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Authors
Griffiths, Shane P
Lezama-Ochoa, Nerea

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RESEARCH ARTICLE

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A 40-year chronology of the vulnerability of spinetail devil ray (*Mobula mobular*) to eastern Pacific tuna fisheries and options for future conservation and management

Shane P. Griffiths[1] | **Nerea Lezama-Ochoa**[1,2,3]

[1]Ecosystem and Bycatch Program, Inter-American Tropical Tuna Commission, La Jolla, CA, USA

[2]Marine Research Division, AZTI-Tecnalia, Pasaia, Spain

[3]Institute of Marine Science, University of California Santa Cruz, Santa Cruz, CA, USA

Correspondence
Shane P. Griffiths, Ecosystem and Bycatch Program, Inter-American Tropical Tuna Commission, La Jolla, CA, USA.
Email: sgriffiths@iattc.org

Present address
Nerea Lezama-Ochoa, Institute Environmental Research Division, NOAA Southwest Fisheries Science Center, Monterey, CA, USA

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Abstract

1. Tuna fisheries are among the largest and most valuable fisheries in the world, but most interact with many non-target species, including several of high conservation importance. The spinetail devil ray (*Mobula mobular*) – listed as 'Endangered' on the IUCN Red List of Threatened Species – is a commonly discarded bycatch species, particularly in the eastern Pacific Ocean, yet insufficient data exist to undertake a traditional population assessment.
2. A new ecological risk assessment approach designed for data-limited settings – Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish) – was used to reconstruct the historical vulnerability status of *M. mobular* and to simulate potential changes in its status under 45 hypothetical conservation and management measures. These involved various temporal closures of the eastern Pacific Ocean tuna fishery, decreasing post-capture mortality by improved handling and release practices, and combinations of the two.
3. The species was classified as 'Least Vulnerable' between 1979 and 1993, but became 'Most Vulnerable' from 1994, which coincided with a rapid spatial expansion of the industrial purse-seine fishery, and especially from 2011 following the rapid increase in the number of sets made on floating objects. Simulating the conservation and management measures in place in 2018 revealed that 31 of the 45 scenarios resulted in a change in classification of the species to 'Least Vulnerable', which primarily involved a reduction of post-capture mortality by as little as 20%.
4. It is fortuitous in that education of fishers to implement appropriate best handling and release practices is simpler, more rapid and more cost-effective than the implementation of fishery closures or gear modifications, which can be expensive and complex to implement and monitor and will probably result in substantial reduction in the catches of target species.

KEYWORDS

data-limited, ecological risk assessment, longline, manta ray, *Mobula japanica*, purse-seine

1 | INTRODUCTION

Industrial marine fisheries are among the world's largest, most valuable and important food production industries. In 2016, around US$80 billion were generated from a global marine capture production of 79.3 million tonnes, which provided 3.2 billion people with approximately 20% of their intake of animal protein (FAO, 2018). Of this global marine catch, tuna fisheries contributed about 7.5 million tonnes (9.5%) of tuna and tuna-like fishes (FAO, 2018). For many coastal states, tuna fisheries represent a significant component of their gross domestic product and provide livelihoods and food security for many hundreds of thousands of people (Bell et al., 2009; Béné et al., 2015; Pilling et al., 2015).

The populations of target species of tunas (e.g. skipjack, yellowfin, bigeye and albacore) are closely monitored and assessed by tuna Regional Fisheries Management Organizations to ensure their sustainable use. Purse-seine and longline gears used in industrial tuna fisheries also catch a variety of non-target species, or "bycatch". Some bycatch species include sea turtles, seabirds, marine mammals and elasmobranchs, many of which have slow growth and low reproductive capacity that make their populations susceptible to decline with additional mortality due to fishing (Gray & Kennelly, 2018). Consequently, many fisheries worldwide have begun to make a transition from a management focus on individual target species to ecosystem approaches that consider the ecological impacts of fishing on non-target species, habitats and the supporting ecosystem more broadly (Pikitch et al., 2004).

The Inter-American Tropical Tuna Commission (IATTC) is responsible for the management of tuna and tuna-like species in the eastern Pacific Ocean (EPO), defined as the region from the coast of the Americas to 150°W between 50°S and 50°N (Figure S1). It is one of the world's six tuna Regional Fisheries Management Organizations but its Convention – the Antigua Convention entering into force in 2010 – is the only one that explicitly requires the consideration of ecosystem impacts in the development of conservation and management measures. However, EPO tuna fisheries interact with at least 117 taxa, many of which lack basic biological and catch information (Duffy et al., 2016; Lezama-Ochoa et al., 2017). Therefore, the IATTC and other tuna Regional Fisheries Management Organizations face the difficulty of quantitatively assessing impacted species using traditional approaches to demonstrate the fulfilment of mandates of their Conventions and other binding international instruments (e.g. the United Nations Fish Stocks Agreement). However, the recent development of the Ecological Assessment of Sustainable Impacts of Fisheries (EASI-Fish) approach allows for the quantitative assessment of data-poor species using conventional biological reference points (BRPs) used in fisheries stock assessment (Griffiths et al., 2019).

One of the most vulnerable bycatch taxa caught in tuna fisheries worldwide that has lacked any formal quantitative assessment – primarily owing to a paucity of biological and fishery catch information – are the mobulids (devil and manta rays). Some international conservation instruments and tuna Regional Fisheries Management Organizations resolutions exist for mobulids. For example, in 2014 all mobulids were added to Appendices I and II of the Convention of Migratory Species (2015) and in 2016 all species of *Mobula* were listed under Appendix II of the Convention on International Trade in Endangered Species (2016) to meet regional conservation goals and curb international trade in mobulid products (e.g. gill plates). In 2015, the IATTC adopted Resolution C-15-04 that prohibits the retention, trans-shipment, landing, storing, sale or offering for sale of any part or whole carcass of mobulid rays by any commercial vessel. Additionally, it recommends the use of the best handling practices of Poisson et al. (2014) to minimize post-capture mortality (PCM). However, implementing these practices can be a challenge for fishers owing to the lack of available deck space, the species' size (some reaching over 3 m in disc width, DW) and morphological characteristics (some have a dangerous tail spine).

In the EPO, the spinetail devil ray, *Mobula mobular*, is one of the most frequently caught mobulid species in purse-seine tuna fisheries (Hall & Roman, 2013; Lezama-Ochoa et al., 2019a). The species has low biological productivity, reaching a maximum size of 310 cm DW (Notarbartolo-di-Sciara, 1988), having a maximum age (t_{max}) of 15–20 years (Pardo et al., 2016), low fecundity (one pup every 2 years), and females reach maturity after 5–6 years (López, 2009). Consequently, *M. mobular* is listed as 'Endangered' by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. The assessment of this species is becoming increasingly urgent as fishing effort in the EPO has rapidly increased since 2008, and in 2018 the purse-seine and longline fisheries deployed a total of 32,500 sets and 195 million hooks, respectively (Figure 1a; IATTC, 2019). In the purse-seine fishery, this increase is due primarily to the use of artificial fish aggregation devices that attract not only small-size classes of target tuna species, but also various non-target species, including mobulids (Dagorn et al., 2013; Lezama-Ochoa et al., 2017).

Mobulids caught by the EPO industrial purse-seine fishery are primarily taken on sets made on free-swimming schools of tuna (NOA) and to a lesser extent in sets made on dolphins (DEL) or floating objects (e.g. fish aggregating devices; Figure 1b). Although mobulids, including *M. mobular*, are known to be caught by the longline fishery in the EPO, unfortunately the observer coverage of this fleet is often less than 5%. This low coverage and there being no requirement to record non-retained species in vessel logbooks has resulted in very few documented interactions with less frequently encountered species such as mobulids. Nonetheless, mobulid catches by the purse-seine fishery show considerable inter-annual variability, and despite increasing effort, catches have decreased from 5,022 to 705 animals for 2010–2018 (Figure 1b). It is unknown what impact the increase in fishing effort by the purse-seine and longline fisheries has had on the population viability of *M. mobular* over the history of the EPO tuna fishery and to what extent the population can be sustained under the current industrial fishing effort regime.

Therefore, the aims of this paper were to use EASI-Fish to reconstruct a chronology of the annual vulnerability status for *M. mobular* over the past 40 years (1979–2018) in the EPO as a result

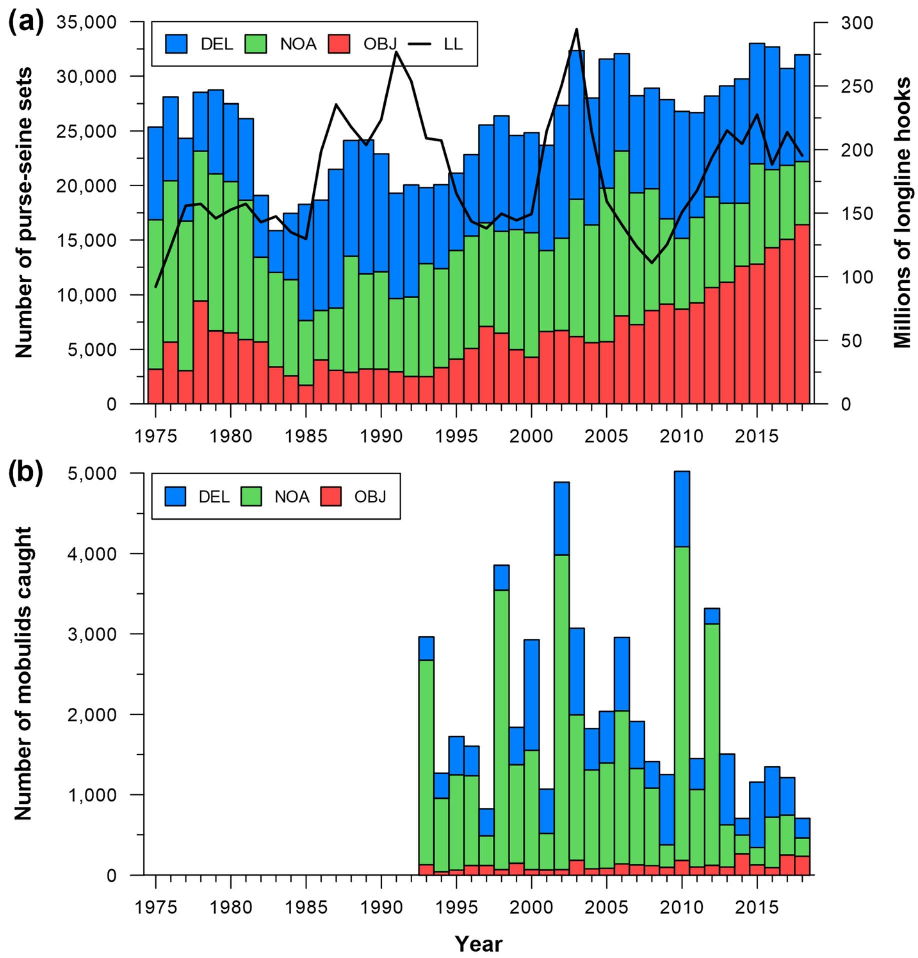

FIGURE 1 Time series of (a) the number of sets made on dolphins (DEL), non-associated tuna schools (NOA) and floating objects (OBJ) for Class 6 purse-seine vessels and the number of hooks deployed by the longline (LL) fishery; and (b) the number of mobulids recorded by scientific observers as being caught by Class 6 purse-seine vessels for each purse-seine set type in the eastern Pacific Ocean (EPO; IATTC, 2019)

of changing fishing effort regimes, and to then explore the influence of potential conservation and management measures on the species' vulnerability status from 2018. In particular, analyses were undertaken to explore the impacts of: (i) increasing the existing EPO-wide fishing closure for large purse-seine vessels (Class 6); (ii) decreasing PCM through fisher education of best handling practices; (iii) decreasing PCM for different size classes of rays to reflect difficulties in releasing larger rays; and (iv) using a combination of EPO-wide temporal closures for large purse-seine vessels with decreasing PCM. The overarching goal of the paper was to identify potentially effective management strategies that may be practically and cost-effectively implemented – individually or together – that may allow *M. mobular* and tuna fisheries to sustainably co-exist in the EPO.

2 | MATERIALS AND METHODS

2.1 | Spatial extent of the assessment region and definition of included fisheries

The present vulnerability assessment of *M. mobular* incorporated the IATTC Convention Area in the EPO (Figure S1) and includes the 'industrial' purse-seine fishery and the fishery by large-scale longline tuna fishing vessels (herein called the 'longline fishery'). The stock structure of *M. mobular* is not well understood. However, a recent genetic study of the species using mitogenome and nuclear sequences found a significant difference between samples collected in the northern EPO (Mexico) and the western Pacific Ocean (Taiwan) (Poortvliet et al., 2015). Therefore, in the absence of evidence suggesting population subdivision within the EPO, it was assumed that *M. mobular* exists as a single stock in the EPO.

The analyses presented in this paper draw upon data obtained from vessel logbooks, collected by on-board scientific observers or submitted to the IATTC by its Members and Cooperating Non-Members (CPCs) under IATTC Resolutions C-03-05 and C-11-08 for the period 1979–2018 for both the purse-seine and longline fisheries. Specifically, the longline fishery data were derived from vessels >24 m length overall included in the IATTC Regional Vessel Register that are authorized to fish for tuna and tuna-like species. These vessels provide monthly reports of catch and fishing effort at a minimum resolution of 5 × 5°, while the scientific observer programme monitors at least 5% of fishing trips by longline vessels over 20 m length overall under Resolution C-19-08.

The purse-seine fishery data were collected by the on-board observer programme of the Agreement on the International Dolphin

Conservation Program, which has covered nearly 100% of the fishing effort by Class-6 purse-seine vessels (carrying capacity >363 t) since 1992. Prior to 1992, effort data were obtained from a combination of observer and logbook records. Because of the distinctly different targeting practices within the purse-seine fishery, this fishery was disaggregated into three separate fisheries based on set type: (i) sets made in association with floating objects (OBJ) that include natural logs and debris as well as artificial fish aggregating devices; (ii) sets made in association with aggregations of dolphins (DEL); and (iii) sets made on free-swimming schools of tuna (NOA).

2.2 | Quantifying vulnerability

The vulnerability status of *M. mobular* was estimated for each year between 1979 and 2018, and subsequently under various hypothetical management scenarios based on data from 2018, using the EASI-Fish approach. A comprehensive description of EASI-Fish is provided in the Supporting Information and by Griffiths et al. (2019). In brief, EASI-Fish is a model comprising two separate components: the 'susceptibility' of a species to being caught by specific gear types, and the biological 'productivity' of the species to withstand a specific level of fishing mortality. Together, these two components quantify the vulnerability of a species to impacts by one or more fishing fleets in the absence of catch data.

The susceptibility component comprises parameters that describe the species':

1. geographic distribution (*G*) by using a species distribution model to predict its presence or absence in each 0.5 × 0.5° grid cell in the EPO;
2. 'availability' to each fishery given the duration of operation over a year (*D*) and the species' seasonal presence (*A*) in the area where a fishery operates;
3. 'encounterability' of the fishing gear when the species is available to the fishery (*N*);
4. 'contact selectivity' (*C*) for an animal of a specific size class to be retained once it encounters the gear; and
5. PCM (*P*) once it is captured and released by a fishery.

In this study, *G* was estimated using a hierarchical Bayesian spatial Generalized Additive Model and implemented in the INLA (Integrated Nested Laplace Approximation) package (http:\\www.r-inla.org; Lindgren & Rue, 2015) in R software (R Core Team, 2017). The habitat model was developed from presence–absence data from IATTC scientific observer data and a set of explanatory variables including set type, month, daily sea surface height (cm), monthly oxygen concentration (mg L^{-1}), monthly nitrate (mg L^{-1}) and monthly chlorophyll (mg m^{-3}). A detailed description of the INLA methodology and the habitat model development for *M. mobular* is provided in the Supporting Information and Lezama-Ochoa et al. (2020). It is possible that the distribution of *M. mobular* has varied naturally through time as a result of varying natural environmental regimes (e.g. ENSO). If the distribution of the species contracted or expanded relative to the distribution of fishing effort, the estimated fishing mortality and vulnerability would increase or decrease, respectively. However, for the purposes of this study, the distribution derived from INLA remained constant across all years.

Although a knife-edge probability-of-occupancy (ψ) threshold value (e.g. 0.8) is required to be applied to each cell to define the geographic distribution of *M. mobular*, the spatial extent of the distribution can differ substantially depending on the threshold value used (Figure S2). While the best fitting INLA model was statistically determined, the final distribution map used to represent the species first required validation by scientific experts to ensure that it was ecologically plausible. Therefore, a series of distribution maps were developed using ψ values in increments of 0.05 and experts asked to select the maps that they believed to best represent the species' distribution. Since the defined species distribution influences the proportion of the population exposed to fishing, this uncertainty was accounted for by running the EASI-Fish model using distribution maps based on ψ values selected by experts (0.40, 0.45 and 0.50) with the most plausible distribution shown in Figure 2. Using this range of ψ values also allowed for possible inter-annual variability in the species' distribution to be accounted for.

Annual fishing effort data for each of the four fisheries was overlaid on the species distribution map – for each ψ value – to calculate the percentage overlap of each fishery. Effort data for purse-seine vessels were used at 0.5 × 0.5° resolution. However, longline data are generally reported to the IATTC at 5 × 5° resolution, so the presence of effort in a longline grid cell conservatively assumes that there was also at least one unit of effort in each occupied 0.5° cell contained within the 5° cell.

Together, the parameters *G*, *D*, *A*, *N* and *P* allow the percentage of the three-dimensional overlap ('volumetric overlap') of fishing effort on the species' distribution to be calculated, which can then be converted to become a proxy for the instantaneous fishing mortality rate ($\tilde{F}$ $year^{-1}$). The value of $\tilde{F}$ is then compared to traditional precautionary fisheries BRPs, such as the fishing mortality value that produces the maximum sustainable yield (F_{MSY}) or maximizes the yield-per-recruit (F_{max}), used in fishery stock assessments that are derived from the productivity component in the form of length-structured yield and spawner biomass per-recruit models (Chen & Gordon, 1997; Quinn & Deriso, 1999). Given the potential conservation concerns for *M. mobular* owing to its slow growth and low reproductive capacity, it was desirable to use precautionary BRPs that are attained at lower levels of fishing mortality compared with BRPs used for commercially important species, such as F_{MSY}. There has been much debate over the past two decades regarding what constitutes a sufficiently precautionary BRP for data-limited species and/or fisheries, with the appropriate BRP depending on the life history of the species of interest (e.g. teleosts, elasmobranchs, marine mammals), the type and quality of data available and management objectives (Gabriel & Mace, 1999; Cortés & Brooks, 2018). Recommended BRPs have generally ranged from 20% (i.e. $F_{20\%}$) to 40% ($F_{40\%}$) of the spawning potential ratio. In the case of $F_{20\%}$, this is

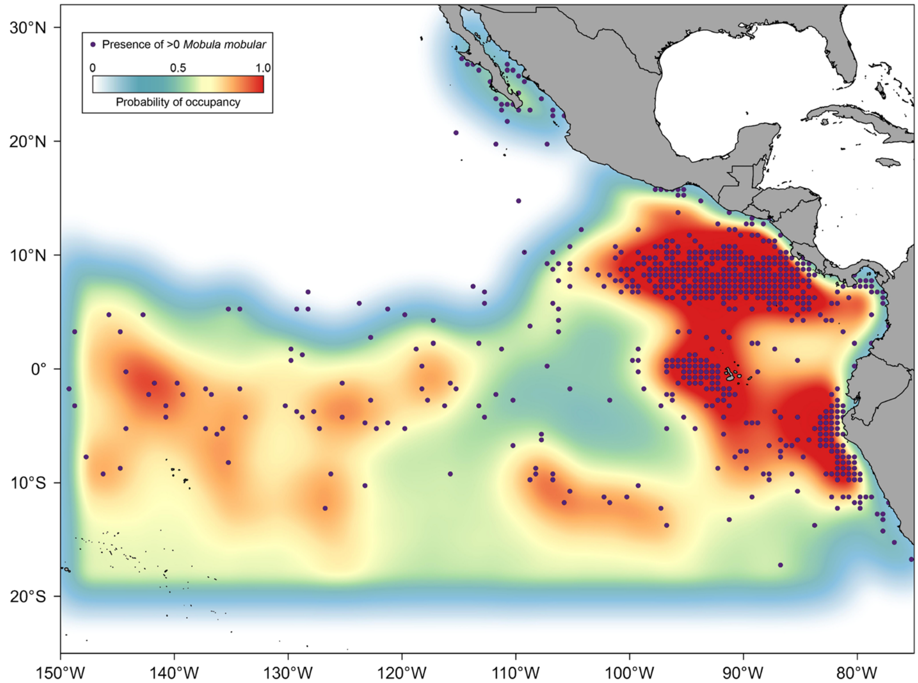

FIGURE 2 Map showing the distribution of *Mobula mobular* in the eastern Pacific Ocean as predicted by the posterior predictive mean of the presence of *M. mobular* bycatch from the tuna purse-seine fishery (Class 6 vessels only) for 2005–2015 from the INLA (Integrated Nested Laplace Approximation) model (Lezama-Ochoa et al., 2020) (0.5 × 0.5° resolution) using a probability-of-occupancy (ψ) threshold of 0.45. Overlaid points show the locations where at least one *M. mobular* was recorded by scientific observers onboard purse-seine vessels

the fishing mortality required to deplete the spawning biomass to 20% of its biomass in the absence of fishing. While $F_{35\%}$ has been an acceptable BRP for some teleosts (Clark, 1991; Ralston, 2002) and elasmobranchs, some authors have suggested a BRP of at least $F_{60\%}$ for species with very low natural mortality rates (Sainsbury, 2008; Brooks, Powers & Cortés, 2010). Therefore, for the purposes of the EASI-Fish assessment, two BRPs ($F_{40\%}$ and $SBR_{40\%}$) were used to determine the vulnerability status of *M. mobular*. Each of the parameters and BRPs are described in detail in the Supporting Information and their values are provided in Table S1.

The vulnerability of *M. mobular* in each hypothetical management scenario was determined using $\tilde{F}$ and the corresponding spawner biomass per-recruit (SBR) values relative to the $\tilde{F}_{40\%}$ and $SBR_{40\%}$ values and displayed on a 'vulnerability phase plot'. This plot is similar to the four-quadrant Kobe plot used in stock assessment for commercially-important species that is familiar to resource managers and scientists (Figure 3). The definitions of these quadrants are: (i) 'Least Vulnerable' (green; $\tilde{F}/\tilde{F}_{40\%}$ <1 and $SBR/SBR_{40\%}$ >1); (ii) 'Increasingly Vulnerable' (orange; $\tilde{F}/\tilde{F}_{40\%}$ >1 and $SBR/SBR_{40\%}$ >1); (iii) 'Most Vulnerable' (red; $\tilde{F}/\tilde{F}_{40\%}$ >1 and $SBR/SBR_{40\%}$ <1); and (iv) 'Decreasingly Vulnerable' (yellow; $\tilde{F}/\tilde{F}_{40\%}$ <1 and $SBR/SBR_{40\%}$ <1). Given that EASI-Fish uses SBR on the *x*-axis, generally only the green and red quadrants are relevant since SBR is maximized in the absence of fishing ($F = 0$) and decays exponentially when exposed to increasing levels of fishing mortality. This means that point estimates of vulnerability will generally be located in the green quadrant where $\tilde{F} > \tilde{F}_{40\%}$ and $SBR < SBR_{40\%}$ and in the red quadrant where $\tilde{F} < \tilde{F}_{40\%}$ and $SBR > SBR_{40\%}$. However, the two-dimensional uncertainty

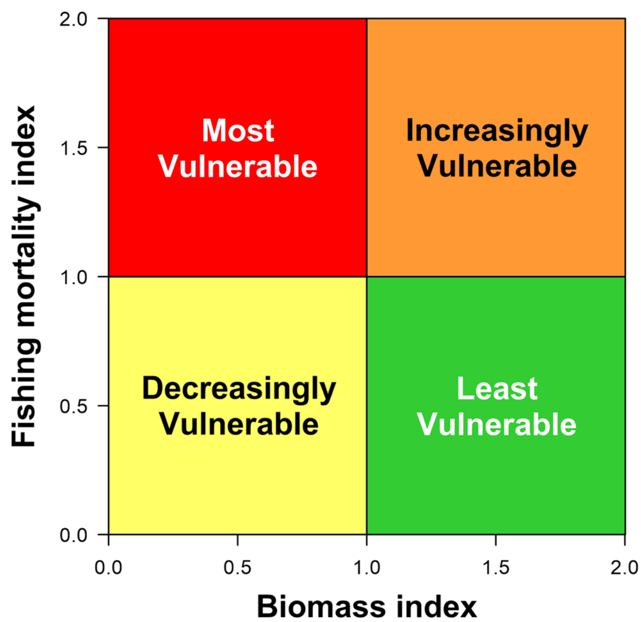

FIGURE 3 Vulnerability phase plot illustrating how vulnerability status was defined for *M. mobular* using $\tilde{F}_{40\%}$ and $SBR_{40\%}$ from the Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish) model as a biological reference point on the *x*- and *y*-axis, respectively. Vulnerability was defined by the position of an annual assessment value within one of four quadrants in the phase plot as: 'Least Vulnerable' (green; $\tilde{F}/\tilde{F}_{40\%}$ <1 and $SBR/SBR_{40\%}$ >1), 'Increasingly Vulnerable' (orange; $\tilde{F}/\tilde{F}_{40\%}$ >1 and $SBR/SBR_{40\%}$ >1), 'Most Vulnerable' (red; $\tilde{F}/\tilde{F}_{40\%}$ >1 and $SBR/SBR_{40\%}$ <1) and 'Decreasingly Vulnerable' (yellow; $\tilde{F}/\tilde{F}_{40\%}$ <1 and $SBR/SBR_{40\%}$ <1). Maximum axis limits of 2.0 are for illustrative purposes only

surface around each point estimate can extend into the orange and yellow quadrants. It should be noted that the nomenclature of the vulnerability categories in EASI-Fish have no relevance to measures or definitions of vulnerability used by other models or organizations, such as the IUCN.

To incorporate uncertainty in the values for EASI-Fish model parameters *G*, natural mortality (*M*), von Bertalanffy growth function parameters (L_∞, *K* and t_0) and maturity ogive parameters (L_{50} and *r*), 10,000 Monte Carlo simulations were run using prior distributions (e.g. normal, triangular or uniform) deemed appropriate for each parameter given the perceived reliability of the data available. The mean and 95% confidence intervals (95% CI) were derived for $\tilde{F}$ and SBR, and the BRPs $\tilde{F}_{40\%}$ and $SBR_{40\%}$ for each scenario.

Although parameter uncertainty was incorporated into the 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. (2019) was used to score the relevance of the data to *M. mobular* for the EPO using a matrix of data quality by ocean basin and taxonomic resolution (Table S5). The parameter quality scores are graphically represented in a radar plot, aiding in the interpretation of relative data quality for each model parameter, primarily to identify key data deficiencies that could affect the vulnerability status.

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

After assessing the vulnerability status of *M. mobular* for each year between 1979 and 2018, specific conservation and management measures for the species were explored – using the 2018 situation as the comparative status quo – in isolation or in concert with length-specific differences in PCM. Forty-five hypothetical scenarios (Table S6) were implemented under four categories as detailed below:

1. *EPO-wide temporal closure* – no closure, 31 days (2002–2003; IATTC Resolution C-02-04), 42 days (2004–2008; C-04-09), 59 days (2009; C-09-01), 62 days (2011–2016; C-11-01 and C-13-01), 72 days (2018–2020; C-17-01), and subsequent increments of an additional 30 days of closure from 90 to 270 days per year.
2. *Changes in handling and release practices of M. mobular to decrease PCM* – current and additional handling practices promoted by the IATTC and its CPCs were assumed to result in decreases in post-capture mortality (PCM) in 10% increments from 100% to 10%.
3. *Size-specific differences in PCM* – the assumed – and precautionary – value of 100% for PCM for all length classes was decreased in 10% increments from 100% to 10% for rays either <150 cm or >150 cm DW to account for the possibility of handling practices having greater efficacy for smaller or larger sizes of rays.
4. *A combination of increased EPO-wide temporal closure duration with plausible PCM values* – EPO-wide closures were maintained at 2018 levels or increased in 30-day increments from 90 to 180 days, combined with plausible PCM values of either 90% or 80%.

For each category of scenarios, specific scenario vulnerability status values were compared with that of the status quo, which was an EPO-wide closure of 72 days, a length at first capture of 50 cm DW (i.e. the length at birth) and an assumed PCM of 100%, given the absence of reliable PCM estimates for *M. mobular* in the EPO. It is important to note that the simulated percentage changed in PCM measures assumes full compliance of this measure by all vessels. Certainly, there may be some vessels that do not fully implement best handling practices that would result in the simulated PCM rate, but in the case of the purse-seine fishery, compliance is likely to be very high given that 100% of trips are monitored by observers, who have the authority to issue an infraction should the measures of the IATTC mobulid resolution (C-15-04) not be adhered to.

3 | RESULTS

3.1 | Historical changes in fishing mortality and vulnerability status

In the early stages of the fishery between 1979 and 1993, the estimated mean (± SD) annual cumulative proxy for fishing mortality ($\tilde{F}$) of *M. mobular* was 0.28 (± 0.02) year^{-1}, with the mean percentage of this mortality contributed by the longline fishery being 89.12 ± 6.87%, and those for NOA, DEL and OBJ fisheries being 5.44 ± 3.32%, 5.19 ± 4.08% and 0.25 ± 0.21%, respectively (Figure 4). Although annual vulnerability increased steadily during this period, the species' vulnerability status was categorized as 'Least Vulnerable' (Figure 5).

From 1994 to 2001 vulnerability continued to increase to the point where the species was deemed 'Most Vulnerable' (Figure 5), which coincided with the spatial expansion of the three purse-seine fisheries (Figure 6) and the marked increase in the annual number of OBJ sets (Figure 1a). In the following years of 2002–2010, vulnerability was variable but generally declined to 'Least Vulnerable' (Figure 5). This was primarily a result of changing spatial distribution of fishing effort relative to the distribution of *M. mobular* coupled with the implementation of an EPO-wide temporal closure for the purse-seine fisheries that increased from 42 to 62 days per year during this period.

During the 2011–2018 period, the average annual fishing mortality increased to 0.39 (± 0.02) year^{-1}. The contribution to $\tilde{F}$ by the longline fishery declined to 61.62 (± 3.60)%, while the combined contribution by the three purse-seine fisheries increased to 38.37 (± 8.56)% (Figure 4). In particular, the contribution by the OBJ fishery to $\tilde{F}$ increased to 18.59 (± 4.01)%, owing to a rapid increase in the number and spatial expansion of OBJ sets (Figures 1a and 6). This coincided with a substantial increase in vulnerability where the species was categorized as 'Most Vulnerable', particularly in the most recent years of the assessment

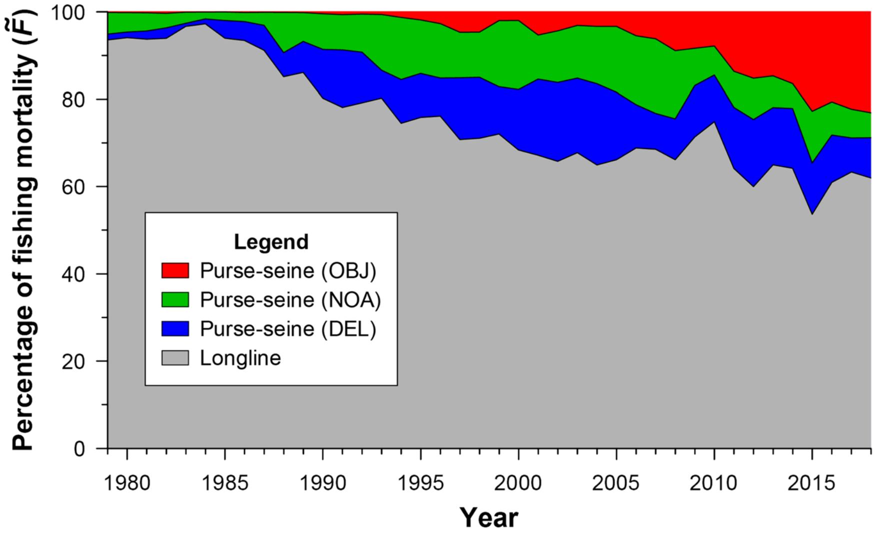

FIGURE 4 Graph showing percentage of the mean annual proxy for fishing mortality ($\tilde{F}$) of *M. mobular* in the EPO for 1979–2018 contributed by the longline fishery (composed of large-scale tuna longline vessels authorized to fish for tunas in the EPO) and the three purse-seine fisheries [comprising Class 6 vessels that set on dolphins (DEL), non-associated tuna schools (NOA) or floating objects (OBJ)]

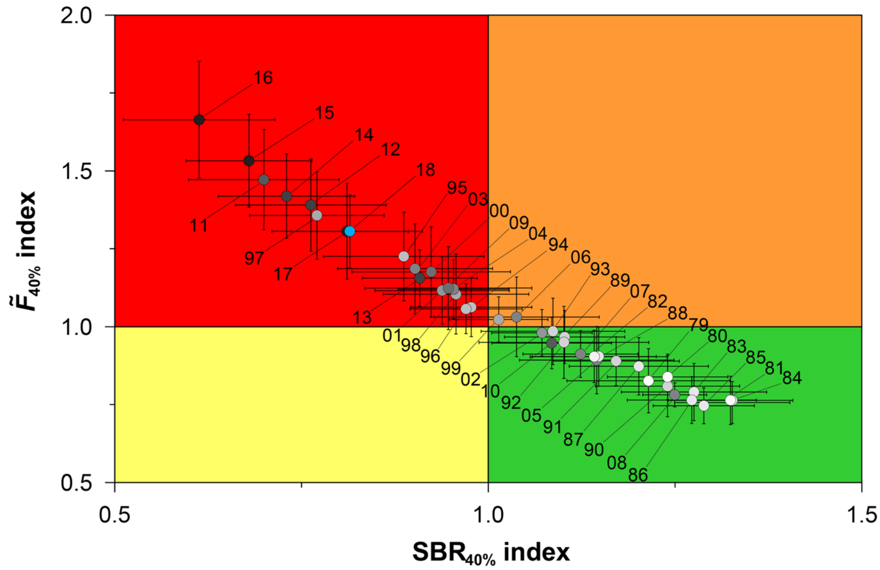

FIGURE 5 Vulnerability phase plot showing the annual status of *M. mobular* for EPO tuna fisheries for 1979–2018 represented by the mean (± 95% confidence intervals) value for biological reference points $\tilde{F}/\tilde{F}_{40\%}$ and SBR/SBR$_{40\%}$. Lighter and darker shaded points show earlier and later years, respectively, and adjacent numbers show the last two digits of the assessment year

period (2015–2018) when closure periods of 62–72 days were in place (Figure 5).

3.2 | Estimates of susceptibility and fishing mortality for 2018

The value for each susceptibility parameter contributing to the overall susceptibility (S_{xj}) estimate in EASI-Fish for 2018 and a description of its derivation are given in Table S1. For the status quo scenario, the horizontal overlap of the longline fishery with the distribution of *M. mobular* was high (89%), mainly owing to the fishery operating across the majority of the species' distribution (Figure 6). With respect to the purse-seine fishery, the percentage of population overlap was lowest for NOA (11%) and DEL (16%) sets and highest for OBJ sets (42%).

Fishing season duration afforded *M. mobular* no protection from the longline fishery (LL) that operates year-round ($D_{LL} = 1.0$), but each purse-seine fishery operated for 80% of the year owing to the 72-day EPO-wide closure.

With a lack of reliable long-term tagging data describing the horizontal movements of *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 all gears effectively fish from the surface to depths of at least 200 m, well beyond the typical depth range of *M. mobular* (0–50 m).

Contact selectivity was highest for the three purse-seine fisheries (C_{DELj}; C_{NOAj}; $C_{OBJj} = 1.0$), for all size classes larger than the length at first capture of 50 cm, owing 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 ($C_{LL} = 0.33$), which is a result of both the depth of hooks used in 'deep sets' (typically around 150–300 m) and the use of fish or squid baits that do not comprise a high proportion of the zooplankton-dominated diets of mobulids (see Sampson et al., 2010).

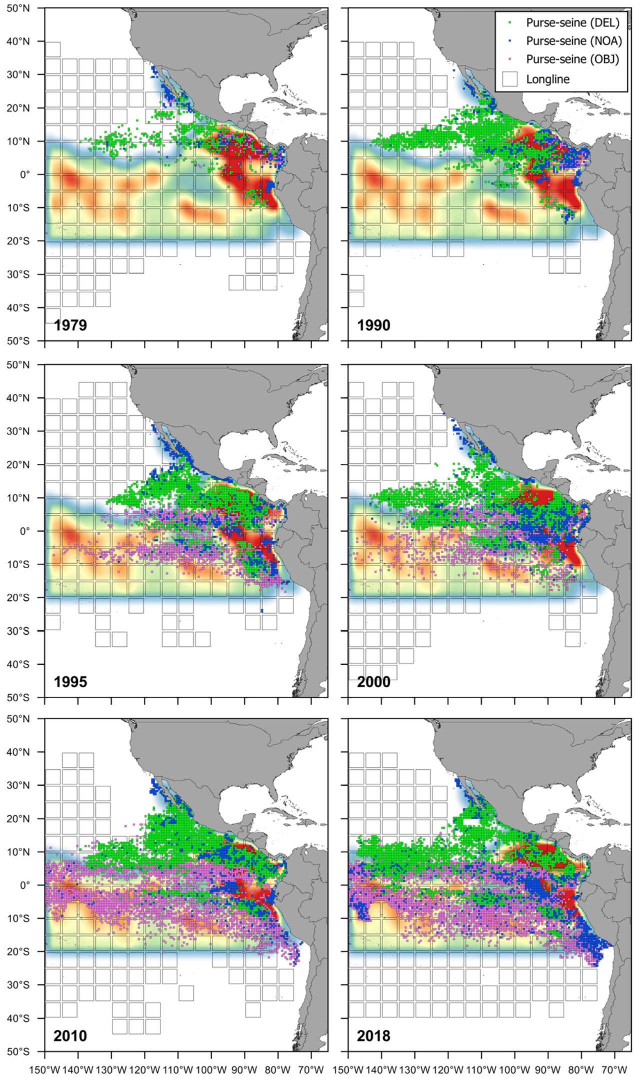

FIGURE 6 Maps showing the distribution of effort by the three set types in the purse-seine fishery (Class 6 vessels only; 0.5 × 0.5°) and the large-scale tuna longline fishery (5 × 5°) in 2018 relative to the habitat distribution of *M. mobular* predicted by the INLA model based on presence-only catch records, and in this graphic, using a probability-of-occupancy (ψ) threshold of 0.45

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

Under the status quo scenario in 2018, the estimated cumulative fishing mortality rate ($\tilde{F}_{2018}$) was 0.39 year^{-1}, with the longline fishery contributing 61.95% ($\tilde{F} = 0.24$ year^{-1}). The purse-seine fisheries OBJ, DEL and NOA contributed 23.12% ($\tilde{F} = 0.09$ year^{-1}), 9.23% ($\tilde{F} = 0.04$ year^{-1}) and 5.70% ($\tilde{F} = 0.02$ year^{-1}) to the cumulative fishing mortality, respectively.

3.3 | Impacts of conservation and management measures on vulnerability status

The biological parameter values, and their sources, used in empirical equations and the per-recruit models for *M. mobular* are shown in Table S3, while estimates of $\tilde{F}_{2018}$ and SBR_{2018} and the $\tilde{F}_{40\%}$ and $SBR_{40\%}$ BRPs are provided in Table 1.

Under the status quo scenario for 2018, $\tilde{F}_{2018}$ and SBR_{2018} exceeded $\tilde{F}_{40\%}$ and $SBR_{40\%}$, resulting in the classification of *M. mobular* as 'Most Vulnerable' (Figure 5; Table 1). Scenarios involving an EPO-wide closure of the purse-seine fishery showed that having no closure resulted in the highest vulnerability value of any of the 45 hypothetical scenarios, indicating that some level of temporal closure is likely to decrease vulnerability. Increasing the duration of the EPO closure reduced vulnerability, although the species' classification only changed from 'Most Vulnerable' to 'Least Vulnerable' when closure periods of greater than 210 days were applied (Figure 7a).

Hypothetically improving best handling and release practices to reduce PCM resulted in some of the largest decreases in vulnerability compared with the status quo scenario. Scenarios where PCM was 80% or less resulted in a change in vulnerability status from 'Most Vulnerable' to 'Least Vulnerable' (Figure 7b).

Scenarios involving a combination of conservation and management measures – reducing PCM for fish <150 cm or >150 cm DW – produced very similar results with substantial decreases in vulnerability resulting from decreasing PCM to at least 70% for rays either <150 cm (Figure 6c) or >150 cm (Figure 6d).

The second category of scenarios that involved a combination of conservation and management measures – reducing PCM coupled with increasing the EPO-wide temporal closure period – resulted in substantial reductions in vulnerability. Scenarios where the classification changed to 'Least Vulnerable' were using 90% PCM combined with at least a 150-day closure (Figure 7e), or an 80% PCM combined with a closure period of at least 72 days (Figure 7f). Overall, of the 45 hypothetical conservation and management measures scenarios, 31 resulted in a desirable change in vulnerability status to 'Least Vulnerable' (Table 1).

The radar plot in Figure 8 shows that data used for *M. mobular* had reasonably high reliability scores of 6 or more for each parameter and thus, the species can be regarded as a legitimate 'Most Vulnerable' species in 2018, that is, it is unlikely that the species is a false positive. The lowest data scores were for the length–weight relationship (6) (used to convert lengths to biomass in the per-recruit models), natural mortality (7) and reproductive parameters and maximum age (8). Together, the uncertainty in these parameters may have slightly overestimated the true vulnerability of *M. mobular*, although any bias in vulnerability estimates owing to parameter value quality would be in the same direction and of similar magnitude for each scenario.

4 | DISCUSSION

Ecological risk assessments have 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

TABLE 1 Estimated mean values for fishing mortality ($\tilde{F}_{2018}$) and spawner biomass per recruit (SBR_{2018}) reference points derived from the Ecological Assessment of the Sustainable Impacts of Fisheries (EASI-Fish) model for *Mobula mobular* caught in tuna fisheries in the eastern Pacific Ocean in 2018 under various hypothetical conservation and management measures

Scenario	Scenario no.	$\tilde{F}_{2018}$	SBR_{2018}	$\tilde{F}_{40\%}$	$SBR_{40\%}$	$\tilde{F}_{2018}/\tilde{F}_{40\%}$	$SBR_{2018}/SBR_{40\%}$
2018 status quo							
72 day PS closure; PCM 100%; $L_c = 50$ cm	1	0.379	363.039	0.250	551.213	1.522	0.670
EPO-wide closure of the purse-seine fishery							
0 day PS closure; PCM 100%; $L_c = 50$ cm	2	0.416	253.997	0.244	455.118	1.712	0.573
90 day PS closure; PCM 100%; $L_c = 50$ cm	3	0.370	352.101	0.260	498.994	1.427	0.714
120 day PS closure; PCM 100%; $L_c = 50$ cm	4	0.355	393.028	0.266	506.199	1.337	0.784
150 day PS closure; PCM 100%; $L_c = 50$ cm	5	0.340	415.787	0.276	511.032	1.225	0.840
180 day PS closure; PCM 100%; $L_c = 50$ cm	6	0.324	416.724	0.288	463.730	1.127	0.906
210 day PS closure; PCM 100%; $L_c = 50$ cm	7	0.309	409.570	0.300	413.243	1.033	0.980
240 day PS closure; PCM 100%; $L_c = 50$ cm	8	0.294	473.080	0.314	435.911	0.940	1.101
270 day PS closure; PCM 100%; $L_c = 50$ cm	9	0.280	526.139	0.322	461.117	0.872	1.180
Reduction in post-capture mortality for all size classes							
72 day PS closure; PCM 90%; $L_c = 50$ cm	10	0.336	455.446	0.276	535.463	1.223	0.868
72 day PS closure; PCM 80%; $L_c = 50$ cm	11	0.296	483.261	0.310	449.188	0.956	1.089
72 day PS closure; PCM 70%; $L_c = 50$ cm	12	0.255	557.759	0.350	422.229	0.730	1.325
72 day PS closure; PCM 60%; $L_c = 50$ cm	13	0.215	752.212	0.400	478.247	0.538	1.578
72 day PS closure; PCM 50%; $L_c = 50$ cm	14	0.178	998.403	0.454	556.764	0.392	1.799
72 day PS closure; PCM 40%; $L_c = 50$ cm	15	0.140	933.488	0.578	462.758	0.244	2.025
72 day PS closure; PCM 30%; $L_c = 50$ cm	16	0.104	1,142.642	0.742	517.908	0.140	2.211
72 day PS closure; PCM 20%; $L_c = 50$ cm	17	0.069	1,312.986	1.086	549.620	0.063	2.390
72 day PS closure; PCM 10%; $L_c = 50$ cm	18	0.034	1,225.187	2.162	492.856	0.016	2.486
Reduction in post-capture mortality for rays <150 cm							
72 day PS closure; PCM 90%; $L_c = 50$ cm	19	0.367	188.072	0.342	188.742	1.301	0.808
72 day PS closure; PCM 80%; $L_c = 50$ cm	20	0.347	189.374	0.285	87.330	1.118	0.930
72 day PS closure; PCM 70%; $L_c = 50$ cm	21	0.326	191.232	0.335	172.208	0.970	1.016
72 day PS closure; PCM 60%; $L_c = 50$ cm	22	0.307	276.746	0.385	208.416	0.870	1.140
72 day PS closure; PCM 50%; $L_c = 50$ cm	23	0.288	161.762	0.373	124.248	0.750	1.250
72 day PS closure; PCM 40%; $L_c = 50$ cm	24	0.270	333.056	0.437	227.152	0.647	1.380
72 day PS closure; PCM 30%; $L_c = 50$ cm	25	0.251	216.342	0.402	144.676	0.550	1.500
72 day PS closure; PCM 20%; $L_c = 50$ cm	26	0.234	280.374	0.483	163.364	0.480	1.620
72 day PS closure; PCM 10%; $L_c = 50$ cm	27	0.217	337.219	0.522	189.750	0.447	1.723
Reduction in post-capture mortality for rays >150 cm							
72 day PS closure; PCM 90%; $L_c = 50$ cm	28	0.365	246.848	0.355	239.881	1.300	0.800
72 day PS closure; PCM 80%; $L_c = 50$ cm	29	0.343	183.616	0.333	172.503	1.095	0.950
72 day PS closure; PCM 70%; $L_c = 50$ cm	30	0.322	152.280	0.355	134.484	0.931	1.084
72 day PS closure; PCM 60%; $L_c = 50$ cm	31	0.302	278.318	0.382	219.803	0.841	1.189
72 day PS closure; PCM 50%; $L_c = 50$ cm	32	0.282	139.400	0.320	119.107	0.740	1.300
72 day PS closure; PCM 40%; $L_c = 50$ cm	33	0.262	250.911	0.437	166.775	0.633	1.430
72 day PS closure; PCM 30%; $L_c = 50$ cm	34	0.244	228.601	0.432	145.034	0.550	1.530
72 day PS closure; PCM 20%; $L_c = 50$ cm	35	0.224	415.534	0.517	240.369	0.447	1.694
72 day PS closure; PCM 10%; $L_c = 50$ cm	36	0.206	264.695	0.578	146.238	0.373	1.813

(Continues)

TABLE 1 (Continued)

Scenario	Scenario no.	$\tilde{F}_{2018}$	SBR_{2018}	$\tilde{F}_{40\%}$	$SBR_{40\%}$	$\tilde{F}_{2018}/\tilde{F}_{40\%}$	$SBR_{2018}/SBR_{40\%}$
EPO-wide closure and post-capture mortality reduced to 90% for all size classes							
72 day PS closure; PCM 90%; $L_c = 50$ cm	37	0.336	443.014	0.274	518.063	1.228	0.864
90 day PS closure; PCM 90%; $L_c = 50$ cm	38	0.328	350.732	0.294	382.094	1.118	0.924
120 day PS closure; PCM 90%; $L_c = 50$ cm	39	0.314	447.389	0.296	459.089	1.064	0.988
150 day PS closure; PCM 90%; $L_c = 50$ cm	40	0.301	470.481	0.306	460.259	0.984	1.035
180 day PS closure; PCM 90%; $L_c = 50$ cm	41	0.287	561.723	0.314	520.270	0.919	1.100
EPO-wide closure and post-capture mortality reduced to 80% for all size classes							
72 day PS closure; PCM 80%; $L_c = 50$ cm	42	0.302	324.525	0.350	276.831	0.972	1.076
90 day PS closure; PCM 80%; $L_c = 50$ cm	43	0.295	217.188	0.358	160.046	0.916	1.140
120 day PS closure; PCM 80%; $L_c = 50$ cm	44	0.283	265.729	0.377	200.452	0.847	1.198
150 day PS closure; PCM 80%; $L_c = 50$ cm	45	0.269	195.372	0.360	146.651	0.788	1.260
180 day PS closure; PCM 80%; $L_c = 50$ cm	46	0.258	289.935	0.413	192.567	0.726	1.321

Abbreviations: L_c, length at first capture; PCM, post-capture mortality; PS, purse-seine.

Note: Colours indicate scenarios where *M. mobular* is classified as 'Most Vulnerable' (red) or 'Least Vulnerable' (green), where $\tilde{F}_{2018}$ and SBR_{2018} exceed, or are less than, the $\tilde{F}_{40\%}$ and $SBR_{40\%}$ reference points, respectively.

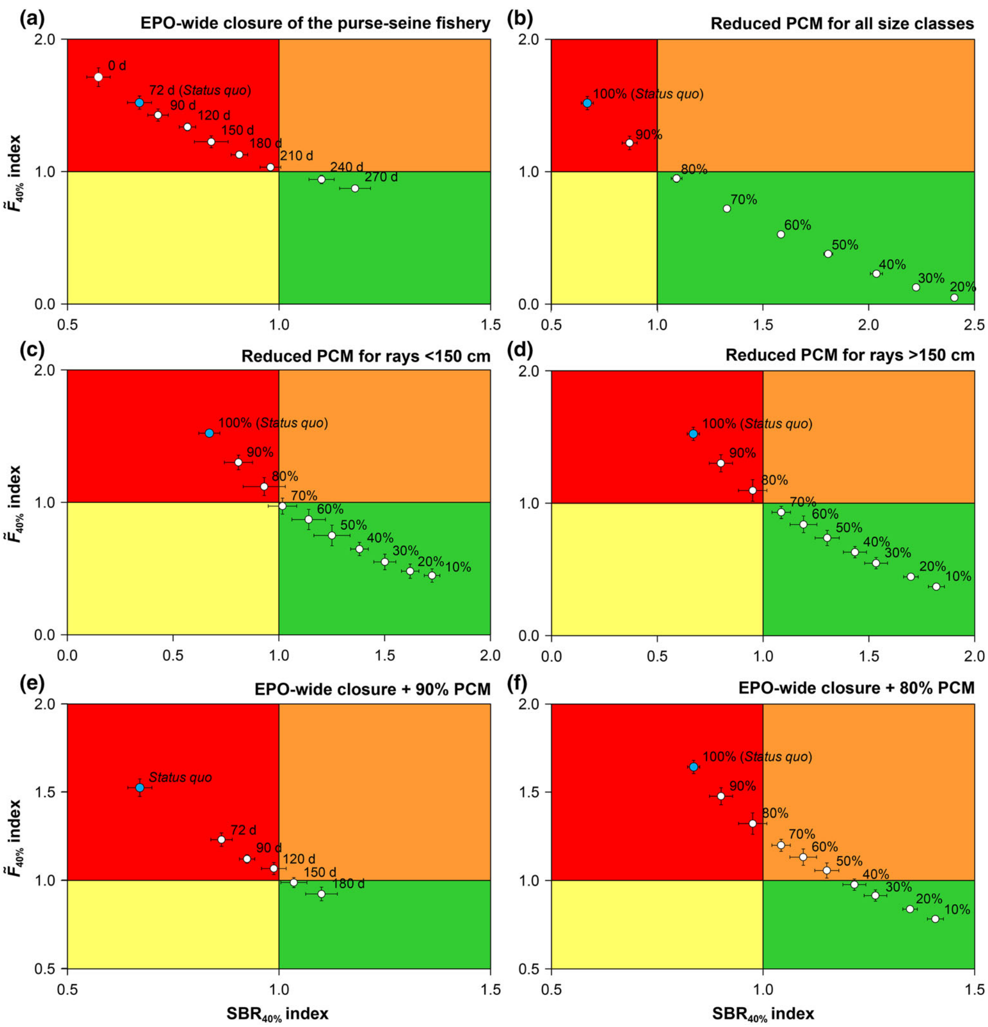

FIGURE 7 Vulnerability phase plots showing the status of *M. mobular* under the 2018 effort regime for EPO tuna fisheries represented by the mean (± 95% confidence intervals) value for biological reference points $\tilde{F}_{2018}/\tilde{F}_{40\%}$ and $SBR_{2018}/SBR_{40\%}$ for 45 hypothetical conservation and management scenarios. Note that the blue symbol in each plot shows the vulnerability status under the status quo fishing effort and management scenario in 2018 (Scenario 1) for comparison with other scenarios. Numbers adjacent to each point show number of closure days (d) for the entire EPO or the percentage of the catch that incurs post-capture mortality (PCM). Specific biological reference point values for each of the 46 scenarios are provided in Table 6

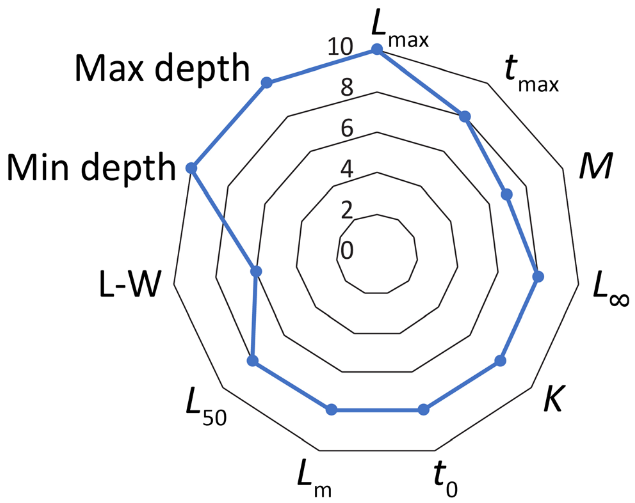

FIGURE 8 Radar plot showing the relative quality of biological and ecological parameters [L_{max}, t_{max} (maximum age), natural mortality (*M*), von Bertalanffy growth function parameters (L_∞, *K* and t_0), L_m, L_{50}, length–weight relationship (L-W), minimum and maximum depth] used in EASI-Fish for *M. 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)

more formal stock assessment (Hobday et al., 2011). There have been at least three ecological risk assessments undertaken on species impacted by individual tuna fisheries in the EPO (Griffiths, Duffy & Aires-da-Silva, 2017; Duffy et al., 2019; Griffiths et al., 2019), each indicating that *M. mobular* is among the most vulnerable species for the specific fishery and years assessed. The present study, however, was able to provide a quantitative estimate of the progressive increase in the cumulative impacts of 40 years of industrial purse-seine and longline fishing on the vulnerability of *M. mobular* in the EPO – assuming that the species' distribution did not change substantially during this period.

An interesting result was that the longline fishery contributed most to the cumulative fishing mortality throughout the entire history of the industrial tuna fishery in the EPO. Mobulids are caught by longlines in industrial fisheries operating on the high seas (Coelho et al., 2012; Mas, Forselledo & Domingo, 2015) and in smaller-scale domestic commercial and artisanal fisheries within the exclusive economic zones of coastal states in the EPO (Cartamil et al., 2011; Swimmer et al., 2011). However, they are mostly caught after becoming foul hooked or entangled in the mainline, branchlines or floatlines of the gear rather than being hooked by consuming a bait (see Mas, Forselledo & Domingo, 2015). As a result, longline fisheries have generally been considered to have less of an impact on mobulid populations compared with gillnet, trawl, harpoon and purse-seine fisheries, which are more selective for mobulids, either as a target or bycatch species (Couturier et al., 2012; Croll et al., 2016). Based on this information, a low contact selectivity value (0.33) was used for the EPO longline fishery. Therefore, the high estimated fishing mortality can be primarily attributed to the high horizontal overlap (89%) of the longline fishery with the distribution of *M. mobular*. It is important to point out that this overlap is probably overestimated owing to the fishing effort data for this fishery being available only at a coarse spatial resolution (5 × 5°) compared with the species distribution map (0.5 × 0.5°). Thus, the presence of longline fishing effort in a 5° grid cell will be interpreted in the model as a presence of effort in each of the one hundred 0.5° grid cells contained within the 5° grid cell. Given the dearth of species-specific bycatch information available for the longline fishery in the EPO, this mismatch in data resolution essentially provides a conservative 'worst case' scenario with respect to the longline fishery impact on *M. mobular*. This also highlights one of the key advantages of EASI-Fish in that the results can be used to identify knowledge gaps that can guide fishery managers in prioritizing data collection, research and management needs to reduce fishing impacts on vulnerable species. In the case of *M. mobular*, the reporting of longline effort data to the IATTC at spatial scales equivalent to the species distribution map will probably reduce the number of 0.5° grid cells that are attributed with a presence of effort by default, and therefore provide a more precise estimate of the horizontal overlap of fishing effort on the species' distribution. Although a requirement for CPCs of the IATTC to report operational level observer data for the longline fishery entered into force in 2019 (IATTC Resolution C-19-08), species-specific information on interactions with *M. mobular* – and other non-target species – is currently limited, but data may soon be available at a high spatial resolution. Unfortunately, the minimum required observer coverage under Resolution C-19-08 is currently only 5% of the fleet, which is often not met by some CPCs. Given the high cost for CPCs – many of which being developing states – to observe all sets, the only feasible options for increasing the spatial resolution of effort day may be to employ less expensive data collection methods such as electronic monitoring (see Gilman et al., 2020) or to increase the minimum required spatial resolution of effort data reported in logbooks.

Despite the fishing mortality by the longline fishery being the highest of all fisheries, it remained reasonably stable over time, whereas the fishing mortality by the purse-seine fishery increased substantially over time, which was the primary driver in the increase in vulnerability of *M. mobular*, particularly since 2011. The increase in vulnerability appeared to be driven primarily by the progressive westward expansion of the purse-seine fishery in the eastern tropical Pacific region (Figure 6). However, the increase in vulnerability was particularly evident after 1993 with the beginning of a steady and significant increase in the number of purse-seine sets made on floating objects, which has continued to 2019 at a rate of about 46% over the preceding 5-year period (Figure 1a). Although OBJ sets account for the lowest mobulid bycatch rates in the EPO purse-seine fishery, the increase in the magnitude of effort and the fishery's spatial footprint, especially after 2010, appeared sufficient to have a detectable impact on the vulnerability status of *M. mobular*.

4.1 | Spatial–temporal closures

There are various conservation and management measures 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), spatial and/or temporal closures are 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. An example of such an approach in the EPO is the annual 30-day closure of the 'corralito', a small and highly productive region north west of the Galapagos Islands where juvenile tuna are abundant at specific times of the year. This measure was originally implemented by the IATTC in 2004 as an attempt to reduce fishing mortality on juvenile bigeye tuna (*Thunnus obesus*). Harley & Suter (2007) showed that spatial–temporal closures of the corralito and other identified catch 'hotspots' reduced the annual bigeye catch by up to 24%. However, these closures alone did not result in a substantive reduction in fishing mortality, leading to their recommendation to increase the area and duration of closures to incorporate the entire stock. The IATTC has since implemented an EPO-wide closure to purse-seine fishing for varying periods – depending on the stock status of the principal tuna species – from 31 days in 2002–2003 to 72 days for 2018–2020. This has reduced the overall fishing mortality of the principal tuna species, but the recent increase in the number (and likely efficiency) of sets made on floating objects has increased the fishing mortality on younger age classes (Minte-Vera et al., 2020; Xu et al., 2020). Therefore, an EPO-wide closure has not been a panacea in avoiding overexploitation of these data-rich tuna species and so other precautionary management strategies are required, especially for non-target species such as mobulids (IATTC, 2020).

Given that there appears to be no single management measure that can fulfil conservation targets for the principal tuna species in EPO tuna fisheries, it is not surprising that the potential management options simulated by EASI-Fish for *M. mobular* in the EPO proved equally complex. Our results from simulating various temporal closures complemented the results of Harley & Suter (2007) in that the duration of recent EPO-wide closures (i.e. 62 and 72 days) reduced the vulnerability of *M. mobular*, but were insufficient to result in changes to the species' vulnerability status, unless the closure period was at least 210 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, which will obviously have negative economic impacts throughout the entire fishery supply chain, involving many developing states.

4.2 | Reducing post-capture mortality as a conservation and management measure

The only feasible scenarios that reduced the vulnerability status of *M. mobular* to 'Least Vulnerable' involved reductions in PCM, that are presumed to have occurred with improved handling and release practices, such as those suggested by Poisson et al. (2014) and subsequently recommended by the IATTC in Resolution C-15-04. These practices include:

- small rays being handled by two to three people and being carried by the side of the animal's pectoral fins;
- avoidance of dragging or lifting the ray by its cephalic lobes, gill slits or spiracles;
- large rays being 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;
- the use of a cargo net or canvas sling to lift the ray by crane and gently release it overboard;
- avoidance of the use of wire around or through the animal to tow or lift it; and
- prohibition of gaffing or the punching of holes through the body (e.g. to pass a cable through for lifting).

IATTC observers have been recording the catch of mobulids in the purse-seine fishery since 1993, but their release condition has only been recorded since 2017. Therefore, it is difficult to glean any reliable indication of the potential extent of PCM from this short-term dataset alone, and delayed mortality cannot be estimated without tagging. In the absence of reliable data relating to PCM in the longline fishery and the three purse-seine set types, we therefore made the precautionary assumption that PCM was 100% for each fishery. However, it should be noted that there is some limited evidence suggesting there is some survival of released mobulids. For example, in a study conducted in a New Zealand purse-seine fishery, Francis & Jones (2017) tagged nine *M. mobular* with pop-up satellite archival tags of which four died – a post-release mortality rate of 44%. A pilot study examining the post-release mortality of *M. mobular* caught by purse-seine in the tropical EPO tagged five specimens with pop-up satellite archival tags, of which only one (20%) died (Stewart et al., 2018).

There is also some evidence to suggest that the PCM of mobulids may be reasonably low for longline fisheries. For example, in the Atlantic Ocean longline fishery the at-vessel mortality rate was estimated to range between 1.4% (Coelho et al., 2012) and 5.4% (Mas, Forselledo & Domingo, 2015). Therefore, a recommendation from the present study would be to undertake electronic tagging studies for both purse-seine and longline fisheries to quantify at-vessel mortality and PCM rates for *M. mobular*. These studies would be of benefit by quantifying PCM using best handling and release practices, such as release directly from the purse-seine, compared with 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. This is a particularly important consideration since our simulations showed that reducing PCM on only small (<150 cm) or large rays (>150 cm) is less effective in reducing vulnerability compared with reducing PCM for all size classes. PCM studies would also benefit from the collection of blood samples that could help determine which environmental and fishing operation variables may differentially affect the survival of *M. mobular* (e.g. release condition, number of operational brailers), which has been suggested in PCM studies for other elasmobranch species (Musyl et al., 2011; Hutchinson et al., 2015; Musyl & Gilman, 2018).

It may be fortuitous that improving PCM has the potential to have such a significant positive effect in reducing 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 more cost-effective to implement – if all fishers maintain a high level of care in the recommended release procedures over time – than temporal closures to reduce the capture of *M. mobular*. However, it is important to consider that the efficacy of best handling and release practices was assumed to be a result of complete adoption and implementation by all vessels in the EPO tuna fishery. Although full adherence to these practices is likely to occur for the purse-seine fishery where all trips are monitored by observers, the longline fishery and other smaller domestic and artisanal fisheries that have little or no observer coverage may not reach simulated PCM rates without the full cooperation of fishers. Therefore, the true PCM may be higher than simulated and the estimated vulnerability be underestimated as a result.

4.3 | Implications for management, data collection and research

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, estimating $\tilde{F}$ and ultimately the vulnerability status. The present study used the INLA approach, designed for modelling the habitat of data-limited species (Lezama-Ochoa et al., 2020). INLA, like all models, has its own sources of uncertainty, which were accounted for by running EASI-Fish using a range of plausible ψ values. However, such distribution models would benefit from the inclusion of tagging data – a value-add from the aforementioned the PCM electronic tagging study – to validate predicted distribution boundaries. Such tagging data would also provide information on vertical movements that may provide a better understanding of the species' encounterability of particular fishing gears (Stewart, 2018; Lezama-Ochoa et al., 2019b).

A further consideration after improving species distribution models is to develop separate distribution maps for each assessment year. The present study required the use of a single species distribution map since only a relatively small number of occurrences of *M. mobular* have been recorded by observers in EPO tuna fishery catches since 1993 when elasmobranchs began to be recorded to the level of species. It is hoped that ongoing improvements to the purse-seine observer programme and the recent IATTC mandate under Resolution C-19-08 for observers onboard longline vessels to submit operational-level catch and effort data will provide mobulid interaction data of sufficient quality to allow reliable annual species distribution maps to be created to improve future EASI-Fish assessments.

A major consideration in this assessment is that all fisheries that impact *M. mobular* in the EPO are not included. *Mobula* species are caught as a target, or as bycatch, in small-scale commercial or artisanal fisheries in many coastal Latin America States – often in far higher numbers than in industrial purse-seine and longline fisheries in the EPO – such as Mexico (Bizzarro et al., 2009; Smith, Bizzarro & Cailliet, 2009), Costa Rica (Swimmer et al., 2011; Whoriskey, Arauz & Baum, 2011), Ecuador (Martínez-Ortiz et al., 2015) and Peru (Alfaro-Cordova et al., 2017). In particular, the Gulf of California is regarded as a 'hotspot' for mobulid rays and purported to have been highly impacted by gillnet fisheries for decades (Croll et al., 2016).

Unfortunately, interactions with non-target species in the large, diverse and disparate artisanal fisheries distributed throughout the Americas are generally documented poorly, if at all (Salas et al., 2007). EASI-Fish was designed to overcome the major obstacle for vulnerability assessments of requiring detailed catch data by estimating fishing mortality from the 'volumetric overlap' of fishing effort overlaid on the species' habitat distribution. However, spatially explicit fishing effort is also lacking for many of these small-scale fisheries, and so they were unable to be included in our assessment. As a result, the estimated fishing mortality and subsequent vulnerability status for each hypothetical scenario in the present study is likely to be underestimated and should be regarded as the species' minimum vulnerability to fishing. However, the IATTC is currently collaborating with Central American IATTC CPCs to improve data collection programmes for these small-scale coastal fisheries (Oliveros-Ramos et al., 2019). Therefore, future assessments of *M. mobular* and other bycatch species are expected to improve as more data become available.

EASI-fish was primarily developed as a tool for assessing the vulnerability of data-poor bycatch species and allowing prioritization of 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. Although the results concurred with those of a recent qualitative assessment of the tuna purse-seine fishery in the EPO that classified *M. mobular* as highly vulnerable (Duffy et al., 2019), this study demonstrated the flexibility and utility of EASI-Fish for quantifying changes in the species' vulnerability through time as a result of changing fishing effort regimes. Furthermore, it easily allows the exploration of the efficacy of potential conservation and management measures and also the identification key data gaps for data-poor species that are impacted by multiple fisheries, rather than defaulting to investing resources into expensive data collection programmes that can prolong the assessment process, delay the implementation of management measures and increase the risk of further population decline in vulnerable species such as *M. mobular*.

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AUTHOR CONTRIBUTIONS

Shane Griffiths and Nerea Lezama-Ochoa conceived the study, gathered required fishery and biological data for modelling, and wrote the manuscript. Nerea Lezama-Ochoa developed and ran the species distribution models and developed the species distribution maps. Shane Griffiths developed the EASI-Fish model, ran the model simulations, and summarized, tabled and graphed the results.

CONFLICT OF INTEREST

The authors confirm that they have no conflict of interest to declare.

ORCID

Shane P. Griffiths https://orcid.org/0000-0002-4418-6666
Nerea Lezama-Ochoa https://orcid.org/0000-0003-3106-1669

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SUPPORTING INFORMATION

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