized Additive Models (GAMs) (Guisan *et al.* 2002), boosted regression trees (Soykan *et al.* 2014; Scales *et al.* 2017) and EcoCast (Hazen *et al.* 2018), are being increasingly used to model the distribution and environmental preferences of large marine species. Lezama-Ochoa *et al.* (In Review) has developed SDMs for *M. mobular* in the EPO using GAMs and Integrated Nested Laplace Approximation (INLA) models, but the outputs were unfortunately unavailable at the time when this assessment was being undertaken. Revising the EASI-Fish assessment using these SDMs—that incorporated over 200,000 absence records of *M. mobular* in the EPO—may yield different results with resect to the vulnerability status of *M. mobular* in the EPO.

4.2. Inclusion of coastal artisanal and small-scale commercial fisheries

A major consideration in this assessment is that it does not include all fisheries that impact *M. mobular* in the EPO, especially coastal artisanal fisheries that apparently have a high impact but is poorly quantified (Couturier *et al.* 2012). For example, *Mobula* species are caught as a target or as bycatch in small-scale commercial or artisanal fisheries in many coastal states of Central and South American—often in far higher numbers than in industrial purse-seine and longline fisheries in the EPO—including Mexico (Bizzarro *et al.* 2009; Smith *et al.* 2009), Costa Rica (Swimmer *et al.* 2011; Whoriskey *et al.* 2011), Ecuador (Martínez-Ortiz *et al.* 2015), and Peru (Alfaro-Cordova *et al.* 2017). As a result, the fishing mortality and subsequent vulnerability value for each hypothetical scenario in the present study is likely to be underestimated.

Unfortunately, the catches of the large, diverse and disparate artisanal fisheries distributed throughout Central and South America are generally poorly documented, if at all (Salas *et al.* 2007). EASI-Fish was designed to overcome such problems of poor catch data by using spatial maps of fishing effort overlaid on the species' habitat distribution. However, there also appears to be insufficient data available on the distribution of fishing effort of these fisheries to warrant their inclusion in the assessment at this time. However, the IATTC is currently collaborating with Central American IATTC Members on a project funded by the Global Environment Facility (GEF) to improve data collection programs for these small coastal fisheries. Therefore, future assessments on bycatch species such as *M. mobular* may be improved as more data become available for use by the IATTC staff.

5. CONCLUSIONS

EASI-fish was primarily developed as a tool for assessing the vulnerability of data-poor bycatch species and allowing the identification of priority species that may be recommended to become candidates for future research and catch monitoring to facilitate more sophisticated quantitative assessment (e.g. formal stock assessment), or the development of mitigation measures to reduce the specific risk(s) that contribute to the vulnerability of the species assessed. Since the mobulids, including *M. mobular*, have previously been identified in an assessment of the Class 6 purse-seine fishery as being highly vulnerable (Duffy *et al.* In Review), this study demonstrated the flexibility and usefulness of the EASI-Fish approach for exploring potential CMMs that may reduce the vulnerability of data-poor species that are impacted by EPO tuna fisheries or identifying key data gaps, rather than defaulting to investing resources into expensive data collection programs.

As more data become available from national and IATTC monitoring programs, post-release mortality studies and improved species distribution models that may better define the stock boundaries of bycatch species caught in EPO tuna fisheries, EASI-Fish may become an increasingly useful tool for the prioritization of vulnerable species for further research. Furthermore, it may be a particularly rapid and inexpensive tool to explore the potential impact of various CMMs that may be cost-effectively implemented by fishery managers to fulfill mandates that require the demonstration of responsible fishing practices that ensure ecological sustainability of all species in which their fisheries interact.

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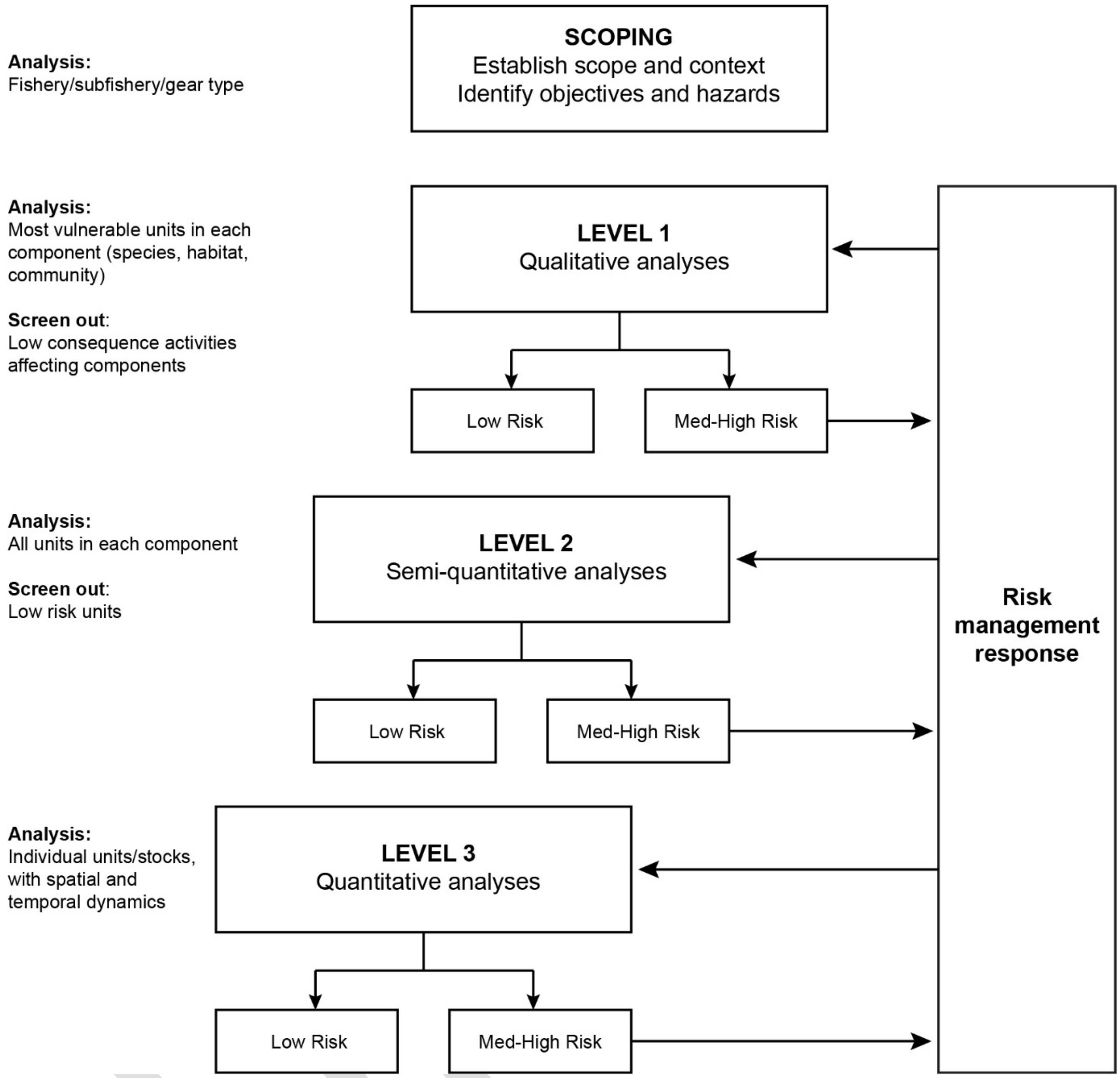

FIGURE 1. Ecological risk assessment framework of Hobday *et al.* (2011), depicting the process of managing ecological risks in fisheries through the use of management responses and increasingly rigorous ecological assessment approaches.

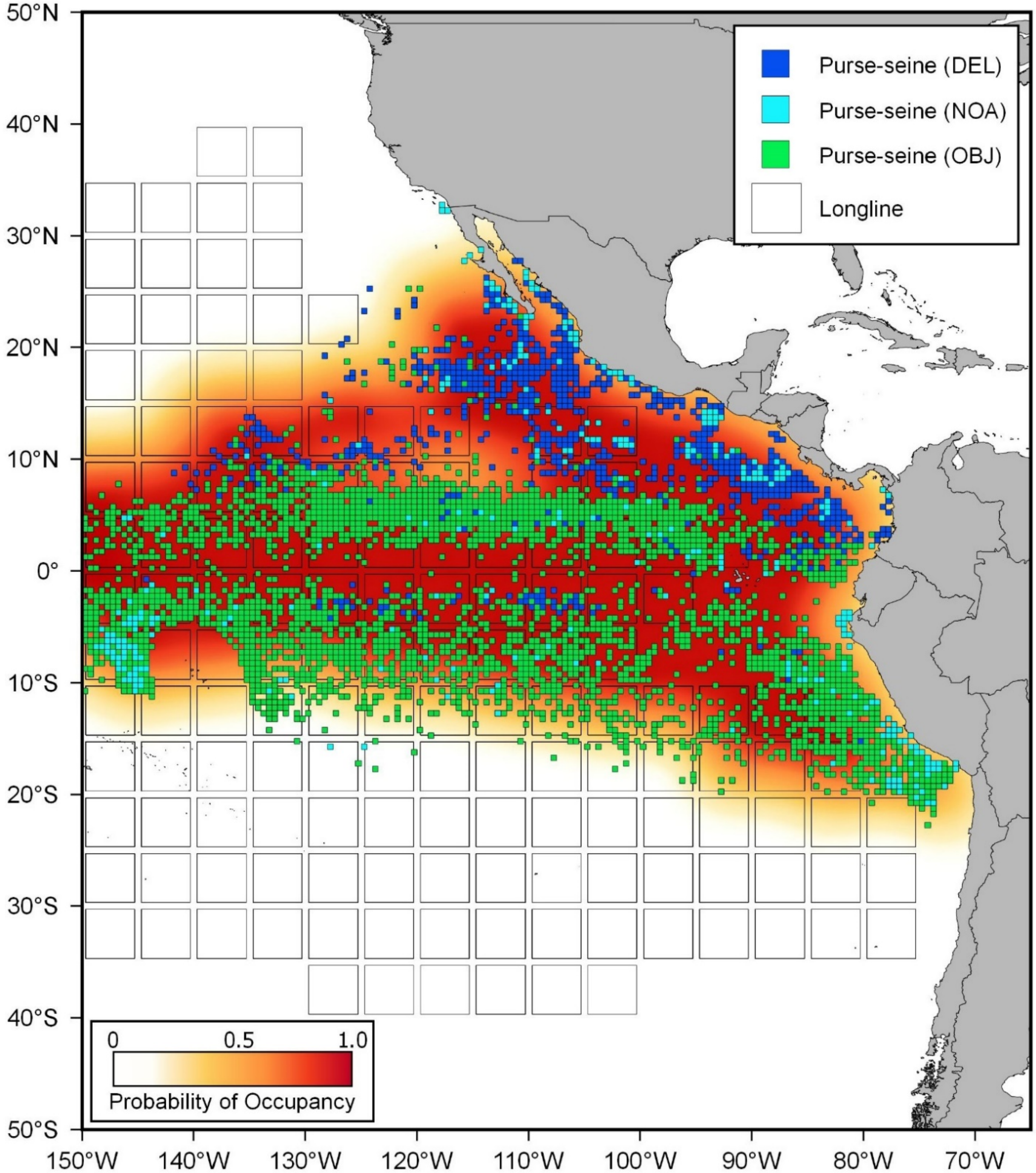

FIGURE 2. Heat map showing the probability of occupancy of *Mobula mobular* in the eastern Pacific Ocean as predicted by a Relative Enironmental Suitability (RES) model (0.5° x 0.5° resolution) overlaid with the distribution of the purse seine (PS) fishery (Class 6 vessels only) (0.5° x 0.5°) and the large-scale tuna longline (LL) fishery (5° x 5°) in 2016.

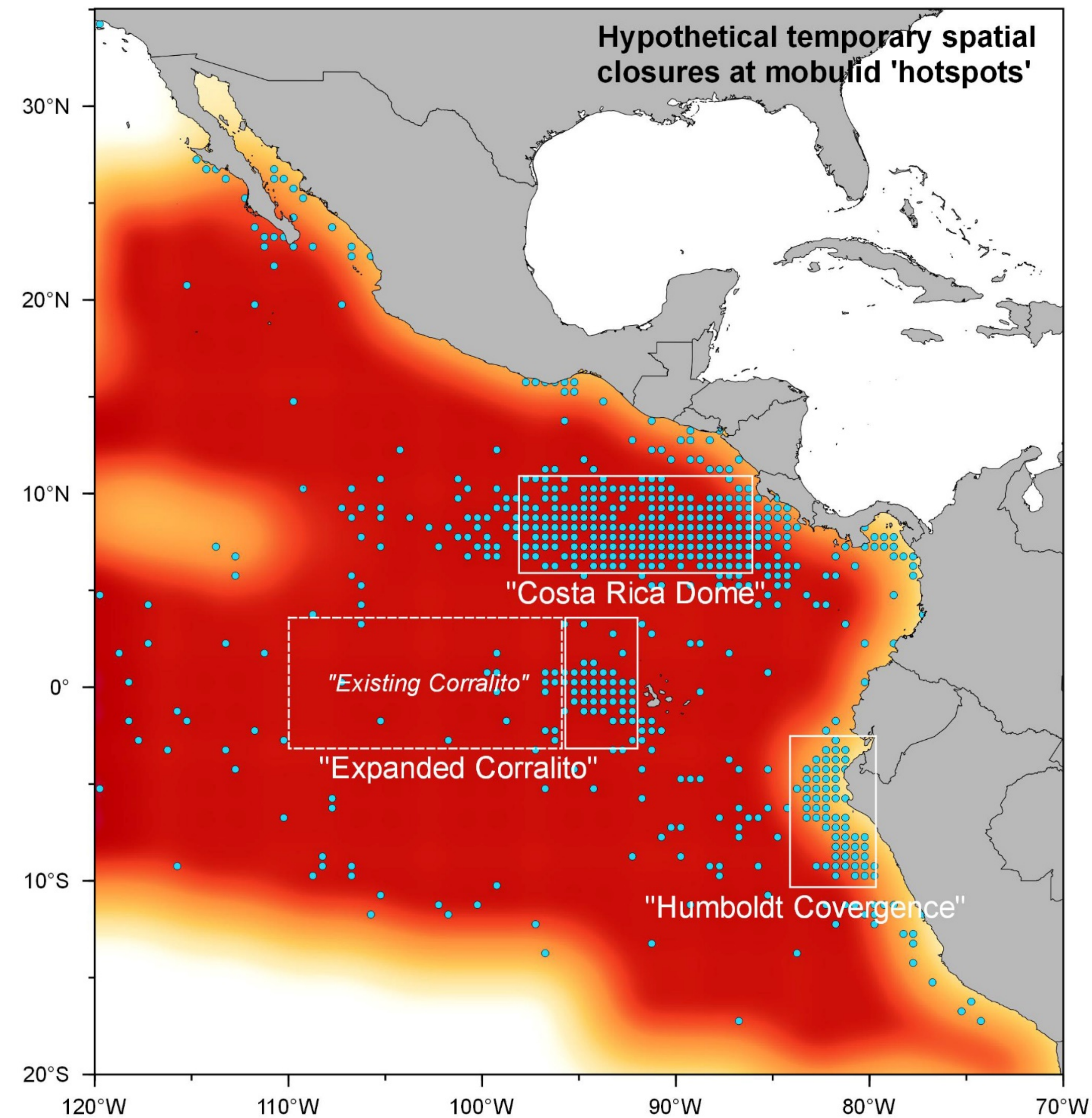

FIGURE 3. Map showing the three prominent 'hotspots' in the catches (blue dots) of one or more *Mobula mobular* made by Class 6 purse-seine vessels in the eastern Pacific Ocean for 1993–2017. Hypothetical temporal closure of the three 'hotspots' ("Costa Rica Dome", "Expanded Corralito", and "Humboldt Convergence") were imposed simulatenously in EASI-Fish for periods of 30, 60, 90 or 180 days.

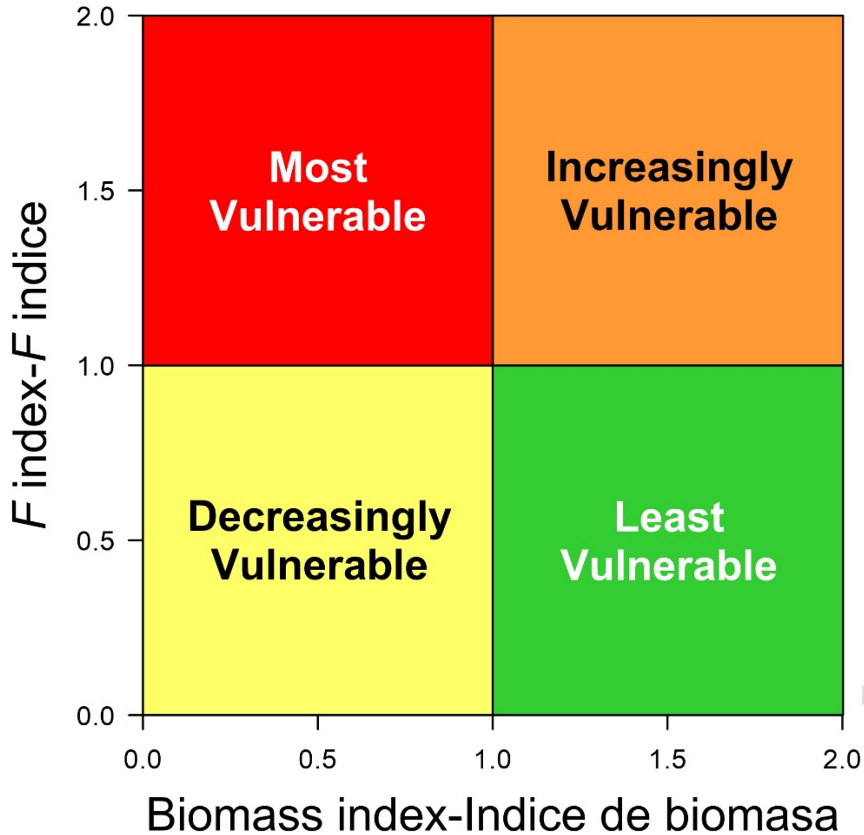

FIGURE 4. Phase plot illustrating how vulnerability status was defined for *Mobula mobular* assessed using $F_{40\%}$ and $SSB_{40\%}$ from the EASI-Fish model as a reference point on the x and y axis, respectively. Vulnerability was defined by its position within one of four quadrants in the phase plot as: "Least vulnerable" (green, $F_{2016}/F_{40\%}$ <1 and $SSB_{2016}/SSB_{40\%}$ >1), "Increasingly vulnerable" (orange, $F_{2016}/F_{40\%}$ >1 and $SSB_{2016}/SSB_{40\%}$ >1), "Most vulnerable" (red, $F_{2016}/F_{40\%}$ >1 and $SSB_{2016}/SSB_{40\%}$ <1), and "Decreasingly vulnerable" (yellow, $F_{2016}/F_{40\%}$ <1 and $SSB_{2016}/SSB_{40\%}$ <1). Maximum axis limits of 2.0 are for illustrative purposes only.

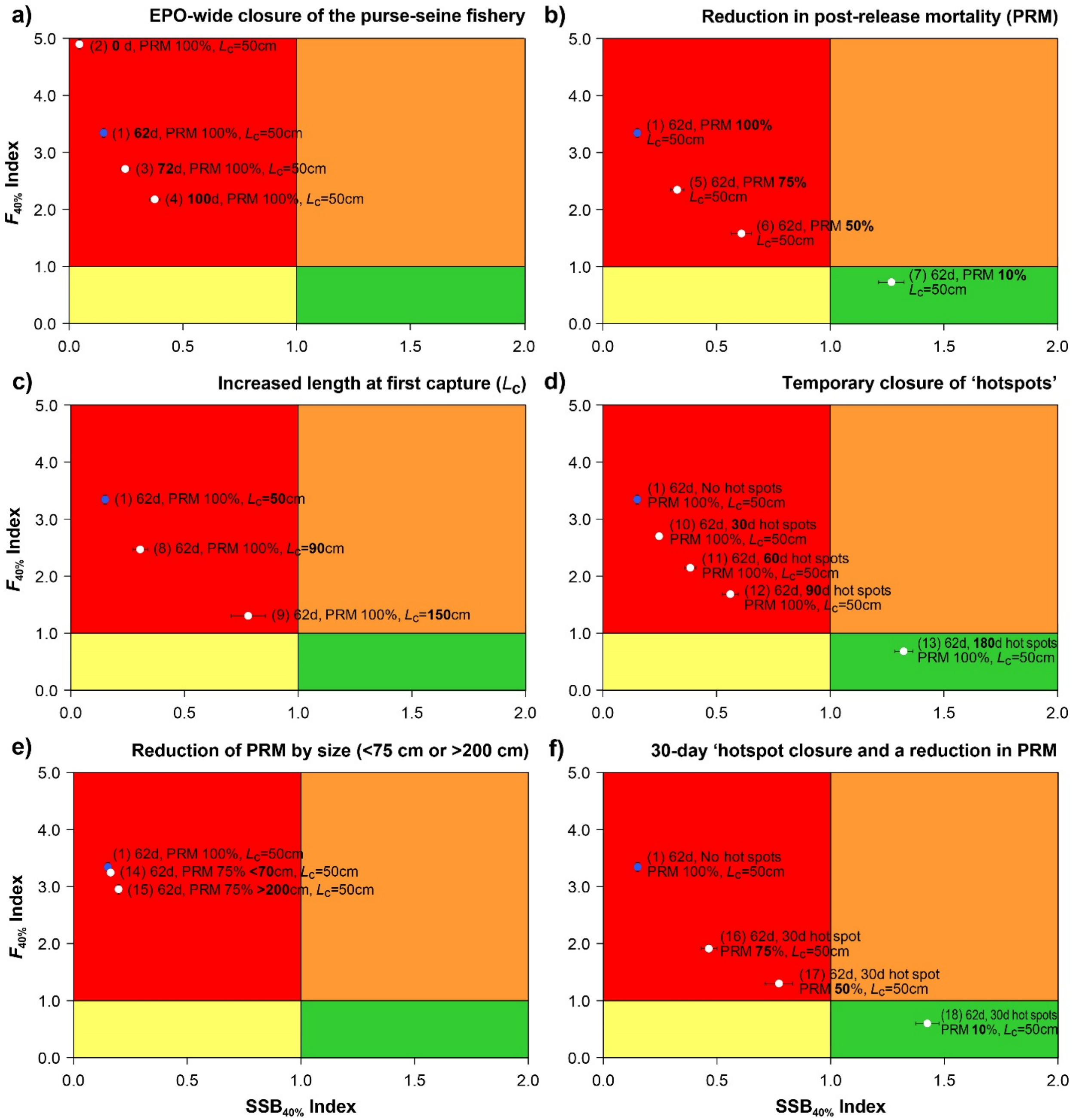

FIGURE 5. Phase plots showing the vulnerability status of *Mobula mobular* produced by EASI-Fish with respect to EPO tuna fisheries represented by the mean (± 95% CI) biological reference points $F_{2016}/F_{40\%}$ and $SSB_{2016}/SSB_{40\%}$ for each hypothetical scenario. Note the blue symbol in each plot shows the vulnerability status under the status quo fishing effort and management scenario in 2016 (sceario 1) for comparison with other scenarios. Numbers in parentheses denote scenario number given in Table 3 and specific values for each of the 18 scenarios are provided in Table 6.

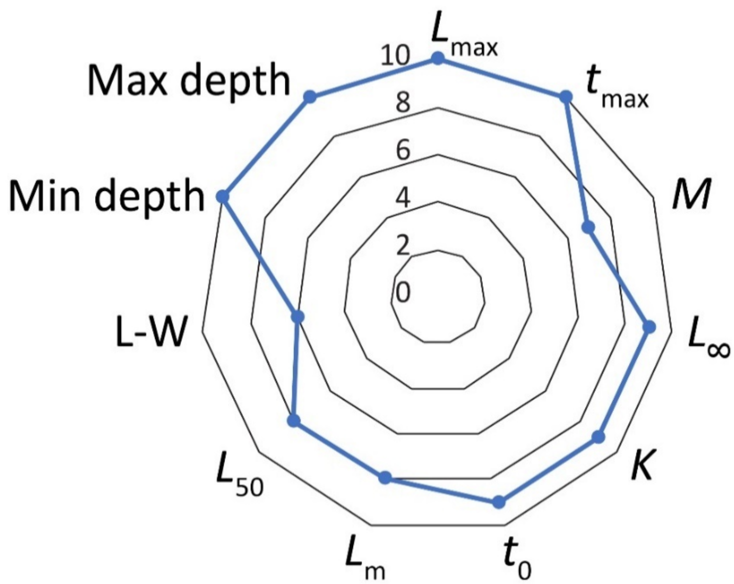

FIGURE 6. Radar plot showing the relative quality of biological and ecological parameters (L_{max}, t_{max}, M, L_∞, K, t_0, L_m, L_{50}, length-weight relationship, minimum and maximum depth) used in EASI-Fish for *Mobula mobular* caught in EPO tuna fisheries. Scale ranges from 0 (data absent for the species and its closely related species) to 10 (high quality species-specific data derived from the EPO).

TABLE 1. Natural mortality (*M*) estimators used in the present study.

Estimator	Equation	Citation
Hoenig_{tmax}	$M = \frac{4.3}{t_{max}}$	Hoenig (1983)
$\text{Hoenig}_{\text{nls}}$	$M = 4.899 t_{max}^{-0.916}$	Then *et al.* (2015)
Jensen	$M = 1.60\ K$	Jensen (1996)
$\text{Pauly}_{\text{nls}}$	$M = 4.118 K^{0.73} L_{\infty}^{-0.33}$	Then *et al.* (2015)
$\text{Pauly}_{\text{LKT}}$	$\log M = -0.0066 - 0.279 \ln L_{\infty} + 0.6543 \ln K + 0.4634 \ln T$	Pauly (1980)

M = instantaneous natural mortality rate (yr^{-1})
t_{max} = maximum observed age of animals in the stock.
L_{∞} = the average length of a fish if it lived to an infinite age, and known as the asymptotic length of fish in the von Bertalanffy growth function (yr^{-1}).
K = the curvature parameter of the von Bertalanffy growth function (yr^{-1}).
T = mean water temperature (°C) at the location and depth range inhabited by the fish.

TABLE 2. Qualitative index used to rank the relative reliability of biological and ecological parameters used for *Mobula mobular* in the EASI-Fish assessment with respect to the reliability of the methodology to estimate the parameter and the precision of parameter estimate, relative to the data source's relevance to the species and region being assessed. EPO: Eastern Pacific Ocean WCPO: Western and Central Pacific Ocean.

		High accuracy		**Medium accuracy**		**Low accuracy**		**No data**
		High precision	Low precision	High precision	Low precision	High precision	Low precision	
Species-specific	EPO	10	9	8	7	6	5	0
	WCPO	9	8	7	6	5	4	0
	Other	8	7	6	5	4	3	0
Related species	EPO	7	6	5	4	3	2	0
	WCPO	6	5	4	3	2	1	0
	Other	5	4	3	2	1	1	0

TABLE 3. Description of the 18 hypothetical conservation and management scenarios implemented in EASI-Fish for Mobula mobular with regards to the tuna fishery in the EPO in 2016.

Scenario description	Scenario no.	EPO closure (days)	'Hotspot' closure (days)	Post-release mortality (%)			Length at first capture (L_c) (cm)
				All sizes	<70 cm	>200 cm	
2016 Status quo	1	62		100			50
EPO-wide closure of the purse-seine fishery	2	0		100			50
	3	72		100			50
	4	100		100			50
Reduction in post-release mortality (PRM)	5	62		75			50
	6	62		50			50
	7	62		10			50
Increased length at first capture (L_c)	8	62		100			90
	9	62		100			150
Temporary closure of 'hotspots'	10	62	30	100			50
	11	62	60	100			50
	12	62	90	100			50
	13	62	180	100			50
Reduction of PRM by size (<75 cm or > 200 cm)	14	62		75	75		50
	15	62		75		75	50
30 d 'hotspot' closure and a reduction in PRM	16	62		75			50
	17	62		50			50
	18	62		10			50

TABLE 4. Parameter values used for variables describing the susceptibility of capture of *Mobula mobular* in the four fisheries defined for the "status quo" situation of the eastern Pacific Ocean tuna fishery in 2016.

Fishery	Proportion of species-occupied grids (G_x/G) fished	Fishing season duration (D_x)	Seasonal availability (A_{xj})	Encounterability (E_{xj})	Contact selectivity (C_{xj})	Post-release mortality (PRM) (P_{xj})
Longline	**0.12**	**1.0** Year-round	**1.0** Species available year-round	**1.0** Deep sets assumed to fish 0-300m. *M. mobular* primarily inhabits 0-50m (Croll *et al*. 2012, Francis and Jones 2017).	**0.33** In absence of selectivity ogive for *M. mobular* for EPO purse seine fleet, assumed knife-edge selectivity from smallest size at birth (49.8cm DW) (White *et al*. 2006). Assumed default "low" selectivity value of 0.33 based on use of fish or squid baits not occuring frequently in the natual diet of mobilids, which are predominatley zooplanktivores (Couturier *et al.* 2012). However, some catch and entaglement in the gear has been documented (Coelho *et al.* 2012; Mas *et al.* 2015).	**1.0** Assumed 100% PRM in absence of PRM data for *M. mobular* or closely related mobulids in longline fisheries.
Purse-seine (DEL)	**0.29**	**0.83** 62-d EPO closure 30-d "Corralito" closure	**1.0** Species available year-round	**1.0** DEL sets assumed to fish 0-200m. Species primarily inhabits 0-50m (Croll *et al*. 2012, Francis and Jones 2017).	**0.87** In absence of selectivity ogive for *M. mobular* for EPO purse-seine fleet, assumed knife-edge selectivity from smallest size at birth (49.8cm DW) (White *et al*. 2006).	**1.0** Electronic tagging study indicated nearly 57% PRM of *M. mobular* caught in tuna purse-seines, but *n* = 7 (Francis and Jones 2017). Therefore, conservatively assumed 100% PRM.
Purse-seine (NOA)	**0.09**	**0.83** 62-d EPO closure 30-d "Corralito" closure	**1.0** Species available year-round	**1.0** NOA sets assumed to fish 0-200m. *M. mobular* primarily inhabits 0-50m (Croll *et al*. 2012, Francis and Jones 2017).	**0.87** In absence of selectivity ogive for *M. mobular* for EPO purse-seine fleet, assumed knife-edge selectivity from smallest size at birth (49.8cm DW) (White *et al*. 2006).	**1.0** Electronic tagging study indicated nearly 57% PRM of *M. mobular* caught in tuna purse-seines, but *n* = 7 (Francis and Jones 2017). Therefore, conservatively assumed 100% PRM.
Purse-seine (OBJ)	**0.15**	**0.83** 62-d EPO closure 30-d "Corralito" closure	**1.0** Species available year-round	**1.0** OBJ sets assumed to fish 0-200m. *M. mobular* primarily inhabits 0-50m (Croll *et al*. 2012, Francis and Jones 2017).	**0.87** In absence of selectivity ogive for *M. mobular* for EPO purse-seine fleet, assumed knife-edge selectivity from smallest size at birth (49.8cm DW) (White *et al*. 2006).	**1.0** Electronic tagging study indicated nearly 57% PRM of *M. mobular* caught in tuna purse-seines, but *n* = 7 (Francis and Jones 2017). Therefore, conservatively assumed 100% PRM.

TABLE 5. Biological parameters and their data sources for *Mobula mobular* used in the EASI-Fish model. The "T" superscript denotes a triangular prior distribution—with peak values derived from t_{max}-based natural mortality estimators—used in 10,000 iterations of Monte Carlo simulations.

	t_{max} (yrs)	L_{inf} (yr^{-1})	K (yr^{-1})	t_0 (yr^{-1})	Length-weight *a*	Length-weight *b*	L_{50} (cm)	r	M (yr^{-1})
Parameter values	14	233.8	0.280	-0.700	0.00429	3.400	201.6	0.200	0.37 $(0.27\text{-}0.44)^T$
Data source	Cuevas-Zimbrón *et al.* (2013)	Cuevas-Zimbrón *et al.* (2013)	Cuevas-Zimbrón *et al.* (2013)	Cuevas-Zimbrón *et al.* (2013)	(Notarbartolo-di-Sciara 1988)	(Notarbartolo-di-Sciara 1988)	(White *et al.* 2006)	(White *et al.* 2006)	*M* estimators (see Table 1)

TABLE 6. Estimated mean (± s.e.) values for fishing mortality (*F*) and spawning stock biomass (SSB) reference points derived from the EASI-Fish model for *Mobula mobular* caught in tuna fisheries in the eastern Pacific Ocean in 2016 under various hypothetical conservation and management measures. Colors indicate scenarios where *M. mobular* is classified as "most vulnerable" (red) or "least vulnerable" (green), where the current fishing mortality rate (F_{2016}) and spawning stock biomass (SSB_{2016}) exceed or are less than the $F_{40\%}$ and $SSB_{40\%}$ reference points, respectively.

Scenario	Scenario No.	F_{2016}	SSB_{2016}	$F_{40\%}$	$SSB_{40\%}$	$F_{2016}/F_{40\%}$	$SSB_{2016}/SSB_{40\%}$
2016 Status quo							
62 d PS closure; PRM 100%; L_c=50 cm	1	0.71 (<0.01)	4.37 (0.043)	0.21 (<0.01)	28.90 (0.30)	3.34 (0.08)	0.15 (0.01)
EPO-wide closure of the purse-seine fishery							
0 d PS closure; PRM 100%; L_c=50 cm	2	0.91 (<0.01)	1.31 (0.02)	0.18 (<0.01)	29.15 (0.31)	4.98 (0.08)	0.05 (0.00)
72 d PS closure; PRM 100%; L_c=50 cm	3	0.62 (<0.01)	7.17 (0.07)	0.23 (<0.01)	29.08 (0.32)	2.71 (0.05)	0.25 (0.02)
100 d PS closure; PRM 100%; L_c=50 cm	4	0.55 (<0.01)	11.21 (0.12)	0.25 (<0.01)	29.81 (0.32)	2.18 (0.03)	0.38 (0.02)
Reduction in post-release mortality (PRM)							
62 d PS closure; **PRM 75%**; L_c=50 cm	5	0.57 (<0.01)	9.60 (0.09)	0.24 (<0.01)	29.36 (0.32)	2.35 (0.03)	0.33 (0.03)
62 d PS closure; **PRM 50%**; L_c=50 cm	6	0.45 (<0.01)	18.15 (0.17)	0.28 (<0.01)	29.76 (0.32)	1.58 (0.03)	0.61 (0.04)
62 d PS closure; **PRM 10%**; L_c=50 cm	7	0.29 (<0.01)	37.81 (0.37)	0.40 (<0.01)	29.79 (0.33)	0.73 (0.01)	1.27 (0.06)
Increased length at first capture (L_c)							
62 d PS closure; PRM 100%; **L_c=90 cm**	8	0.59 (<0.01)	9.03 (0.08)	0.24 (<0.01)	29.58 (0.33)	2.47 (0.05)	0.31 (0.03)
62 d PS closure; PRM 100%; **L_c=150 cm**	9	0.44 (<0.01)	22.81 (0.20)	0.34 (<0.01)	29.23 (0.31)	1.30 (0.05)	0.78 (0.08)
Temporary closure of 'hotspots'							
62 d PS closure; PRM 100%; L_c=50 cm; **30 d 'hotspot' closure**	10	0.62 (<0.01)	7.14 (0.07)	0.23 (<0.01)	28.87 (0.31)	2.70 (0.06)	0.25 (0.02)
62 d PS closure; PRM 100%; L_c=50 cm; **60 d 'hotspot' closure**	11	0.54 (<0.01)	11.25 (0.11)	0.25 (<0.01)	29.27 (0.32)	2.15 (0.02)	0.38 (0.03)
62 d PS closure; PRM 100%; L_c=50 cm; **90 d 'hotspot' closure**	12	0.47 (<0.01)	16.93 (0.16)	0.28 (<0.01)	30.20 (0.33)	1.68 (0.03)	0.56 (0.04)
62 d PS closure; PRM 100%; L_c=50 cm; **180 d 'hotspot' closure**	13	0.28 (<0.01)	39.50 (0.38)	0.42 (<0.01)	29.85 (0.32)	0.68 (0.02)	1.32 (0.04)
Reduction of PRM by size (<75 cm or > 200 cm)							
62 d PS closure; **PRM 75% on rays <70 cm**; L_c=50 cm	14	0.69 (<0.01)	4.79 (0.05)	0.21 (<0.01)	29.31 (0.32)	3.25 (0.05)	0.16 (0.01)
62 d PS closure; **PRM 75% on rays >200 cm**; L_c=50 cm	15	0.65 (<0.01)	5.81 (0.06)	0.22 (<0.01)	29.24 (0.31)	2.95 (0.08)	0.20 (0.01)
30 d 'hotspot' closure and a reduction in PRM							
62 d PS closure; **PRM 75%**; L_c=50 cm; **30 d 'hotspot' closure**	16	0.51 (<0.01)	13.75 (0.12)	0.26 (<0.01)	29.61 (0.31)	1.91 (0.07)	0.46 (0.04)
62 d PS closure; **PRM 50%**; L_c=50 cm; **30 d 'hotspot' closure**	17	0.41 (<0.01)	23.16 (0.21)	0.31 (<0.01)	29.98 (0.31)	1.30 (0.04)	0.77 (0.06)
62 d PS closure; **PRM 10%**; L_c=50 cm; **30 d 'hotspot' closure**	18	0.26 (<0.01)	42.81 (0.42)	0.44 (<0.01)	30.04 (0.32)	0.60 (0.01)	1.43 (0.05)

d = days; PRM = post-release mortality, L_c = length at first capture