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VULNERABILITY ASSESSMENT AND SIMULATION OF POTENTIAL CONSERVATION AND MANAGEMENT MEASURES FOR SILKY AND HAMMERHEAD SHARKS CAUGHT IN EASTERN PACIFIC OCEAN PELAGIC FISHERIES

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SUMMARY

Silky and hammerhead sharks are frequently caught—either as a target or incidental catch (i.e., bycatch)—in the industrial and artisanal pelagic fisheries in the eastern Pacific Ocean (EPO). These species are slow growing, long-lived, and have low reproductive output, leading to concerns about their long-term sustainability in the EPO. In 2016, the IATTC implemented Resolution C-16-05, which called for, among other things, a workplan to complete stock assessments for four species: silky shark (*Carcharhinus falciformis*), scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*Sphyrna mokarran*), and smooth hammerhead (*Sphyrna zygaena*). However, a lack of reliable long-term time series of abundance has hampered stock assessments for silky shark, which was attempted by the IATTC in 2014 and expanded to a Pacific-wide stock assessment in 2018.

To address this critical data need, the IATTC has conducted research to develop shark sampling programs in Central America. In the meantime, the IATTC has used the EASI-Fish ecologically risk assessment approach developed by IATTC staff for data-limited species and fisheries, to assess the vulnerability of these species under 43 hypothetical scenarios involving practical conservation and management measures (CMMs)—used in isolation and concert—to guide future research and management efforts.

Several of the 43 CMM scenarios resulted in a significant reduction in the vulnerability status of all four species, although none resulted in a species being reclassified as "least vulnerable". The CMMs having the greatest positive impact was similar for all four species, imposing EPO-wide closures of 120 or 180 days, especially for the industrial longline fishery, due to its large spatial effort footprint that overlaps significantly with the distribution of the four species. Although other scenarios such as banning wire traces, imposing a 100 cm total length minimum retention length for all sharks, and even prohibiting landing of all sharks was predicted to greatly reduce at-vessel mortality, this positive effect on vulnerability was mostly negated due to high post-release mortality of these species. These results highlighted that the most effective mitigation measure for these sharks is to avoid interaction with EPO fisheries. However, there are significant socioeconomic factors to consider, as temporary fishery closures, especially for industrial and artisanal longline fisheries, are likely to greatly reduce the catch of target species (e.g., tuna and billfish) or move effort to the eastern region of the western and central Pacific Ocean where these fisheries may continue to impact the species that the measure was designed to protect.

An order of magnitude estimate of the catches of silky and hammerhead sharks by artisanal fisheries of coastal states in the EPO indicate that these catches are likely to be significantly higher than previously estimated (SAC-14 INF-L). These results are inconsistent with the EASI-Fish results showing that the relative impact across fisheries is heavily dominated by the industrial longline fishery. This indicates that improvements in data and assumptions in the EASI-fish analysis could potentially be made. For example, sensitivity analyses were conducted and showed that model results were sensitive to catchability estimates for each fishery and the coarse spatial resolution of data reported to the IATTC by the industrial longline fishery and therefore, require further investigation.

The assessment identified several major data gaps that need to be addressed through a strategic collaborative research approach between the IATTC and its CPCs, including basic biology and improved species-specific catch and size composition data in artisanal fisheries and the industrial longline fishery. Addressing these data needs will not only help to improve short-term rapid assessments such as EASI-Fish, but also develop longer-term time series data required to undertake new and conventional methods such as close-kin mark recapture or traditional stock assessments from the which population status of these vulnerable species can be determined.

1. INTRODUCTION

Sharks are high order predators in all marine ecosystems of the world, playing a crucial role in regulating ecosystem structure and function by applying top-down predation pressure on various prey across multiple trophic levels, from cephalopods to large marine mammals (Kitchell et al., 2002; Myers et al., 2007; Baum and Worm, 2009). Sharks share similar habitats and prey as commercially important pelagic species like tuna and billfish, which makes them an unavoidable incidental catch (i.e., bycatch), by industrial and artisanal pelagic fisheries. However, in some pelagic fisheries, sharks are a particularly important target species, or at least a retained bycatch. Unfortunately, sharks are generally long-lived, slow growing, and have low reproductive potential, which raises conservation concerns for many species impacted by fishing. These traits makes them less resilient to fishing pressure than tunas and billfish, which are fast-growing, early maturing, and highly fecund (Schindler et al., 2002). Consequently, tuna fisheries have the potential to compromise the long-term sustainability of shark populations and disrupt the ecological processes of marine ecosystems (Kitchell et al., 2002).

The Inter-American Tropical Tuna Commission (IATTC) has formally recognized the potential negative ecological consequences of tuna fisheries and adopted an ecosystem approach to the management of its tuna fisheries in the eastern Pacific Ocean (EPO). The Antigua Convention (IATTC, 2003), which entered into force in 2010, includes Article VII 1(f) that requires the IATTC to "*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…*". In particular, the IATTC has implemented a range of conservation and management measures since at least 2005 to limit or prohibit the capture of sharks, or to encourage handling practices that maximize their post-release survival (C-16-05). This is especially important for species of high conservation concern such as the whale shark (C-19-06) and oceanic whitetip shark (C-11-10).

Unfortunately, many shark species in the EPO lack sufficient catch and biological data to undertake conventional stock assessment to determine their population status under, from which fishery managers can use to take management action, if required. However, the Antigua Convention requires the application of the precautionary approach (Article IV) whereby "*the absence of adequate scientific information shall not be used as a reason for postponing or failing to take conservation and management measures*". To address this issue, the IATTC formalized a research strategy for data-limited bycatch species, including sharks in their 2018–2023 Strategic Science Plan (SSP) to "*develop analytical tools to identify and prioritize species at risk*". The staff achieved this goal through the development of a flexible spatially-explicit quantitative ecological risk assessment approach called the Ecological Assessment of Sustainable Impacts of Fisheries (EASI-Fish). This approach is specifically designed to quantify the cumulative impacts of multiple fisheries for data-limited bycatch species (Griffiths et al., 2019).

The utility of EASI-Fish was first demonstrated for the purpose of prioritizing vulnerability of 24 bycatch species, including epipelagic and mesopelagic teleosts, elasmobranchs, sea turtles, and cetaceans caught in EPO tuna fisheries (Griffiths et al., 2019). Subsequently, EASI-Fish was applied to individual bycatch species in the EPO to explore the efficacy of potential conservation and management measures (CMMs) for the spinetail devil ray (*Mobula mobular*) (Griffiths and Lezama-Ochoa, 2021) and the critically endangered east Pacific stock of leatherback turtle (*Dermochelys coriacea*) (Griffiths et al., 2020; BYC-11-02). The use of EASI-Fish has since been extended outside of the IATTC to assess the ecological impacts of longline fisheries in the central Pacific Ocean (Gilman et al., 2021) and to assess the vulnerability of elasmobranchs caught as bycatch in the tuna fisheries of the western and central Pacific Ocean (Phillips et al., 2021).

In 2022, the IATTC staff conducted a comprehensive vulnerability assessment of 32 shark species that have been recorded to interact with industrial (purse-seine and longline) and artisanal (longline and gillnet) pelagic fisheries in the EPO for the reference year 2019. Estimates of a proxy for fishing mortality ($\tilde{F}_{2019}$) and the spawning stock biomass per recruit (SBR_{2019}) for the reference year 2019 exceeded biological reference points ($F_{40\%}$ and $SBR_{40\%}$) for 20 of these species, classifying them as "most vulnerable". These included hammerhead sharks (4 species), requiem sharks (10 species), threshers (*Alopias superciliosus and A. pelagicus*), mesopelagic sharks (3 species) and the commercially important blue shark (*Prionace glauca*) and shortfin mako (*Isurus oxyrinchus*). Since stock assessments are routinely undertaken by the ISC for blue shark and shortfin makos in the north Pacific (ISC, 2018; 2022), the IATTC staff used the EASI-Fish assessment results to prioritize research and assessment of the remaining most vulnerable species.

As a result, the staff decided to conduct a detailed investigation of four species: silky shark (*Carcharhinus falciformis*), scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*Sphyrna mokarran*), and smooth hammerhead (*Sphyrna zygaena*)—herein referred to in the abbreviated form of "SHH"—since Resolution C-16-05 states they are the "*principal species known to be caught by vessels and gears fishing for species under the purview of the Commission in the Convention Area*". The resolution also requires the development of a workplan to conduct full stock assessments for these species, which has not been possible due to a lack of reliable catch time series for coastal states where most catches are believed to occur (see SAC-14-INF-L).

A conventional stock assessment for silky sharks in the EPO was attempted using Stock Synthesis in 2014 for the period 1993–2010 (IATTC, 2014). However, the model was unable to fit the main index of abundance derived from CPUE of floating object sets in the purse seine fishery. This was attributed to incomplete catch data for the 1990s and early 2000s. The staff recommended improving catch, effort, and sex-specific length-composition data for all fisheries capturing silky sharks in the EPO to develop a reliable index of abundance for stock assessment.

This paper explores the potential vulnerability of SHH sharks to recent fishing impacts using EASI-Fish, until sufficient reliable data are available for stock assessment. The assessment year chosen was 2019, as it was considered the last complete fishing year that could represent contemporary fishing effort regimes in the EPO, before the COVID-19 pandemic significantly impacted fishing effort, data collection and provision, starting around March 2020. With the flexibility and spatially-explicit framework of EASI-Fish, this study explored a range of hypothetical CMMs that could be implemented—in isolation or in combination—to reduce fishery impacts on these species within the EPO.

2. METHODS

2.1 Definition of the assessment region and included fisheries

The present assessment of sharks is limited to the IATTC Convention Area in the EPO (defined as the region from the coast of the Americas to 150°W between 50°S and 50°N) and characterizes the shark populations and EPO fisheries for 2019. Although it is possible that some of the assessed shark species are comprised of more than one stock across the Pacific Ocean (e.g., Kraft, 2020), and even within the EPO (e.g., Rodríguez Matus, 2020), there is insufficient information to clearly delineate stock boundaries for any of the four SHH species. Therefore, for the present study, each species was assumed to represent a single homogenous stock within the IATTC Convention Area. The converse may also be true for some pelagic species whereby species caught in the EPO are part of a larger continuous stock across the Pacific Ocean. While work is being planned to undertake Pacific-wide assessments for some species in collaboration with the Secretariat of the Pacific Community (SPC), the inclusion of Western and Central Pacific Fisheries Commission (WCPFC) fisheries at this point was considered premature, especially considering that a conventional a Pacific-wide stock assessment for silky shark was unsuccessful in 2018 (Clarke et al., 2018).

Industrial longline

The industrial fisheries included the fishery by large-scale tuna longline fishing vessels (LSTLFVs) (herein called the "industrial longline fishery") and two purse-seine fisheries (Class 6 with a carrying capacity >363 mt and Classes 1–5 ≤363 mt; see below). The data for these fisheries were obtained from vessel logbooks, collected by on-board scientific observers, or submitted to the IATTC by its Members under Resolutions C-03-05 and C-19-08 and described in SAC-08-07b. Specifically, the industrial 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 in the EPO. These vessels primarily provide monthly reports of catch and fishing effort at a resolution of at least 5° x 5°, although a few CPCs submit data at 1° x 1°. Additionally, data were collected from national scientific observer programs that monitor at least 5% of the fishing effort by LSTLFVs over 20 m LOA, as required by Resolution C-19-08.

Purse-seine (Class 6)

The effort data characterizing the fishery by Class 6 purse-seine vessels were collected by the onboard observer program of the Agreement on the International Dolphin Conservation Program (AIDCP) and National Programs in 2019, which covered 100% of the fishing effort. This fishery comprises three distinct sub-fisheries based on set type: i) sets associated with natural or artificial floating objects (OBJ), ii) sets associated with dolphins (DEL), and iii) sets on schools of tuna that are neither associated with dolphins or floating objects (NOA).

Purse-seine (Classes 1-5)

There are a range of smaller purse-seine vessels that operate in the EPO (Classes 1–2) that are generally confined to coastal areas, to larger commercial vessels (Classes 3–5) that frequently fish on the high seas. The AIDCP does not require these smaller vessels to carry an observer, except in specific situations. Of the 59 Class 1–5 vessels that fished in the EPO in 2022, only 18 (30.5%) carried an observer. However, the Tuna Conservation Group (TUNACONS)—a consortium of Ecuadorian tuna fishing companies—has deployed observers on a voluntary-basis on their vessels since 2018, with coverage being 26% of the total number of trips reported for all Class 1–5 vessels in the EPO in 2022 (IATTC, unpublished data). It has yet to be determined by IATTC scientists whether the data collected to date by TUNACONS is representative of the fleet in terms of gear characteristics, catch composition, and spatio-temporal distribution of effort. However, given the paucity of information on this fishery in the past, we included these data that were considered to represent the minimum spatial coverage of the fishery. Copies of logbook entries summarizing the fishing activities of vessels of Classes 1–5 were available via opportunistic collection by IATTC field staff at various landing ports. The fishery comprising Classes 1–5 vessels can also be separated on the same set type as the Class 6 fleet, except Class 1–5 vessels (i.e., <363 mt) are not permitted to make DEL sets (AIDCP, 2017). Each set position for Class 1–6 vessels was allocated to the nearest 0.5° x 0.5° grid cell to define each sub-fishery.

Artisanal longline and gillnet

In contrast to the industrial purse-seine and longline fisheries in the EPO, the numerous small-scale artisanal fleets that operate within the EEZs of countries in the EPO are generally poorly documented by national fisheries agencies. However, SHH sharks have been shown to be heavily impacted by coastal gillnet and longline fisheries (Alfaro-Shigueto et al., 2010; Cartamil et al., 2011; Martínez-Ortiz et al., 2015; Sosa-Nishizaki et al., 2020) that seasonally catch neonates and juveniles—particularly *S. lewini*—in their coastal nursery habitats throughout Central America (Zanella et al., 2019; Guzman et al., 2020; Arriatti et al., 2021; Corgos and Rosende-Pereiro, 2022; Rodriguez-Arana Favela et al., 2022) and South America (Castañeda, 2001; Mason et al., 2020; López-Angarita et al., 2021b; Jaramillo Torres, 2022). Therefore, it was necessary to gather any available data sources on fishing effort for artisanal fisheries to include in the assessment.

There are distinct sub-fisheries within the coastal artisanal longline and gillnet fisheries of Central and South America. The artisanal longline fishery can be separated by gear configuration, area, and season of operation to target either dorado, or dolphinfish, (*Coryphaena hippurus*) or a mixture of tunas, billfish and sharks (Alfaro-Shigueto et al., 2010; Andraka et al., 2013; Doherty et al., 2014). The dorado fishery (DOL) operates in the Austral summer between about October to March in neritic to offshore waters, while the tunas-billfish-shark (TBS) fishery operates between April to September further offshore, although the timing and duration of these fishing seasons vary slightly with latitude. In the southern EPO off Peru, the DOL fishery operates from December to March (Alfaro-Shigueto et al., 2010; Doherty et al., 2014), while the season is less definitive in more northern regions off Mexico (Andraka et al., 2013). Both fisheries use similar gear configurations, although the TBS fishery tends to deploy slightly longer mainlines, has fewer and longer branchlines to fish slightly deeper than the DOL fishery (Andraka et al., 2013; Martínez-Ortiz et al., 2015). The main difference between the two fisheries is that only the TBS fishery typically uses wire leaders (Alfaro-Shigueto et al., 2010)—an exception being Ecuador where wire leaders have been banned in all longline fisheries since 2007 (Tribunal Constitucional del Ecuador, 2007).

Reasonably detailed effort data for artisanal longline vessels throughout Central America was available from IATTC's long-term research program that examined the effects of different hook types on bycatch rates, partly reported by Andraka et al. (2013), and by the 2-year GEF-ABNJ shark sampling program (Oliveros-Ramos et al., 2020). Some fragmented information was available from fishing effort maps in published scientific papers (Martínez-Ortiz et al., 2015) and reports (*e.g.*, Ayala et al., 2008; Martínez et al., 2017) or maps of unpublished observer data. These maps were digitized, geo-referenced and fishing effort allocated to grid cells of appropriate resolution—usually 0.5° x 0.5°—in QGIS software. Unfortunately, some large spatial gaps in catch and/or effort data existed in some areas where artisanal fisheries are known to operate. However, in many of these areas, detailed data were available pertaining to the locations of fishing ports for artisanal fleets. For example, Ortíz-Álvarez et al. (2020) mapped coastal artisanal fishing ports from the northern Gulf of California, Mexico to the southern border of Colombia, while Alfaro-Shigueto et al. (2018) mapped fishing ports from Ecuador to Chile. Because these two studies focused on port-based interviews with fishermen pertaining to the characteristics of their fishing operations and interactions with protected species such as sea turtles, spatially explicit effort data were not available to determine where vessels fished from these ports. However, artisanal fishers frequently traverse over one degree of latitude (~111 km) to reach their preferred fishing grounds (see Oliveros-Ramos et al., 2020), although many travel significantly further offshore to target large pelagic fishes in offshore waters (see Martínez-Ortiz et al., 2015). Therefore, it was reasonable to assume that at least one unit of fishing effort was expended in 2019 within each 0.5° x 0.5° grid cell adjacent to each active fishing port.

In some coastal States in the EPO, there is often not a clear distinction between artisanal, semi-industrial and industrial vessels, as the former are often multi-gear (longline and gillnets) and multi-species, shifting their target among tuna, billfish, sharks and dorado on a seasonal basis (Martínez-Ortiz et al., 2015; Siu and Aires-da-Silva, 2016). Although some of these vessels can reach offshore waters (*e.g.*, medium and large-scale fleets), the majority are less than 15 m LOA (generally called "pangas") and are more coastal in their operation. Because effort data for these domestic fleets were not available by vessel size, these fleets were collectively classified as "artisanal". In contrast, the domestic Mexican longline fishery target sharks using vessels (often >27 m LOA) and surface-set gear configurations similar to those used by the distant water longline fleet (Sosa-Nishizaki et al., 2020). Therefore, for the purposes of the present study, available data for this domestic Mexican longline fishery was included as part of the industrial longline fleet.

Most coastal States have some form of a landings-fishing inspection program conducted mainly for compliance purposes (Siu and Aires-da-Silva, 2016). Unfortunately, observer coverage of these fleets is extremely low and data are very limited for scientific purposes. Although sampling programs are being developed for the coastal nation fleets (see Oliveros-Ramos et al., 2019), data coming from well-established long-term programs are not yet available. Therefore, using high-resolution fishing effort distribution maps from publications was considered the only feasible alternative to represent the spatial 'footprint' of these fisheries in the current assessment. As was the case with the fishing port data, fishing effort maps were imported into QGIS software, georeferenced, and where the presence of a single set in any 0.5° x 0.5° grid cell—5° x 5° or 1° x 1° for the industrial longline fishery—was considered presence of effort.

A detailed description of the datasets included in the assessment is provided in Table 1 and maps of the effort footprint of each fishery is shown in Figure 1.

2.2 Estimating susceptibility as a proxy for instantaneous fishing mortality ($\widetilde{F}$)

The vulnerability of each shark species was quantified using the EASI-Fish ecological risk assessment approach (Griffiths et al., 2019). EASI-Fish is comprised of separate susceptibility and productivity components. The susceptibility component 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 spawning biomass-per-recruit models.

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

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

where G is the total number of grid cells occupied by the species and G_x is the number of occupied grid cells containing at least one unit of fishing effort by fishery x during 2019. In this study, G was estimated for each species using SDMs developed at a resolution of 0.5° x 0.5° using the methodology described by Griffiths et al. (2022) for developing SDMs for 32 shark species in the EPO. The SDM predictions for the four species are shown in Figure 2. The final appearance of an SDM prediction can change significantly depending on the threshold upon which the predicted probability of presence (ψ) is used to create binary values of species presence. For example, at a threshold of 0.4, predicted probabilities of presence above and below 0.4 are predicted to be presence and absence records, respectively. Consequently, the selected value of the threshold for the SDM outputs influences the proportion of the stock exposed to fishing. Therefore, we sought to incorporate uncertainty in the SDM by running EASI-Fish with a range of plausible ψ values determined by Griffiths et al. (2022). Further details pertaining to the SDM methodology can be found in Phillips et al. (2021).

Fishing effort for each fishery in 2019 was overlaid on the SDM predictions to calculate G_x. The proportional overlap of each fishery was calculated by dividing G_x by G. Effort data for purse-seine vessels and artisanal effort from published maps were resolved at 0.5° x 0.5° as described above. However, data for the industrial longline fleet were available at 5° x 5° or 1° x 1° resolution, so, in the absence of better-quality data, it was conservatively assumed that there was at least one unit of effort in each 0.5° x 0.5° cell contained within each of these larger grid cells 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 stock assessments, which combines, often implicitly, "population availability" (the relative probability that a shark of length class j is located in the area and time where the fishery is operating) and “contact selectivity” (the relative probability that a shark of length class *j* will be retained once it comes in contact with the gear) (Millar and Fryer, 1999). Because selectivity curves were not available for the three hammerhead species in each fishery, it was considered important to disaggregate selectivity components as far as practicable. These components are described hereafter.

Fishing season duration (*D*)

Fishing season duration (D_x) is the proportion of the year that the population is available to fishery *x*, expressed as the number of fishing days divided by 365. Between 2018 and 2020 in the EPO, Resolution C-17-02 mandated an annual 72-day closure for purse-seine vessels of Class 4–6 (>182 mt carrying capacity), including a 30-day closure of the area known as the “corralito” (4°N–5°S, 96°–110°W).

Seasonal availability (*A*)

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 most shark species in the EPO 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*)

Encounterability (N_{xj}) is the proportion of length class *j* that may potentially encounter the gear used by fishery *x* based on the species’ vertical distribution in the water column relative to the normal fishing depth range of the gear. Minimum, maximum, and mean dive depths of each shark species were defined using the results from electronic tagging studies or longline experiments using time-depth recorders. The effective fishing depth range for each fishery in the EPO was defined as:

- 0–300 m for industrial longlines, which covers the depth range of both ‘shallow’ and ‘deep’ sets since insufficient data are currently available from effort data submitted to the IATTC to separate the two set types as separate fisheries (see Griffiths et al., 2017),
- 0–150 m, 0–150 m and 0–200 m for Class 6 purse-seine vessels deploying DEL, NOA and OBJ sets, respectively. These values are based on the upper quartile of net construction depths documented by Lopez et al. (2021) to be used in DEL, NOA and OBJ sets in the EPO in 2019, being about 210 m, 210 m, and 280 m, respectively, and assuming an effective fishing depth of 45–75% of the net depth (see Hall and Roman, 2013),
- 0–120 m for purse-seine vessels Classes 1–5 for both NOA and OBJ sets (Ernesto Altamirano, IATTC, pers. comm.),
- 0–100 m for surface-set gillnets set by the artisanal fishery that typically target sharks (Ayala et al., 2008).
- 0–100 m for surface-set longlines set by the artisanal fishery, which covers the depth range to the deepest hook of both shallow ‘dorado’ sets and deeper ‘tuna/billfish/shark’ sets (see Andraka et al., 2013).

Contact selectivity (*C*)

Contact selectivity (C_{xj}) refers to the proportion of length class *j* that is retained once it encounters the gear used by fishery *x*. Since reliable gear selectivity curves for most shark species are lacking, previous EASI-Fish assessments that included elasmobranchs (Griffiths et al., 2019; Griffiths and Lezama-Ochoa, 2021; Griffiths et al., 2022) have taken a precautionary approach of applying knife-edge selectivity (C_{xj} = 1.0) from the smallest shark recorded in each fishery to the largest length class defined in the model.

However, Griffiths et al. (2022) established that the four SHH species are among the most vulnerable shark species in the EPO, so an effort was made to obtain published or unpublished length-frequency data to better characterize selectivity for each fishery, especially to determine the significant seasonal impact of coastal fleets on neonates in Central America, including Mexico (Pérez-Jiménez et al., 2005; Alejo-Plata et al., 2007; Ramirez-Amaro et al., 2013), Guatemala (Tewfik et al., 2022) and Costa Rica (Zanella and López-Garro, 2015).

Once the length data were compiled by species and fishery, published length-length relationships were used to convert the length data of various measures to total length (TL), where required, for *C. falciformis* (Bonfil et al., 1993; Oshitani et al., 2003), *S. lewini* (Compagno, 1984; Stevens and Lyle, 1989), *S. mokarran* (Stevens and Lyle, 1989; Froese and Pauly, 2023) and *S. zygaena* (Bartes and Braccini, 2023; Froese and Pauly, 2023), as TL was the predominant length measurement used in the biological studies used to derive biological parameter values in the present study. A normal or double normal curve was then fitted to the length-frequency data for each fishery, as appropriate, using the methodology described in Appendix A of Methot and Wetzel (2013).

To ensure that fishing mortality was not being applied to unborn fetuses or those resulting from of capture-induced parturition (Adams et al., 2018), the ascending limb of each selectivity curve was truncated to the smallest recorded length at birth for each species. Knife-edge selectivity was only applied to *S. zygaena* in the industrial longline fishery and the artisanal gillnet fisheries from the smallest recorded length (147 cm TL) and length at birth (70 cm TL), respectively, as insufficient length data were available. Graphs showing selectivity curves and the underlying length data used to fit the curves are shown in Figures 3–6. Figure 3 also shows selectivity for silky shark in the EPO stock assessment (IATTC, 2014).

Post-capture mortality (PCM)

IATTC Resolution C-16-05 mandates the release of silky sharks for all EPO purse-seine fisheries, and in some instances, the industrial longline fishery. Therefore, fishing mortality would be overestimated unless the component of the catch that survives mandatory release is accounted for. In previous versions of EASI-Fish, this was represented as post-capture mortality (PCM) (P_{xj}), which is the proportion of length class *j* that is caught by fishery *x* and dies between the point of capture and some period after release (e.g., 30 days). However, some experimental research has been able to estimate both at-vessel mortality (AVM) and post-release mortality (PRM) for some pelagic shark species in EPO purse-seine (Eddy et al., 2016) and longline fisheries (Schaefer et al., 2019; 2021). Therefore, PCM was disaggregated into these two mortality components, represented as:

$$PCM_{xj} = AVM_{xj} + \left(\left[1 - AVM_{xj}\right] PRM_{xj}\right) \quad \text{(Eq. 2)}$$

where AVM_{xj} is the proportion of length class *j* in fishery *x* that dies between the point of retention by the gear (i.e., hooked by longlines, encircled by purse-seine, meshed by a gillnet, or entangled in a gear) and being brought alongside the vessel for landing or release (by bringing onboard or released *in situ*), while PRM_{xj} is the proportion of length class *j* in fishery *x* surviving capture but die soon after release.

Estimating the proxy for fishing mortality ($\widetilde{F}$)

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 2019 ($\widetilde{F}_{2019}$) for each shark species caught by all fisheries was estimated as:

$$\widetilde{F}_{2019} = -\,ln\left[1 - \sum_{x=1} q_x E_x \left(\frac{\sum_{j=1}^{n} S_{xj}}{n}\right)\right] \tag{Eq. 3}$$

Here, n is the number of length classes from zero to the average length at which a shark may grow if it were to live indefinitely (L_∞). Fishing effort (E_x) is total effort, scaled from zero to 1, of fishery x applied in area G_x in 2019, 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 settings values for q and E are unknown, and consequently, previous EASI-Fish assessments applied a precautionary approach by assuming both parameters are equal to 1, meaning all sharks in a grid cell are caught if all other susceptibility parameters are fully realized. However, sensitivity analyses were undertaken for *C. falciformis* to explore how vulnerability status might change under alternative values of q and resolution of G_x (Appendix 3).

The $\widetilde{F}_{2019}$ estimate was then compared with values for F for the selected BRPs derived from the per-recruit models (described below). However, it needs to be reiterated that, because of the several conservative assumptions and likely uncertainty in the parameters used in deriving the $\widetilde{F}_{2019}$ estimate, it should only be considered a proxy for F—and potentially an overestimate. For this reason, the results from EASI-Fish should not be used to define the biological status of a species' population, *sensu* a stock assessment, but rather to quantify the vulnerability of species.

2.4 Characterizing species productivity using per-recruit models

A yield-per-recruit (YPR) model was used to characterize the biological dynamics of each shark species using the generic approach of Ricker (1975), which Chen and Gordon (1997) adapted for lengths as:

$$YPR = \sum_{j=1}^{n} \frac{W_j b_j F}{b_j F + M}\left[1 - e^{-(b_j F + M)\Delta T_j}\right] e^{-\sum_{k=1}^{j-1}(b_k F + M)\Delta T_k} \tag{Eq. 4}$$

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 shark 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:

$$b_j = \sum_{x=1}^{n} S_{xj} \tag{Eq. 5}$$

In the absence of age or length-specific estimates of the instantaneous natural mortality rate (M) for the three hammerhead species in the EPO (but see Duncan and Holland, 2006 for exceptionally high natural mortality of neonates in a Hawaiian nursery habitat), M was estimated by taking the average of up to natural mortality estimators (Table 2; see Section 2.6) and assumed to be constant across all length classes. However, for silky shark where an estimate of M was derived for Pacific stock assessments (e.g., Clarke et al., 2018), the estimate was applied to all length classes. F was disaggregated into increments of 0.01, from zero to L_∞ from the specialized von Bertalanffy growth function (VBGF) that can be represented as:

$$L_t = L_\infty(1 - exp[-K(t - t_0)]) \tag{Eq. 6}$$

where L_t = length at age t, L_∞ = the mean asymptotic length that an animal may attain if it lived indefinitely, K = the Brody growth parameter, and t_0 = the hypothetical age at length zero. Although this is a widely accepted model to characterize growth in broadcast-spawning teleosts, the VBGF can underestimate length-at-age for young ages for sharks. This is because many sharks are viviparous (i.e., give birth to live young) and the VBGF does not consider the substantial fetal growth that occurs before birth, which would normally be characterized by t_0. Therefore, the VBGF was reparametrized where length at birth (L_0) was substituted for t_0 and expressed as:

$$L_t = L_\infty - (L_\infty - L_0)\, exp[-Kt]) \tag{Eq. 7}$$

The parameter ΔT in Eq. 4 describes the time taken for a fish to grow from one length class to the next, represented as:

$$\Delta T_j = \frac{1}{K} ln \frac{L_\infty - L_j}{L_\infty - L_j - d_j} \tag{Eq. 8}$$

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

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

$$SBR = \sum_{j=1}^{n} W_j m_j \prod_{x=r}^{j-1} e^{-(b_j F + M)} \tag{Eq. 9}$$

where W_j is the mean weight of a shark in length class j (L_j) taken from the most appropriate regionally specific length-weight relationship, m_j is the proportion of mature females at the mean length of length class j, and the product operator describes the number of sharks surviving from the length at recruitment (L_r) to L_j. Because the model calculates relative SBR, the initial number of breeding females was set to a value of one. The value for m_j for each species was taken from a female maturity ogive, represented in the logistic form:

$$m_j = \frac{1}{1 + e^{\left(-r\left(L_j - L_{50}\right)\right)}} \tag{Eq. 10}$$

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

All biological parameters used in the productivity component of EASI-Fish and their sources are provided in Tables 3 and 4.

2.5 Natural mortality

The instantaneous natural mortality rate (M yr^{-1}) is one of the most influential parameters in stock assessment models but is notoriously difficult to estimate directly (Kenchington, 2014; Then et al., 2015). Consequently, empirical equations based on life history traits, $t_{\max}$ and VBGF parameters (L_∞, K, t_0), are often used as an alternative. Over 30 natural mortality estimators exist, but none has been proven to perform better than another for all species (Kenchington, 2014). Consequently, it is common to run stock assessment models using a range of M values derived from multiple estimators. For each hammerhead species, *M* was calculated using six estimators recommended by Kenchington (2014) and Then et al. (2015) (Table 2). Priority was given to *M* values that were estimated directly (*e.g.,* from tagging or stock assessment), followed by t_{max}-based estimators (Hoenig$_{\text{nls}}$ and Hoenig$_{\text{tmax}}$) for long-lived species such as elasmobranchs, and finally *K*-based estimators (Jensen, Pauly$_{\text{nls}}$, Pauly$_{\text{LKT}}$ and Pauly$_{\text{KT}}$).

2.6 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 time period or specific year. EASI-Fish uses a similar approach, but it is important to emphasize that its BRPs are used to quantify the relative vulnerability of a population that would be expected to hinder the lifetime yield of an animal—regardless of the present population size—rather than to determine stock status. YPR models assume that recruitment is constant and independent of stock size—equivalent to a steepness (*h*) value of 1 (Gabriel and Mace, 1999). Therefore, use of a *F* value at which yield is maximized (F_{MAX}) can be overly optimistic owing to sharks often having a strong stock-recruitment relationship (*i.e.*, h<1). 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.

In a comparison of BRPs used in EASI-Fish to assess bycatch species with diverse life histories from teleosts to marine mammals, Griffiths et al. (2019) suggested that $F_{40\%}$ is appropriate for elasmobranchs and is therefore adopted in the present study. Explicitly, $F_{40\%}$ is the *F* value corresponding to 40% of the spawning potential ratio (SPR), which is the SBR at the F_{2019} value divided by the SBR if *F*=0. The corresponding $\text{SBR}_{40\%}$ BRP is the SBR value at $F_{40\%}$. However, it is worth noting that Cortés and Brooks (2018) suggested that for slow-growing and long-lived species, such as elasmobranchs, a BRP as high as $F_{80\%}$ should be used.

To determine the vulnerability of each shark species in 2019, the study used the $\tilde{F}_{2019}$ and corresponding SBR value (SBR_{2019}) relative to the $F_{40\%}$ and $\text{SBR}_{40\%}$ values and displayed them on a 4-quadrant "vulnerability phase plot" (Fig. 7). The vulnerability definitions of these quadrants are: i) "Least vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ <1 and $\text{SBR}_{2019}/\text{SBR}_{40\%}$ >1), ii) "Increasingly vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ >1 and $\text{SBR}_{2019}/\text{SBR}_{40\%}$ >1), iii) "Most vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ >1 and $\text{SBR}_{2019}/\text{SBR}_{40\%}$ <1), and iv) "Decreasingly vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ <1 and $\text{SBR}_{2019}/\text{SBR}_{40\%}$ <1).

2.7 Implementation of the model

The model was configured to perform Monte Carlo simulations, which generated uncertainty estimates for specific model parameters using a uniform distribution prior that ranged between a defined minimum and maximum value. The YPR and SBR models were then run 10,000 times using Monte Carlo permutations, each time drawing a random sample from the distribution prior defined for each parameter. The mean and 95% confidence intervals (95% CI) were derived for the BRPs $\tilde{F}_{2019}$, $F_{40\%}$, SBR_{2019}, and $\text{SBR}_{40\%}$.

2.8 Scenario modelling

One of the key advantages of the EASI-Fish approach is that it facilitates the implementation of specific 'what if' scenarios in a rapid and cost-effective manner, allowing an understanding a scenario's potential efficacy for reducing the vulnerability of a species. In this study, we implemented a total of 43 CMM scenarios (plus the status quo) aimed at determining the efficacy of measures under five broad categories described below. The modified parameter values for each species in each scenario are detailed in Table 5.

1) Use of best handling and release practices to minimize post-release mortality

In fisheries where a species is unavoidably caught incidentally, the only way to reduce fishing mortality is often through handling and release practices that minimize post-release mortality. SHH sharks are an unavoidable bycatch in EPO purse-seine fisheries and IATTC resolutions C-16-05 and C-16-06 have been implemented as conservation measures for these species by prohibiting retention and requiring their safe release. Although the IATTC plans to develop a manual for best handling and release practices for various bycatch species groups (e.g., sharks, sea turtles) for IATTC fisheries following a recent review of existing and potential practices EB-01-01, there are currently only rudimentary handling and release recommendations in C-16-05 for sharks caught by the purse-seine fishery. Since there are currently no operational-level measures used by the fleet to avoid the encirclement or to release sharks before the net is sacked to reduce AVM (but see experimental work in the Atlantic Ocean by Hutchinson et al., 2020), scenarios only involved reductions in PRM as a result of hypothetical improvements in handling and release practices. Three levels of PRM—low, medium, and high—were simulated for each species whereby the PRM value range for each level was arbitrarily determined based on the available PRM estimates. For example, PRM of silky sharks released from large purse-seine vessels was estimated to range between 81% (Poisson et al., 2014) and 84% (Hutchinson et al., 2015). Therefore, the three level values were 100% (high; no use of handling practices where sharks are retained), 70–90% (medium), and 50-70% (low).

2) EPO-wide temporal closure to complement existing purse-seine fishery measures and hypothetical extensions

A reduction in the duration in which SHH sharks are exposed to fishing effort can decrease fishing mortality—and subsequent vulnerability—assuming effort is distributed equally throughout the year within the defined effort footprint of each fishery. To maximize the practicality of implementing temporal closures across a range of EPO fisheries, an annual 72-day closure was simulated for each fishery to align with the existing purse-seine fishery closure (2018-2021; Resolution C-17-01). Extensions to the 72-day closure were also implemented across all fisheries—simulated individually or on concert—as closure to:

i. All EPO purse-seine fisheries only for 72 (status quo), 120, or 180 days,

ii. The EPO industrial longline fishery only for 72, 120, or 180 days,

iii. The EPO artisanal longline fisheries (DOL and TBS) for 72, 120, or 180 days,

iv. All EPO industrial and artisanal longline fisheries for 72, 120, or 180 days,

v. All artisanal gillnet fisheries (Neonates and Shark-teleost) for 72, 120, or 180 days,

vi. All EPO industrial and artisanal fisheries for 72, 120, or 180 days.

3) Prohibition of wire (steel) leaders in longline fisheries

Wire, or steel, leaders are frequently used in longline fisheries to prevent sharks from biting through the softer monofilament leaders and escaping. However, this can result in the shark remaining hooked until the longline is retrieved, either dead or exhausted, thus reducing their chances of survival if released. As a result, the IATTC has sought to minimize the use of wire leaders in Resolution C-16-06 (Article 6) "*For those multi-species fisheries using surface longlines that have captured more than 20% of silky sharks in weight on average, CPCs shall prohibit the use of steel leaders during a period of three consecutive months each year*".

This set of scenarios simulates a hypothetical extension of C-21-06, which would prohibit the use of wire leaders for all trips year-round for SHH sharks, assuming it would result in a reduction in AVM due to a greater incidence of 'bite-offs'. However, there is limited quantitative data pertaining to the differences in AVM between wire-caught and monofilament-caught sharks in industrial or artisanal longline fisheries. Two studies undertaken in the western and central Pacific Ocean estimate AVM to range between 31%

(Bigelow et al., 2022) and 41% (Scott et al., 2022). In the absence of operational data that is representative of the entire industrial and artisanal longline fisheries to determine the frequency of surface sets deployed with wire leaders, and whether the length distribution of hooked sharks differs between monofilament and wire leaders, it was assumed that all sets currently use wire leaders and that the contact selectivity of each fishery would not change after banning the use of wire leaders.

A PRM component was implemented with AVM (see Eq. 2) in particular combination scenarios to account for the proportion of sharks that escaped mortality, either as 'bite-offs', where the leader was cut in close proximity to the vessel, or where the shark was brought onboard, unhooked and released. It was assumed that PRM would be the same as determined by tagging studies in industrial (Gallagher et al., 2014a; Musyl and Gilman, 2018; Francis et al., 2023) and artisanal (Schaefer et al., 2019; 2021) longline fisheries. Although recent work has shown the amount of trailing gear left in released sharks can affect PRM (Bègue et al., 2020; Hutchinson et al., 2021; Francis et al., 2023), this was not considered in applied PRM estimates given the lack of information on the type and length of trailing gear typically attached to released sharks in EPO longline fisheries.

Three combinations of AVM were simulated, including the industrial longline fishery only, artisanal longline fisheries (DOL and TBS) only, and all EPO longline fisheries.

4) Increase minimum length of retention to 100 cm TL

Increasing the minimum length of retention is a common fisheries management strategy to reduce the fishing mortality on fish that are not sexually mature and have likely not had an opportunity to contribute to the spawning population. To reduce the fishing mortality on small silky sharks by EPO longline fisheries, Resolution C-16-06 (article 3) requires "…*multi-species fisheries using surface longlines to limit the catch of silky sharks of less than 100 cm total length to 20% of the total number of silky sharks caught during the trip*". This scenario simulates a hypothetical extension of Resolution C-16-06 to include all industrial and artisanal longline trips year-round and to all four species of SHH sharks. Although the length-distribution of the catch after implementation is expected to change, the size selectivity of each fishery was assumed to remain unchanged, and that length-based mortality would decrease for size classes <100 cm TL by rates determined by relevant PRM studies. Three combinations of the minimum length of retention measure were simulated, which included the industrial longline fishery only, artisanal longline fisheries (DOL and TBS) only, and in all EPO longline fisheries.

5) Close the gillnet fishery for neonates

SHH sharks—particularly *S. lewini*—have been shown to be heavily impacted by coastal gillnet fisheries (Cartamil et al., 2011; Martínez-Ortiz et al., 2015; Sosa-Nishizaki et al., 2020) that seasonally catch neonates, either as a target or bycatch, in their coastal nursery habitats throughout Central America (Zanella et al., 2019; Arriatti et al., 2021; Corgos and Rosende-Pereiro, 2022) and South America (Castañeda, 2001; Mason et al., 2020; López-Angarita et al., 2021b). This has great potential to negatively impact shark populations as fishing mortality added to the high natural mortality rates of young sharks (see Duncan and Holland, 2006) may not be biologically sustainable. Consequently, in an attempt to reduce the mortality on juvenile sharks, particularly hammerheads, shark fisheries have been subjected to 3-month fishing closures in Peru (Mason et al., 2020) and Mexico (Sosa-Nishizaki et al., 2020) during the main pupping seasons, and even complete ban on all forms of commercial and artisanal fishing for sharks within its EEZs of Colombia (Castellanos-Galindo et al., 2021) and Ecuador (Ecuador, 2007). Despite these efforts, the catches of juvenile sharks in many of these and other Central and South American countries remain significant (Jaramillo Torres, 2022; Tewfik et al., 2022). This scenario involved a closure of the artisanal gillnet fishery that catch neonates for a period of five months simply by reducing the value of parameter D in Eq. 1 to 0.58 for all size classes of each species. During the open fishing season, AVM and PRM estimates of 100% were applied (Ellis et al., 2017).

6) Non-retention of silky and hammerhead sharks

In situations where the fishing mortality of a species cannot be reliably controlled or monitored by conventional measures, prohibition of landing is often a last resort, especially for particularly vulnerable species. For example, the precipitous decline in catches of the oceanic whitetip shark (*Carcharhinus longimanus*) in the EPO resulted in Resolution C-11-10 mandating the prohibition of "…*retaining onboard, transhipping, landing, storing, selling, or offering for sale any part or whole carcass of oceanic whitetip sharks in the fisheries covered by the Antigua Convention*".

This scenario hypothetically extends Resolution C-11-10 to include SHH sharks. This measure alone is assumed not change the interaction rate of longlines with SHH sharks, size selectivity of the gear, or AVM rates, but fishing mortality was reduced by implementing published estimates of PRM for SHH species for industrial (Gallagher et al., 2014a; Musyl and Gilman, 2018; Hutchinson et al., 2021; Francis et al., 2023) and artisanal (Schaefer et al., 2019; 2021) longline fisheries, and all purse-seine fisheries (Poisson et al., 2014; Hutchinson et al., 2015). Scenarios were not undertaken for the artisanal gillnet fisheries since AVM and PCM have been estimated to be around 100% (Eddy et al., 2016), so it was assumed that non-retention was unlikely to change vulnerability from the status quo situation. Five combinations of the measure were simulated, which included the following EPO longline fisheries:

i. All EPO purse-seine fisheries (noting landing of silky shark already prohibited in C-21-06),

ii. The EPO industrial longline fishery only,

iii. All EPO artisanal longline fisheries (DOL and TBS),

iv. All EPO industrial and artisanal longline fisheries,

v. All EPO industrial and artisanal fisheries.

7) Combination measures

Although individual measures may not be sufficient to reduce the vulnerability status of a species, where practical, it may be possible to use multiple measures in concert to achieve greater reductions in fishing mortality and to reduce vulnerability (Griffiths et al., 2020; Griffiths and Lezama-Ochoa, 2021). For example, implementing a temporal closure of one or more EPO fisheries in combination with a retention ban on sharks may be effective in reducing fishing mortality and could also be practical to implement and monitor compliance. A total of 14 combination measures were implemented, each adding the best performing single measures incrementally.

2.9 Sensitivity analyses

Catchability

Catchability is a highly influential parameter in conventional in stock assessment models and is also important in EASI-Fish. Since EASI-Fish was designed to be applied to data-poor species and fisheries, q is usually unknown because the standing biomass of the species to which catch data, if available, can be compared to understand the efficiency of the gear are also often unknown. Furthermore, standardization of catchability is difficult between different gears as their efficiency and effective fishing area differ markedly. Given the difficulties in empirically estimating q in data-limited settings the appropriate precautionary approach is to assume q equals 1. However, as will be shown in Section 3.2, EASI-Fish estimated artisanal longline and gillnet fisheries—where catches of SHH sharks are significant (see SAC-14 INF-L)—to have an extremely low impact on SHH species relative to other fisheries where catches are well documented to be relatively minor (e.g., purse-seine DEL sets). Therefore, a novel approach to the scaling of q was explored using the principles of the “domain of potential interaction” described by (Griffiths et al., 2007) to determine whether the vulnerability results could corroborate the relative differences in catches between EPO fisheries.

Increased effort data resolution for the industrial longline fleet

In contrast to the artisanal fleets, the industrial longline fishery had a significantly higher fishing mortality on SHH species, despite the catches of these species being significant in both fisheries (see SAC-14 INF-L). The disproportionately higher impact by the industrial longline fleet in this and previous EASI-Fish studies was thought to be attributed to a significant mismatch in the spatial resolution of effort data reported to the IATTC (5° x 5°) relative to that of the SDM (0.5° x 0.5°), which can lead to a significant overestimate in fishing mortality by this fishery. Ideally, fishery data at 0.5° x 0.5° would result in the lowest bias, however, the length of mainlines deployed in a typical industrial longline set is often about 100 km, meaning a resolution of 1° x 1° is probably appropriate to encapsulate the full extent of a set. To examine the effect of using higher resolution 1° x 1° effort data on species vulnerability, the centroid of each 5° x 5° cell where effort was present was assumed to be the centroid of a 1° x 1° cell. This effectively reduced effort by a factor of 25 as one hundred 0.5° x 0.5° cells contained within a 5° x 5° cell was reduced to four 0.5° x 0.5° cells surrounding the centroid of the 5° x 5° cell.3. RESULTS

3.1 Estimates of susceptibility and a proxy for fishing mortality ($\widetilde{F}$)

All susceptibility parameter values contributing to the overall susceptibility (S_{xj}) estimate for each species assessed in EASI-Fish for the status quo scenario and detailed descriptions of the source or derivation of these values are provided in Appendix 1 and 2, respectively.

The industrial longline fishery overlapped with the distribution of all four species by 56–79%. This fishery had the areal overlap with *C. falciformis* (74–79%). This high overlap was due to the fishing effort being distributed across most of the EPO between 40°N and 40°S, which is substantially larger than the other fisheries (Fig. 1).

The fishery with the next highest areal overlap with the four species was by the Class 6 purse-seine vessels deploying OBJ sets, which was similar for all species between 30–42%. Other purse-seine set types by Class 6 vessels had lower overlap with SHH species being 20-32% and 9–15% for DEL and NOA sets, respectively.

For purse-seine Class 1-5 vessels, the areal overlap was substantially lower than for Class 6 vessels due to effort being restricted to the region surrounding the Galapagos Islands (Fig. 1). OBJ sets had the highest overlap 8–17%, while NOA sets was substantially lower (2–4%).

The artisanal gillnet fisheries—both the neonate and shark–teleost utilized the same effort data—had the lowest areal overlap of any fisheries assessed for 4 species (1–4%) as effort was restricted to neritic waters. The artisanal longline fisheries—both dorado and the TBS utilized the same effort data—had considerably higher overlap with the four species (13–38%), with overlap being highest for *S. mokarran* (16–38%). The overlaps by the artisanal longline fisheries were much higher than for the gillnet fisheries as they operated across a much larger area from the coast to about 100°W (Fig. 1).

When taking other susceptibility factors into account (*e.g*., encounterability, contact selectivity) to assess the cumulative impacts of the ten fisheries included in the assessment, *S. mokarran* had the highest mean proxy for fishing mortality ($\widetilde{F}_{2019}$) of 0.98 yr^{-1}, followed by *S. zygaena* (0.82 yr^{-1}), S. lewini (0.74 yr^{-1}), and *C. falciformis* (0.61 yr^{-1}), (Fig. 8a–d). The industrial longline fishery made the highest contribution to the fishing mortality for each of the four species, followed by the Class 6 purse-seine fishery OBJ and DEL sets. By comparison, the artisanal gillnet and longline fisheries made a negligible contribution to the overall fishing mortality on the four species, especially for *C. falciformis* (Fig. 8a–d).

3.2 Vulnerability status of shark species in the EPO

The biological parameter values and their sources used in the YPR and SBR models for the SHH species to derive their vulnerability status are shown in Table 3 and Appendix 3, respectively, while EASI-Fish estimates of the $F_{40\%}$ and $SBR_{40\%}$ BRPs for the status quo scenario in 2019 are provided in Table 4.

Based on estimated mean values of BRPs for the status quo, all four species exceeded the $F_{40\%}$ and $SBR_{40\%}$ BRP threshold values (Table 6), resulting in the vulnerability classification of these species as "most vulnerable".

Several of the 43 CMM scenarios resulted in significant reduction in the vulnerability status of all four species, although none resulted in a species being reclassified as "least vulnerable". The CMMs having the greatest positive impact was remarkably consistent for all four species. Of the most impactful scenarios involving a single CMM, only EPO-wide closures of 120 or 180 days resulted in a marked reduction in vulnerability for all four species, which was primarily due to the reduction in fishing mortality by the industrial longline fleet (Fig. 8). An exception was for *C. falciformis* where non-retention of landing sharks in scenarios involving the industrial longline fishery (scenarios 28 and 30) decreased the mean fishing mortality from 0.61 yr^{-1} to 0.41 yr^{-1} and 0.43 yr^{-1}, respectively (Fig. 8a), which resulted in a substantial reduction in vulnerability (Fig. 9). These scenarios were ineffective for the three hammerhead species since they had high rates of AVM (up to 94%) and reasonably high PRM (up to 100%) in the fisheries that contributed most to their overall fishing mortality (i.e., industrial longline and purse-seine). A similar explanation can be given for the low efficacy of prohibiting wire leaders (scenarios 21–23) and landing SHH sharks (scenarios 28–30) in that the high AVM rates remained unchanged, but the PRM rates are also high for released sharks.

Although the gillnet fishery has a documented impact on SHH sharks, completely closing the gillnet fishery for neonates resulted in less than a 1% decrease in fishing mortality for each SHH species, which was likely due to the low areal overlap (1-4%) of this fishery with these species.

The scenarios that resulted in the highest reduction in fishing mortality, and thus vulnerability, were those where several measures were used in combination, especially those involving the industrial longline fishery. Scenarios 43 and 44 incorporated four and five single measures, respectively, which resulted in significant reductions in fishing mortality and vulnerability, especially for *C. falciformis* and *S. lewini* (Fig. 9). Again, these reductions were primarily due to the industrial longline fishery having the highest fishing mortality on all four species (Fig. 8), as the most single measures within these scenarios pertained to longline fisheries.

3.3 Sensitivity analyses

Using *C. falciformis* as a test case, both increasing the resolution of effort data by the industrial longline fishery and reducing *q* values resulted in remarkably similar results; both significantly reducing the overall fishing mortality by about half (Fig. 9), which resulted in a significantly more optimistic vulnerability status (Fig. 10). Changing *q* values increased the relative impact of the artisanal fleets, albeit still being significantly less than the industrial longline fleet (Fig. 9, top panel). In both sensitivity analyses, vulnerability decreased in all 43 scenarios that simulated CMMs individually and in combination. In contrast to the results in section 3.2 where no scenario moved the species into the "least vulnerable" category, EPO closures of 120 and 180 days, prohibition of retention, and the use of these two measures in combination resulted in significant reductions in vulnerability to where the species attained a "least vulnerable" classification (Fig. 10).

4. DISCUSSION

Silky and hammerhead sharks have been a major focus of conservation and management measures by the IATTC for its fisheries over at least the past decade due to their high prevalence as bycatch in both industrial and artisanal fisheries throughout the EPO.

However, available biological and catch data have been considered insufficient to undertake conventional stock assessments for these species. Stock assessments were attempted for silky shark in the EPO (IATTC, 2014) and Pacific-wide (Clarke et al., 2018), both of which were unsuccessful due to a lack of reliable long-term time series of abundance. Consequently, EASI-Fish was used as an alternative approach to assess the relative vulnerability of all shark species caught in in EPO pelagic industrial and artisanal fisheries (Griffiths et al., 2022), which confirmed that silky and hammerhead sharks among the most vulnerable species.

This assessment focuses on four species prioritized for stock assessment in Resolution C-16-05: silky shark (*Carcharhinus falciformis*), scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*Sphyrna mokarran*), and smooth hammerhead (*Sphyrna zygaena*). EASI-Fish was successfully applied in the present study for quantifying potential impacts of EPO fisheries on each of the four species under 43 hypothetical management scenarios involving practical measures used in isolation or in concert to determine the most plausible approaches that may reduce the vulnerability of all four species or to identify key data deficiencies that may require additional research and monitoring before re-assessment.

The industrial longline fishery was estimated to have the highest impact on all four species due to its distributional overlap with the modeled distributions of these species. The large effort footprint of this fishery in the EPO resulted in a real overlaps of 63-79% with the species' distributions, while the assumed 300 m effective fishing depth of the gear completely encompassed the entire vertical habitat of all four species—ascertained from electronic tagging (Musyl et al., 2003; Bessudo et al., 2011; Francis, 2016; Guttridge et al., 2022). Furthermore, the non-selective nature of passive longline gear meant that it generally impacted a wider range of size classes than more selective gears, such as purse-seine and gillnet. Although selectivity of a broad range of species and sizes does not necessarily indicate high fishing mortality if the less desirable species and sizes can survive release, the long soak times that frequently exceed 10 hours often result in high AVM (Beerkircher et al., 2002; Fernandez-Carvalho et al., 2015; Hutchinson et al., 2021) and PRM rates that are often in the range of 15–50% for sharks that survive until they can be released (Gallagher et al., 2014b; Musyl and Gilman, 2018; Francis et al., 2023).

The only alternative that may allow fisheries to have sustainable interactions with sharks is to implement measures that significantly improve post-release survival beyond what has been documented to date. Although the IATTC mandates or recommends the safe release of sharks through resolutions C-16-05 and C-19-06, specific methods of release are not provided. Consequently, C-21-06 calls for research to improve handling and release practices for all impacted shark species. Despite some recent research being conducted in the EPO on the post-release survival of sharks caught in the industrial purse-seine fishery (Eddy et al., 2016) and artisanal longline fisheries (Schaefer et al., 2019; Schaefer et al., 2021) fisheries, there is significant scope for further research to delve further into the efficacy of existing release methods and explore the potential efficacy of new handling and release practices and mitigation measures.

For example, only one study (Eddy et al., 2016) has quantified the PRM of sharks from the purse-seine fishery in the EPO, and this study was limited to *C. falciformis* (13 tagged), *Isurus oxyrinchus* (1 tagged) and *S. lewini* (3 tagged) caught in floating object sets. Further studies are warranted with significantly larger sample sizes to gain a better understanding of PRM of SHH sharks caught in the three main set types and vessel classes in the purse-seine fishery as they each employ slightly different operations and can catch different sizes of sharks (see Figs 3 and 4). In this regard, the IATTC is currently conducting, in collaboration with the fleet, experiments to better assess the PRS of sharks in Class-6 (Project M.1.d) and Class-1-5 (Project M.2.e) purse-seine vessels using different bycatch releasing devices.

It is surprising that despite PRM of sharks caught by industrial longline being has attracted significant research interest in the western and central Pacific Ocean over the past decade (Musyl et al., 2011; Musyl and Gilman, 2018; Hutchinson et al., 2021; Francis et al., 2023), similar studies have not been attempted in the EPO, where industrial longline effort has increased by 25% since 2011 and as much as 6-fold for some distant water fleets (IATTC, 2023). PRM studies need to be a research priority to first quantify the efficacy of implemented mitigation measures for both industrial and artisanal longline fisheries (EB-01-01), such as limiting or banning the use of wire leaders (C-21-06) or prohibiting the catch of particular shark species (e.g. C-11-10), as well as new measures that may further reduce PRM such as limiting the amount of trailing gear attached to released sharks (see Hutchinson et al., 2021; Scott et al., 2022; Francis et al., 2023).

4.3 Data quality considerations

An important caveat of the assessment of silky and hammerhead sharks is their common misidentification for morphologically similar species (Román-Verdesoto and Orozco-Zöller, 2005), or at least their recording as generic taxonomic groupings such as “requiem sharks” or “hammerhead sharks”. Although observers on large purse-seine vessels in the EPO have been specifically trained on the identification of carcharhinid sharks since 2004 with the introduction of a dedicated shark data collection form (Fuller et al., 2022), prior to this time observed catches of silky sharks are uncertain and were believed to be one of the main reasons for the poor performance of the stock assessment model constructed for silky sharks in the EPO in 2014 (IATTC, 2014). Although there are some fishery monitoring programs for sharks in operation by CPCs, it is unknown as to the level of training of observers and fishers who are responsible for recording the interactions with sharks in their industrial longline fishery and the artisanal gillnet and longline fisheries. The issue of misidentification or poor reporting presents two major issues for assessment. First, to pursue the ultimate goal of undertaking conventional stock assessments reliable species-specific catch and effort data for all fisheries where the species is caught is required to develop standardized indices of abundance.

In the shorter-term, species-specific occurrence records are essential for developing reliable SDMs, which form the foundation for EASI-Fish assessments. Despite the apparent widespread distribution of the three species of hammerheads throughout the EPO (Gallagher and Klimley, 2018), the SDM used in the present study that was developed by Griffiths et al. (2022) predicted reasonably low probability of occurrence in the neritic regime between southern Mexico and northern Chile, which appears to be directly attributable to the low number of presence records for these species in this region (Appendix 3). This appears to have created the false impression that these species prefer more offshore waters, where they have higher overlap with fisheries operating on the high seas, when in fact this may not be the case.

For example, *S. lewini* is one of the most commonly caught hammerhead species in the coastal fisheries of Central and South America (Rojas et al., 2000) with Jaramillo Torres (2022) recording 6,281 occurrences in 2007–2019 from the coastal fisheries of Ecuador. By comparison, less than 100 of the 2017 occurrence records uncovered in the present study for *S. lewini* were derived from South American countries. Most of the records of hammerhead sharks were derived from fishery dependent sources operating on the high seas, which has resulted in higher probability of occurrence in this region. The absence of presence records from regions outside of where industrial fisheries operates where environmental variables may differ could have compromised the quality of the final prediction maps and ultimately the precision of the subsequent fishing mortality estimates.

A particularly significant result from the present assessment was the high vulnerability of *S. zygaena* relative to the other three SHH species. This is likely a result of its low biological productivity, but also because a lack of sufficient length data required an assumption of knife-edge selectivity from the smallest recorded size and the length at birth in industrial longline and gillnet fisheries, respectively (Fig. 6). However, this result may reflect the true vulnerability of this species in the EPO, given its apparent rarity. Between 2012–2022, this species has been recorded in only 367 instances from 290,024 and 31,749 observed sets in EPO purse-seine and industrial longline fishery, respectively. The species is believed to be widely distributed, particularly, in the coastal regime as indicated by the SDM (Fig. 1) but is rarely recorded in the catches of artisanal fisheries. The rarity of this species in catch records may be a result of misidentification—especially if inspections are made of fresh or frozen trunks—or recording as a generic "hammerhead" taxonomic group. However, as whole fresh specimens this species has distinct diagnostic morphological characteristics (Gallagher and Klimley, 2018), and so it would be expected to feature more prominently in catch records of trained scientists and observers should they be present in catch. However, trained scientists employed in the 2-year shark sampling program undertaken by the IATTC did not record any specimens among the 20,698 sharks they recorded from nearly 1400 landing sites throughout Central America (IATTC unpublished data). In a review of historical catch and survey records from Mexican Pacific waters, Pérez-Jiménez (2014) raised concerns for the potential extirpation of *S. zygaena* in this region as a result of decades of fishing impacts, with only 61 individuals recorded from over 207,000 sharks caught in shark surveys conducted in 1962–2010. Given the potentially significant conservation implications for this species, it is recommended that it be a priority species for further research and management efforts.

A related issue to the need for recording species-specific occurrence is that of improving collection of species-specific length data (for selectivity and length-based SDM). It is well documented that the three hammerhead species included in the present study undergo distinct ontogenetic shifts in their distributions from mating and pupping in shallow coastal habitats (Francis, 2016; Zanella et al., 2019; López-Angarita et al., 2021a; Macdonald et al., 2021; Corgos and Rosende-Pereiro, 2022). However, currently methodologies for developing SDMs do not readily accommodate size data to capture ontogenetic shifts in distribution. As a result, grid cells where a species is predicted to occur implicitly assumes that all size classes are present. Although the use of selectivity components in EASI-Fish accounts for differential fishing mortality by size class, EASI-Fish interprets fishing impacts in a similar way as SDMs in that where a species is predicted to be present in a cell, and if that cell is fished, then all size classes are equally susceptible to capture when all selectivity parameters are fully realized. This becomes an issue in the productivity component of EASI-Fish where there is an implicit equal weighting of fishing mortality across size classes. In the case of hammerheads, this results in fishing mortality being underestimated for small size classes, which would compromise the ability of the YPR model to account for growth overfishing and generate an overly optimistic vulnerability status as a result. It is believed this issue resulted in the estimated negligible impacts by the artisanal fisheries, particularly the complete closure of the neonate gillnet fishery that was included in the assessment to specifically explore the impacts of this fishery on hammerheads.

A possible way to circumvent this problem would be to have an index of abundance for each size class from which each grid cell could be weighted. However, if such detailed data were available, conventional stock assessment would be a more suitable approach to assess true population status, rather than to improve EASI-Fish outcomes that provides only a measure of vulnerability. Alternatively, and if data quality improves, size-specific SDMs could be developed, as done in SAC-10 INF-D for bigeye tuna, for each size category (e.g., small, medium, large) using, for example, information collected by IATTC observers on purse-seine vessels or other programs collecting size-specific geolocated information. The susceptibility component of EASI-Fish (Eq. 3) could then be used to estimate the fishing mortality for each size category, which can then be added to produce a final fishing mortality estimate that is then used in the per-recruit models to assess vulnerability status.

Another way to improve the estimation of fishery-specific impacts is to improve estimates of the catchability parameter, *q* (Eq. 1), which in conventional terms, is the fraction of the stock biomass that is caught by one unit of effort (E_x) in fishery *x*. Although catchability estimates for silky shark were available for each fishery from the Pacific-wide stock assessment they were not used as in the present study as Clarke et al. (2018) considered them to be unreliable due to conflicting trends in abundance depicted by fisheries in the WCPO and the EPO. Furthermore, these *q* values were not used as adoption of *q* values from stock assessment in EASI-Fish had not yet been validated. EASI-Fish was designed to estimate relative vulnerability—either between species or between scenarios for the same species—in data-poor settings where the level of effort and its impact on population biomass is unknown. Therefore, these parameters can be precautionarily assigned a value of 1 and the impact of a fishery in a cell assumed to be knife-edged, where fishing is either present or absent. It is therefore assumed that in a cell where a fishery is present, 100% of sharks in that grid cell are initially susceptible to capture by the fishery—regardless of how much effort is applied in that cell—but attrition in the proportion of the population impacted by fishing occurs with each successive susceptibility parameter that is introduced. Therefore, the mathematical meaning of parameters *q* and *E* in EASI-Fish may fundamentally differ to their meaning in conventional stock assessment models where the stock quantity of a continuous and dimensionless variable (i.e., biomass or numbers of individuals) is estimated through accretion of catch quantities as successive fisheries are introduced into the model. The sensitivity analysis (Section 3.3) clearly demonstrated the model's sensitivity to different values of *q* and the subsequent influence on the vulnerability status of SHH sharks. Further work is needed to examine whether conventional estimates of *q* and *E* can be used directly in EASI-Fish, whether modifications such as normalization or standardization is required, or if other novel approaches (Griffiths et al., 2007) may be appropriate. Nonetheless, some type of weighting of *q* is warranted to better reflect the relative contribution of each fishery to the overall fishing mortality of each species. However, this will require significantly more data from each fishery, especially the artisanal fishery where the impacts on SHH sharks are significant (SAC-14 INF-L).

4.4 Guiding management from scenario modelling

While the precision of fishing mortality estimates may be affected by the aforementioned issues, hence why a proxy for fishing mortality ($\tilde{F}$) is estimated within the scope of the simplistic EASI-Fish model assumptions detailed at length in Griffiths et al. (2019), the current EASI-Fish assessment was able to fulfill the objectives of the study to assess the relative efficacy of the 43 hypothetical CMM scenarios. Although many of the scenarios predicted a reduction in vulnerability, none moved any of the SHH species into the "least vulnerable" category. The CMMs having the greatest positive impact was remarkably consistent for all four species. The single measures that had the post positive impact on vulnerability were implementing EPO-wide closures, particularly where multiple fisheries including the industrial longline fishery were closed for 120 or 180 days. Unlike the purse-seine fishery that has be subjected to EPO-wide closure of 72 days since 2018 (Resolutions C-17-01 and C-21-04), the IATTC had never imposed spatial or temporal closure of the industrial longline fishery as a management measure to reduce the fishing mortality of their target or predominant species. However, since 2011, Resolution C-11-02 has mandated gear restrictions for industrial longline vessels >20 m LOA for the area 20°N to 30°S to reduce seabird bycatch.

The simulated temporal closures of the industrial longline fishery were effective due the complete avoidance of shark interactions for the entire closure period, which resulted in a reduction in fishing mortality across the large area in which the industrial longline fishery operates. Several authors have recently developed mitigation hierarchies for fisheries bycatch and advocate for avoidance of interaction as being the preferred option for the mitigation of species that are unavoidably caught, even with specific measures in place (Milner-Gulland et al., 2018; Booth et al., 2020; Gilman et al., 2023). Such is the approach that has been adopted by Colombia and Ecuador where all industrial and artisanal fishing for sharks has been prohibited withing their EEZs (Tribunal Constitucional del Ecuador, 2007; Mason et al., 2020). Although avoidance of shark interactions would obviously be the most effective measure to mitigate shark bycatch in the EPO, the pragmatic implications for the closure of such a large area for 120 days or more is that it is unlikely to be a viable management measure as it will result in significant reduction in catch, which may have significant socio-economic impacts on some longline fishing nations, especially for coastal States where a 3-month seasonal closure to shark fishing is already in place within the EEZ, such as Mexico (Sosa-Nishizaki et al., 2020) and Peru (Mason et al., 2020). Furthermore, if such lengthy closures are accepted by IATTC Members, this is likely to result in a significant temporary relocation of effort to the eastern portion of the WCPFC Convention area, which may result in competition among island nation fleets and/or cause localized depletion of the shark species for which the closure is intended to protect. Because of these challenges, the IATTC staff has been exploring the benefits of dynamic ocean management (Hazen et al., 2018) as a means to reduce the interaction of the fishery with vulnerable species (e.g., SAC-10 INF-D, BYC-11-04, Pons et al., 2022).

For these reasons, multiple measures implemented in combination may be the most feasible option if it can be demonstrated that each of the individual measures is likely to be implemented to reach their full mitigation potential. Although multiple measures may be more difficult to implement and monitor for compliance, this has been the approach taken by the IATTC in the management of other bycatch species such as seabirds (Resolution C-11-02), where at least 2 mitigation measures can be selected from a ‘menu’ of mitigation options.

Unfortunately, the scenarios that simulated the use of some of the more easily implemented measures CMMs in combination, such as prohibiting the use of wire leaders, or even prohibiting the retention of sharks, resulted in only modest reductions in vulnerability since most of the individual measures aim to reduce AVM. Some measures, such as prohibiting wire traces in longline fisheries have been estimated to reduce AVM of some shark species by 31– 41% (Bigelow et al., 2022; Scott et al., 2022). However, the potential reduction in fishing mortality by these measures will be negated if there is no associated measure in place to prohibit retention of sharks, or if PRM is high, such as the estimated 85%–100% mortality of *C. falciformis* and *S. lewini* released from the purse-seine nets (Hutchinson et al., 2015; Eddy et al., 2016).

4.5 Recommendations and directions for future work

The current study has collated existing datasets and conducted scenario modelling of potential management measures, which provides valuable knowledge for the IATTC to plan future research, monitoring, assessment, or management efforts for silky and hammerhead sharks in the EPO. This assessment builds on the 2022 assessment of 32 shark bycatch species in the EPO (Griffiths et al., 2022), which included the four SHH species addressed here. The study incorporates new data published by researchers from CPCs and ongoing research efforts by the IATTC staff, including the ANBJ shark monitoring program (SAC-14 INF-L). However, the lack of fundamental biological or catch information for all four species highlights the needs for future work priorities of the IATTC to improve data inputs, not only for more immediate needs such as EASI-Fish, but also for longer-term goals such as stock assessment and transparent reporting of catches from all fisheries.

4.3.1 Artisanal fisheries

One of the most important requirements for EASI-Fish is to have an understanding of the effort footprint of each fishery for the chosen assessment year(s). This is fundamentally simple, requiring only the presence of one or more units of fishing effort across the full spatial extent of the fishery. Unfortunately, the artisanal longline and gillnet fisheries throughout the EPO are poorly monitored, if at all, resulting in a lack of even simple presence of effort data from which to characterize these fisheries. This required the collation of effort data from published reports or unpublished studies, often for years outside of the 2019 assessment year. However, it is apparent that some fisheries may already collect some data useful for EASI-Fish assessments, which may not be readily available for some artisanal fisheries (see Jaramillo Torres, 2022).

For example, a recent collaborative project between the IATTC, the Inter-American Sea Turtle Convention (IAC) and their Members assessing the vulnerability of the leatherback turtle in the EPO (Griffiths et al., 2020), IATTC staff worked directly with representatives from coastal States to access confidential effort data to develop improved SDMs and effort footprints for the artisanal longline and gillnet fisheries, which were substantially larger than was achieved using the fragmented data derived from various sources in the present study. As a result, it is likely that the estimated fishing mortality of each of the four SHH species by the artisanal longline and gillnet fisheries included in the present study is likely to be underestimated.

Even for the semi-industrial purse-seine fishery comprised of smaller Class 1–5 vessels lack adequate monitoring of shark bycatch, as the IATTC currently mandates a minimum of 5% observer coverage for vessels less than 24 m LOA. In the present study, effort data were derived primarily from observed sets by TUNACONS on a voluntary basis, which covered 12% of the effort by the fleet in 2019 (IATTC, unpublished data). As a result, it is unknown whether the catch composition is representative of the fleet and the distribution of effort was considered to represent the minimum spatial coverage of the fishery. However, the IATTC is working on improving data provision for this and other fleets through a proposed update of its data provision resolution (see SAC-12-09), the development of the FAD form (09-2018), and the implementation of electronic monitoring systems (EMS) (see EMS-01-02), and is planning to analyze the representativeness of the information collected under voluntary Class 1–5 purse-seine vessels program in the near future.

Given the requirement by EASI-Fish for diversity of data inputs to characterize population and fishery dynamics, future EASI-Fish assessments would greatly benefit from the close collaboration with CPCs in order to optimize the quality of model inputs. Such collaboration would likely develop trust among researchers and managers that may increase the potential for more effective collaborations to conduct research at the scale relevant to EPO pelagic fisheries. One of the key areas of research is likely to be the artisanal fisheries, not only in relation to shark catches, but also tuna, billfish and dorado, which comprise a significant component of the catches (Dapp et al., 2013; Martínez-Ortiz et al., 2015). Despite artisanal vessels being small, their fleet sizes can be large and their impacts on sharks have been shown to be significant (Alfaro-Shigueto et al., 2010; Cartamil et al., 2011; Martínez-Ortiz et al., 2015; Sosa-Nishizaki et al., 2020). In 2023, the IATTC produced order of magnitude estimates of the shark catch from the ABNJ shark sampling program (Oliveros-Ramos et al., 2020), which indicated that shark catches are significant in the region and should not be ignored for both silky and hammerhead sharks (SAC-14 INF-L).

This highlights a clear need for coastal CPCs to establish or improve data collection programs for artisanal fleets to not only facilitate domestic fisheries management but assist the IATTC in fulfilling its responsibilities under the Antigua Convention, which has been hindered in many instances by a lack of data from these fleets. In recent years the IATTC collaborated with Central American IATTC Members in a project funded by the Global Environment Facility (GEF) to develop a data collection program for small coastal shark fisheries (Siu and Aires-da-Silva, 2016; Oliveros-Ramos et al., 2019). Although the project developed a sampling program that significantly improved our understanding of artisanal fisheries, unfortunately the staff's proposal for the implementation of a long-term sampling program for shark fisheries in Central America has not yet succeeded in gaining financial support (IATTC-98-02c). Funds from GEF ABNJ-2 for a subsequent pilot sampling project are currently underway where the project could be expanded to other countries like Ecuador, Peru and Mexico (SAC-14 INF-M). However, for the IATTC to be able to undertake future stock or vulnerability assessments on shark species in the EPO as agreed to by its Members (see Resolution C-16-05), a long-term solution to securing sufficient resourcing to facilitate ongoing monitoring programs is required. Furthermore, updating of Resolution C-03-05 on data provision is essential to align with mandates described in the Antigua Convention and IATTC's SSP to include mandates on reporting of, at a minimum, vulnerable species (e.g., elasmobranchs) incidentally caught by the various fisheries operating in the EPO (see C-12-09).

4.3.2 Industrial longline fishery

The industrial longline fishery had by far the largest impact on the four SHH sharks in the present study by virtue of not only its widely dispersed effort throughout the EPO that covers a large proportion of the distributions of the SHH shark species, but also due to the coarse spatial resolution of its reported effort. Unfortunately, industrial longline effort data is commonly reported by CPCs at 5° x 5°, or occasionally at 1° x 1°, which is the coarsest resolution permitted under Resolution C-03-05. Furthermore, this resolution does not require CPCs to report on incidental catches of non-target species, which may include sharks. The major issue arising from the coarse resolution of the effort data is that the grid cell size greatly exceeds that of the SDM predictions (0.5° x 0.5°), which was shown in the sensitivity analysis (Section 3.3) to significantly overestimate overlap with a species. This is because in cases where the SDM predicts a species to be present in all one hundred 0.5° grid cells contained within a 5° grid cell that is fished, it is assumed that fishing is present within each 0.5° grid cell.

The coarse spatial resolution of these reported data also compromises the precision of species presence locations. Because the spatial distribution of longline fishing effort covers almost the entire Convention Area, it can be a valuable source of data for developing SDMs because of the broad environmental gradient in which the fishery covers. However, the oceanographic environment can vary significantly within a 5° grid cell for which catch data is reported due to the influence of fronts (Wang et al., 2021), mesoscale eddies (Hasson et al., 2019), and other fine and mesoscale environmental features, thus compromising the potential strength of modelled relationships between a species' relative abundance and environmental variables.

Another significant shortcoming of the reported industrial longline data is the temporal resolution of reporting, which aggregates all sets into monthly time steps that lack operational characteristics from which a set type can be determined. The industrial longline fishery typically deploys one of two sets: deep sets where 20–32 hooks per float are deployed during the day to depths of around 300 m to target bigeye tuna and albacore, and shallow sets where less than 6 hooks are deployed at night to depths of around 100 m to target swordfish, but also a range of species such as tuna, marlin, and sharks that vertically migrate to epipelagic waters during the night (Griffiths and Duffy, 2017). As a result, the susceptibility of sharks to being caught depends heavily on the set type and gear configuration. Therefore, in the absence of information on set type, a precautionary assumption was made that all sets were deep sets where any species occupying the 0-300 m depth range of the gear could be caught and estimates of fishing mortality of SHH sharks was likely biased high.

An alternative to using the coarse logbook data to establish an effort footprint and to improve the precision of species occurrences is to use the operational level data mandated in Resolution C-19-08. Although these data provide high quality data on operational details and shark catch in each observed set, the resolution requires only a minimum of 5% observer coverage of the effort by the longline fleets of each CPC. A recent analysis of these data revealed that they are not representative of the activities of the fleet nor do they cover the full spatial footprint of the fleet (Griffiths et al., 2021). Although these data alone could not be used in the present study to define the effort footprint of the fishery, they did provide some very useful length data for the SHH species, especially for *C. falciformis*, which greatly improved the selectivity curves for this fishery since the EPO silky shark stock assessment was undertaken (IATTC, 2014). If the recommendations by the IATTC scientists to increase observer coverage to a minimum of 20% or more (see Resolution C-19-08; Griffiths et al., 2021), observer data is likely to help significantly improve the assessment of sharks in future but also for routine catch monitoring and reporting. In 2023, the staff undertook a workshop to seek the input by Members to improve data provision for the industrial longline fishery (WSDAT-01). Similar workshops are planned for other fisheries, including the artisanal fleets.

4.3.3 Biological studies

The four SHH species assessed were among the most data rich of shark bycatch species in EPO pelagic fisheries as their frequency of interaction with fisheries has afforded them some attention in biological research in most oceans of the world. Although some biological studies have been undertaken for the majority of these species in the EPO, unfortunately many suffer from small sample sizes or are restricted in spatial or temporal scope, thus limiting their usefulness to represent the broader population dynamics of the species at the scale of the EPO. With the exception of a few reproductive studies conducted in the EPO (Nava Nava and Márquez-Farías, 2014; Estupiñán-Montaño et al., 2021) it was necessary to adopt key biological parameter values describing growth and reproduction of SHH species from well-designed studies from the western Pacific Ocean (e.g., Joung et al., 2008; Harry et al., 2011). Despite the frequency of SHH sharks in industrial and artisanal fisheries in the EPO, even the most fundamental biological information such as a length-weight and length-length relationships are either unavailable or do not cover an adequate size range for a species.

In 2023 the IATTC staff have proposed a project and workplan to evaluate the feasibility of developing a sampling program, with potential phased-based upscaling to a pilot and EPO-wide sampling program, for collecting morphometric data from fisheries operating in the EPO (SAC-14 INF-J). If endorsed and funded, this project will significantly narrow the knowledge gap for morphometric relationships, at least for some key species. As discussed throughout this paper, the sizes of SHH sharks caught by the industrial fleet can differ significantly to those of the artisanal fleets, which are more coastally orientated where neonate and juveniles of several species reside. Therefore, it will be important to use the outcomes from the feasibility study and extend sampling to the artisanal fleets in close collaboration with IATTC CPCs (see Table 2, SAC-14 INF-J). This may serve as a collaborative blueprint to extend the morphometric study to include the collection of biological material in order to undertake critical biological studies for SHH species at scale relevant to their population(s) in the EPO. Not only would these collaborative efforts reduce operational costs and provide access to samples that may be inaccessible by IATTC staff alone, but it will instill fisheries research capacity within the institutions of developing coastal States, which has been an important goal of the IATTC's SSP (Goal Q: Provide training opportunities for scientists and technicians of CPCs).

5. CONCLUSIONS

Over the past two decades, there has been a dramatic shift in the traditional approach to fisheries management from focusing on individual target species to a more holistic approach that considers the broader ecosystem context (Hall and Mainprize, 2004). As such, the roles and responsibilities of the IATTC, its Members and their fisheries have also undergone substantial change to ensure the long-term sustainability of all species impacted by fishing activities. This is explicitly reflected in the Antigua Convention (IATTC, 2003), particularly in 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…*". This has led to a focus on sharks, which are frequently retained as catch or discarded as bycatch in industrial and artisanal fisheries in the EPO. However, due to a lack of reliable biological and catch data for these species, conventional stock assessment methods cannot be used to demonstrate that their populations are being impacted at biologically sustainable levels.

To address this issue, the IATTC staff designed EASI-Fish, a tool that quantifies the cumulative impacts of multiple fisheries on data-poor species and transparently determines the vulnerability status of a species' population based on proxies for biological reference points widely used in fisheries stock assessment. While EASI-Fish integrates length-structured yield- and spawning biomass-per-recruit models, it, and other ERA methods, should not be used as a substitute for stock assessment to assess stock status for shark species and be the endpoint for management advice.

In the present study, EASI-Fish was used to explore the potential efficacy of a range of potential CMMs for four SHH shark species that might otherwise be difficult, time-consuming, and costly to explore using field studies. The results identify the most effective measures—either applied individually or in combination—to reduce the vulnerability of these species. These findings can guide the IATTC in planning future research and management efforts for sharks. In the interim period until reliable data are available to undertake conventional stock assessments or other modern population assessment methods such as close-kin mark recapture (Bravington et al., 2016), the results of this study serve an important role prioritizing IATTC shark efforts.

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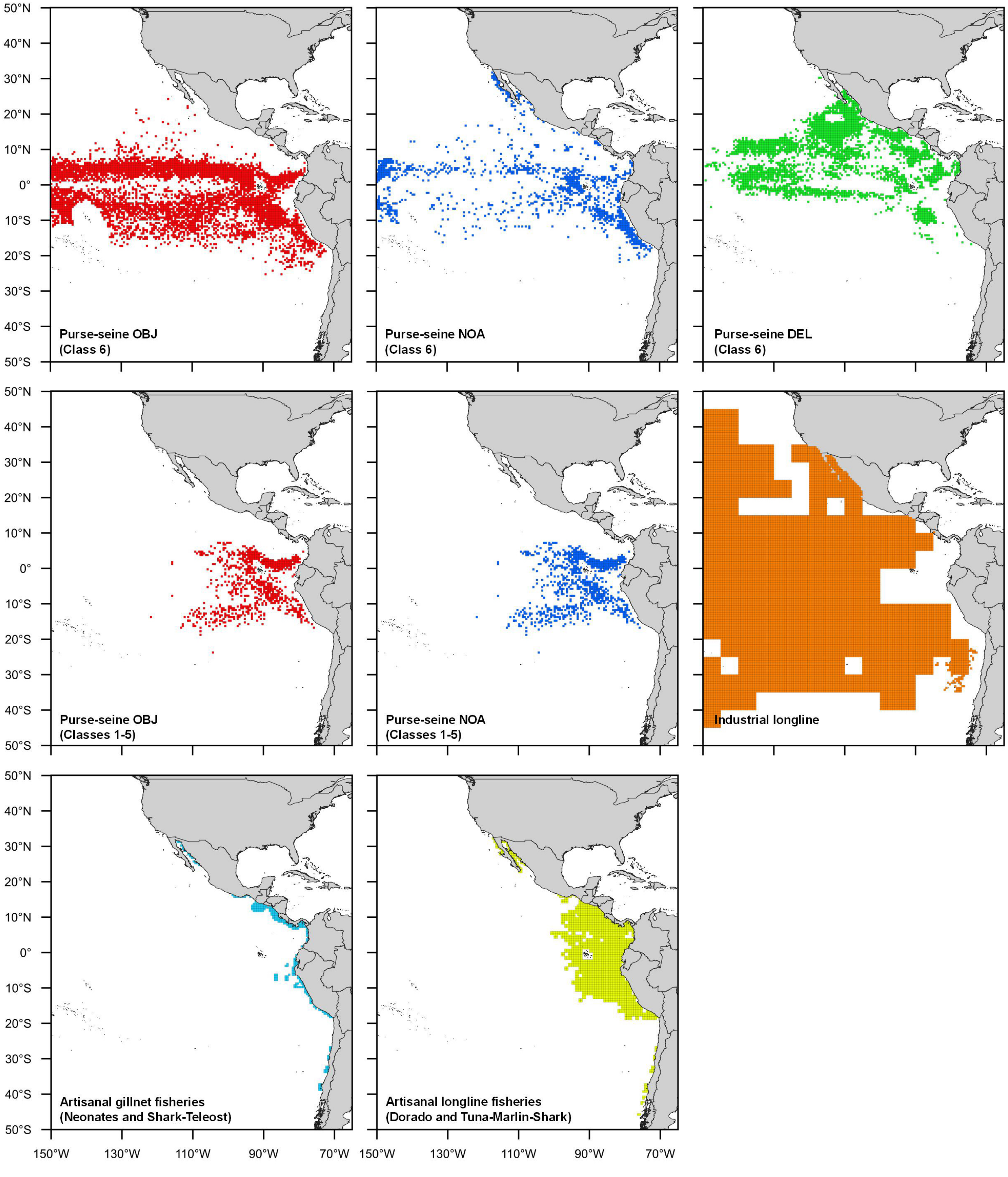

FIGURE 1. Maps showing the distribution of fishing effort (at 0.5° x 0.5° resolution; 5° x 5° and 1° x 1° for the industrial longline fishery) by eight fisheries in the eastern Pacific Ocean in 2019. Set types for the purse-seine fisheries are: i) sets associated with floating objects (OBJ), ii) sets on unassociated schools of tuna (NOA), and iii) sets associated with dolphins (DEL).

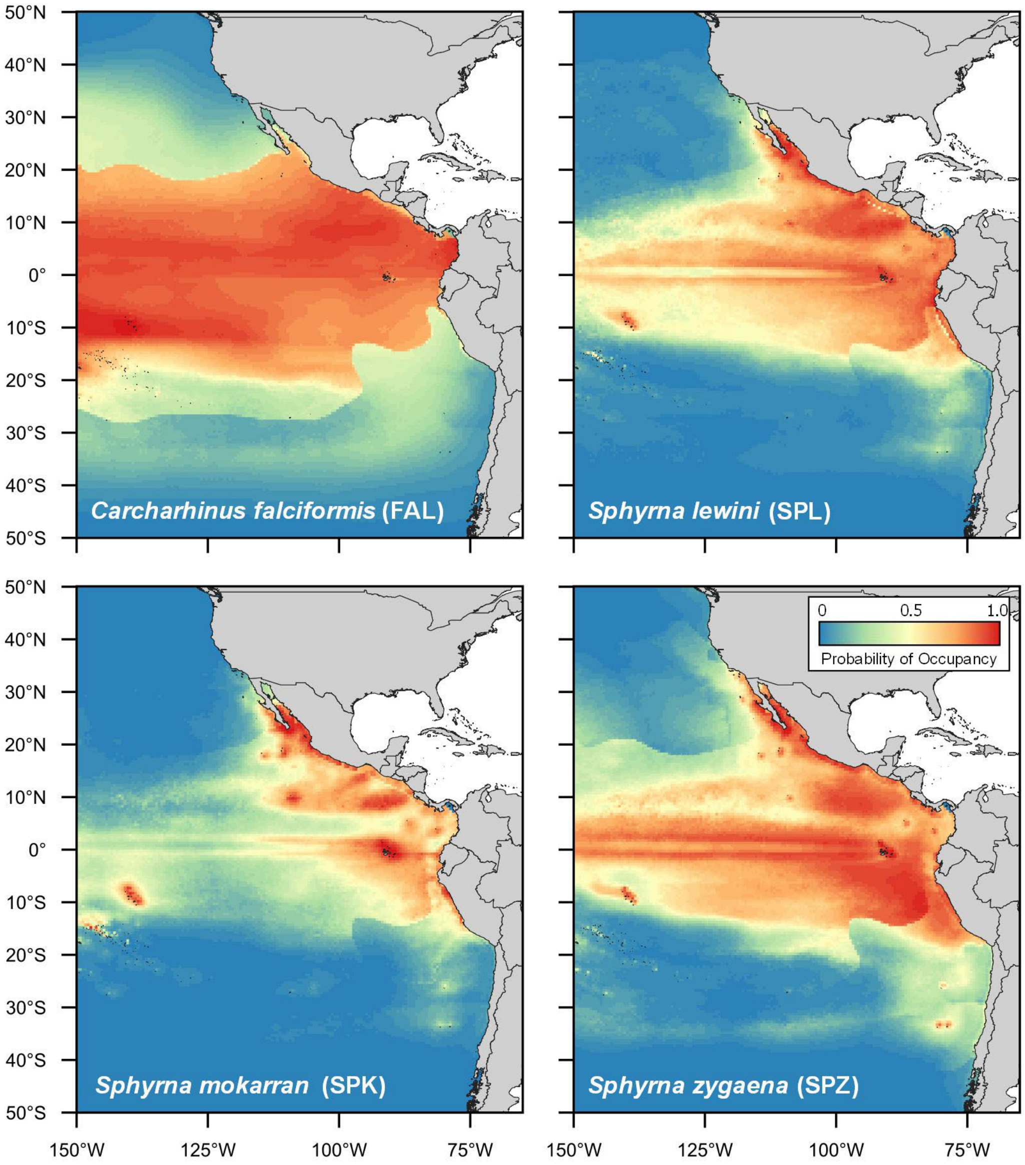

FIGURE 2. Maps showing the predicted distributions of silky shark (*Carcharhinus falciformis;* FAL), scalloped hammerhead (*Sphyrna lewini;* SPL), great hammerhead (*S. mokarran;* SPK), and smooth hammerhead (*S. zygaena;* SPZ) caught in eastern Pacific Ocean pelagic fisheries modelled using presence-only data in an ensemble of species distribution models (for details see Griffiths et al., 2022). Colored gradient bar in legend shows probability of occupancy (ψ) for each species in 0.5° x 0.5° cells.

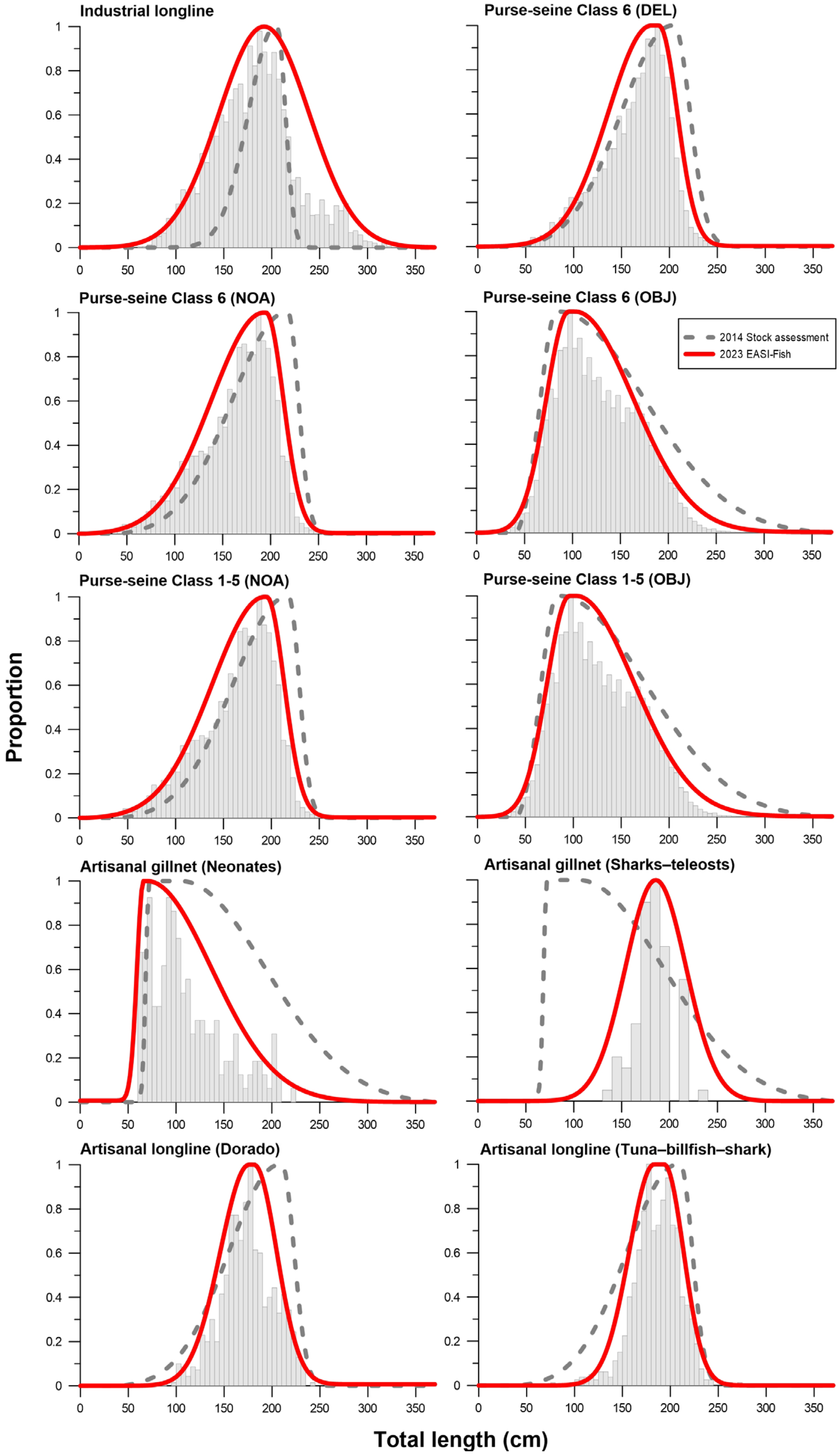

FIGURE 3. Selectivity curves for silky shark (*Carcharhinus falciformis*) for each of the 10 pelagic fisheries in the eastern Pacific Ocean that were used in the 2014 stock assessment (IATTC, 2014) (dashed lines) and the present study (red lines), which were based on the best available length-frequency data (grey bars) (data sources shown in Appendix 2).

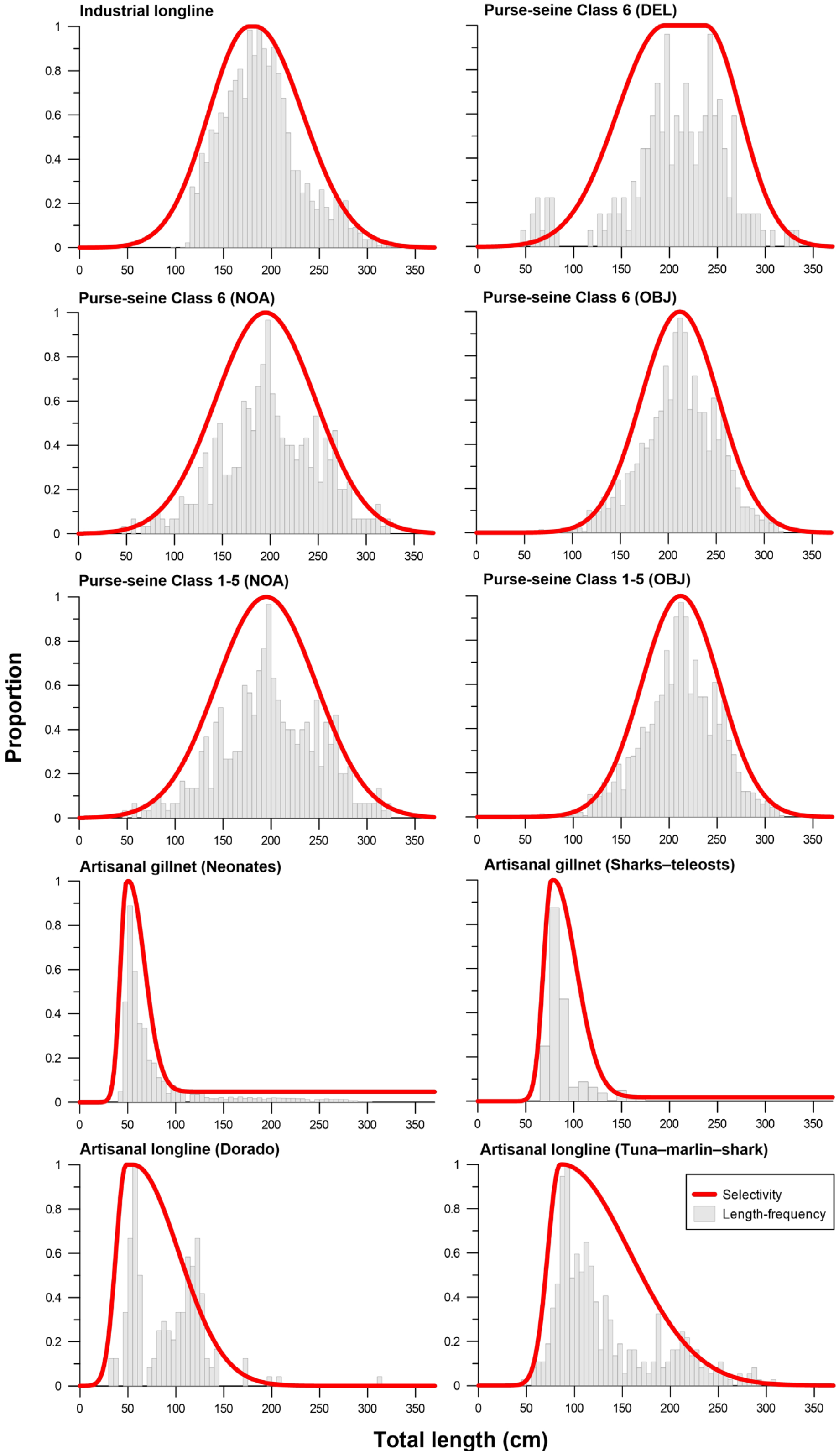

FIGURE 4. Selectivity curves for scalloped hammerhead (*Sphyrna lewini*) for each of the 10 pelagic fisheries in the eastern Pacific Ocean that were used in the EASI-Fish assessment (red lines), which were based on the best available length-frequency data (grey bars) (data sources shown in Appendix 2).

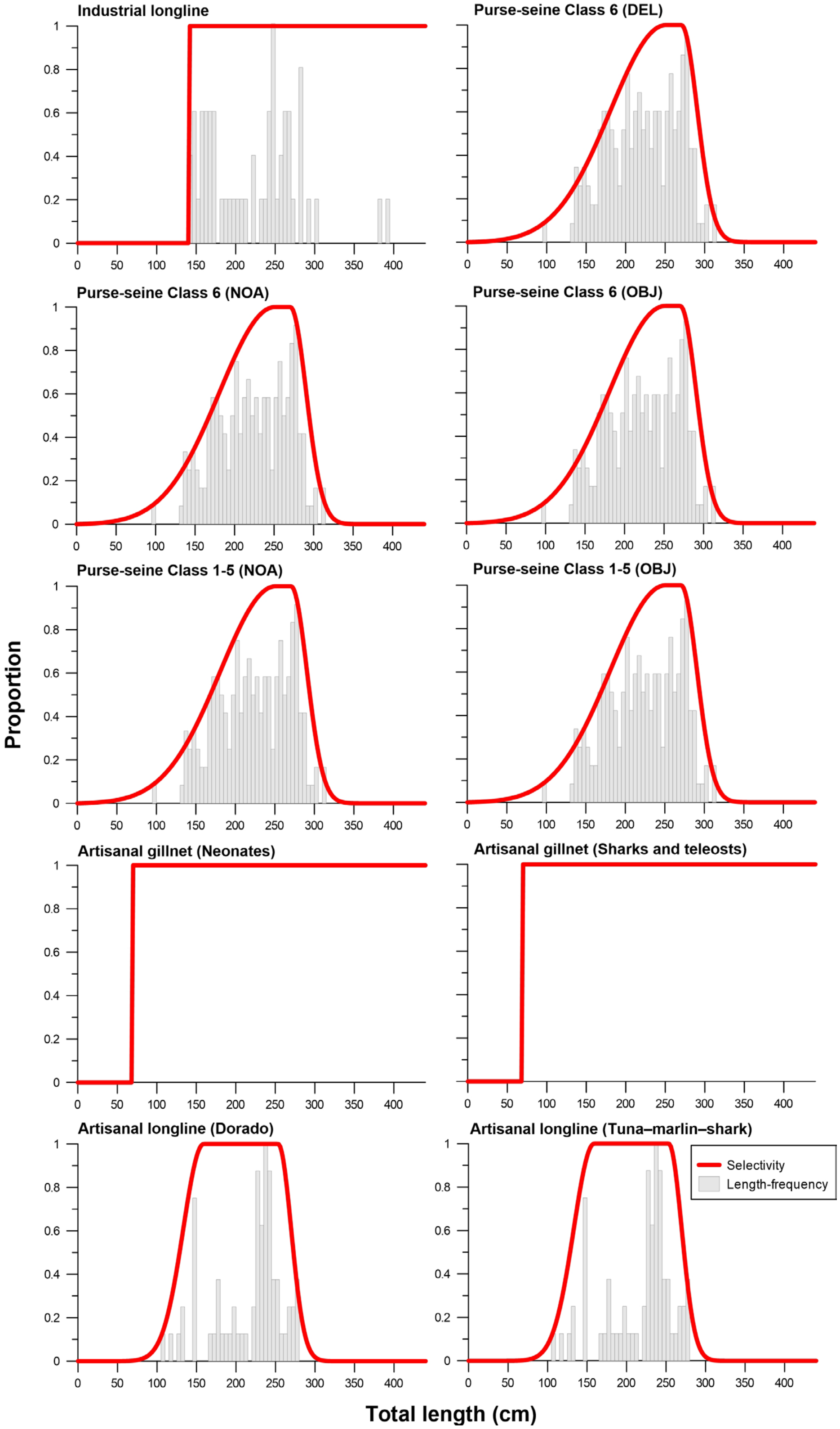

FIGURE 5. Selectivity curves for the great hammerhead (*Sphyrna mokarran*) for each of the 10 pelagic fisheries in the eastern Pacific Ocean that were used in the EASI-Fish assessment (red lines), which were based on the best available length-frequency data (grey bars) (data sources shown in Appendix 2).

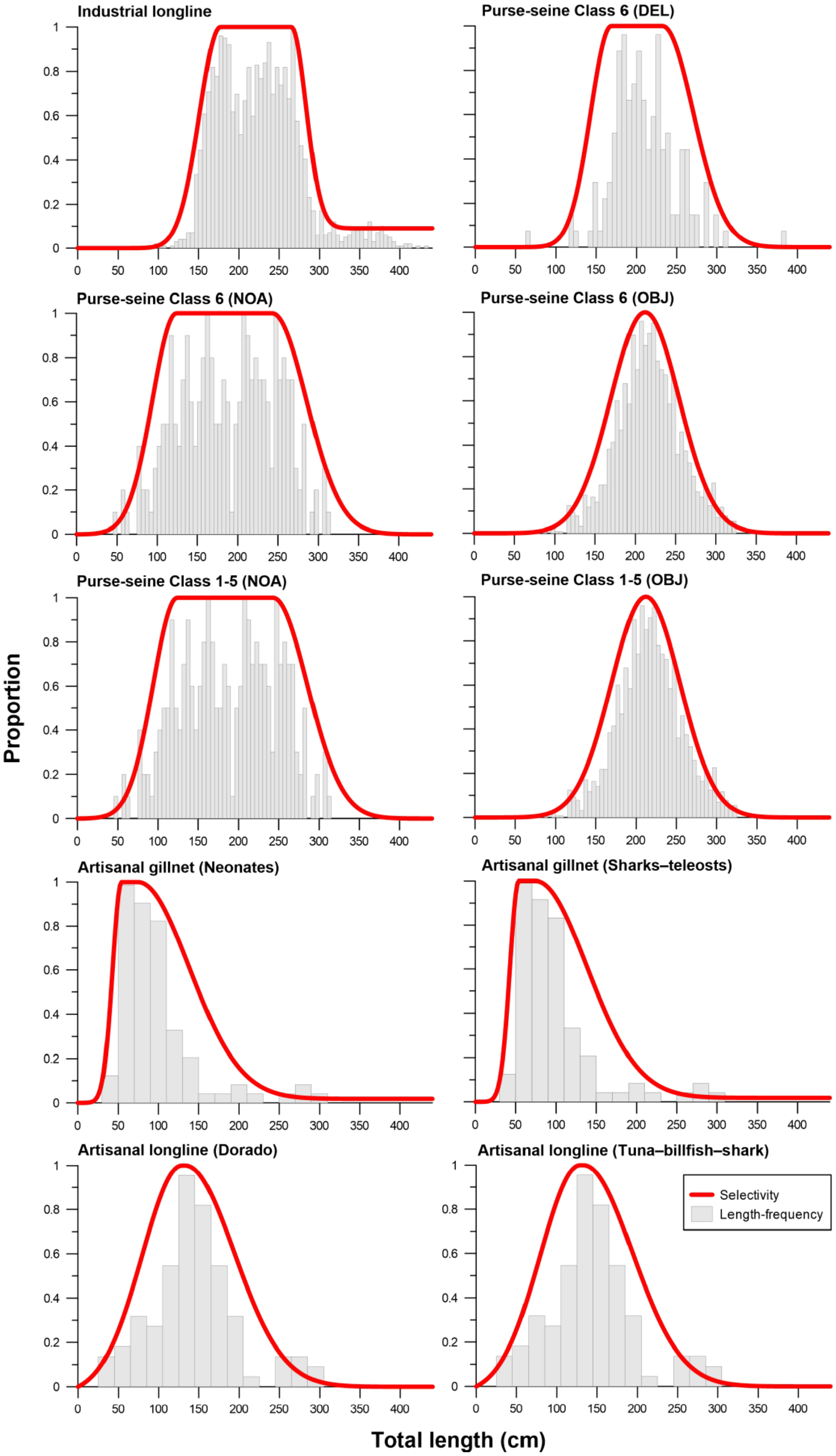

FIGURE 6. Selectivity curves for the smooth hammerhead (*Sphyrna zygaena*) for each of the 10 pelagic fisheries in the eastern Pacific Ocean that were used in the EASI-Fish assessment (red lines), which were based on the best available length-frequency data (grey bars) ((data sources shown in Appendix 2).

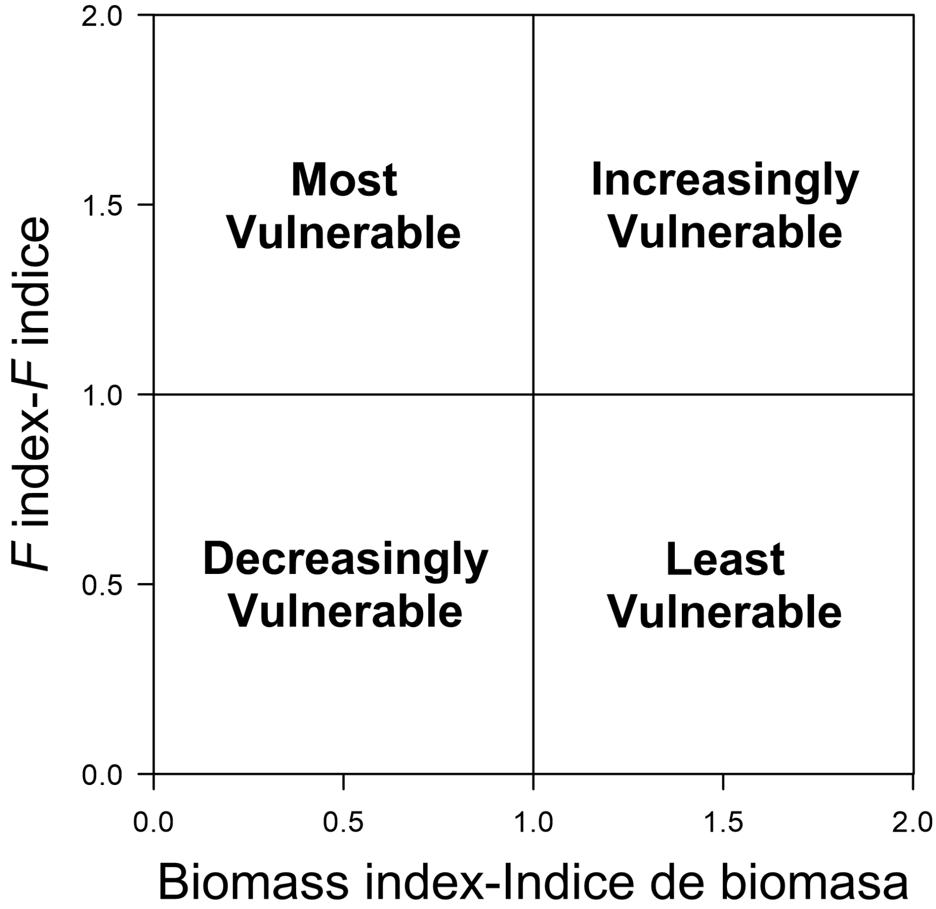

FIGURE 7. Phase plot illustrating how vulnerability status was defined for the shark species assessed using $F_{40\%}$ and $SBR_{40\%}$ from the EASI-Fish model as a reference point on the x and y axis, respectively. Vulnerability was defined by its position within one of four quadrants in the phase plot as: "Least vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ <1 and $SBR_{2019}/SBR_{40\%}$ >1), "Increasingly vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ >1 and $SBR_{2019}/SBR_{40\%}$ >1), "Most vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ >1 and $SBR_{2019}/SBR_{40\%}$ <1), and "Decreasingly vulnerable" ($\tilde{F}_{2019}/F_{40\%}$ <1 and $SBR_{2019}/SBR_{40\%}$ <1). Maximum axis limits of 2.0 are for illustrative purposes only.

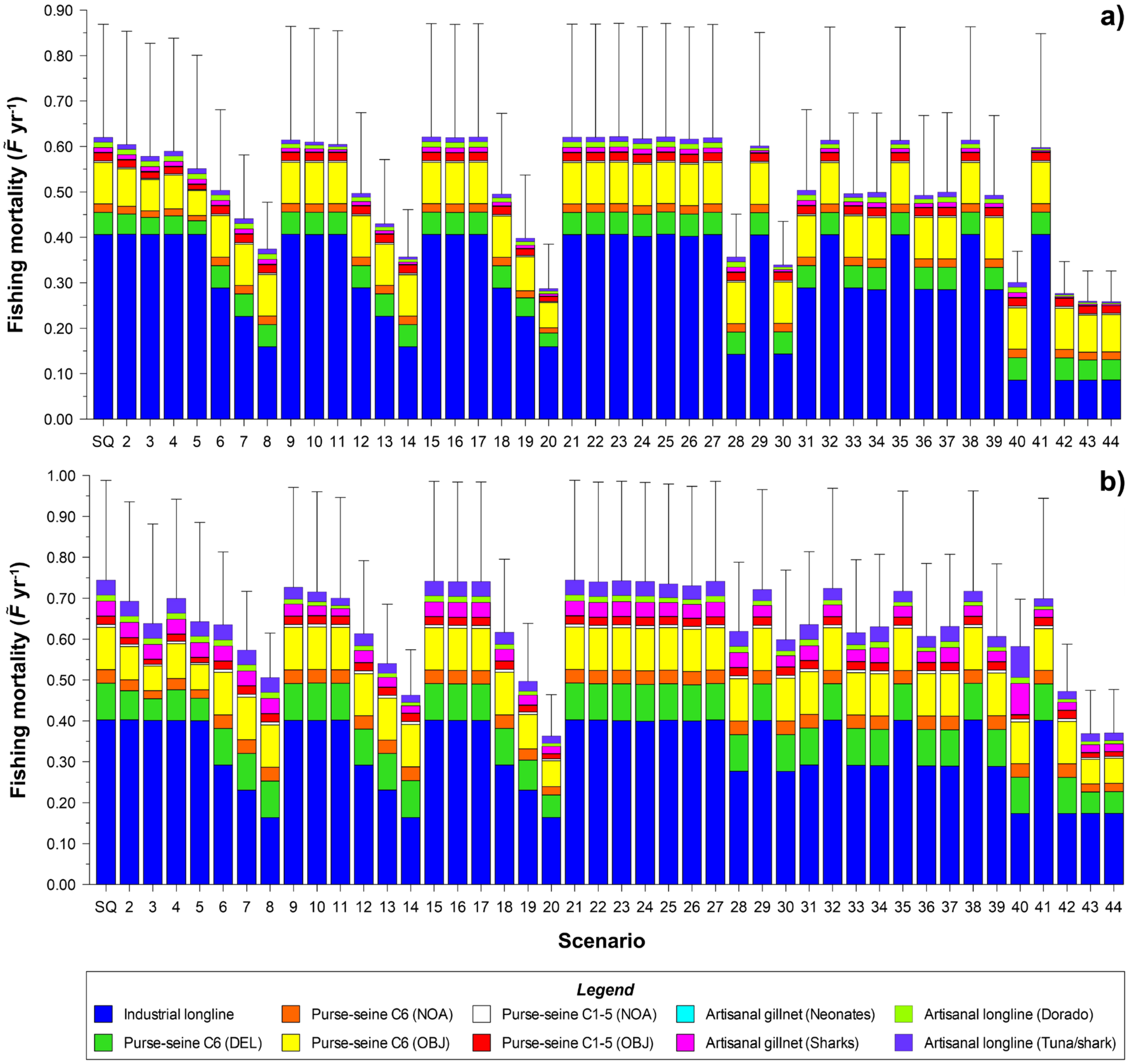

FIGURE 8. Mean (± 95% confidence intervals) fishing mortality proxy for a) silky shark (*Carcharhinus falciformis*), b) scalloped hammerhead (*Sphyrna lewini*), c) great hammerhead (*S. mokarran*), and d) smooth hammerhead (*S. zygaena*) estimated by EASI-Fish for the status quo scenario in 2019 ($\tilde{F}_{2019}$) and for each of the 43 scenarios simulating hypothetical management measures (see Table 5 for descriptions) for pelagic fisheries in the eastern Pacific Ocean. Bars are disaggregated by the contribution to $\tilde{F}_{2019}$ by each fishery.

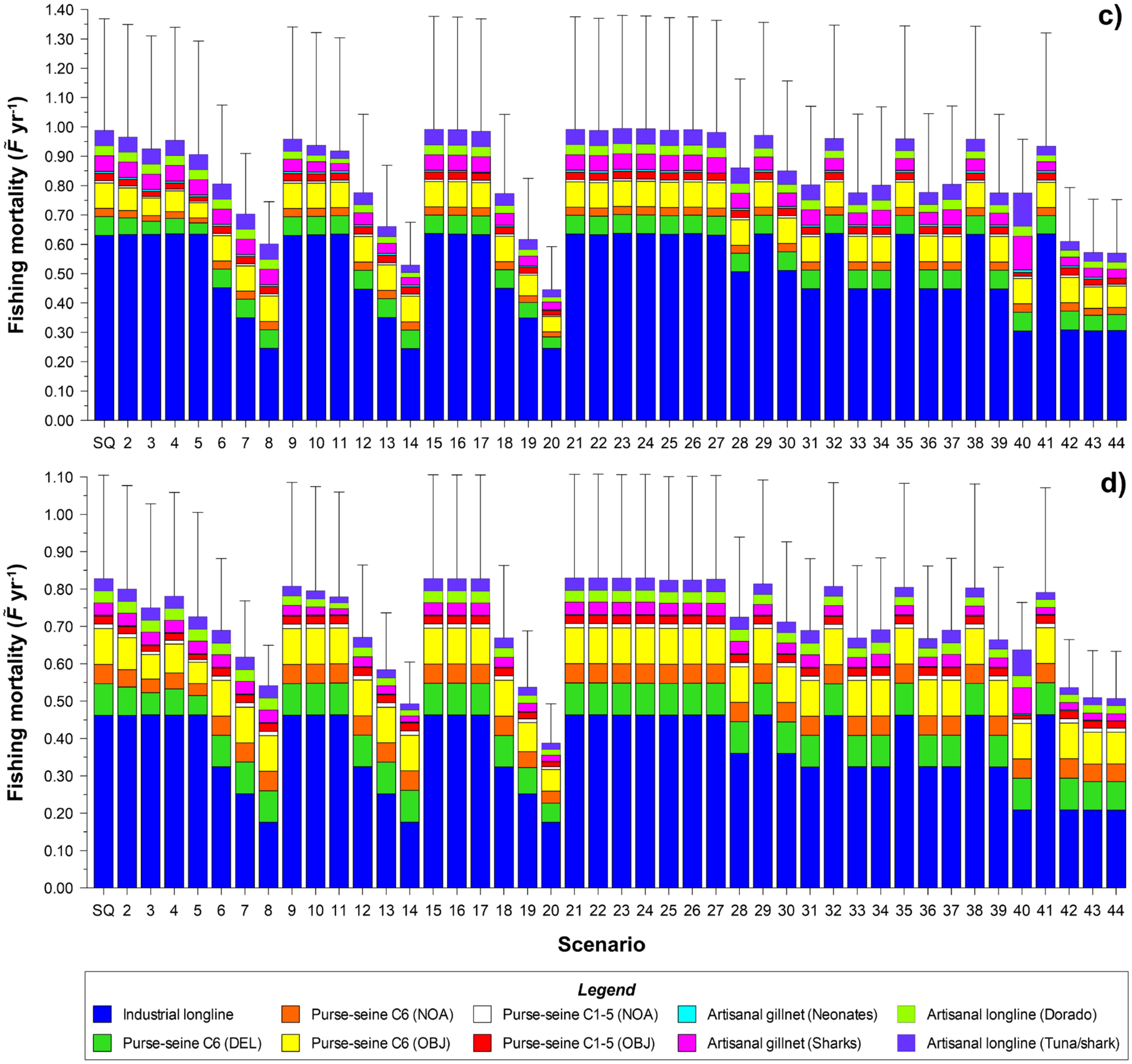

Figure 8 continued.

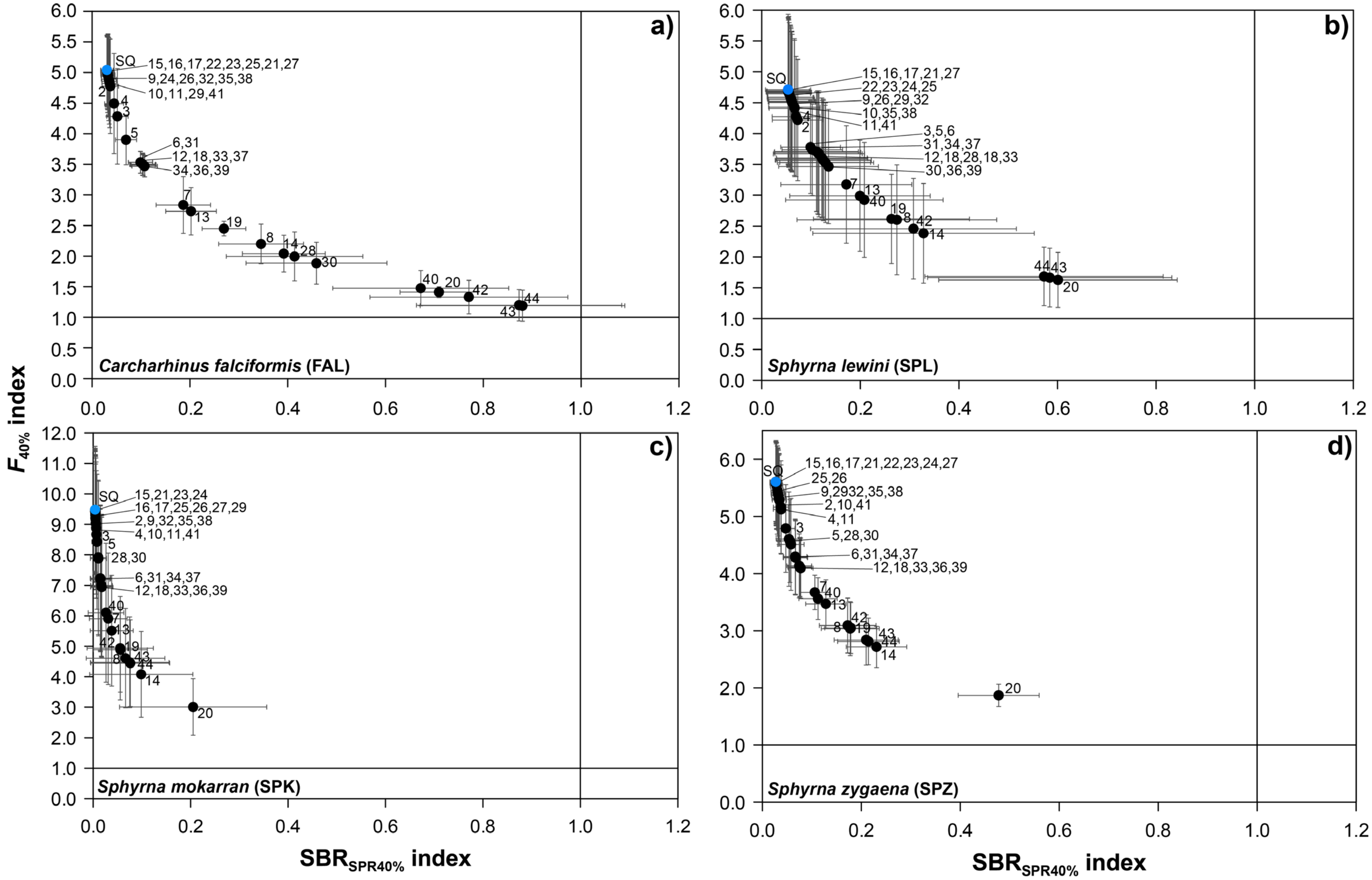

FIGURE 9. Vulnerability phase plots showing the relative vulnerability of a) silky shark (*Carcharhinus falciformis*), b) scalloped hammerhead (*Sphyrna lewini*), c) great hammerhead (*S. mokarran*), and d) smooth hammerhead (*S. zygaena*) estimated by EASI-Fish for the status quo scenario in 2019 ($\tilde{F}_{2019}$) (blue symbol) and 43 scenarios simulating hypothetical management measures (see Table 5 for descriptions) for pelagic fisheries in the eastern Pacific Ocean. Vulnerability status is depicted by the mean (± 95% confidence intervals) estimate of the biological reference points $\tilde{F}_{2019}/F_{40\%}$ and $SBR_{2019}/SBR_{40\%}$. Labels adjacent to symbols denote scenarios defined in Table 4. Vulnerability status values for each species are provided in Table 5**.**

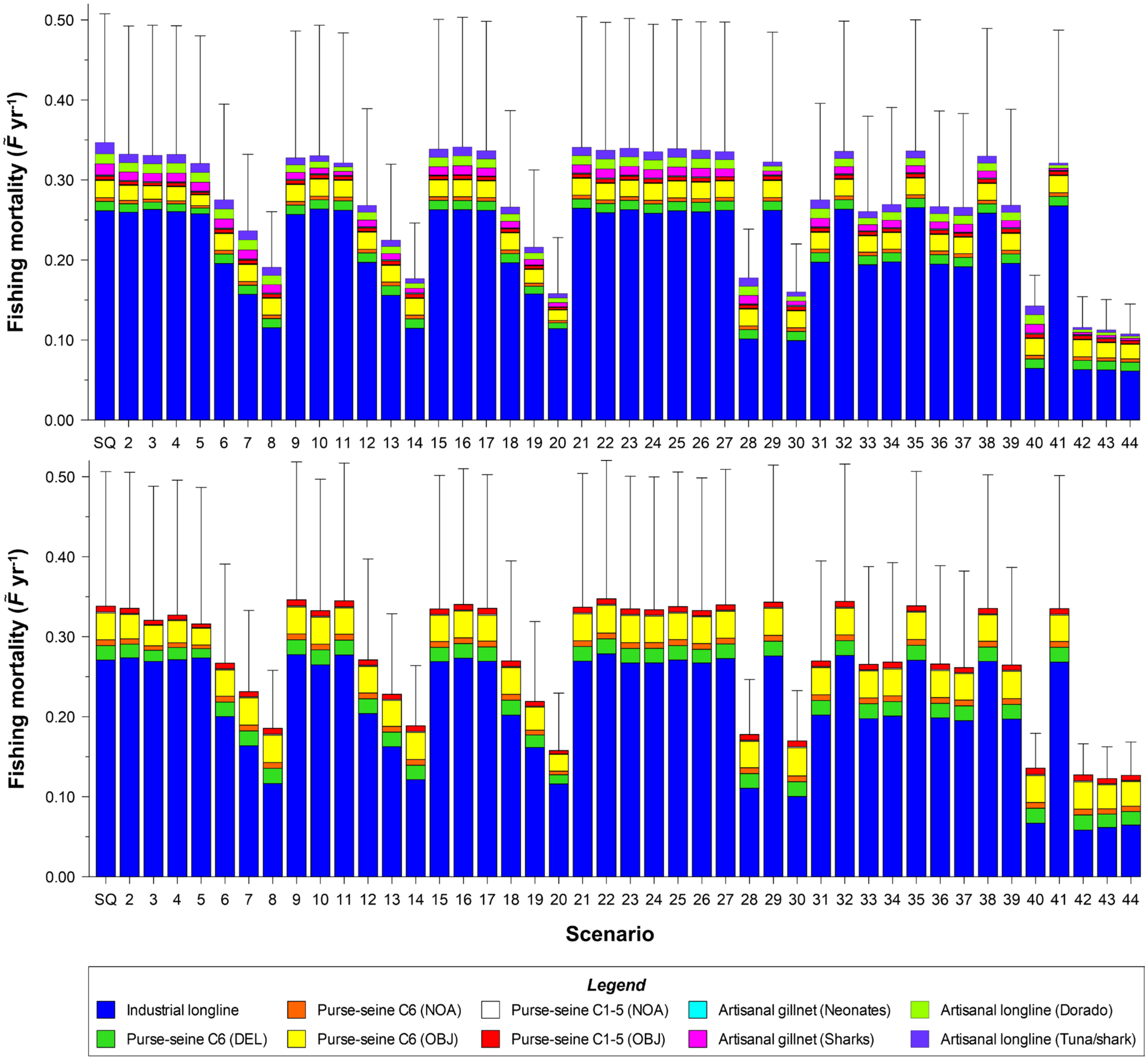

FIGURE 10. Results of sensitivity analyses showing the mean (± 95% confidence intervals) fishing mortality proxy for silky shark (*Carcharhinus falciformis*) estimated by EASI-Fish for the status quo scenario in 2019 ($\widetilde{F}_{2019}$) and for each of the 43 scenarios simulating hypothetical management measures (see Table 5 for descriptions) for pelagic fisheries in the eastern Pacific Ocean after decreasing the q values for industrial longline and purse-seine fisheries (top panel), and increasing the resolution of the industrial longline data from 5° x 5° to 1° x 1° (bottom panel). Bars are disaggregated by the contribution to $\widetilde{F}_{2019}$ by each fishery.

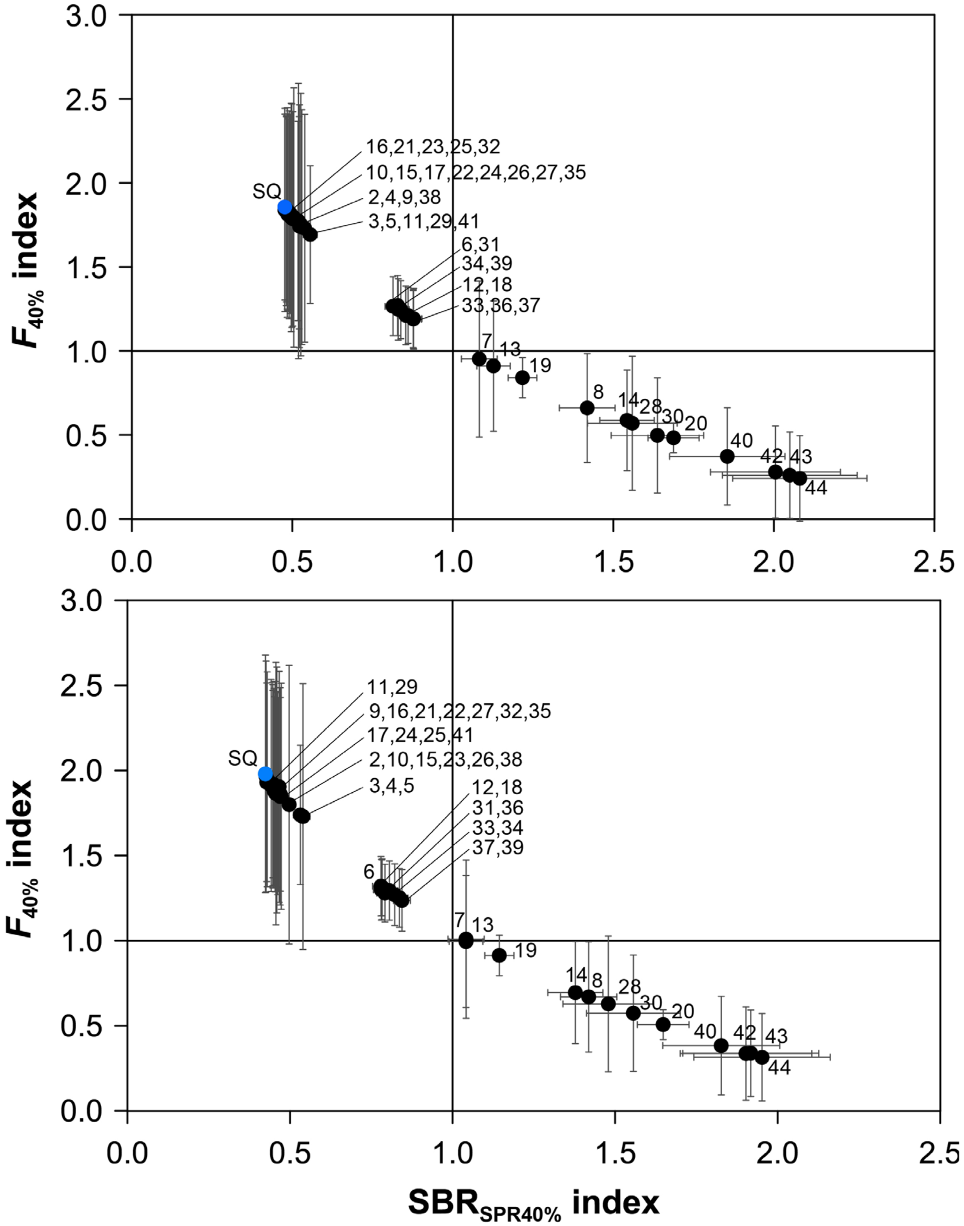

FIGURE 11. Results of sensitivity analyses represented in vulnerability phase plots showing the relative vulnerability of silky shark (*Carcharhinus falciformis*) estimated by EASI-Fish for the status quo scenario in 2019 ($\tilde{F}_{2019}$) (blue symbol) and 43 scenarios simulating hypothetical management measures (see Table 5 for descriptions) for pelagic fisheries in the eastern Pacific Ocean after decreasing the q values for industrial longline and purse-seine fisheries (top panel), and increasing the resolution of the industrial longline data from 5° x 5° to 1° x 1° (bottom panel). Vulnerability status is depicted by the mean (± 95% confidence intervals) estimate of the biological reference points $\tilde{F}_{2019}/F_{40\%}$ and $SBR_{2019}/SBR_{40\%}$. Labels adjacent to symbols denote scenarios defined in Table 4. Vulnerability status values for each species are provided in Table 5**.**

TABLE 1. Data sources and period of coverage of fishing effort data used to define the spatial distribution of effort by each fishery in the EPO. Data sources with an asterisk (*) contained fishing effort distribution maps that were manually georeferenced and the locations of each fishing event attributed to an appropriate grid cell to indicate presence of fishing.

Fishery	Country	Year	Data resolution	Comments and data source
Industrial fisheries				
Longline	IATTC Convention Area	2019	Monthly aggregates of number of hooks deployed at 5°x5° resolution (reports by CPCs); positional set data upscaled to 0.5°x0.5° resolution (observer data).	Unpublished data from logbooks and national observer programs submitted to the IATTC.
	Mexico (Pacific Ocean and Gulf of California)	2006–2009; 2006–2013; 2009–2012; 2018	Positional set data upscaled to 0.5°x0.5° resolution.	Castillo-Geniz et al. (2016)*; Castillo-Geniz et al. (2017)*; Carreón-Zapiain et al. (2018)*; Pacific Large Pelagics Program, INAPESCA*.
	Mexico (Central Pacific coast)	2003–2011	Positional set data upscaled to 0.5°x0.5° resolution.	Hernández and Valdez Flores (2016)*
Purse-seine (Class 6 - all set types)	IATTC Convention Area	2019	Positional set data upscaled to 0.5°x0.5° resolution.	Unpublished data collected by the AIDCP and National observer programs and held by the IATTC.
Purse-seine (Class 1–5 - all set types)	IATTC Convention Area	2019	Positional set data upscaled to 0.5°x0.5° resolution.	Unpublished data from logbooks, national observer programs and the TUNACONS observer program submitted to the IATTC.
Artisanal fisheries				
Surface-set gillnet	Ecuador	2016	Positional set data upscaled to 0.5°x0.5° resolution.	Martínez et al. (2017)*
	Guatemala, El Salvador, Nicaragua, Costa Rica, Panama	2018	Positions of access and unloading points allocated to adjacent 0.5°x0.5° grid cells	Oliveros-Ramos et al. (2019)
	Mexico (Northwestern Gulf of California)	1998–1999	Positions of fishing camps allocated to adjacent 0.5°x0.5° grid cells	Smith et al. (2009)*
	Mexico (Southwestern Gulf of California)	1998–1999	Positions of fishing camps allocated to adjacent 0.5°x0.5° grid cells	Bizzarro et al. (2009a)*
	Mexico (Northeastern Gulf of California)	1998–1999	Positions of fishing camps allocated to adjacent 0.5°x0.5° grid cells	Bizzarro et al. (2009b)*
	Mexico, Panama	2017–2018	Positions of fishing ports allocated to adjacent 0.5°x0.5° grid cells	Ortíz-Álvarez et al. (2020)
	Nicaragua, Costa Rica, Colombia	2016–2017	Positions of fishing ports allocated to adjacent 0.5°x0.5° grid cells	Ortíz-Álvarez et al. (2020)
	Peru and Chile	2005–2007;	Positional set data upscaled to 0.5°x0.5° resolution.	Alfaro-Shigueto et al. (2011)*
	Peru	2007	Positional set data upscaled to 0.5°x0.5° resolution.	Ayala et al. (2008)*
Surface-set longline	Chile (Northern and Central)	2001–2005; 2016	Positional set data upscaled to 0.5°x0.5° resolution.	Donoso and Dutton (2010);
	Chile (Southern)	2002	Positional set data upscaled to 0.5°x0.5° resolution.	Moreno et al. (2006)*
	Chile and Peru	2005–2010	Annual aggregates of number of sets at 0.5°x0.5° resolution.	Doherty et al. (2014)*
	Ecuador	2008–2012	Positional set data upscaled to 0.5°x0.5° resolution.	Martínez-Ortiz et al. (2015)
	Ecuador, Panama, Costa Rica	2004–2010	Positional set data upscaled to 0.5°x0.5° resolution.	Unpublished IATTC observer data.
	Guatemala, El Salvador, Nicaragua, Costa Rica, Panama	2018	Positions of access and unloading points allocated to adjacent 0.5°x0.5° grid cells	Oliveros-Ramos et al. (2019)
	Mexico (Western Sea of Cortez)	1998–1999	Positions of fishing camps allocated to adjacent 0.5°x0.5° grid cells	Bizzarro et al. (2009a)*
	Mexico (Northeastern Gulf of California)	1998–1999	Positions of fishing camps allocated to adjacent 0.5°x0.5° grid cells	Bizzarro et al. (2009b)*
	Mexico, Panama	2017–2018	Positions of fishing ports allocated to adjacent 0.5°x0.5° grid cells	Ortíz-Álvarez et al. (2020)
	Nicaragua, Costa Rica, Colombia	2016–2017	Positions of fishing ports allocated to adjacent 0.5°x0.5° grid cells	Ortíz-Álvarez et al. (2020)
	Peru	2004–2006; 2007	Positional set data upscaled to 0.5°x0.5° resolution.	Ayala et al. (2008)*; Alfaro-Shigueto et al. (2011)*

TABLE 2. Natural mortality (M) estimators used in the EASI-Fish assessment of silky shark (*Carcharhinus falciformis;* FAL), scalloped hammerhead (*Sphyrna lewini;* SPL), great hammerhead (*S. mokarran;* SPK), and smooth hammerhead (*S. zygaena;* SPZ) in the eastern Pacific Ocean in 2019.

Estimator	Equation	Citation
Hoenig$_{\text{tmax}}$	$M = \frac{4.3}{t_{max}}$	Hoenig (1983)
Hoenig$_{\text{nls}}$	$M = 4.899 t_{max}^{-0.916}$	Then *et al.* (2015)
Jensen (J)	$M = 1.60\,K$	Jensen (1996)
Pauly$_{\text{nls}}$	$M = 4.118 K^{0.73} L_{\infty}^{-0.33}$	Then *et al.* (2015)
Pauly$_{\text{LKT}}$	$\log M = -0.0066 - 0.279 \ln L_{\infty} + 0.6543 \ln K + 0.4634 \ln T$	Pauly (1980)
Pauly$_{\text{KT}}$	$M = K e^{-0.22 + 0.3 \ln T}$	Froese and Pauly (2017)
Pauly$_{\text{LT}}$	$M = 10^{0.566 - 0.718 \ln L_{\infty}} + 0.02T$	Froese and Pauly (2017)

M = instantaneous natural mortality rate (yr^{-1})
$t_{\max}$ = maximum observed age of animals in the stock.
L_{∞} = the average length of an animal if it lived to an infinite age, and known as the asymptotic length of an animal in the von Bertalanffy growth function.
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 species.

TABLE 3. Biological parameters for silky shark (*Carcharhinus falciformis*), scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*S. mokarran*), and smooth hammerhead (*S. zygaena*) assessed using EASI-Fish including maximum recorded age ($t_{\max}$), von Bertalanffy growth parameters (L_∞, K, t_0), length-weight relationship parameters a and b, length at 50% maturity (L_{MAT}), length at birth (L_0), and natural mortality (M). Values for M show the fixed value derived from stock assessments (source shown), or the mean value derived from various mortality estimators defined in Table 2. Values shown in parentheses are the minimum and maximum values uniform ($^{\mathrm{U}}$) distribution priors used in 10,000 iterations of Monte Carlo simulations. All lengths are total length. Sources of biological parameter values are shown in Table 4.

Species	$t_{\max}$ **(yrs)**	$L_{\inf}$ **(yr^{-1})**	K **(yr^{-1})**	t_0 **(yr^{-1})**	**L-W *a* L-W *b***	L_{50} **(cm)**	L_0 **(cm)**	M **(yr^{-1})**	M **method**
Carcharhinus falciformis	16	332.0	0.084	-2.76	0.0000273; 2.860	215.0 $^{L_{50}}$	48	0.18	H_{tmax}, H_{nls}, P_{nls}, P_{LKT}, J, Clarke et al. (2018), IATTC (2014)
Sphyrna lewini	21	289.6	0.161	-1.00	0.00000399; 3.030	219.4 $^{L_{50}}$	47	0.23 (0.21-0.30)$^{\mathrm{U}}$	López-Martínez et al. (2020)
Sphyrna mokarran	39	402.7	0.079	-2.00	0.00000123; 3.240	227.9 $^{L_{50}}$	70	0.13 (0.11-0.17)$^{\mathrm{U}}$	H_{tmax}, H_{nls}, P_{nls}, P_{LKT}, J
Sphyrna zygaena	25	375.2	0.111	-1.31	0.0000024; 3.150	200.0 $^{L_{50}}$	55	0.15 (0.15-0.26)$^{\mathrm{U}}$	Tsai et al. (2018)

Table 4. Sources of biological parameters used in EASI-Fish for assessing silky shark (*Carcharhinus falciformis*), scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*S. mokarran*), and smooth hammerhead (*S. zygaena*) in ten pelagic fisheries in the eastern Pacific Ocean, including maximum recorded age ($t_{\max}$), the growth parameters (L_∞, K, t_0), length-weight (L-W) relationship parameters *a* and *b*, length-at-maturity (L_{MAT}), and length-at-birth (L_0). Parameter values are shown in Table 3.

Species	$t_{\max}$ (years)	L_∞, K, t_0	L-W *a* & b	L_{MAT} (cm)	L_0 (cm)
Carcharhinus falciformis	Sánchez-de Ita et al. (2011)	Joung et al. (2008)	Oshitani et al. (2003)	Joung et al. (2008)	Oshitani et al. (2003)
Sphyrna mokarran	Tovar-Ávila and Gallegos-Camacho (2014)	Harry et al. (2011)	Stevens and Lyle (1989)	Harry et al. (2011)	Harry et al. (2011)
Sphyrna lewini	Drew et al. (2015)	Drew et al. (2015)	Stevens and Lyle (1989)	Estupiñán-Montaño et al. (2021)	Estupiñán-Montaño et al. (2021)
Sphyrna zygaena	Rosa et al. (2017)	Chow (2004)	Chow (2004)	Nava Nava and Márquez-Farías (2014)	Nava Nava and Márquez-Farías (2014)

Table 5. Modified EASI-Fish model parameter values to define 43 hypothetical conservation and management scenarios (plus the status quo) for silky shark (*Carcharhinus falciformis;* FAL), scalloped hammerhead (*Sphyrna lewini;* SPL), great hammerhead (*S. mokarran;* SPK), and smooth hammerhead (*S. zygaena;* SPZ) in ten pelagic fisheries in the eastern Pacific Ocean. All other parameter values in each scenario were the same as for the status quo (see Appendix 1).

Scenario	Industrial longline	Purse-seine (Class 6)	Purse-seine (Class 1-5)	Artisanal gillnet (Neonates)	Artisanal gillnet (Sharks–teleosts)	Artisanal longline (Dorado)	Artisanal longline (Tuna–billfish–shark)
Status quo (SQ)							
1	SQ	SQ	SQ	SQ	SQ	SQ	SQ
Improved handling and release practices in purse-seine fisheries							
2		FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.85-0.95 SPZ: PRM = 0.85-0.95	FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.85-0.95 SPZ: PRM = 0.85-0.95				
3		FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.65-0.75 SPZ: PRM = 0.65-0.75	FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.65-0.75 SPZ: PRM = 0.65-0.75				
Temporary EPO-wide closure							
4		D = 120d	D = 120d				
5		D = 180d	D = 180d				
6	D = 72d						
7	D = 120d						
8	D = 180d						
9						D = 72d	D = 72d
10						D = 120d	D = 120d
11						D = 180d	D = 180d
12	D = 72d					D = 72d	D = 72d
13	D = 120d					D = 120d	D = 120d
14	D = 180d					D = 180d	D = 180d
15				D = 72d	D = 72d		
16				D = 120d	D = 120d		
17				D = 180d	D = 180d		
18	D = 72d			D = 72d	D = 72d	D = 72d	D = 72d
19	D = 120d	D = 120d	D = 120d	D = 120d	D = 120d	D = 120d	D = 120d
20	D = 180d	D = 180d	D = 180d	D = 180d	D = 180d	D = 180d	D = 180d
Prohibition of wire leaders							
21	FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54						
22							FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54
23	FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54						FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54

Table 5 continued

Scenario	Industrial longline	Purse-seine (Class 6)	Purse-seine (Class 1-5)	Artisanal gillnet (Neonates)	Artisanal gillnet (Sharks–teleosts)	Artisanal longline (Dorado)	Artisanal longline (Tuna–billfish–shark)
Minimum retention length of 100 cm TL							
24	FAL: PRM = 0.1-0.4 (<100 cm) SPL: PRM = 0.43-0.5 (<100 cm) SPK: PRM = 0.46-0.50 (<100 cm) SPZ: PRM = 0.46-0.50 (<100 cm)						
25						FAL: PRM = 0.1-0.4 (<100 cm) SPL: PRM = 0.43-0.5 (<100 cm) SPK: PRM = 0.46-0.50 (<100 cm) SPZ: PRM = 0.46-0.50 (<100 cm)	FAL: PRM = 0.1-0.4 (<100 cm) SPL: PRM = 0.43-0.5 (<100 cm) SPK: PRM = 0.46-0.50 (<100 cm) SPZ: PRM = 0.46-0.50 (<100 cm)
26	FAL: PRM = 0.1-0.4 (<100 cm) SPL: PRM = 0.43-0.5 (<100 cm) SPK: PRM = 0.46-0.50 (<100 cm) SPZ: PRM = 0.46-0.50 (<100 cm)					FAL: PRM = 0.1-0.4 (<100 cm) SPL: PRM = 0.43-0.5 (<100 cm) SPK: PRM = 0.46-0.50 (<100 cm) SPZ: PRM = 0.46-0.50 (<100 cm)	FAL: PRM = 0.1-0.4 (<100 cm) SPL: PRM = 0.43-0.5 (<100 cm) SPK: PRM = 0.46-0.50 (<100 cm) SPZ: PRM = 0.46-0.50 (<100 cm)
Close neonate gillnet fishery							
27				D = 0			
Non-retention of silky and hammerhead sharks							
28	FAL: PRM = 0.1-0.4 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50						
29						FAL: PRM = 0.1-0.4 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	FAL: PRM = 0.1-0.4 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50
30	FAL: PRM = 0.1-0.4 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50					FAL: PRM = 0.1-0.4 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	FAL: PRM = 0.1-0.4 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50
COMBINATION MEASURES							
Closure (longlines) + Wire leader ban							
31	D = 72d FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54						
32						D = 72d	D = 72d FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54
33	D = 72d FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54					D = 72d	D = 72d FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ: AVM = 0.4-0.54

Table 5 continued

Scenario	Industrial longline	Purse-seine (Class 6)	Purse-seine (Class 1-5)	Artisanal gillnet (Neonates)	Artisanal gillnet (Sharks–teleosts)	Artisanal longline (Dorado)	Artisanal longline (Tuna–billfish–shark)
Closure (longlines) + Wire leader ban + Minimum retention length							
37	D = 72d For sharks (<100 cm) FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ : AVM = 0.4-0.54 For sharks (>100 cm) FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5						
38						D = 72d For sharks (<100 cm) FAL: PRM = 0.1-0.3 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	D = 72d For sharks (<100 cm) FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ : AVM = 0.4-0.54 For sharks (>100 cm) FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5
39	D = 72d For sharks (<100 cm) FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ : AVM = 0.4-0.54 For sharks (>100 cm) FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5					D = 72d For sharks (<100 cm) FAL: PRM = 0.1-0.3 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	D = 72d For sharks (<100 cm) FAL: AVM = 0.17-0.25 SPL: AVM = 0.3-0.4 SPK: AVM = 0.39-0.66 SPZ : AVM = 0.4-0.54 For sharks (>100 cm) FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5
Closure (longlines) + Wire leader ban + Bannon-retention of sharks							
40	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5						
41						D = 72d FAL: PRM = 0.1-0.3 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5
42	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5					D = 72d FAL: PRM = 0.1-0.3 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5

Table 5 continued

Scenario	Industrial longline	PS (Class 6)	PS (Class 1-5)	Art GN NEO	Art GN Shark	Art LL Dorado	Art LL Shark
Closure (longlines) + Wire leader ban + non-retention + best release and handling practices							
43	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5	FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.85-0.95 SPZ: PRM = 0.85-0.95	FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.85-0.95 SPZ: PRM = 0.85-0.95	FAL: PRM = 1 SPL: PRM = 1 SPK: PRM = 1 SPZ: PRM = 1	FAL: PRM = 1 SPL: PRM = 1 SPK: PRM = 1 SPZ: PRM = 1	D = 72d FAL: PRM = 0.1-0.3 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5
Closure (longlines) + Wire leader ban + non-retention + best release and handling practices + closure of neonate gillnet fishery							
44	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5	FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.85-0.95 SPZ: PRM = 0.85-0.95	FAL: PRM = 0.5-0.7 SPL: PRM = 0.7-0.9 SPK: PRM = 0.85-0.95 SPZ: PRM = 0.85-0.95	D = 365d	FAL: PRM = 1 SPL: PRM = 1 SPK: PRM = 1 SPZ: PRM = 1	D = 72d FAL: PRM = 0.1-0.3 SPL: PRM = 0.43-0.5 SPK: PRM = 0.46-0.50 SPZ: PRM = 0.46-0.50	D = 72d FAL: AVM 0.17-0.25+PRM 0.1-0.3 SPL: AVM 0.3-0.4+PRM 0.43-0.5 SPK: AVM 0.39-0.66+PRM 0.46-0.5 SPZ: AVM 0.4-0.54+ PRM 0.46-0.5

TABLE 6. Estimated mean (+/- 95% confidence intervals) values for proxy fishing mortality ($\tilde{F}_{2019}$) and spawning stock biomass-per-recruit (SBR$_{2019}$) relative to values for the biological reference points $F_{40\%}$ and SBR$_{40\%}$ in the status quo (SQ) and 43 hypothetical conservation and management scenarios for silky shark (*Carcharhinus falciformis*), scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*S. mokarran*), and smooth hammerhead (*S. zygaena*) in 2019 caught in pelagic fisheries of the eastern Pacific Ocean. Model parameter values used in each scenario are shown in Table 5.

	Carcharhinus falciformis		***Sphyrna lewini***		***Sphyrna mokarran***		***Sphyrna zygaena***	
Scen.	**$F_{2019}/F_{40\%}$ (95% CI)**	**SBR$_{2019}$/SBR$_{40\%}$ (95% CI)**	**$F_{2019}/F_{40\%}$ (95% CI)**	**SBR$_{2019}$/SBR$_{40\%}$ (95% CI)**	**$F_{2019}/F_{40\%}$ (95% CI)**	**SBR$_{2019}$/SBR$_{40\%}$ (95% CI)**	**$F_{2019}/F_{40\%}$ (95% CI)**	**SBR$_{2019}$/SBR$_{40\%}$ (95% CI)**
1 (SQ)	5.029 (0.554)	0.031 (0.012)	4.694 (1.188)	0.053 (0.043)	9.423 (2.008)	0.004 (0.006)	5.584 (0.716)	0.027 (0.012)
2	4.776 (0.772)	0.037 (0.017)	4.219 (0.984)	0.073 (0.052)	9.170 (2.053)	0.005 (0.007)	5.312 (0.755)	0.033 (0.014)
3	4.284 (0.781)	0.052 (0.022)	3.736 (0.742)	0.103 (0.061)	8.668 (2.090)	0.007 (0.009)	4.788 (0.766)	0.047 (0.019)
4	4.493 (0.819)	0.045 (0.019)	4.275 (0.973)	0.070 (0.048)	9.036 (1.944)	0.005 (0.007)	5.120 (0.781)	0.038 (0.016)
5	3.901 (0.409)	0.069 (0.022)	3.781 (0.754)	0.099 (0.061)	8.428 (2.215)	0.008 (0.010)	4.568 (0.725)	0.056 (0.022)
6	3.532 (0.175)	0.099 (0.025)	3.697 (0.998)	0.113 (0.088)	7.231 (2.373)	0.015 (0.002)	4.281 (0.656)	0.067 (0.025)
7	2.835 (0.465)	0.187 (0.056)	3.174 (0.952)	0.172 (0.133)	5.903 (2.152)	0.031 (0.039)	3.670 (0.301)	0.106 (0.030)
8	2.199 (0.324)	0.345 (0.087)	2.601 (0.891)	0.274 (0.203)	4.608 (1.630)	0.066 (0.081)	3.036 (0.471)	0.178 (0.059)
9	4.977 (0.631)	0.032 (0.014)	4.589 (1.171)	0.058 (0.047)	9.202 (2.021)	0.005 (0.007)	5.425 (0.765)	0.031 (0.013)
10	4.939 (0.638)	0.033 (0.014)	4.514 (1.137)	0.061 (0.048)	9.015 (2.161)	0.006 (0.008)	5.306 (0.795)	0.034 (0.014)
11	4.893 (0.678)	0.034 (0.015)	4.430 (1.109)	0.066 (0.052)	8.880 (2.170)	0.006 (0.009)	5.163 (0.812)	0.038 (0.015)
12	3.498 (0.174)	0.103 (0.026)	3.566 (0.971)	0.125 (0.096)	6.986 (2.343)	0.017 (0.022)	4.135 (0.559)	0.075 (0.025)
13	2.733 (0.388)	0.202 (0.052)	2.989 (0.901)	0.199 (0.142)	5.512 (1.816)	0.038 (0.044)	3.469 (0.421)	0.128 (0.041)
14	2.041 (0.299)	0.392 (0.085)	2.383 (0.808)	0.328 (0.225)	4.078 (1.410)	0.099 (0.106)	2.716 (0.361)	0.231 (0.061)
15	5.033 (0.569)	0.030 (0.013)	4.675 (1.194)	0.054 (0.044)	9.430 (2.063)	0.004 (0.006)	5.576 (0.726)	0.028 (0.012)
16	5.004 (0.604)	0.031 (0.013)	4.673 (1.223)	0.055 (0.045)	9.420 (2.043)	0.004 (0.006)	5.567 (0.724)	0.028 (0.012)
17	5.025 (0.575)	0.031 (0.013)	4.669 (1.189)	0.055 (0.044)	9.333 (2.055)	0.004 (0.006)	5.560 (0.727)	0.028 (0.012)
18	3.487 (0.167)	0.104 (0.025)	3.591 (0.945)	0.123 (0.092)	6.939 (2.298)	0.018 (0.023)	4.113 (0.519)	0.076 (0.024)
19	2.449 (0.119)	0.270 (0.045)	2.615 (0.725)	0.263 (0.158)	4.884 (1.390)	0.056 (0.055)	3.047 (0.445)	0.179 (0.053)
20	1.411 (0.089)	0.709 (0.080)	1.627 (0.447)	0.601 (0.242)	3.006 (0.929)	0.205 (0.151)	1.869 (0.197)	0.478 (0.082)
21	5.035 (0.550)	0.031 (0.013)	4.712 (1.220)	0.053 (0.046)	9.445 (2.040)	0.004 (0.006)	5.593 (0.719)	0.027 (0.012)
22	5.026 (0.584)	0.031 (0.013)	4.660 (1.183)	0.055 (0.044)	9.419 (1.988)	0.004 (0.006)	5.606 (0.692)	0.027 (0.011)
23	5.042 (0.566)	0.030 (0.013)	4.684 (1.157)	0.054 (0.043)	9.472 (2.083)	0.004 (0.006)	5.582 (0.745)	0.027 (0.012)
24	4.955 (0.679)	0.032 (0.014)	4.673 (1.218)	0.055 (0.046)	9.480 (2.014)	0.004 (0.006)	5.604 (0.700)	0.027 (0.012)
25	5.032 (0.581)	0.030 (0.013)	4.645 (1.154)	0.056 (0.043)	9.423 (2.046)	0.004 (0.006)	5.530 (0.756)	0.029 (0.012)
26	4.958 (0.665)	0.032 (0.014)	4.585 (1.160)	0.058 (0.046)	9.443 (2.031)	0.004 (0.006)	5.540 (0.754)	0.029 (0.013)
27	5.010 (0.591)	0.031 (0.013)	4.679 (1.189)	0.054 (0.043)	9.346 (2.077)	0.004 (0.006)	5.576 (0.690)	0.028 (0.011)
28	1.996 (0.398)	0.414 (0.140)	3.571 (0.984)	0.125 (0.098)	7.915 (2.534)	0.010 (0.016)	4.603 (0.824)	0.054 (0.026)
29	4.855 (0.698)	0.035 (0.015)	4.553 (1.147)	0.060 (0.046)	9.305 (1.968)	0.004 (0.006)	5.461 (0.771)	0.030 (0.013)
30	1.885 (0.342)	0.459 (0.144)	3.465 (0.926)	0.136 (0.101)	7.877 (2.539)	0.011 (0.017)	4.510 (0.804)	0.058 (0.026)
31	3.533 (0.179)	0.099 (0.025)	3.707 (0.971)	0.111 (0.085)	7.216 (2.399)	0.015 (0.021)	4.296 (0.659)	0.066 (0.023)
32	4.971 (0.623)	0.032 (0.014)	4.560 (1.163)	0.059 (0.048)	9.214 (2.076)	0.005 (0.007)	5.406 (0.799)	0.031 (0.014)
33	3.494 (0.170)	0.104 (0.025)	3.605 (0.970)	0.122 (0.092)	6.981 (2.311)	0.017 (0.022)	4.113 (0.516)	0.075 (0.024)
34	3.498 (0.182)	0.104 (0.027)	3.672 (1.022)	0.116 (0.093)	7.190 (2.304)	0.015 (0.019)	4.283 (0.656)	0.067 (0.024)
35	4.966 (0.619)	0.032 (0.013)	4.504 (1.106)	0.062 (0.047)	9.216 (2.039)	0.005 (0.007)	5.379 (0.798)	0.032 (0.014)
36	3.468 (0.174)	0.108 (0.026)	3.528 (0.971)	0.129 (0.098)	6.998 (2.319)	0.017 (0.022)	4.106 (0.507)	0.076 (0.024)
37	3.502 (0.181)	0.103 (0.026)	3.673 (0.986)	0.115 (0.089)	7.231 (2.405)	0.015 (0.021)	4.276 (0.644)	0.067 (0.024)
38	4.984 (0.593)	0.032 (0.014)	4.524 (1.133)	0.061 (0.048)	9.210 (2.023)	0.005 (0.007)	5.364 (0.791)	0.032 (0.014)
39	3.470 (0.173)	0.107 (0.026)	3.531 (0.927)	0.129 (0.092)	6.957 (2.287)	0.017 (0.022)	4.094 (0.526)	0.077 (0.025)
40	1.475 (0.289)	0.672 (0.180)	2.925 (0.931)	0.208 (0.160)	6.103 (2.280)	0.026 (0.037)	3.561 (0.365)	0.112 (0.039)
41	4.821 (0.722)	0.036 (0.016)	4.408 (1.105)	0.067 (0.052)	9.025 (2.147)	0.006 (0.008)	5.285 (0.802)	0.034 (0.014)
42	1.330 (0.274)	0.770 (0.202)	2.456 (0.816)	0.308 (0.209)	4.936 (1.696)	0.056 (0.068)	3.091 (0.481)	0.172 (0.057)
43	1.196 (0.257)	0.873 (0.210)	1.664 (0.477)	0.584 (0.248)	4.473 (1.489)	0.075 (0.081)	2.838 (0.440)	0.210 (0.065)
44	1.189 (0.254)	0.88 (0.209)	1.683 (0.475)	0.573 (0.242)	4.443 (1.423)	0.076 (0.081)	2.811 (0.409)	0.214 (0.062)

APPENDIX 1. Susceptibility parameter values (see Eq. 1) used for the status quo scenario in the EASI-Fish vulnerability assessment of silky shark (*Carcharhinus falciformis;* FAL), scalloped hammerhead (*Sphyrna lewini;* SPL), great hammerhead (*S. mokarran;* SPK), and smooth hammerhead (*S. zygaena;* SPZ) in ten pelagic fisheries in the eastern Pacific Ocean in 2019. Selectivity (C_{xj}) value shows length at first capture (cm of total length) and the distribution type as normal (^{N}), double normal (^{D}) or uniform (^{U}) provided in Figures 3–6. Parameter values provided as a value range denotes a uniform distribution prior.

		Industrial longline							Purse-seine - Class 6 (DEL)							Purse-seine - Class 6 (NOA)						
Code	**Scientific name**	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*
FAL	*Carcharhinus falciformis*	0.74-0.79	1	1	1	48^{N}	0.29-0.36	1	0.21-0.25	0.80	1	0.91-1	48^{D}	0.59-0.69	0.81-0.84	0.08-0.10	0.80	1	0.91-1	48^{D}	0.59-0.69	0.81-0.84
SPL	*Sphyrna lewini*	0.65-0.73	1	1	1	47^{N}	0.51-0.61	1	0.20-0.31	0.80	1	0.55-1	47^{D}	0-0.05	1	0.09-0.14	0.80	1	0.55-1	47^{N}	0-0.05	1
SPK	*Sphyrna mokarran*	0.56-0.69	1	1	1	70^{U}	0.56-0.94	1	0.23-0.32	0.80	1	0.50-1	70^{D}	0-0.10	1	0.10-0.15	0.80	1	0.50-1	70^{D}	0-0.10	1
SPZ	*Sphyrna zygaena*	0.68-0.73	1	1	1	55^{D}	0.62-0.84	1	0.20-0.29	0.80	1	1	55^{D}	0-0.10	1	0.09-0.13	0.80	1	1	55^{D}	0-0.10	1

		Purse-seine - Class 6 (OBJ)							Purse-seine - Class 1-5 (NOA)							Purse-seine - Class 1-5 (OBJ)						
Code	**Scientific name**	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*
FAL	*Carcharhinus falciformis*	0.3-0.36	0.80	1	1	48^{D}	0.59-0.69	0.81-0.84	0.02-0.02	0.80	1	0.72-1	48^{D}	0.59-0.69	0.81-0.84	0.07-0.09	0.80	1	0.72-1	48^{D}	0.59-0.69	0.81-0.84
SPL	*Sphyrna lewini*	0.3-0.42	0.80	1	0.73-1	47^{N}	0-0.05	1	0.02-0.04	0.80	1	0.44-1	47^{N}	0-0.05	1	0.07-0.13	0.80	1	0.44-1	47^{N}	0-0.05	1
SPK	*Sphyrna mokarran*	0.3-0.34	0.80	1	0.67-1	70^{D}	0-0.10	1	0.02-0.06	0.80	1	0.40-1	70^{D}	0-0.10	1	0.08-0.17	0.80	1	0.40-1	70^{D}	0-0.10	1
SPZ	*Sphyrna zygaena*	0.3-0.42	0.80	1	1	55^{N}	0-0.10	1	0.02-0.03	0.80	1	0.83-1	55^{D}	0-0.10	1	0.07-0.11	0.80	1	0.83-1	55^{N}	0-0.10	1

		Artisanal gillnet (Neonates)							Artisanal gillnet (Sharks)							Artisanal longline (Dorado)						
Code	**Scientific name**	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*
FAL	*Carcharhinus falciformis*	0.01-0.01	0.42	1	0.61-1	48^{D}	1	1	0.01-0.01	0.58	1	0.61-1	48^{N}	1	1	0.13-0.14	0.50	1	0.61-1	48^{N}	0.29-0.36	1
SPL	*Sphyrna lewini*	0.02-0.03	0.42	1	0.36-1	47^{D}	1	1	0.02-0.03	0.58	1	0.36-1	47^{D}	1	1	0.14-0.25	0.50	1	0.36-1	47^{D}	0.51-0.61	1
SPK	*Sphyrna mokarran*	0.02-0.04	0.42	1	0.33-1	70^{U}	1	1	0.02-0.04	0.58	1	0.33-1	70^{U}	1	1	0.16-0.38	0.50	1	0.33-1	70^{D}	0.56-0.94	1
SPZ	*Sphyrna zygaena*	0.02-0.02	0.42	1	0.69-1	55^{D}	1	1	0.02-0.02	0.58	1	0.69-1	55^{D}	1	1	0.14-0.22	0.50	1	0.69-1	55^{D}	0.62-0.84	1

		Artisanal longline (Tuna/billfish/sharks)						
Code	**Scientific name**	*Gx/G*	*Dx*	*Axj*	*Exj*	*Cxj*	*AVMxj*	*PRMxj*
FAL	*Carcharhinus falciformis*	0.13-0.14	0.50	1	1	48^{D}	0.29-0.36	0.1-0.29
SPL	*Sphyrna lewini*	0.14-0.25	0.50	1	1	47^{D}	0.51-0.61	0.46-0.51
SPK	*Sphyrna mokarran*	0.16-0.38	0.50	1	1	70^{D}	0.56-0.94	0.46-0.56
SPZ	*Sphyrna zygaena*	0.14-0.22	0.50	1	1	55^{D}	0.62-0.84	0.46-0.62

APPENDIX 2. Justifications and assumptions for the use of parameter values (see Appendix 1) for describing the susceptibility of silky shark (*Carcharhinus falciformis;* FAL), scalloped hammerhead (*Sphyrna lewini;* SPL), great hammerhead (*S. mokarran;* SPK), and smooth hammerhead (*S. zygaena;* SPZ) in the ten fisheries included in the EASI-Fish assessment for the eastern Pacific Ocean in 2019.

Species code	**Fishery**	**Resolution of grid cells for (G_x)**	**Fishing season duration (D_x)**	**Seasonal availability (A_{xj})**	**Encounterability (E_{xj})**	**Contact selectivity (C_{xj})**	**Post-capture mortality (PCM) (P_{xj})**
FAL	Industrial longline	5°x5°	Year-round	Year-round	Deep sets fish 0-300 m. Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Normal curve fit to 10,278 lengths reported to IATTC by its CPC's longline observer programs (IATTC unpublished data).	Assumed no release of marketable species. AVM estimates from studies in industrial pelagic longline fisheries in the Pacific Ocean are 29% (Gilman et al., 2016) and 29–35.8% (Hutchinson et al., 2021), which may be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) for carcharhinid sharks by banning wires leaders. PRM estimated at 15% (CI 2.4-25.9) (Francis et al., 2023) and 20% (CI 10-36) (Musyl and Gilman, 2018) in the WCPO and 6% (CI 0-13)% (Schaefer et al., 2019) and 15.2% (CI 0-29%) in the EPO (Schaefer et al. 2021).
	Purse-seine C6 (DEL)	0.5°x0.5°	72-d closure	Year-round	DEL sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Double normal curve fit to 11,329 lengths recorded by IATTC observers from C6 DEL sets (IATTC unpublished data).	IATTC Resolution C-21-06 prohibits retention. AVM from purse-seine 58.5% (Eddy et al. 2016) to 69% (Poisson et al. 2014) and PRM 81-84% (Poisson et al. 2014, Hutchinson et al. 2015).
	Purse-seine C6 (NOA)	0.5°x0.5°	72-d closure	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Double normal curve fit to 6142 lengths recorded by IATTC observers from C6 NOA sets (IATTC unpublished data).	IATTC Resolution C-21-06 prohibits retention. AVM from purse-seine 58.5% (Eddy et al. 2016) to 69% (Poisson et al. 2014) and PRM 81-84% (Poisson et al. 2014, Hutchinson et al. 2015).
	Purse-seine C6 (OBJ)	0.5°x0.5°	72-d closure	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Double normal curve fit to 147,450 lengths recorded by IATTC observers from C6 OBJ sets (IATTC unpublished data).	IATTC Resolution C-21-06 prohibits retention. AVM from purse-seine 58.5% (Eddy et al. 2016) to 69% (Poisson et al. 2014) and PRM 81-84% (Poisson et al. 2014, Hutchinson et al. 2015).
	Purse-seine C1–5 (NOA)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Double normal curve mirrors EPO C6 fleet for NOA sets.	IATTC Resolution C-21-06 prohibits retention. AVM from purse-seine 58.5% (Eddy et al. 2016) to 69% (Poisson et al. 2014) and PRM 81-84% (Poisson et al. 2014, Hutchinson et al. 2015).
	Purse-seine C1–5 (OBJ)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Double normal curve mirrors EPO C6 fleet for OBJ sets.	IATTC Resolution C-21-06 prohibits retention. AVM from purse-seine 58.5% (Eddy et al. 2016) to 69% (Poisson et al. 2014) and PRM 81-84% (Poisson et al. 2014, Hutchinson et al. 2015).
	Artisanal gillnet (Neonates)	0.5°x0.5°	April-August	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Double normal curve fit to 187 lengths recorded by observers in the Ecuadorian gillnet fishery (Martínez, unpublished data).	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM due to absence of PRM studies for gillnets.
	Artisanal gillnet (Sharks–Teleosts)	0.5°x0.5°	September-March	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Double normal curve fit to 79 lengths recorded by observers in the Ecuadorian gillnet fishery (Martínez, unpublished data).	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM due to absence of PRM studies for gillnets.
	Artisanal longline (Dorado)	5°x5°	October-March	Year-round	Surface sets fish 0-100 m (Santana-Hernandez et al., 1998). Species assumed to primarily inhabit 0 m to 100 (± 70-165) m (Musyl et al. 2003).	Normal curve fit to 722 lengths recorded by observers in the Ecuadorian gillnet fishery (Martínez, unpublished data).	Assumed no release of marketable species. AVM estimates from studies in industrial pelagic longline fisheries in the Pacific Ocean are 29% (Gilman et al., 2016) and 29–35.8% (Hutchinson et al., 2021), which may be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) for carcharhinid sharks by banning wires leaders. PRM estimated at to be 6% (CI 0-13)% (Schaefer et al., 2019) to 15.2% (CI 0-29%) in EPO artisanal longline fisheries (Schaefer et al. 2021).
	Artisanal Longline (Tuna–billfish–	5°x5°	April-September	Year-round	Assumed to fish similar to the industrial longline fleet where deep sets fish 0-300 m. Species assumed to primarily inhabit 0 m to 100 (± 70-	Normal curve fit to 814 lengths recorded by observers in the Ecuadorian gillnet fishery (Martínez, unpublished data).	Assumed no release of marketable species. AVM estimates from studies in industrial pelagic longline fisheries in the Pacific Ocean are 29% (Gilman et al., 2016) and 29–35.8% (Hutchinson et al., 2021), which may be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) for carcharhinid sharks

	sharks)				165) m (Musyl et al. 2003).		by banning wires leaders. PRM estimated at to be 6% (CI 0-13)% (Schaefer et al., 2019) to 15.2% (CI 0-29%) in EPO artisanal longline fisheries (Schaefer et al. 2021).
SPK	Industrial longline	5°x5°	Year-round	Year-round	Deep sets fish 0-300 m. Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Knife-edge selectivity from smallest (142 cm TL) of 55 observed lengths to L_{∞}. (IATTC observer data).	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific, but from studies of pelagic longline fisheries in the Atlantic and Indian Ocean between 56% (Gulak et al., 2015) and 93.8% (Morgan & Burgess, 2007). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks. PRM from experimental drum lines was 46% (Gallagher et al., 2014b) and 50% from recreational fishery (Binstock et al., 2023).
	Purse-seine C6 (DEL)	0.5°x0.5°	72-d closure	Year-round	DEL sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Double normal curve fit to 190 lengths recorded by IATTC observers for C6 purse-seine vessels (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C6 (NOA)	0.5°x0.5°	72-d closure	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Double normal curve fit to 190 lengths recorded by IATTC observers for C6 purse-seine vessels (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C6 (OBJ)	0.5°x0.5°	72-d closure	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Double normal curve fit to 190 lengths recorded by IATTC observers for C6 purse-seine vessels (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C1–5 (NOA)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Double normal curve mirrors EPO C6 fleet for NOA sets.	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C1–5 (OBJ)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Double normal curve mirrors EPO C6 fleet for OBJ sets.	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Artisanal gillnet (Neonates)	0.5°x0.5°	April-August	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	In absence of observed length data, knife-edge selectivity assumed from size at birth (70 cm TL) to L_{∞}.	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM for hammerhead sharks due to absence of PRM studies for gillnets.
	Artisanal gillnet (Sharks–Teleosts)	0.5°x0.5°	September -March	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	In absence of observed length data, knife-edge selectivity assumed from size at birth (70 cm TL) to L_{∞}.	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM for hammerhead sharks due to absence of PRM studies for gillnets.
	Artisanal longline (Dorado)	5°x5°	October-March	Year-round	Surface sets fish 0-100 m (Santana-Hernandez et al., 1998). Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Double normal curve fit to 69 lengths recorded by IATTC observers in Central America artisanal longline fisheries (IATTC unpublished data).	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific, but from studies of pelagic longline fisheries in the Atlantic and Indian Ocean between 56% (Gulak et al., 2015) and 93.8% (Morgan & Burgess, 2007). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks PRM from experimental drum lines was 46% (Gallagher et al., 2014b) and 50% from recreational fishery (Binstock et al., 2023).
	Artisanal Longline (Tuna–billfish–sharks)	5°x5°	April-September	Year-round	Assumed to fish similar to the industrial longline fleet where deep sets fish 0-300 m. Species assumed to primarily inhabit 0 m to 60 (± 50-300) m (Guttridge et al., 2022).	Double normal curve fit to 69 lengths recorded by IATTC observers in Central America artisanal longline fisheries (IATTC unpublished data).	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific, but from studies of pelagic longline fisheries in the Atlantic and Indian Ocean between 56% (Gulak et al., 2015) and 93.8% (Morgan & Burgess, 2007). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks PRM from experimental drum lines was 46% (Gallagher et al., 2014b) and 50% from recreational fishery (Binstock et al., 2023).
SPL	Industrial longline	5°x5°	Year-round	Year-round	Deep sets fish 0-300 m. Species assumed to primarily inhabit 0 m to	Normal curve fit to 10,202 lengths reported to IATTC by its CPC’s	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific. AVM estimate ranges from studies in industrial pelagic

					100 (± 80-275) m (Bessudo et al., 2011).	longline observer programs (IATTC unpublished data).	longline fisheries in the Atlantic are 51% (Coelho et al., 2012) to 61% (Beerkircher et al., 2002). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks No PRM estimates available, but the related *S. mokarran* has PRM estimates of 43% (Gallagher et al., 2014b) to 50% (Binstock et al., 2023).
	Purse-seine C6 (DEL)	0.5°x0.5°	72-d closure	Year-round	DEL sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Double normal curve fit to 206 lengths recorded by IATTC observers from C6 DEL sets (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) (Eddy et al., 2016).
	Purse-seine C6 (NOA)	0.5°x0.5°	72-d closure	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Normal curve fit to 453 lengths recorded by IATTC observers from C6 NOA sets (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) (Eddy et al., 2016).
	Purse-seine C6 (OBJ)	0.5°x0.5°	72-d closure	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Normal curve fit to 1966 lengths recorded by IATTC observers from C6 OBJ sets (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) (Eddy et al., 2016).
	Purse-seine C1–5 (NOA)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Normal curve mirrors EPO C6 fleet for NOA sets.	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) (Eddy et al., 2016).
	Purse-seine C1–5 (OBJ)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Normal curve mirrors EPO C6 fleet for OBJ sets.	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) (Eddy et al., 2016).
	Artisanal gillnet (Neonates)	0.5°x0.5°	April-August	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Double normal curve fit to 2509 lengths recorded in artisanal gillnet fisheries in central Mexico (Pérez-Jiménez et al., 2005)	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM for hammerhead sharks due to absence of PRM studies for gillnets.
	Artisanal gillnet (Sharks–Teleosts)	0.5°x0.5°	September-March	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Double normal curve fit to 380 lengths recorded by IATTC staff at landing ports in Central America fishery (ABNJ project, unpublished data).	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM for hammerhead sharks due to absence of PRM studies for gillnets.
	Artisanal longline (Dorado)	5°x5°	October-March	Year-round	Surface sets fish 0-100 m (Andraka et al., 2013). Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Double normal curve fit to 69 lengths recorded by IATTC observers in Central America artisanal longline fisheries (IATTC unpublished data).	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific. AVM estimate ranges from studies in industrial pelagic longline fisheries in the Atlantic are 51% (Coelho et al., 2012) to 61% (Beerkircher et al., 2002). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks No PRM estimates available, but the related *S. mokarran* has PRM estimates of 43% (Gallagher et al., 2014b) to 50% (Binstock et al., 2023).
	Artisanal Longline (Tuna–billfish–sharks)	5°x5°	April-September	Year-round	Surface sets fish 0-100 m (Santana-Hernandez et al., 1998). Species assumed to primarily inhabit 0 m to 100 (± 80-275) m (Bessudo et al., 2011).	Double normal curve fit to 69 lengths recorded by IATTC observers in Central America artisanal longline fisheries (IATTC unpublished data).	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific. AVM estimate ranges from studies in industrial pelagic longline fisheries in the Atlantic are 51% (Coelho et al., 2012) to 61% (Beerkircher et al., 2002). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks No PRM estimates available, but the related *S. mokarran* has PRM estimates of 43% (Gallagher et al., 2014b) to 50% (Binstock et al., 2023).

SPZ	Industrial longline	5°x5°	Year-round	Year-round	Deep sets fish 0-300 m. Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 2201 lengths reported to IATTC by its CPC's longline observer programs (IATTC unpublished data).	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific. AVM estimate from industrial pelagic longline fisheries in the Atlantic and Indian Oceans between 62% (Fernandez-Carvalho et al., 2015) and 84% (Coelho et al., 2011). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks No PRM estimates available, but the related *S. mokarran* has PRM estimates (Gallagher et al., 2014b) of 46% (Gallagher et al., 2014b) to 50% (Binstock et al., 2023).
	Purse-seine C6 (DEL)	0.5°x0.5°	72-d closure	Year-round	DEL sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 156 lengths recorded by IATTC observers for C6 purse-seine vessels (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C6 (NOA)	0.5°x0.5°	72-d closure	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 257 lengths recorded by IATTC observers for C6 purse-seine vessels (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C6 (OBJ)	0.5°x0.5°	72-d closure	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 2127 lengths recorded by IATTC observers for C6 purse-seine vessels (IATTC unpublished data).	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C1–5 (NOA)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	NOA sets fish 0-150 m. Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve mirrors EPO C6 fleet for NOA sets.	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Purse-seine C1–5 (OBJ)	0.5°x0.5°	72-d closure (Class-4-5)	Year-round	OBJ sets fish 0-200 m. Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve mirrors EPO C6 fleet for OBJ sets.	Assumed no release of marketable species. The only AVM estimate from the EPO purse seine fishery was 0% (n = 6) and a PRM of 100% (n = 3) for the related *Sphyrna lewini* (Eddy et al., 2016).
	Artisanal gillnet (Neonates)	0.5°x0.5°	April-August	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 276 lengths recorded in artisanal gillnet fisheries in Baja, Mexico (Ramirez-Amaro et al., 2013)	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM for hammerhead sharks due to absence of PRM studies for gillnets.
	Artisanal gillnet (Sharks–Teleosts)	0.5°x0.5°	September-March	Year-round	Gillnets fish 0–42 m (Martínez et al., 2017). Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 276 lengths recorded in artisanal gillnet fisheries in Baja, Mexico (Ramirez-Amaro et al., 2013)	Assumed no release of marketable species. AVM of pelagic sharks in gillnets >91% (Ellis et al., 2017). Assumed 100% PRM for hammerhead sharks due to absence of PRM studies for gillnets.
	Artisanal longline (Dorado)	5°x5°	October-March	Year-round	Surface sets fish 0-100 m (Santana-Hernandez et al., 1998). Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 197 lengths recorded in artisanal longline fisheries in Baja, Mexico (Ramirez-Amaro et al., 2013)	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific. AVM estimate from industrial pelagic longline fisheries in the Atlantic and Indian Oceans between 62% (Fernandez-Carvalho et al., 2015) and 84% (Coelho et al., 2011). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks No PRM estimates available, but the related *S. mokarran* has PRM estimates of 46% (Gallagher et al., 2014b) to 50% (Binstock et al., 2023).
	Artisanal Longline (Tuna–billfish–sharks)	5°x5°	April-September	Year-round	Assumed to fish similar to the industrial longline fleet where deep sets fish 0-300 m. Species assumed to primarily inhabit 0 m to 60 (± 50-144) m (Francis, 2016).	Double normal curve fit to 197 lengths recorded in artisanal longline fisheries in Baja, Mexico (Ramirez-Amaro et al., 2013)	Assumed no release of marketable species. No AVM or PRM estimates from the EPO or Pacific. AVM estimate from industrial pelagic longline fisheries in the Atlantic and Indian Oceans between 62% (Fernandez-Carvalho et al., 2015) and 84% (Coelho et al., 2011). AVM after banning wires leaders assumed to be reduced by 31% (Bigelow et al., 2022) to 41% (Scott et al., 2022) as for carcharhinid sharks No PRM estimates available, but the related *S. mokarran* has PRM estimates of 46% (Gallagher et al., 2014b) to 50% (Binstock et al., 2023).

APPENDIX 3. Maps showing the predicted distributions of silky shark (*Carcharhinus falciformis;* FAL), scalloped hammerhead (*Sphyrna lewini;* SPL), great hammerhead (*S. mokarran;* SPK), and smooth hammerhead (*S. zygaena;* SPZ) caught in eastern Pacific Ocean pelagic fisheries overlaid with presence records used to model these distributions.