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VULNERABILITY STATUS AND EFFICACY OF POTENTIAL CONSERVATION MEASURES FOR THE EAST PACIFIC LEATHERBACK TURTLE (*DERMOCHELYS CORIACEA*) STOCK USING THE EASI-FISH APPROACH

Inter-American Tropical Tuna Commission

Inter-American Convention for the Protection and Conservation of Sea Turtles

IATTC-IAC East Pacific Leatherback *Ad Hoc* Joint Working Group

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SUMMARY

Industrial and small-scale coastal (*i.e.*, 'artisanal') pelagic fisheries in the eastern Pacific Ocean (EPO) interact with one of the most vulnerable fishery bycatch species, the East Pacific (EP) stock of leatherback turtle (*Dermochelys coriacea*). As a result of the species' longevity, slow growth, low reproductive output, and critically low population size, it is currently classified as "Critically Endangered" by the International Union for Conservation of Nature (IUCN). EPO tuna fisheries have been mandated since 2008 (Resolution C-07-03) to ensure, by all practical means, the safe handling and release of captured sea turtles. On 1 January 2021, a revised resolution on sea turtles (C-19-04) entered into force that requires EPO tuna fisheries to implement various measures designed to reduce the bycatch of sea turtles, in particular the use of circle hooks and finfish baits in shallow longline sets. The low encounter rates of sea turtles by fishing vessels make these 'rare event' data difficult to analyze using conventional approaches for assessing the status of sea turtle populations. Consequently, alternative means are needed to better assess vulnerability status and better understand the potential efficacy of different conservation and management measures (CMMs) to improve sea turtle conservation. In response, the spatially-explicit ecological risk assessment (ERA) approach—Ecological Assessment for the Sustainable Impacts of Fisheries (EASI-Fish)—was developed by Inter-American Tropical Tuna Commission (IATTC) staff to quantify the vulnerability of bycatch species, such as the EP leatherback stock, to the cumulative impacts of multiple fisheries in the EPO and to simulate hypothetical CMM scenarios that may mitigate fishery-imposed risks to the species. This paper describes a collaborative research project conducted by an *ad hoc* joint working group of participants from the IATTC, the Inter-American Convention on the Protection and Conservation of Sea Turtles (IAC), and international sea turtle experts where EASI-Fish was used to explore the changes in the vulnerability status of the EP leatherback turtle subpopulation. This working group developed 70 different hypothetical CMM scenarios simulated for EPO industrial (purse-seine and longline) and artisanal (longline and gillnet) fisheries for a recent representative year (2019). CMMs involved decreasing bycatch rates (*i.e.*, "contact selectivity" in EASI-Fish) and post-capture mortality (PCM), implementing the use of circle hooks and/or finfish bait in longline fisheries, illuminated gillnets, best practices for safe handling and release of leatherbacks, and combinations of CMMs. The "*status quo*" scenario revealed a proxy for fishing mortality ($\tilde{F}_{2019}$) and the breeding stock biomass per recruit (BSR_{2019}) exceeded precautionary biological reference points ($F_{80\%}$ and $BSR_{80\%}$), classifying the EP leatherback turtle stock as "most vulnerable". Industrial and artisanal longline fisheries had the highest $\tilde{F}_{2019}$ values, likely because they also had the highest areal overlap with the modelled EP leatherback species distribution (61% and 34%, respectively). Of the 70 scenarios, 42 resulted in significant improvements in EP leatherback vulnerability status (*i.e.*, less vulnerable). Although use of circle hooks, finfish bait, and to a lesser extent best handling and release practices were each predicted to decrease vulnerability when examined individually, by far the most effective scenarios involved using these three measures in concert, followed by using circle hooks with either finfish bait or best practices. However, benefits predicted from EASI-Fish for CMM scenarios assume 1) 100% compliance with CMM implementation to the full extent of each applicable fishery, and 2) that CMMs achieve the estimated levels of efficacy reflected in the model inputs. Thus, the results of the model scenarios provide estimates of what may be possible under such conditions in comparison to the *status quo* under ideal conditions. This modelling exercise provided detailed results that enable evaluation of the potential efficacy of CMMs established in in IATTC Resolution C-19-04 in reducing impacts of fisheries bycatch on EP leatherbacks and can inform development of fisheries-specific strategies to implement CMMs described.

INTRODUCTION

Fisheries worldwide are undergoing a significant shift in the traditional fisheries management paradigm, from a focus on single species of economic importance, to considering the ecological impacts of fishing on non-target species, habitats, and the ecosystem more broadly. Under the Antigua Convention (IATTC, 2003), the Inter-American Tropical Tuna Commission (IATTC) has formally adopted an ecosystem-based approach to the management of tuna fisheries in the eastern Pacific Ocean (EPO). For example, Article VII 1(f) of the Convention mandates 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…*".

However, such ecological sustainability objectives can be difficult to demonstrate in practice owing to the paucity of reliable biological and catch information for the vast array of non-target species with which fisheries interact, either directly or indirectly, especially those of little or no economic (*i.e.*, consumption) value. Therefore, assessing all impacted species using traditional stock assessment approaches is often both cost-prohibitive and impractical. To address this problem, the IATTC staff developed a flexible spatially-explicit quantitative ecological risk assessment approach—Ecological Assessment of Sustainable Impacts of Fisheries (EASI-Fish)—specifically designed to quantify the cumulative impacts of multiple fisheries for data-limited bycatch species (Griffiths *et al*., 2019a). The approach has recently been applied in the EPO to prioritize the vulnerability of various bycatch species groups caught in industrial tuna fisheries (Griffiths *et al*., 2019a) and shark species caught in industrial and artisanal fisheries (SAC-13-11), to explore the efficacy of potential conservation and management measures (CMMs) for the spinetail devil ray (*Mobula mobular*) in the EPO (Griffiths *et al*., 2019b).

EPO tuna fisheries have been documented to interact with at least 117 taxa including teleosts, elasmobranchs, sea turtles, seabirds, and marine mammals (Duffy *et al*., 2016). Under current fishing practices, some of these species are unavoidable bycatch and present significant conservation issues to be addressed by the IATTC and its Members and Cooperating Non-members (CPCs). Sea turtles are a particularly vulnerable group of bycatch species in the EPO. Despite the low frequency of turtle interactions in the EPO purse-seine fishery (Hall and Roman, 2013; Lezama-Ochoa *et al*., 2017), their slow growth rates, late ages at maturity, low fecundity (Avens *et al*., 2020), and, depending upon species, small population sizes make their populations particularly sensitive to anthropogenic sources of mortality, such as fishing. This makes sea turtle bycatch a significant conservation issue for EPO tuna fisheries, where at least 33,125 purse-seine sets were made and 147 million longline hooks were deployed in 2019 (IATTC, 2020). Sea turtle species also face similar threats by tuna (and other) fisheries throughout their worldwide distribution (Wallace *et al*., 2013a). Therefore, improved assessment of the relative effects of bycatch in tuna fisheries would provide valuable information for fisheries managers and conservationists.

Some international conservation instruments have been developed for sea turtles, such as their inclusion in Appendices I and II of the Convention of Migratory Species (CMS) (CMS, 2015) and in Appendix I of the Convention on International Trade in Endangered Species (CITES) (CITES, 2016). These measures were required to meet regional conservation goals as well as to curb international trade of sea turtle products (*e.g.*, eggs, meat, shell material). In addition, conservation measures have been developed by some tuna Regional Fisheries Management Organizations (tRMFOs), specifically to reduce the bycatch of sea turtles in longline and purse-seine fisheries. In the EPO, for example, IATTC Resolution C-19-04, entering into force on 1 January 2021, prohibits the retention of sea turtles by all vessels and requires their immediate release using best handling and release practices such as those detailed by the Food and Agriculture Organization of the United Nations (FAO, 2009), to reduce post-capture mortality (PCM). Resolution C-19-04 also requires use of one or more CMMs from a 'menu' of options (*i.e.*, use of large circle hooks or finfish bait) for potential mitigation techniques that have been demonstrated to reduce the frequency and severity of interactions between longline fishing gear and sea turtles, including use of large circle hooks and finfish bait. Further, the Inter-American Convention for the Protection and Conservation of Sea Turtles (IAC) is a binding, intergovernmental treaty that provides the legal framework for countries in the North and South America continents to take actions to benefit the conservation, protection, and recovery of sea turtle populations, at both nesting beaches and in the IAC Parties' territorial waters. Concerned with the critical status of leatherback turtles (*Dermochelys coriacea*) in the EPO, the IAC adopted in 2015 Resolution CIT-COP7-2015-R2 that requests IAC Parties to make efforts to reduce the bycatch of leatherbacks in the EPO using recommendations from IAC Resolution COP3/2006/R-2 to exercise FAO guidelines to reduce sea turtle mortality in fishing operations (FAO, 2009).

In 2011, the IAC and the IATTC established a Memorandum of Understanding (MoU) to promote collaboration on conservation measures focused on sea turtles. Understanding the extent to which these measures previously implemented by the IATTC might decrease the vulnerability of sea turtles to fishing impacts would facilitate effective implementation of Resolution C-19-04. To address this need, the IATTC's Bycatch Working Group and Scientific Advisory Committee recommended collaborative research between the IAC and the IATTC[1], under the MoU between the two conventions, to assess the vulnerability of leatherback turtles in the EPO under different management scenarios described in C-19-04.

The leatherback turtle is distributed circumglobally in tropical to temperate regions and can be found in both coastal and oceanic pelagic waters (Pritchard, 2015). The species has a maximum recorded age ($t_{\max}$) of 48 years (Jones *et al*., 2011), exhibits low fecundity (~65 eggs per clutch, ~5 clutches per season, nests every 3–4 years; average hatching success <50%; Laúd OPO Network, 2020), and female age of maturity is approximately 12-20 years (Avens *et al*., 2009; Avens *et al*., 2020). For the East Pacific (EP) leatherback turtle population in particular, a combination of this low productivity and high susceptibility to fisheries bycatch—and to other threats such as human consumption of eggs or habitat loss—in the EPO have caused an estimated decline of over 90% in the number of nesting females since the 1980s (Laúd OPO Network, 2020). Thus, the EP leatherback population is listed as "Critically Endangered" by the International Union for Conservation of Nature (IUCN), Red List of Threatened Species (Wallace *et al*., 2013b).

There is much evidence that the EP leatherback turtle stock has been severely affected by bycatch mortality, which has driven the long-term population decline, and likely continues to prevent recovery (Wallace *et al*., 2013b). A recent population viability analysis of the EP stock predicted that the population, currently estimated to be fewer than 1,000 adults, may be extirpated in the region within 60 years under current fishing and environmental conditions (Laúd OPO Network, 2020). In contrast, the analysis predicted that the population could eventually stabilize and increase if conservation efforts successfully increase adult and sub-adult survival (*i.e.*, reduce fishing mortality) by at least 20% and increase hatchling production through enhanced protection and nest management. Because fishing appears to be the only significant anthropogenic source of late-stage mortality currently affecting this population, reduction in late-stage mortality can be considered a proxy for reduction in bycatch mortality.

Recent reports of EP leatherback turtle capture rates indicate relatively low frequency in industrial purse-seine and longline fisheries in the EPO (Hall and Roman, 2013; Griffiths and Duffy, 2017; Lezama-Ochoa *et al*., 2017; Lezama-Ochoa *et al*., 2019), which may be due to some combination of depleted population abundance, improved implementation of conservation measures (*e.g.,* C-04-07 and C-07-03) in some fleets (*e.g.*, use of circle hooks, best handling practices), and low reporting due to low observer coverage

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[1] As such, the IATTC scientific staff, the IAC Secretariat and their Contracting Parties country representatives, and other sea turtle experts created the EP leatherback *ad hoc* joint working group in 2020 (hereafter referred as to the "working group")

in most fleets (*e.g.*, ~5% or less in the high seas and EPO coastal nation longline fleets). Because reported leatherback encounter rates are very low compared to catch frequencies of target species, insufficient data exists for the population to undertake traditional fisheries stock assessments.

The overarching goal of this paper is to provide IATTC and IAC Members and CPCs information relevant to the implementation of Resolution C-19-04 and IAC Resolution CIT-COP7-2015-R2 by identifying potentially effective conservation and management measures (CMMs) that may—individually or in unison—improve the conservation status of the leatherback turtle population in the EPO. To accomplish this goal, the working group sought to evaluate the potential efficacy of various CMMs—mainly those required by C-19-04—in reducing impacts of fisheries on the EP leatherback population. Specifically, the IATTC-IAC working group developed hypothetical scenarios that incorporated different CMMs to understand the potential improvements in vulnerability status of the EP leatherback turtle stock due to: i) decreasing post-capture mortality (PCM) on specific size classes of turtles through improved handling and release practices, ii) implementing the use of circle hooks and/or finfish bait to reduce the interaction rate and fishing mortality due to hooking injuries, iii) increasing the duration of the existing EPO-wide fishing closure for the industrial purse-seine fishery, iv) using illumination to reduce interactions with artisanal gillnets, and v) using a combination of the aforementioned CMMs simultaneously. This paper builds on a previous exploratory effort (Griffiths *et al.*, 2020) and should be considered one of numerous steps to quantify 1) the current impacts of EPO fisheries bycatch on leatherbacks, and 2) the potential efficacy of efforts to reduce bycatch of EP leatherback turtles. The analyses presented herein include new data (*e.g.*, a species-specific habitat suitability model, catch data from small-scale fisheries), scenarios, and results that provide valuable insights about conservation scenarios relevant for decreasing EP leatherback vulnerability to EPO fisheries.

METHODS

1.1 Data compilation

EASI-Fish requires inputs of multiple types of information to be able to generate a measure of a species' vulnerability to fishing impacts. The most fundamental types of information are the areas where fishing occurs and the area of occurrence of the species of interest. This is because EASI-Fish's estimations of fishing mortality, and ultimately of species vulnerability to fishing impacts, are made only for areas where fishing effort and species occurrence overlap. Therefore, compiling the data necessary to generate reliable maps of overlap between fishing effort and species occurrence is essential to producing useful results from EASI-Fish.

During the initial phase of this project (Griffiths *et al.*, 2020), we compiled fishing effort maps from industrial fisheries (*i.e.*, IATTC longline and purse-seine observer data) and inferred fishing areas for artisanal fisheries within Exclusive Economic Zones (EEZs) from available studies. In addition, because a quantitatively derived species distribution model was unavailable, we used a static species distribution based on the defined boundaries for the EP leatherback turtle stock (Wallace *et al.*, 2011) and a knife-edge probability-of-occupancy of 1 for each 0.5° x 0.5° within these boundaries to generalize areas of leatherback presence in the EPO. However, we recognized that both essential data types required significant additions and enhancements to ensuring improved, robust EASI-Fish results in subsequent phases of the project. More comprehensive fishing effort coverage, including data from as many relevant fisheries as possible, as well as a more sophisticated species distribution map, were identified as key recommendations from the initial phase of this project (Griffiths *et al.*, 2020).

Thus, given the fundamental importance of including robust information about the distributions of the species of interest and the fisheries with which it incidentally interacts, the working group focused during this phase of the project (2019 to present) on compiling maps of fishing areas and leatherback occurrence data, particularly from within countries' EEZs. In particular, we compiled fishing effort information from 18 different fisheries (seven industrial fisheries and 11 national or artisanal fisheries) (Table 1) and developed novel, region-wide maps of leatherback occurrence over a nearly 20-year period as primary inputs to EASI-Fish model calculations of leatherback vulnerability to fishing impacts. We describe these datasets, as well as other inputs to EASI-Fish parameters, in the following sections.

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

The present assessment of leatherback turtles incorporated the entire 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 turtle population and EPO fisheries for a recent representative year only; 2019 in this case. However, based on evidence from genetic studies (Dutton *et al*., 1999) and movement studies using conventional (Sarti Martínez *et al*., 2007; Troëng *et al*., 2007) and electronic tags (Benson *et al*., 2011; Shillinger *et al*., 2011; Schick *et al*., 2013), the EPO supports two distinct stocks of leatherback turtles (Laúd OPO Network, 2020). Such evidence was used by Wallace *et al*. (2011) in the development of two Regional Management Units (RMUs)—hereafter referred to as "stocks"—for the species in the Pacific Ocean; the West Pacific (WP) stock, and the EP stock (Fig. 1), classified based on the location of the nesting beaches used by each stock. Within the EP stock, leatherbacks occur in offshore areas well beyond the abyssal plain off South America (Donoso and Dutton, 2010; Shillinger *et al*., 2011; Bailey *et al*., 2012), and in coastal neritic areas in South American waters where they feed on scyphozoan jellyfishes (Quiñones *et al*., 2021; Fig. 1).

Because this large distribution overlaps with several different habitat types, leatherbacks are vulnerable to bycatch interactions with industrial as well as artisanal fisheries in the region. The IATTC Convention Area overlaps to a much greater degree with the distribution of the EP stock (100%) than the WP stock (11%). In fact, of the 112 leatherback turtle interactions recorded by observers onboard purse-seine vessels operating in the EPO in 1993–2019, 105 (94%) occurred within the EP stock boundary defined by Wallace *et al*. (2011) (Unpublished IATTC observer data). Therefore, the present study includes only the EP stock and assesses its vulnerability to the activities of industrial and small-scale coastal (herein termed "artisanal") fishing fleets. The data sources, period of data coverage and processing of datasets for each industrial and artisanal fishery included in the assessment are detailed in Table 1.

Industrial fisheries

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

Effort data for 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 fisheries based on set type: i) sets associated with floating objects (OBJ), ii) sets associated with dolphins (DEL), and iii) sets on unassociated schools of tuna (NOA).

There are a range of smaller purse-seine vessels that operate in the EPO from small vessels (Classes 1–2) that are generally confined to coastal areas, to larger commercial vessels (Classes 3–5) that frequently fish on the high seas. Of the 75 Class 1–5 vessels that fished in the EPO in 2019, only 10 carried an observer. However, the Tuna Conservation Group (TUNACONS)—a consortium of Ecuadorian tuna fishing companies—has deployed observers on voluntary Ecuadorian vessels since 2018, with coverage being 12% of the total number of trips reported for this fleet component in 2019 (IATTC, unpublished data). It has yet to be determined by IATTC scientists whether the data collected to date by TUNACONS is representative of the Class 1–5 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, although no dolphin sets are made by this fleet. Each set position for Class 1–6 vessels was allocated to the nearest 0.5° x 0.5° grid cell to define each fishery.

Artisanal fisheries

In contrast to the industrial purse seine and longline fisheries in the EPO, effort by the numerous artisanal fleets that operate within the EEZs of countries in the EPO generally have very low (if any) observer coverage, and are poorly documented in general. Lack of reliable effort data has been the primary reason why artisanal fleets have not been included in previous EASI-Fish bycatch assessments in the EPO (Griffiths *et al*., 2019a; Griffiths *et al*., 2019b). However, leatherback turtles—as well as most other species of sea turtles—have been shown to be heavily impacted by coastal, artisanal gillnet and longline fisheries, particularly in foraging areas, but also in migratory and reproduction areas (Wallace *et al*., 2013a). Therefore, it was considered especially important to collate available fishing effort data sources for artisanal fisheries for their inclusion in the assessment.

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, in part reported by Andraka *et al*. (2013). During the initial phase of this project (2018–2019; Griffiths *et al*., 2020), some information was available from fishing effort maps in published scientific papers (*e.g.*, Martínez-Ortiz *et al*., 2015) and reports (*e.g*., Ayala *et al*., 2008; Martínez *et al*., 2017) or maps of unpublished observer data supplied by Mexico's Shark Observer Program of Fideicomiso de Investigación para el desarrollo del Programa Nacional de Aprovechamiento del Atún y Protección de Delfines y Otros en torno a Especies Acuáticas Protegidas (FIDEMAR). However, significant spatial gaps throughout the EPO in catch and/or effort data persisted, including unregulated, unreported artisanal fisheries (*e.g.*, Doherty *et al*., 2014). Filling these gaps and creating more comprehensive fishing effort maps was a key recommendation stemming from the first phase of this project (Griffiths *et al*., 2020).

Thus, in the second phase of this project (2019–2022), the working group compiled fishing effort maps for several artisanal fisheries operating in territorial waters of five countries in the EPO (Table 1). These maps were digitized and georeferenced and fishing effort allocated to grid cells of appropriate resolution—usually 0.5° x 0.5°—in QGIS software (QGIS, 2022) (see example in Fig. 2). As in the first phase of this work, we augmented these contributions with information from published studies that assessed leatherback bycatch in artisanal fisheries throughout the EPO (Alfaro-Shigueto *et al*., 2018; Ortíz-Álvarez *et al*., 2020). 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, several sources of evidence suggest that artisanal fishers frequently traverse over

1 degree of latitude (~111 km) to reach their preferred fishing grounds, although many travel significantly further offshore to target large pelagic fishes (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° grid cell adjacent to each fishing port.

The distinction between artisanal and industrial vessels is sometimes unclear at the EPO regional scale (although usually clear at national scales) 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). Further, fishing fleets from South American countries have different characteristics from those of Mesoamerican countries, a detail that has not been considered in the present analysis. Although some of these artisanal vessels can reach offshore waters (*e.g.*, medium and large-scale fleets), the majority are less than 15 m LOA and are more coastal in their operation. In contrast, the domestic Mexican longline fishery targets sharks using vessels (often >27 m LOA) and surface-set gear configurations similar to those used by the far seas industrial longline fleet (Sosa-Nishizaki *et al*., 2020). Therefore, for the purposes of the present study, 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 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° grid cell—5° x 5° for the industrial longline fishery—was considered presence of effort (Fig. 2).

Other anthropogenic threats to leatherbacks

Illegal collection of leatherback turtle eggs on nesting beaches in the EPO can be a major source of anthropogenic-induced mortality for the EP leatherback turtle stock (Troëng *et al*., 2007; Santidrián Tomillo *et al*., 2008). Therefore, this was included in the EASI-Fish model as the "egg collection fishery". Specifically, nesting locations provided by La Red de la Conservación de la Tortuga Laúd del Océano Pacífico Oriental (hereafter referred to as the Laúd OPO Network) and the State of the World's Sea Turtles (SWOT) (http://seamap.env.duke.edu/swot) and reported in IAC Annual Reports (http://www.iacseaturtle.org/informes-eng.htm) were allocated to the nearest 0.5° x 0.5° grid cell to define the spatial extent of the 'fishery,' and mortality estimates were applied to these cells based on a recent population assessment (Laúd OPO Network, 2020).

1.1.2. EP leatherback species distribution model

To estimate the degree to which fisheries interact with the leatherback stock, it is necessary to develop a reliable species distribution model (SDM) on which the effort by each fishery can be overlaid. To develop the SDM, the working group collated data on observations of leatherbacks, primarily from fisheries operations in the region, including bycatch interactions as well as sightings. Each leatherback observation included its geographic coordinates and date. The complete dataset included 1,088 observations made between 1995 and 2020, which came from 18 different fisheries operating in the EEZs of at least eight countries, as well as areas beyond national jurisdiction (Table 2; Fig. 1). In addition to leatherback observation data, we also compiled coordinates and dates of fishing sets across fisheries, which served as "absence" data. Bycatch data are typically zero-inflated and thus highly imbalanced (*e.g.*, Kuhnert *et al*., 2011), and leatherback bycatch data are a clear example of this pattern. Compared to the 1,088 leatherback records (obtained primarily by on-board observers) in our dataset, there were nearly 500,000 fishing sets in which leatherbacks were absent. The Critically Endangered status of leatherbacks and their severely depleted population abundance mean that the probability of encountering (or catching) a leatherback in normal fishing operations was extremely low. This was a critical factor to consider in interpreting and applying our results. Because of this, we used boosted regression trees (BRT) (Elith *et al*. 2006) to build the SDM, a machine learning algorithm designed to accomodate non-linear relationships, large high-dimensional datasets, imbalanced classes, and limited species occurrences (Elith *et al.* 2008; Mi *et al.* 2017).

We note two important issues with our observation dataset: 1) these are fishery-dependent observation data, and 2) satellite telemetry data (*e.g*., Shillinger *et al*., 2008) were unavailable for this analysis. As for the first issue, Degenford *et al*. (2021) used a similar dataset of leatherback bycatch observations in national-level fisheries to generate a presence-only SDM in an area largely within the EEZs of South American countries. In our case, we combined national-level, fisheries-dependent leatherback observation data (*i.e.*, mainly bycatch observations) from Panamá, Colombia, Costa Rica, Ecuador, Peru, and Chile, with IATTC's observer data from the entire EPO, including the high-seas. Thus, the spatio-temporal distribution of the available leatherback observation data, and the fact that they came from multiple types of fisheries operations (high-seas vs. coastal, multiple distinct gear types targeting different species), make this the most comprehensive leatherback observation dataset available (Table 2; Fig. 1).

As for the second issue, telemetry data would have been important in migratory areas through which leatherbacks move (*e.g.*, southward from nesting beaches; Bailey *et al*., 2012) but might not have been observed in fisheries operations, possibly because of short residency periods (Hoover *et al*., 2019). However, available telemetry data were limited to post-nesting adult female turtles and typically cover only 6–9 months of a 3–4-year remigration interval (*i.e.*, the length of time between consecutive breeding seasons that turtles spend away from breeding areas) (Hoover *et al*., 2019). Future iterations of EP leatherback distribution models could combine the observation dataset we compiled with available satellite telemetry data.

Detailed methods about how the SDM was developed are provided in BYC-11-01. We used the SDM outputs to develop a map of occurrence predictions for the species (Fig. 1) for determining volumetric overlap with each fishery within the EASI-Fish modeling framework.

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

A quantitative evaluation of the vulnerability of the leatherback turtle stock under various hypothetical management scenarios was made using the EASI-Fish approach detailed in Griffiths *et al*. (2019a). Similar to other ecological risk assessment approaches, EASI-Fish is comprised of separate susceptibility (Table 3) and productivity (Table 4) components. The susceptibility component in EASI-Fish is used to approximate the instantaneous fishing mortality rate (*F*) that is compared to biological reference points (BRPs) used in the productivity component, specifically length-structured yield and biomass per-recruit models.

EASI-Fish estimates the proportion of a length class (*j*)—with all reference to turtle lengths being curved carapace length (CCL)—of the EP leatherback turtle stock that is susceptible to incurring mortality by fishery *x* (S_{xj}) in a given year, and is represented as:

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

where *G* is the total number of grid cells occupied by leatherback turtles 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 from the SDM described in the previous section. We then used the defined boundaries for the

EP leatherback turtle stock (Wallace *et al.*, 2011) to eliminate predicted presences to the northeast of the EPO, and then applied three probability-of-occupancy (ψ) threshold values (0.1, 0.2, and 0.3) to each 0.5° cell (see Fig. 1), based on statistically determined thresholds and verification by experts. Given the critically endangered status of EP leatherbacks, we selected relatively low ψ values to conservatively include areas where leatherbacks are likely to occur, even if in relatively low numbers and for limited periods of time. This decision was critical to ensuring that EASI-Fish would be inclusive rather than exclusive—*i.e.*, we erred on the side of inclusion versus exclusion—in its calculations of fishery impacts on leatherbacks throughout their distribution and across fisheries known to interact with the species.

Fishing effort for each fishery in 2019 was overlaid on the stock map to calculate G_x. The percentage overlap of each fishery was calculated by dividing G_x by G. Effort data for purse-seine vessels and artisanal effort were resolved at 0.5° as described above. However, data for the industrial longline fleet were available at 5° x 5° and 1° x 1° resolution, so it was conservatively assumed that there was at least one unit of effort in each 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 conventional stock assessments, which combines, often implicitly, "population availability" (the relative probability that a turtle of length class j is located in the area and time where the fishery is operating) and "contact selectivity" (the relative probability that a turtle of length class j will be retained once it comes in contact with the gear) (Millar and Fryer, 1999). Because leatherback turtle selectivity curves were not available for each fishery, it was considered important to disaggregate selectivity components as far as practicable as described hereafter.

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_{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 that electronic tagging studies of leatherback turtles in the EPO indicate wide-ranging movements throughout the year (Shillinger *et al.*, 2008; Schick *et al.*, 2013), value of 1.0 was used for length class j in fishery x.

Encounterability (N_{xj}) is the proportion of length class j that may potentially encounter the gear used by fishery x based on the species' distribution in the water column relative to the normal fishing depth range of the gear. Minimum (0 m), average maximum (~200 m), and overall average (~50 m) dive depths of leatherback turtles were defined using the results from electronic tagging studies (Shillinger *et al.*, 2011). The effective fishing depth range for each fishery in the EPO was defined as:

- 0–200 m for purse-seine vessels Class 6 (Hall and Roman, 2013),
- 0–120 m for purse-seine vessels Classes 1–5 (Ernesto Altamirano, IATTC, pers. comm.),
- 0–300 m for longlines, which covers the depth range of both 'shallow' and 'deep' sets (see Griffiths *et al.*, 2017),
- 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/billfishes/shark' sets (see Andraka *et al.*, 2013),
- 0–100 m for surface-set gillnets set by the artisanal fishery that typically target sharks (Ayala *et al.*, 2008).

Therefore, given the nearly complete overlap between fishing depth ranges and leatherback dive depth range, a value of 1 was used for length class *j* after the length of first capture (see below) in fishery *x*.

For the egg collection "fishery" that operates on land, fishing depth is irrelevant and so a different, and a more precise, estimate of encounterability was used. Leatherback turtle nesting locations in Mexico, Central America, and South America have been comprehensively mapped by the Laúd OPO Network, SWOT, and IAC. Collection of leatherback turtle eggs has been estimated to occur in 1% and 4% of these nests in Costa Rica (Santidrián Tomillo *et al*., 2008) and Mexico (Sarti Martínez *et al*., 2007), respectively (Laúd OPO Network, 2020). Therefore, a precautionary approach was taken by assuming that the egg collection fishery encounters 4% of all nests at documented nesting sites in the southeastern EPO.

Contact selectivity (C_{xj}) describes the proportion of length class *j* that is retained once it encounters the gear used by fishery *x*. In the absence of reliable gear selectivity curves for leatherback turtles, knife-edge selectivity ($C_{xj} = 1.0$) was assumed from 90 cm (Swimmer *et al*., 2011). Smaller leatherbacks have been documented (*e.g.*, Swimmer *et al*., 2011; Unpublished IATTC observer data), but these are exceptional records. Estimated reductions in bycatch rates from published research (*e.g.*, Swimmer *et al*., 2017; Allman *et al*., 2021) and the workgroup's expert assessment afforded by CMMs such as circle hooks, finfish bait, and gillnet illumination were applied to this contact selectivity term (Table 3), which is detailed further in Section 1.7.

IATTC Resolution C-19-04 mandates the release of sea turtles in all fisheries. Therefore, fishing mortality would be overestimated unless the component of the catch that survives mandatory release is accounted for. This is introduced in the model as post-capture mortality (PCM) (P_{xj})—incorporating two separate components—the proportion of length class *j* that is caught by fishery *x* and 1) dies before or upon arrival at the vessel (*i.e.*, "at-vessel mortality") or 2) dies soon after release ("post-release mortality"). PCM was highest for the egg collection fishery ($P_{xj} = 1.0$) since this "fishery" intentionally harvests eggs for human consumption. In the absence of reliable data relating to PCM in the longline fishery and the multiple set types made by the all size classes of purse-seine vessels, we needed to make the precautionary assumption that PCM > 0% for each fishery. PCM estimates for all fisheries are described in detail below; and Table 3 details each parameter value used in each scenario.

Industrial longline fisheries

Available PCM estimates for sea turtles consider both at-vessel and post-release components after capture by commercial longline gear, specifically 27% for externally hooked turtles and 42% for turtles with internal injuries (*e.g.*, hook lodged in esophagus) (Ryder *et al*., 2006). A summary of published PCM estimates for sea turtles in longlines ranged between 0 to ~0.9, with most values centering around 0.3 (Swimmer and Gilman, 2012). These values vary widely depending on severity of the injury and how the animal is handled after capture and prior to release. Considering this information, particularly the uncertainties about the post-release component of PCM, we used a range of PCM values for industrial longlines between 0.1 and 0.6, with a 'most likely' value of 0.3 (*i.e.*, 30% of leatherbacks that interact with industrial longline gear die as a result) (Table 3).

Artisanal longline fisheries

Values for PCM in artisanal fisheries are generally scarce (Alfaro-Shigueto *et al*., 2011; Alfaro-Shigueto *et al*., 2018), and post-release mortality estimates are particularly lacking. However, there is some evidence to suggest that leatherback PCM may be relatively low for small-scale longline fisheries. For example, in the Chilean pelagic longline fishery, the at-vessel mortality rate for leatherback turtles was estimated to be 7% (Donoso and Dutton, 2010). Further, Alfaro-Shigueto *et al*. (2011) reported zero at-vessel mortality of leatherback turtles in the Peruvian artisanal longline fishery. However, because safe handling and release practices are rarely implemented in artisanal fisheries, post-release mortality is likely to be higher than reported. PCM for the industrial longline fleet was assumed to be higher than for the artisanal longline fishery due to longer mainline length (120 km *vs*. 6 km) and deployment of more hooks per set (average ~2500 vs. <1000) (IATTC unpublished observer data for the industrial longline fleet in 2017; Alfaro-Shigueto *et al*., 2010). For these reasons, PCM for the artisanal longline fleet was assumed to range between 0.1 and 0.4, with a most likely value of 0.25 (Table 3).

Artisanal drift gillnet fisheries

Artisanal drift gillnets in the EPO region, particularly Ecuador, Peru, and Chile, are characterized by long soak times approximately equivalent to the artisanal longline fishery, and mesh sizes used are typically for targeting large pelagic fish and elasmobranchs, and thus frequently entangle sea turtles, including leatherbacks (see Alfaro-Shigueto *et al*., 2010). However, in contrast to surface-set longlines, gillnets can inhibit enmeshed turtles from reaching the surface to breathe, thus resulting in a higher PCM rate. This is particularly true for large mesh gillnets in Peru and Ecuador, where observed at-vessel mortality in drift gillnets is >30% (Alfaro-Shigueto *et al*., 2011; 2018). Further, although post-release mortality estimates are unavailable, it is likely to be greater than zero, and thus would increase the total PCM in these fisheries. Thus, PCM for the artisanal gillnet fishery was assumed to range between 0.2 and 0.6 with a most probable value of 0.5 (Table 3).

Purse-seine fisheries

Limited available evidence suggests leatherbacks are infrequently captured in purse-seine fisheries and tend to survive these interactions. A total of 109 leatherback turtle interactions have been recorded as bycatch—with only one confirmed mortality—in the 522,675 observed sets made by Class-6 purse-seine vessels in 1993–2019 (IATTC unpublished data). However, mortality of other sea turtle species has been observed in the EPO purse-seine fleet, and thus we could not completely discount the possibility of leatherback turtle PCM in our scenarios.

The lowest PCM estimates were in all purse-seine fisheries (most probable value: 0.05, range: 0.01–0.1; Table 3) where the set times are short, turtles can swim to the surface to breathe during the net pursing procedure, and can be brailed or removed from the net relatively quickly, thus reducing at-vessel and presumed post-release mortality. In fact, leatherback bycatch is very rarely observed in IATTC purse-seine operations (IATTC Unpublished Data; Table 2).

Across all fisheries included in the model the PCM values used assume that current implementation of CMMs (*e.g.*, large circle hooks in longlines and safe handling and release practices) is negligible . In contrast, scenarios that include such measures assume full implementation throughout each relevant fishery. We recognize that implementation of conservation measures in fisheries in practice would be incremental over time and achieving full compliance might not be realistically achievable. Therefore, these model estimates represent what could be possible under ideal conditions, which, when compared to *status quo* conditions, provide a reasonable range of potential effects of CMMs on leatherback vulnerability.

1.3 Productivity

Following the estimation of the overall susceptibility of length class *j* to incurring mortality from fishery *x* (S_{xj}), a proxy for the instantaneous fishing mortality rate in 2019 ($\widetilde{F}_{2019}$) for leatherback turtles caught by all fisheries was estimated as:

$$\widetilde{F}_{2019} = -\,ln\left[1 - \sum_{x=1} q_x\, E_x \left(\frac{\sum_{j=1}^{n} S_{xj}}{n}\right)\right] \qquad \text{(Eq. 2)}$$

Here, n is the number of length classes (in 2-cm increments) extending to the average length at which a leatherback turtle 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 fisheries values for q and E are unknown. A precautionary approach was used to assume both parameters are equal to 1, meaning all leatherback turtles in a grid cell are caught if all other susceptibility parameters are fully realized.

$\widetilde{F}_{2019}$ was then compared with values for F for the selected BRPs derived from the per-recruit models (described below; productivity parameters presented in Table 4). 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. It is for this reason that the results from EASI-Fish should not be used to define the status of a species' population, *sensu* a stock assessment.

1.4 Characterizing species productivity using per-recruit models

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

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

Here, new recruits and fully recruited length classes are denoted by the subscripts j and k, respectively. W_j is the mean weight of a turtle 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:

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

Length-specific estimates of the instantaneous natural mortality rate (M yr^{-1}) were taken from concurrent long-term studies of leatherback turtles returning to nesting sites in Mexico and Costa Rica (Laúd OPO Network, 2020) (Table 4). These were 0.53–0.69 yr^{-1}, 0.937 yr^{-1}, 0.5 yr^{-1}, and 0.212–0.295 yr^{-1} for size classes 0–5 cm, 5–40 cm, 40–100 cm, and >100 cm, respectively. Value ranges for M were assumed to be equally plausible and so uniform distribution priors was used for M. F was disaggregated into increments of 0.01 from zero to an L_∞ value of 147.6 cm (Zug and Parham, 1996). The parameter ΔT represents the time taken for a turtle to grow from one length class to the next, represented as:

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

where K and L_∞ are parameters from the von Bertalanffy growth function (Table 3), and d is the width of the length class, calculated as $L_{j+1} - L_j$.

The spawning stock biomass-per-recruit (SSB/R) model of Quinn and Deriso (1999)—herein termed breeding stock biomass-per-recruit (BSR) to be specific to turtle life histories—is complementary to YPR, and can be modified to suit the analysis of length rather than age classes and be represented as:

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

where W_j is the mean weight of a leatherback turtle in length class j (L_j) taken from a length-weight relationship (Table 3), m_j is the proportion of mature females at the mean length of length class j, and the product operator describes the number of turtles surviving from the length at recruitment (L_r) to L_j. Because the model calculates relative BSR, the initial number of breeding females was set to a value of one. The value for m_j was taken from a female maturity ogive for leatherback turtles in the EPO (Avens *et al.*, 2020), represented in the logistic form:

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

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

1.5 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 an F value at which yield is maximized (F_{MAX}) can be overly optimistic owing to sea turtles often having a strong stock-recruitment relationship (*i.e.*, h<1) (Gallaway *et al.,* 2016). 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.

An assessment of tuna fishery bycatch species in the EPO using EASI-Fish used $F_{40\%}$ (Griffiths *et al.*, 2019a), which had been generally regarded as precautionary for most marine finfish stocks (see Ralston, 2002). However, recent work by Cortés and Brooks (2018) suggests that for slow-growing and long-lived species, such as elasmobranchs, a BRP of between $F_{60\%}$ and $F_{80\%}$ should be used. Considering leatherbacks' life history traits of slow growth and low fecundity, $F_{80\%}$ was adopted for the present assessment. Explicitly, $F_{80\%}$ is the F value corresponding to 80% of the breeding potential ratio (BPR), which is the BSR at the $\widetilde{F}_{2019}$

value divided by the BSR where F=0. The corresponding $\mathrm{BSR}_{80\%}$ BRP is the BSR value at $F_{80\%}$.

The vulnerability of leatherback turtles in each hypothetical management scenario was determined using $\tilde{F}_{2019}$ and the corresponding BSR value (BSR_{2019}) relative to the $F_{80\%}$ and $\mathrm{BSR}_{80\%}$ values and displayed on a 4-quadrant "vulnerability phase plot" (Fig. 3). The vulnerability definitions of these quadrants are: i) "Least vulnerable" (green; $\tilde{F}_{2019}/F_{80\%}<1$ and $\mathrm{BSR}_{2019}/\mathrm{BSR}_{80\%} >1$), ii) "Increasingly vulnerable" (orange; $\tilde{F}_{2019}/F_{80\%} >1$ and $\mathrm{BSR}_{2019}/\mathrm{BSR}_{80\%} >1$), iii) "Most vulnerable" (red; $\tilde{F}_{2019}/F_{80\%} >1$ and $\mathrm{BSR}_{2019}/\mathrm{BSR}_{80\%} <1$), and iv) "Decreasingly vulnerable" (yellow; $\tilde{F}_{2019}/F_{80\%} <1$ and $\mathrm{BSR}_{2019}/\mathrm{BSR}_{80\%} <1$). Since EASI-Fish incorporates uncertainty in model parameters for each scenario, in order to be precautionary in the interpretation of the results only those scenarios where the mean and associated error are within the confines of the green quadrant are given the status of "least vulnerable".

1.6 Implementation of the model

The model was built using Visual Basic for Applications (VBA) in Microsoft Excel in order to generate uncertainty estimates for specific model parameters using uniform or normal prior distributions. The YPR and BSR models were then run 10,000 times using Monte Carlo simulations, each time using a random sample from the distribution prior defined for each parameter. The mean, standard deviation, standard error, and 95% confidence intervals (95% CI) were derived for the BRPs $\tilde{F}_{2019}$, $F_{80\%}$, BSR_{2019}, and $\mathrm{BSR}_{80\%}$.

1.7 Definition of hypothetical scenarios aiming to reduce vulnerability status of leatherback turtles

The flexibility of EASI-Fish allows specific spatial and temporal CMMs for the leatherback turtle stock in the EPO to be explored in isolation or in concert. Using the CMMs described in IATTC Resolution C-19-04, as well as other existing CMMs (*e.g.*, 72-day EPO-wide closure), we developed a total of 72 hypothetical CMMs under five categories (Table 6):

1) Mandatory use of large circle hooks in industrial and/or artisanal longline fisheries;
2) Mandatory use of finfish bait in industrial and/or artisanal longline fisheries;
3) Improved handling and release practices;
4) Illumination in drift gillnets;
5) Extension of the existing EPO-wide closure for purse-seine fishing, and to also apply this closure to the industrial longline fishery;
6) Various combinations of the above CMMs.

It is important to note that our CMM scenarios are intentionally general, and they intended to focus mainly on the CMMs required by C-19-04. However, we included artisanal fishing gears in addition to IATTC gears to which the C-19-04 applies because we wanted to produce estimates of impacts across fishing gears known to interact with leatherbacks. This approach allows managers to evaluate the relative potential efficacy of different scenarios of CMM implementation in the more realistic, regional context of multiple fisheries that affect leatherback vulnerability, rather than simply focusing on IATTC fisheries, which might have produced insufficient estimates of impacts and potential benefits of implementing CMMs. Below, we present the evaluation and conclusions of the working group about estimated efficacy of the CMMs examined in the hypothetical scenarios described briefly above.

1.7.1. Estimates of CMM efficacy

For each category of CMMs, specific scenario values were compared to the "*status quo*" fishery situation for 2019 ("S1"), which was an EPO-wide closure of 72 days, a 30-day closure of the existing "corralito", a length-at-first-capture of 90 cm for all fisheries, and a 'most probable' PCM rate of 0.3, 0.05, 0.5, 0.25, and 1.0 for industrial longline, purse-seine, artisanal gillnet, artisanal longline, and the egg collection fisheries, respectively. The S1 scenario also includes some existing national-scale conservation measures, such as marine protected areas (*e.g.,* Revillagigedo Archipelago, Mexico; Cocos Island National Park, Costa Rica; Galápagos Marine Reserve, Ecuador), that might affect leatherback bycatch. However, we did not introduce additional spatio-temporal management scenarios (*e.g.*, migratory corridors in areas beyond national jurisdiction), because adequate information about how such scenarios would be constructed (*e.g.*, defined boundaries of areas to be managed) was not available. We recognize that there may be other small spatial and/or temporal closures implemented by coastal States that are not represented in the model scenarios. Such national-level conservation measures could be evaluated in finer-scale versions of EASI-Fish to estimate their potential efficacy in reducing fisheries impacts of leatherbacks and other protected species at a domestic and/or EP stock level.

For each of the 72 scenarios in EASI-Fish, inputs for CMM effects on leatherback bycatch values were assumed to reflect 100% compliance for the entire fleet for each relevant fishery. This approach provides information about the extent of possible effects of CMMs on the vulnerability of the EP leatherback turtle stock. However, future model iterations could explore interim input values to reflect incremental or incomplete implementation of CMMs. For all scenarios in which CMMs were expected to reduce PCM, we applied three values of estimated reduction that corresponded to low, intermediate, and high efficacy. In this way, were able to analyze the variation in potential effect size for each CMM as well as the uncertainty around the estimates for PCMs in *status quo* and CMM scenarios. Descriptions of the derivation of all susceptibility values are given in Table 3. Estimated efficacy of individual and combined CMMs were based on inferences from published literature and/or augmented by assessments of experts participating in the working group (Table 5).

Status quo scenario

We attempted to estimate *status quo* values for both components of PCM for all fisheries (Table 3) because the proportion of the population that could die due to interactions with fishing gear changes depending on which CMMs are applied, and which model parameter those CMMs affect. For example, best handling and release practices do not apply to at-vessel mortality, but they specifically reduce the post-release mortality component of PCM (Ryder *et al*., 2006; Parga, 2012). However, the proportion of the population that could be affected by implementing best handling practices, and thus the relative effect size of this CMM, depends on the proportion of the population still available. Put another way, reducing impacts of a fishery with high at-vessel mortality—*e.g.*, gillnets (Alfaro-Shigueto *et al*., 2018; Allman *et al*., 2021)—requires CMMs that either reduce the lethality of interactions or avoids or at least reduces the frequency of those interactions altogether. In general, CMMs that reduce or avoid interactions in the first place should have the largest relative effect on fishery impacts.

Circle hooks and finfish bait

The use of large circle hooks and finfish bait were included in the 'menu of options' in C-19-04 to allow flexibility in applying CMMs to reduce impacts on sea turtles. Circle hooks have been shown to reduce the frequency of interactions as well as severe injuries that occur when turtles bite and/or swallow hooks (Parga, 2012; Swimmer and Gilman, 2012; Andraka *et al*., 2013; Parga *et al*., 2015), which should improve post-release survivorship of bycaught sea turtles (Ryder *et al.*, 2006; Swimmer *et al.*, 2017). However, leatherback interactions with longlines are more commonly entanglements with line material and/or external hooking on their large front flippers (Watson *et al*., 2005; Ryder *et al.,* 2006). Thus, for leatherbacks, the working group concluded that large circle hooks (typically 18/0, and to a lesser degree 16/0 in the studies reviewed) could be expected to reduce bycatch rates of leatherbacks (*i.e.*, selectivity) but not PCM; the same observations and conclusions apply to the use of finfish bait (*e.g.*, Swimmer *et al.*, 2017). Specifically, the working group estimated that selectivity of longline fisheries could be reduced through implementation of circle hooks, finfish bait, or both together by between ~30% and ~70% (range 10% to 80%, depending on the combination) (Table 5).

Illuminated gillnets

Drift gillnets in nearshore, national waters in the EPO are considered a primary source of leatherback mortality (Alfaro-Shigueto *et al*., 2011; Alfaro-Shigueto *et al*., 2018; Laúd OPO Network, 2020). Recent studies have shown great promise in reducing sea turtle bycatch rates and mortality using illumination in artisanal gillnets in Mexico (Senko *et al.*, 2022), Ecuador (Darquea *et al*., 2020), Peru (Bielli *et al*., 2020), and Ghana (Allman *et al.*, 2021). Specifically, green LED lights attached to float lines of gillnets have been associated with significant (*i.e.*, > 20%) reductions of bycatch of sea turtles and other species such as cormorants and small cetaceans (*e.g.,* Bielli *et al*., 2020). This apparent efficacy has been documented in the eastern Atlantic Ocean for leatherback bycatch reduction; researchers documented reductions between 50% and 80% in leatherback bycatch in small-scale gillnets across years in Ghana (Allman *et al.,* 2021). For these reasons, we introduced scenarios that applied net illumination with an estimated efficacy of leatherback bycatch reduction between 30% and 80% (Table 5).

Best practices for safe handling and release of bycaught turtles

Fate of turtles that interact with fishing gear can be improved by proper implementation of best practices for handling and release of affected turtles (Parga, 2012). Such best practices are well-documented, including in the FAO Code of Conduct for Responsible Fishing (FAO, 2009), and were included as CMMs in the previous (C-07-03) and current (C-19-04) resolutions to reduce bycatch impacts on sea turtles. If implemented properly by well-trained fishing crews, best practices can reduce the post-release component of PCM. This is a particularly important CMM because it can reduce impacts of fishing without significantly curtailing normal fishing operations. However, the efficacy of best practices varies tremendously depending on several factors, especially the severity of interactions (*i.e.*, selectivity and at-vessel mortality), the expertise of the crew, and the extent to which best practices are or can be implemented (Ryder *et al*., 2006; Parga, 2012; Swimmer and Gilman, 2012). Further, estimates of post-release mortality improvements due to implementation of best practices are fraught with uncertainty (*e.g*., Ryder *et al*., 2006; Swimmer and Gilman, 2012).

Considering the available information, the working group concluded that implementation of best practices would have different levels of estimated efficacy depending on the gear type, and that the uncertainty associated with these estimates was significant (Table 5). We relied on available estimates of post-release mortality in industrial longlines when best practices are implemented (*e.g.*, Swimmer and Gilman, 2012) and concluded efficacy of 25% (range 10–50%). We assumed a similar level of efficacy for best practices in drift gillnet fisheries because most of the impact of drift gillnets is at-vessel mortality, and there is virtually no information about the efficacy of best practices on post-release mortality of leatherbacks released alive. For artisanal longlines, we assumed that injuries to leatherbacks that survive interactions would be relatively minor (Parga, 2012; Parga *et al*., 2015), so implementation of best practices could have significantly positive effects on estimated post-release survival. Thus, we estimated an efficacy value for best practices in artisanal longlines of 75% (range 50– 95%). Finally, because leatherback interactions with purse-seine gear are so rare, and turtles are generally uninjured by such interactions, we estimated 90% efficacy (range 80–95%) for best practices implemented in those operations.

1.8. Caveats and additional considerations

As noted, the full suite of scenarios that we constructed in this collaborative analysis examines the potential efficacy of various CMMs, mainly focused on those described in IATTC Resolution C-19-04, in a "what if?" framework to provide managers and decision-makers with actionable information for reducing bycatch impacts on leatherbacks. While this suite of 70 hypothetical scenarios is comprehensive and has produced an enormous amount of results and related insights, there are several important issues that we did not include explicitly in this analysis. For example, there are several CMMs that are already being implemented to some extent in various countries, whose potential benefits for leatherback survival were not accounted for in this project. For example, Costa Rica currently protects 30% of its marine territory through the existence of National Wildlife Refuges, National Parks, Marine Management Areas, Responsible Fishing Marine Areas, or other effective area-based conservation measures for the conservation of marine biodiversity. The Cocos Island National Park and the Montes Submarinos Marine Management Area, in the Costa Rican Pacific, protects a marine area of 161,129 km^2, which benefits EPO leatherbacks. Additionally, Chile maintains multiple marine protected areas (*e.g.*, Nazca-Desventuradas, Motu Motiro Hiva) that protect various marine ecosystems and resources, including sea turtles.

In addition, there are several characteristics of each fishing gear type considered in this analysis that can influence frequency as well as severity of interactions. For example, different gear characteristics (*e.g.*, mesh size of gillnets) types of material used in longlines and gillnets are associated with different levels of entanglement risk and severity for leatherbacks; monofilament is considered to have higher risk of entanglement than polypropylene material (working group members, unpublished observations). Similarly, bait types can vary greatly within and among longline sets, which can also affect selectivity of these fishing gears (Swimmer *et al*., 2017). There are other CMMs that could be implemented in the gear types we examined (*e.g.*, low-profile and "buoyless" drift gillnets; Gilman *et al.,* 2010).

Further, there are other fishing gears that may interact incidentally with leatherbacks but were not included in this analysis, such as trawl gears and bottom-set gillnets (Hall and Roman, 2013). Importantly, potential effects of illegal, unregulated, and unreported fisheries as well as derelict or unattended fishing gear (*e.g.*, 'ghost' nets, artificial fish aggregation devices) on leatherback vulnerability were not included, but could contribute significantly to leatherback mortality in the EPO region.

With adequate information, many of these considerations could be included in future assessments of leatherback—and other species'—vulnerability. Managers could consider these additional gear characteristics, fisheries, or impacts when developing actual implementation plans to enhance leatherback survival in the EPO.

RESULTS

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

The extent of areal overlap of fisheries with the EPO leatherback species distribution (Fig. 4) was a significant influence of potential effects on leatherback vulnerability (Fig. 5). Based on the preferred SDM for leatherback turtles ($\psi = 0.2$) in the *status quo* scenario (S1), the areal overlap by the industrial longline fishery was high (61%), due to the fishery being distributed across most of the EPO between 45°N and 45°S (Fig. 4). With respect to Class-6 purse-seine vessels, areal overlap was 7%, 6%, and 20% for DEL, NOA, and OBJ sets, respectively. For purse-seine vessels of Classes 1–5, areal overlap was 2% (NOA) and 5% (OBJ), with effort concentrated around the Galapagos Islands and the waters of Ecuador and Peru (Fig. 4).

With respect to artisanal fisheries, the gillnet fleet overlapped with just 4% of the EP leatherback stock distribution, while the longline fleet had an areal overlap of 34%, with effort being widely dispersed from the coastline between Guatemala and Chile to as far east as the 100°W longitude (Fig. 4). The egg collection "fishery" overlapped with 0.007% of the stock, but because this fishery operates where the entire EP stock lays their eggs each year, this was interpreted in the model as a 100% overlap of the population.

The fishing season duration provided no protection from the industrial longline fishery and the artisanal longline and gillnet fisheries that all fish year-round (D_x =1.0), except for a 3-month closure in Mexican waters. Each purse-seine fishery fished for 81% of the year due to the 72-day EPO-wide closure and the 30-day closure of the "corralito".

Electronic tagging studies of the EP leatherback turtle stock confirm year-round presence of leatherback turtles within the IATTC Convention Area (see Benson *et al.*, 2011; Shillinger *et al.*, 2011; Schick *et al.*, 2013); leatherbacks were therefore considered to be available to all fisheries year-round (A_{xj}=1.0). Encounterability was fully realized (E_{xj}=1.0) for all fisheries because each gear fishes from the surface to depths that include typical depths occupied by leatherback turtles. The only exception was the egg collection "fishery", which was assumed to encounter only 4% of the total leatherback turtle nests within the EP stock boundaries.

Contact selectivity was fully realized (C_{xj}=1) for all fisheries for all size classes from the length-at-first-capture of 90 cm to the last size class in the model—the L_∞ value of 147.6 cm. An exception was the egg collection "fishery" where contact selectivity was C_{xj}=1 only for pre-hatchling sizes of 0–5 cm.

Under the *status quo* scenario (S1) in 2019, the industrial longline fishery imposed the highest fishing mortality ($\tilde{F}_{2019}$=0.103 yr^{-1}) (Fig. 5), mainly due to its high volumetric overlap with the stock (Fig. 4). The artisanal longline fishery had the second highest volumetric overlap and second highest fishing mortality (0.031 yr^{-1}) (Fig. 5), despite its overlap with the stock being approximately half that of industrial longlines (Fig. 4). The artisanal gillnet fishery had a comparatively low fishing mortality (0.006 yr^{-1}) (Fig. 5), owing to a very low (4.1%) areal overlap with the stock (Fig. 4). The remaining fisheries (purse-seine and egg collection) each contributed a fishing mortality of less than 0.007 yr^{-1} (Fig. 5). In the purse-seine fisheries, this is attributed to a very low PCM rate (5%), despite relatively high volumetric overlap with the stock (up to 20%) (Fig. 4), while the egg collection fishery had low encounterability of nests (4%) and only impacted a narrow range of size classes.

The fishing mortality contributed by each fishery to the total fishing mortality in each scenario is shown in the top panel of Fig. 5, while the lower panel shows the proportional contribution of each fishery to the total fishing mortality. For most scenarios, industrial longline and artisanal longline contributed most to fishing mortality, and to a lesser extent artisanal gillnet and OBJ sets by purse-seine Class-6 vessels.

2.2. Vulnerability status of leatherback turtles in the EPO

The biological parameter values (and their sources) used in the YPR and BSR models are shown in Table 4, while EASI-Fish estimates of the $F_{80\%}$ and BSR$_{80\%}$ BRPs for each scenario are provided in Table 7.

Under the S1 scenario characterizing the fishery in 2019, $\tilde{F}_{2019}$ and BSR$_{2019}$ exceeded the $F_{80\%}$ and BSR$_{80\%}$ BRPs, resulting in the classification of the EP leatherback turtle stock as "most vulnerable" (Fig. 6a; Table 7). Given the variability in the mean estimate, it is plausible that vulnerability may be markedly high or lower, but even in the most optimistic case, the likelihood that S1 would be classified as "least vulnerable" is low.

Use of large circle hooks in longline fisheries

The hypothetical introduction of large (*i.e.*, typically 18/0; Swimmer *et al.*, 2017) circle hooks to longline fisheries (S2–7) was assumed to reduce contact selectivity (*i.e.*, bycatch rates). When applied to the industrial longline fishery (S2–4) and all longline fisheries (S5–7) the low and intermediate selectivity values (*i.e.*, maximum [80% reduction] and intermediate [69%] potential efficacy values; Table 5) resulted in the stock's vulnerability status changing markedly from "most vulnerable" (red quadrant) to "least vulnerable" (green quadrant) (Fig. 6a; Table 7). However, the use of the highest selectivity value (*i.e.*, lowest potential estimated efficacy [20% reduction]) resulted in a decrease in vulnerability but insufficient to improve the status to "least vulnerable" due to large error bars extending beyond the green quadrant (Fig. 6a).

Use of finfish bait in longline fisheries

Similar to circle hooks, the hypothetical introduction of finfish bait to longline fisheries (S8–13) was assumed to reduce contact selectivity. When applied to the industrial longline fishery (S8–10) and all longline fisheries (S11–13) the low and intermediate selectivity values (*i.e.*, maximum [50% reduction] and intermediate [34%] potential efficacy values; Table 5) resulted in the stock's vulnerability status improving to "least vulnerable" (Fig. 6b; Table 7). However, the use of the highest selectivity value (*i.e.*, lowest estimate efficacy [10% reduction]) did not change the status from "most vulnerable" (Fig. 6b).

Use of best handling and release practices

The use of best handling and release practices (S14–S25) were assumed to reduce PCM by varying degrees in each fishery (Table 5). When applied to industrial longline only (S14–S16), all longline fisheries (S17–S19), or all industrial fisheries (S20–S22), only scenarios with low and intermediate PCM (*i.e.*, maximum and intermediated efficacy; Table 5) resulted in the status changing to "least vulnerable" (Fig. 6c; Table 7). However, when best practices were applied to all fisheries (S23–S25), status changed to "least vulnerable" for low, intermediate, and high values of reduced PCM (Fig. 6c; Table 7).

Use of a combination of CMMs

Combining the assumed benefits of using circle hooks in the industrial longline fishery or in all longline fisheries with the use of finfish bait (S26-31), or with best handling and release practices (S32-37), or with both finfish bait in all longline fisheries and best handling and release practices in all fisheries (S38-46) significantly decreased vulnerability (Fig. 6d-e; Table 7). Apart from S28 and S34, which had the highest selectivity values, all other scenarios resulted in a status change to "least vulnerable" (Fig. 6d-e).

Similarly, combining the use of finfish bait with best handling and release practices (S47–52) resulted in significant reductions in vulnerability. With the exception of S49, all scenarios resulted in a change in status to "least vulnerable" (Fig. 6g; Table 7).

Use of illuminated gillnets

Although gear illumination was not one of the CMMs listed in Resolution C-19-04, it was investigated in isolation (S53–55) and in combination with best handling and release practices (S56-58) (Table 6) because it was assumed to reduce contact selectivity in the artisanal drift gillnet fishery *(e.g.*, Allman *et al*., 2021). In additional scenarios, these CMMs were also combined with CMMs that used large circle hooks and finfish bait in longline fisheries, and with PCM values related to implementation of best handling and release practices in all fisheries (S59-61). Neither illuminated gillnets alone nor in combination with best handling and release practices were sufficient to change leatherback vulnerability status from "most vulnerable" (Fig. 6h; Table 7). However, when combined with the use of the full suite of CMMs applied to other fisheries (S59–61) vulnerability decreased dramatically to "least vulnerable", including the most effective scenario (S60; Fig. 6h; Table 7).

Temporal closures for industrial fishing fleets

The EPO purse-seine fishery has had a long history in the effective use of using temporal fishing closures to reduce the fishing mortality on target tuna species. Scenarios were developed to further extend the existing 72-day closure period to 90, 120, 150 and 180 days for the purse-seine fishery alone (S62–66) and for both the purse-seine and longline fisheries, respectively (S67–71). Extending the closure period for the purse-seine fishery resulted in a negligible change in vulnerability status (Fig. 6i). When including the industrial longline fishery in the closure, vulnerability decreased with increasing closure period, although a change in status to "least vulnerable" occurred only for closure periods of 150 and 180 days (Fig. 6i; Table 7).

Most effective scenarios for reducing EP leatherback vulnerability in EPO fisheries

Scenarios with largest reduction in proxy fishing mortality values (*i.e.*, $\widetilde{\boldsymbol{F}}_{\mathbf{2019}}$ < 0.1; S35-36, S41-42, S44-45, S51, and S59-60; Table 7) all included moderate to high estimated reductions in both contact selectivity and PCM in multiple fisheries (Fig. 5). Scenarios that included the same CMMs as the best-performing scenarios highlighted above, but assumed low estimated efficacy values for contact selectivity and PCM, were able to significantly reduce EP leatherback vulnerability, but had $\widetilde{\boldsymbol{F}}_{\mathbf{2019}}$ values an order of magnitude higher (Fig. 6; Table 7).

DISCUSSION

3.1 EASI-Fish demonstrates the potential efficacy of several CMMs in Resolution C-19-04

Ecological risk assessment (ERA) has been widely used in fisheries as a rapid and cost-effective means by which fisheries managers can identify species most vulnerable to fishing impacts and take steps to mitigate identified risks, or collect further information to facilitate more formal stock assessment (Hobday *et al*., 2011). There have been at least three ERAs undertaken in the EPO (Griffiths *et al*., 2017; Griffiths *et al*., 2018; Duffy *et al*., 2019), one of which included leatherback turtles, that indicated this species is among the most vulnerable species among those impacted by tuna fisheries (Griffiths *et al*., 2018).

However, this paper has provided a demonstration of the utility of the EASI-Fish approach to quantify the cumulative impacts of multiple fisheries—including artisanal fisheries for the first time—on critically endangered EP leatherbacks under several hypothetical CMM scenarios. The advantage of using the EASI-Fish approach over other ERA methods is that various management measures may be simulated either individually or in combinations to determine their potential efficacy of reducing the vulnerability of the EP leatherback turtle stock to becoming unsustainable in the long-term.

However, EASI-Fish, like many other ERA approaches, was not designed to serve as a replacement for formal stock assessment—despite having a simple stock assessment model at its core—to assess stock status for bycatch species. Nonetheless, EASI-Fish clearly demonstrated the potential benefits of fisheries employing apparently effective mitigation measures, such as the use of circle hooks, finfish bait, and best handling and release practices, to reduce contact selectivity and PCM of leatherback turtles in the pelagic fisheries of the EPO. Overall, our results suggest that CMMs described in IATTC Resolution C-19-04 and IAC Resolution CIT-COP7-2015-R2 have the potential to reduce the vulnerability of the EP leatherback turtle stock to fishing impacts in the EPO, especially when coupled with implementation of CMMs in artisanal fisheries not addressed in the IATTC Resolution.

3.2 Characteristics of best-performing CMM scenarios

Our results provide a large amount of information to support effective implementation of the IATTC Resolution C-19-04 to mitigate sea turtle bycatch in EPO fisheries. Fisheries managers can use the results of this study to make decisions about which CMMs to implement to achieve potential conservation benefits to leatherbacks. However, the potential management options simulated by EASI-Fish for infrequently encountered bycatch species such as leatherback turtles in the EPO seem complex. Considering the full and complex suite of scenarios, we can draw some general conclusions to guide further discussions about how to implement C-19-04. The following statements describe scenarios that significantly improved EP leatherback vulnerability status (see Figs. 5 and 6; Tables 5 and 8; Table S1):

- The best-performing scenarios (*i.e.,* $\widetilde{F}_{2019}/F_{80\%}$ < 0.1; S35-36, S41-42, S44-45, S51, and S59-60) included moderate to high estimated efficacy of multiple CMMs that assumed reduced both contact selectivity and post-capture mortality and implemented in multiple fisheries;
- Contact selectivity in longline fisheries—achieved in this study by implementing either circle

hooks, finfish bait, or both—must be reduced by at least 50%; even 20% reductions in all industrial and artisanal longline fisheries were insufficient (Scenarios 2-13);

- Post-capture mortality—achieved in this study by effective implementation of best handling and release practices—must be reduced by at least 50% in industrial longlines alone (*e.g.*, S15), or;
- Post-capture mortality must be reduced by at least 25% in industrial longlines and 75% in artisanal longlines (*e.g.*, S17); even 10% and 50% reductions, respectively, were insufficient;
- Minimum estimated reductions in post-capture mortality values (*e.g.*, S16, S19, S22, S25) were only sufficient if combined with at least two other CMMs *and* implemented in multiple fisheries (*e.g.*, S31, S37, S43, S52, S61);
- EPO-wide closures of both industrial longline and purse seine fisheries must be implemented and extend 150 days or more to effectively reduce leatherback vulnerability beyond the current 72 days for the purse-seine fishery; such extensive closures will likely be infeasible.

It is important to reiterate that the benefits predicted from EASI-Fish for CMM scenarios assume 1) 100% compliance with CMM implementation to the full extent of each applicable fishery, and 2) that CMMs achieve the estimated levels of efficacy reflected in the model inputs (Table 5). Further, EASI-Fish focuses on estimating vulnerability of species to fisheries impacts but does not evaluate potential effects of CMM implementation on target catch. Thus, the results of the model scenarios provide estimates of what is possible under such conditions in comparison to current conditions, that is, the ideal target for CMMs. In reality, improvements to leatherback vulnerability should be expected to occur incrementally as CMMs are implemented—*i.e.*, fishing crews gradually employ more effective methods of handling captured turtles, circle hooks are gradually implemented in more longline operations. This highlights the need for a sustained, long-term strategy for widespread implementation of effective CMMs across the IATTC Convention Area to improve EP leatherback status.

If a precautionary assumption is made that any scenario involving an individual CMM is unlikely to be fully implemented across all EPO fisheries, then consideration should be given to scenarios that incorporated multiple CMMs, which tended to result in greater reductions in vulnerability than for individual CMMs (Fig. 6; Table 7). Although using a combination of CMMs may be more effective in reducing leatherback vulnerability, ultimate success will depend on whether the measure can be implemented in a practical, safe, and cost-effective manner over the long term. To realize the full potential benefits illustrated in our results, 1) fisheries managers would need to develop and implement robust, effective training programs and provide necessary materials and other resources to respective fishing fleets under their authority, and 2) fishing crews would need to implement the CMMs effectively and consistently during fishing operations. Ensuring effective implementation and efficacy of CMMs would require robust verification protocols developed and enforced by national fishery agencies as well as continuous capacity building with stakeholders.

Regardless of the specific combination of CMMs, CMM implementation strategies must account for the critically endangered status of EP leatherbacks, and their high vulnerability to bycatch impacts (Fig. 6) to produce significant conservation benefits. This would require careful consideration about uncertainties related to implementation efficacy and extent in relevant fisheries, as well as adequate provision of necessary resources to achieve full implementation and maintain enforcement of CMMs in the long-term.

3.3 Specific conservation measures and their potential benefits to EP leatherback conservation

Our results demonstrate that effective, comprehensive implementation of best handling and release practices—especially in combination with other measure in C-19-04—has significant potential for reducing EP leatherback vulnerability to fisheries bycatch (Figs 5 and 6; Table 7). This is an encouraging result because best handling and release practices have been included as CMMs in IATTC and IAC resolutions since 2007 (IATTC Resolution C-07-03), and 2006 (IAC Resolution COP3/2006/R-2), respectively, and are variably familiar already to most fishing fleets. Therefore, we recommend the best performing combinations of CMMs that reduce contact selectivity (*i.e.*, the use of circle hooks, finfish bait, and illuminated gillnets) and PCM (*i.e.*, implementation of best practices) in either all industrial fisheries (at minimum), all longline fisheries, or all EPO fisheries (ideally). If fishery managers believe that these measures cannot be implemented in unison, our minimum recommendation—while noting its lower predicted effectiveness—would be the use of large circle hooks coupled with best handling and release practices in industrial longline fisheries.

The efficacy of circle hooks (and finfish bait) in reducing the hooking rate and fishing-induced mortality of sea turtles, potentially including leatherbacks, has been published in several studies of longline fisheries (Watson *et al*., 2005; Gilman *et al*., 2006; FAO 2009; Sales *et al*., 2010; Andraka *et al*., 2013; Swimmer *et al*., 2017). As for safe handling and release techniques, IATTC Resolution C-19-04 requires that purse-seine and longline operations "*Ensure that vessel operators and/or at least one crew member on board of vessels targeting species covered by the Convention in fisheries that have reported sea turtle interactions, and particularly those without observers, are trained in techniques for handling and release of sea turtles to improve survival after release*." These techniques are described in the 2009 FAO *Guidelines to Reduce Sea Turtle Mortality in Fishing Operations* (FAO 2009). There are, however, added challenges to reducing post-capture mortality from small-scale vessels that should be considered, since animal handling may be more difficult, resources and available equipment are more limited, and it may not be possible to bring leatherbacks onboard (Parga, 2012).

Nonetheless, it may be fortuitous that minimizing PCM has the potential to significantly reduce the mortality of leatherback turtles in EPO tuna fisheries, which are already subjected to a range of spatial and temporal closures as a means of managing fishing mortality of target tuna species. Handling and release practices that may allow a significant proportion of captured turtles (and other vulnerable, non-target species) to survive the effects of bycatch interactions are much simpler and cost-effective to implement—if fishers maintain a high level of care in the recommended release procedures—than small-scale spatial and temporal closures to reduce the capture of leatherback turtles. Nonetheless, it is important to recognize that uncertainties persist in PCM estimates both under current practices and projected reductions of PCMs with CMMs.

3.4 Spatial and temporal closures

Spatial and/or temporal closures are CMMs commonly used by fisheries managers to reduce the fishing impacts on target species or species of conservation concern if particular areas and periods can be identified where a species is abundant and susceptible to capture. One such example in the EPO that the IATTC has implemented is the EPO-wide closure of purse-seine fishing for varying periods through the history of the fishery—depending on the status of the target stocks—from 31 days in 2002–2003 (Resolutions C-02-04 and C-03-03) to 72 days in 2018–2020 (Resolution C-17-01). In addition, the IATTC later implemented an annual 30-day closure of the "corralito" to further reduce fishing mortality on juvenile bigeye tuna (*Thunnus obesus*) (see Resolution C-02-04), but now serves a concomitant purpose for reducing the mortality on the complex of small-sized tunas caught in the same region including yellowfin tuna (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*). Although spatial-temporal closures of the "corralito" and other tuna catch 'hotspots' were predicted by Harley and Suter (2007) to reduce the catch of bigeye tuna by up to 24%, they were insufficient for reducing fishing mortality to biological sustainable levels. As an alternative, increasing the area and duration of closures or exploring dynamic management measures has been recommended (Harley and Suter, 2007; Pons *et al*., 2022).

Simulations of various spatial-temporal closures in the present study complemented the results of Harley and Suter (2007) in that the duration of recent EPO-wide closures (*i.e.*, 72 days) were insufficient to reclassify the stock's vulnerability status to "least vulnerable". Further, the first phase of this project included closures of coastal areas immediately adjacent to key nesting areas in addition to these EPO-wide closures, and results also showed that these combined closures were insufficient to improve leatherback status (Griffiths *et al*., 2020). Extending the EPO-wide closure duration reduced the species' vulnerability, but the only scenarios where the species' classification changed to "least vulnerable" was that achieved by assuming a closure of both the purse-seine and industrial longline fisheries for at least 150 days per year (Fig. 6i; Table 7). This is unlikely to be a feasible management option due to its consequential major reduction in the catch of tuna target species.

There are several countries already contributing by implementing important measures that include their nesting beaches in management categories (*e.g.*, National Parks, Wildlife Refuges, Sanctuaries). For those nesting sites and their adjacent areas, as well as marine areas under various levels of management and/or protection that do not fall under these categories, the implementation of management measures identified and developed through participative governance could be analyzed as well. Further, significant collaborative efforts are required to define high-seas areas that could be candidates for spatio-temporal management (*e.g*., Shillinger *et al*., 2008). Such scenarios would involve multiple actors, under country-specific and convention-specific mechanisms, in management and implementation of best practices for responsible use of fishing resources within relevant marine areas.

RECOMMENDATIONS FOR FUTURE WORK

This paper examined potential effects of multiple CMM scenarios on leatherback vulnerability, including gear modifications (*e.g.*, circle hooks, illumination of gillnets), best practices (*e.g.*, safe handling and release of turtles), spatio-temporal fishing closures of the EPO, as well as combinations of CMMs. While the results of these model scenarios provided ample information to inform strategies for implementing conservation measures in EPO fisheries, they also highlighted information needs and priorities for future work.

4.1. Improved EASI-Fish parameter estimates

Although some information exists to inform estimated values for EASI-Fish parameters such as reduction in contact selectivity (*i.e.*, bycatch rates) related to use of large circle hooks and/or finfish bait in some fisheries, there remain significant information needs for many fundamental variables for most fisheries we considered in this study, specifically reliable values for PCM and CMM efficacy. Along these lines, improved data collection and reporting of bycatch events remains a fundamental need in most fisheries. Observer coverage by each IATTC CPC industrial longline fleet in the EPO has often failed to reach the 5% requirement under Resolution C-19-08. Availability of data from onboard observers during fishing operations is a critical need to inform and improve decision making processes. Therefore, promoting permanent observer programs onboard industrial as well as artisanal fleets for vessels <24 m LOA by human and/or electronic monitoring is critical to access reliable leatherback turtle interaction information. However, these programs require ongoing financial and political commitment to be successful in the long term.

To help provide better information to improve estimates of PCM and CMM efficacy we recommend that robust observer programs be developed for the fleet of LSTLFVs—where electronic monitoring could be trialed as a possible cost-effective method to complement human observers—to comply with existing requirements of IATTC Resolution C-19-08, and IAC Resolution CIT-COP7-2015-R2. We also recommend undertaking studies using satellite transmitted behavior data (*e.g.*, diving, displacement) to quantify PCM rates for leatherback turtles in EPO longline and gillnet fisheries, though we recognize logistical and technological challenges associated with such studies. Further, sample sizes required to confidently refine current PCM estimates may not be practical to obtain, especially given the many variables that can influence PCM. Although estimates of PCM may be refined by ongoing and future studies, they likely will always require various degrees of inference, extrapolation, and expert opinion that carries uncertainty and must be acknowledged. These studies would benefit by estimating PCM using best handling and release practices, such as *in situ* release after cutting the leader, compared to release from the deck. The experimental design could be further stratified by animal size and handling time to release to better understand the efficacy of each release procedure. In addition, best handling practices are currently required in these fisheries and training to ensure compliance is a logical goal of sea turtle conservation efforts. Current practices and the effects of outreach and education should be better characterized to improve our understanding of the efficacy of this CMM.

4.2. Improved reporting of spatially explicit fishing effort

Previous ERAs have not included coastal artisanal fisheries that commonly interact with leatherback turtles since they are generally poorly documented, if at all (Salas *et al*., 2007). For example, sea turtles are caught as bycatch in small-scale commercial or artisanal fisheries throughout Mexico (Bizzarro *et al*., 2009a; Smith *et al*., 2009), Central America (Swimmer *et al*., 2011; Whoriskey *et al*., 2011), and South America (Alfaro-Shigueto *et al*., 2007; Martínez-Ortiz *et al*., 2015; Alfaro-Shigueto *et al*., 2018; Ortíz-Álvarez *et al*., 2020)—often in far higher numbers than in industrial purse-seine and longline fisheries in the EPO (Wallace *et al*., 2013a). In addition to accidental capture, retention of turtles for human consumption still occurs in artisanal fisheries in central Peru. For example, approximately 1,000 turtles were found in several dumping sites near Pisco, Peru between 2009 and 2015, where 95% were believed to be used for human consumption, of which 1.4% were leatherback turtles (Quiñones *et al*., 2017).

EASI-Fish was designed to overcome such problems of scant or unreliable catch data by using spatial maps of fishing effort overlaid on a species' habitat distribution. As a result, the current assessment is the first ERA that has included artisanal fisheries to quantify the cumulative impact of all fisheries on a species in the EPO. However, for some regions, information could only be sourced opportunistically from published sources as there are large areas of coastline of the Americas for which artisanal fisheries operate, but no data are available, such as the central mainland of Mexico, and areas beyond the conservative limits on putative fishing areas that we imposed within 0.5° of each fishing port in this study. Furthermore, although a large amount of fishing effort data was contributed to the assessment from coastal states, which significantly improved the assessment since the previous assessment of Griffiths *et al*. (2020), the absence of dedicated monitoring programs for artisanal fisheries in some countries meant that the data available for use represented only a subset of all effort, for example, only those sets where an observer was onboard. Due to such limitations in coverage of all fisheries that are likely to have leatherback turtle bycatch and the several conservative assumptions of the model, the estimated fishing mortality ($\tilde{F}_{2019}$) and the subsequent vulnerability status of the EP leatherback turtle stock for 2019 and for each hypothetical scenario is likely to be underestimated. Therefore, the results presented in this paper should be considered a useful contribution toward informing precautionary management of fisheries bycatch impacts on the critically endangered EP leatherback turtle stock.

However, the IATTC now has some survey data of these small coastal fisheries through the collaboration with Central American IATTC Members in a project funded by the Global Environment Facility (GEF) (Siu and Aires-da-Silva, 2016; Oliveros-Ramos *et al*., 2019). Although this work has now ceased, the sampling approach will be expanded in Mexico, Ecuador and Peru in 2022, which should provide further data on catches and fishing effort of these small coastal fisheries. In addition, the MoU between IATTC and IAC provides opportunities for further collaboration and information sharing between the two conventions. Further, innovative approaches to compile bycatch data in artisanal approaches, such as radio communication with fishers (*e.g.*, Alfaro-Shigueto *et al*., 2012), should be expanded to fill these important information gaps using practical techniques. Therefore, future assessments on bycatch species such as leatherback turtles may be improved as high resolution spatially explicit fishing effort data become available for use by the IATTC staff.

4.3 Evaluation of management feasibility and ecosystem effects of implementing CMMs

Fisheries management must balance commercial and livelihood interests with ecosystem health considerations, including responsible management of endangered and protected species like leatherback turtles. Our results provide ample information for one part of that equation: potential efficacy of implementing various CMMs on EP leatherback vulnerability to fisheries bycatch. Therefore, an important next step would be to estimate the logistical requirements and potential cost-benefits to tuna fisheries of implementing the CMMs included in this model. Such an exercise would provide opportunities for CPCs to explore feasibility of implementing potentially effective CMM scenarios highlighted in our results. In addition, the best-performing CMMs could be explored in a multi-species EASI-Fish framework to explore potential benefits—or tradeoffs—for other bycatch species with the aim to craft a sound ecosystem approach to managing both target and non-target species affected by EPO fisheries.

CONCLUSIONS

EASI-fish was primarily developed as a tool for quantitatively assessing the relative vulnerability of data-poor bycatch species and allowing the identification of priority species that may be recommended to become candidates for future research and catch monitoring. However, this study demonstrated the flexibility and usefulness of the EASI-Fish approach for estimating the relative efficacy of potential CMMs in reducing the vulnerability of leatherback turtles that are impacted by multiple pelagic fisheries in the EPO.

As more data become available from national and IATTC monitoring programs, post-release mortality studies, EASI-Fish’s utility will increase as a particularly rapid and inexpensive tool to explore potential impacts of various CMM scenarios that reduce vulnerability of other vulnerable non-target bycatch species. Further, refined EASI-Fish outputs will highlight CMMs that may be cost-effectively implemented by fishery managers to comply with existing mandates and resolutions that require the demonstration of responsible fishing practices that ensure ecological sustainability of all species in which their fisheries interact.

This study represented an important and successful collaboration between the IAC and the IATTC in fulfillment of their 2011 MoU that outlined areas of cooperation, specifically sharing information to inform bycatch reduction and conservation strategies to benefit sea turtles in both the IATTC and IAC Convention Areas. The detailed results generated by this effort will inform development of strategies to implement CMMs described in C-19-04 and provide managers with significant flexibility and improved clarity with respect to the types of CMMs that could be implemented to achieve conservation benefits for leatherbacks. Several EASI-Fish modelling scenarios indicated potential benefits of various CMMs to leatherback conservation status, whether implemented individually or in combination with other CMMs. However, because these benefits are dependent upon 100% implementation and compliance in fisheries in question, necessary protocols and control systems are needed to effectively enforce the implementation of CMMs and to monitor their efficacy to achieve conservation and fisheries goals.

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Zug, G.R., Parham, J.F., 1996. Age and growth in leatherback turtles, *Dermochelys coriacea* (Testudines: Dermochelyidae): a skeletochronological analysis. *Chelonian Conservation and Biology* **2**, 244-249.

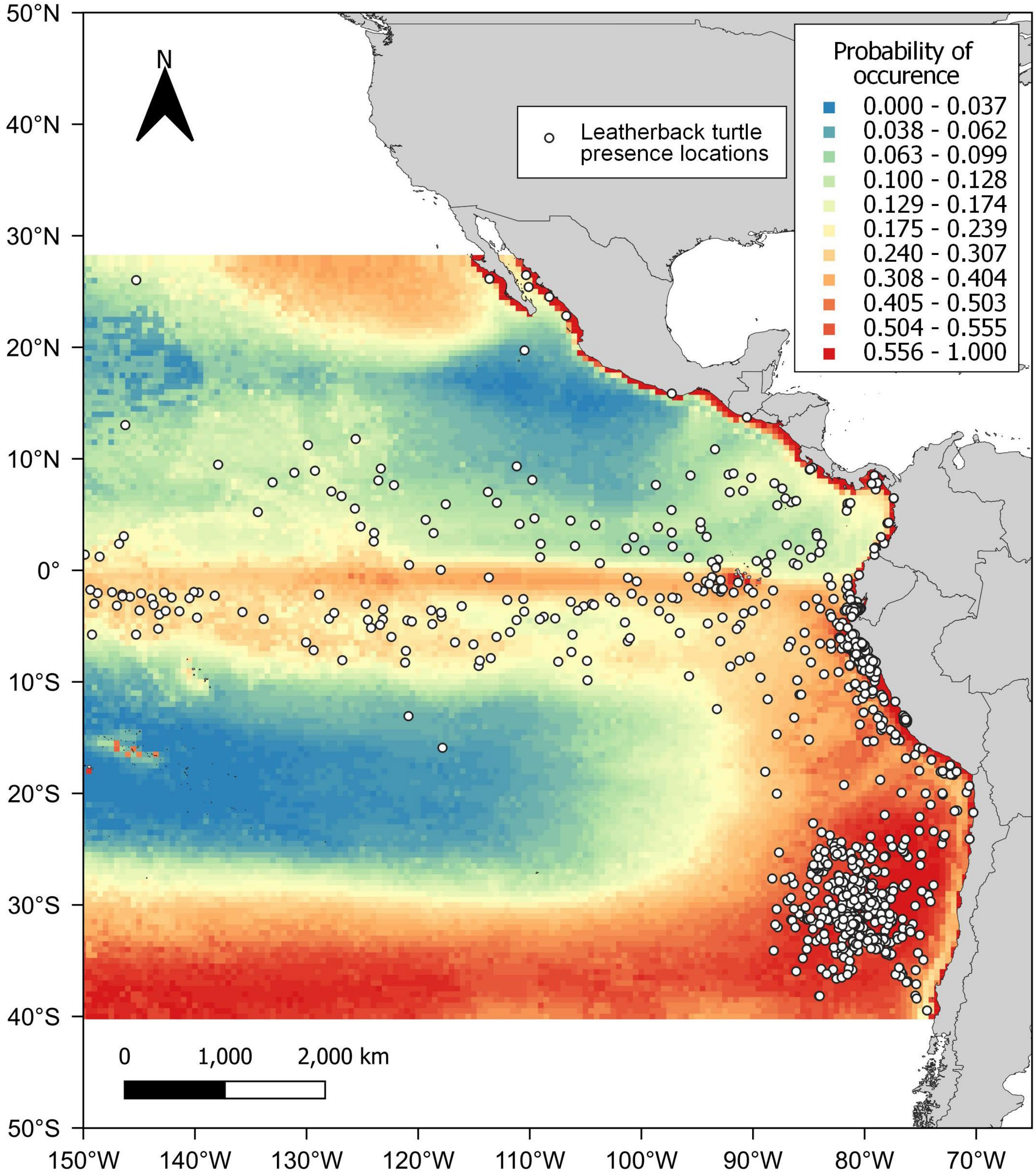

FIGURE 1. Maps showing the presence data (white circles) used to generate the predicted distribution of the east Pacific stock of leatherback turtles (*Dermochelys coriacea*). To account for uncertainty in the model's predicted distribution of the species, EASI-Fish was run using three probability-of-occupancy (ψ) threshold values of 0.1, 0.2, and 0.3.

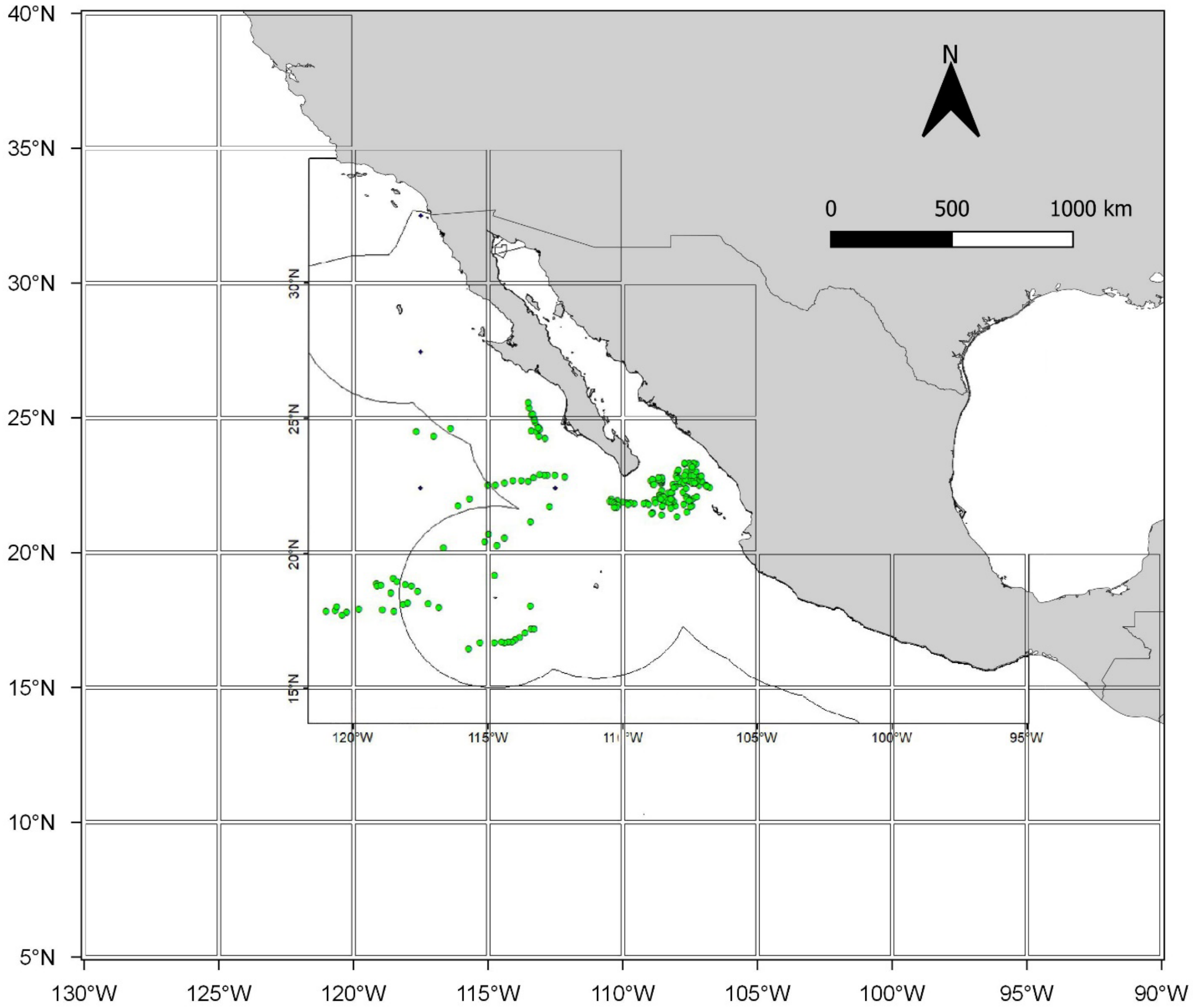

FIGURE 2. Map showing how publicly available fishing effort distribution maps were geo-referenced in QGIS software and effort allocated to cells in the C-squares global spatial indexing system. In this case, a map of observed sets made by the commercial Mexican shark longline fleet in 2018 (supplied by Mexico's Shark Observer Program) was overlaid with 5° x 5° cells in order for these data to be added to the 'industrial' longline fleet in the EASI-Fish model to assess the vulnerability of the southeastern EPO stock of leatherback turtles (*Dermochelys coriacea*) in the eastern Pacific Ocean.

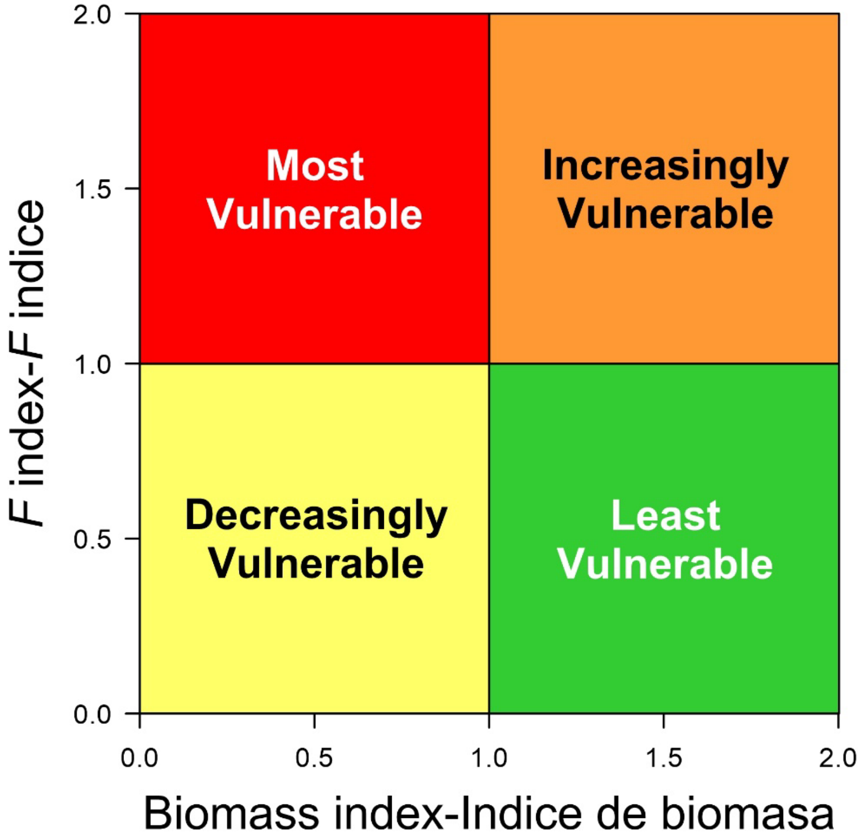

FIGURE 3. Phase plot illustrating how vulnerability status was defined for the East Pacific leatherback turtle stock assessed using $F_{80\%}$ and $BSR_{80\%}$ from the EASI-Fish model as a reference point on the x and y axis, respectively. Vulnerability was defined by its position within one of four quadrants in the phase plot as: "Least vulnerable" (green, $\tilde{F}_{2019}/F_{80\%} <1$ and $BSR_{2019}/BSR_{80\%} >1$), "Increasingly vulnerable" (orange, $\tilde{F}_{2019}/F_{80\%} >1$ and $BSR_{2019}/BSR_{80\%} >1$), "Most vulnerable" (red, $\tilde{F}_{2019}/F_{80\%} >1$ and $BSR_{2019}/BSR_{80\%} <1$), and "Decreasingly vulnerable" (yellow, $\tilde{F}_{2019}/F_{80\%} <1$ and $BSR_{2019}/BSR_{80\%} <1$). Maximum axis limits of 2.0 are for illustrative purposes only.

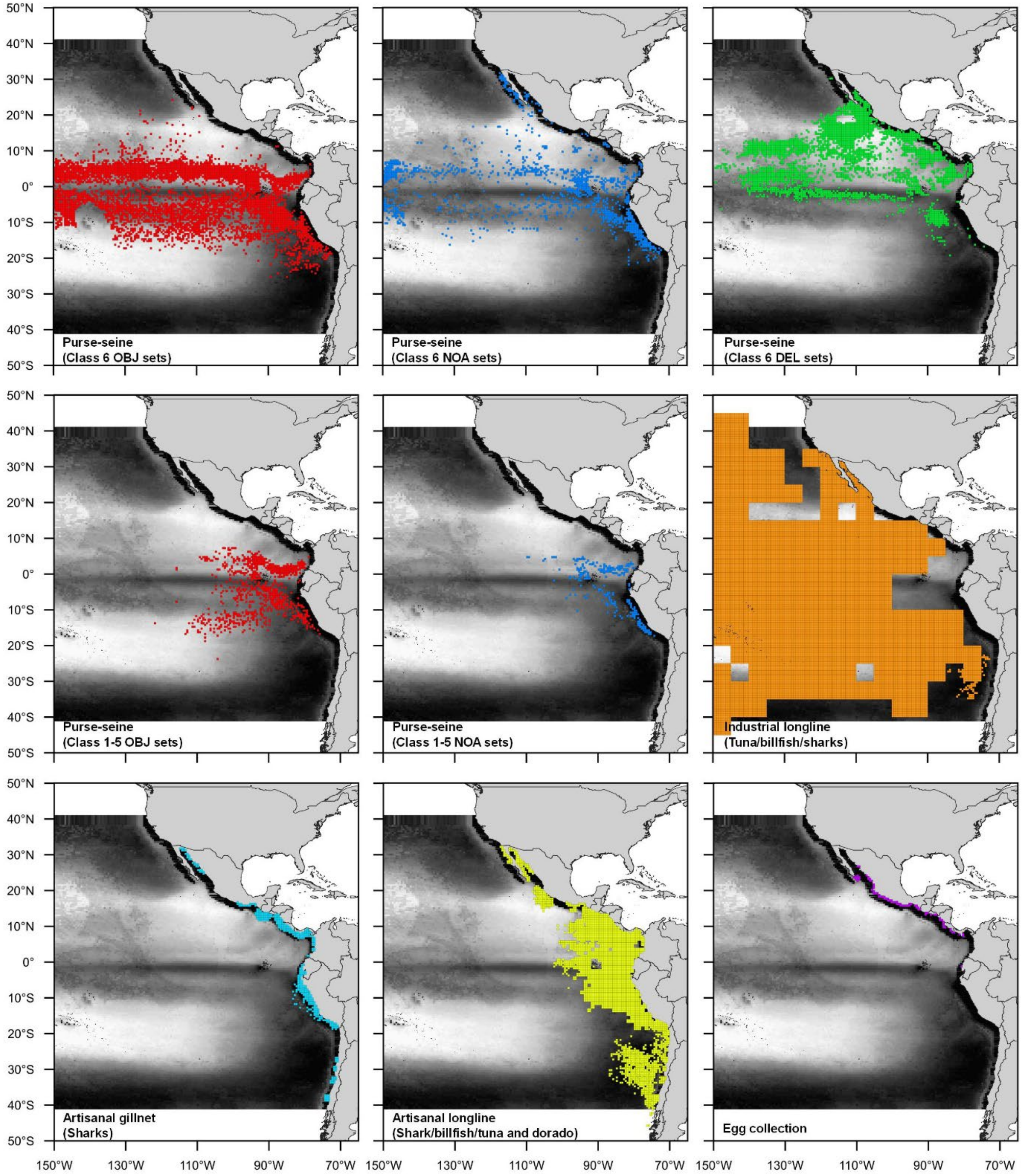

FIGURE 4. Maps showing the distribution of fishing effort (at 0.5° x 0.5° resolution) by nine fisheries in the eastern Pacific Ocean in 2019 relative to the East Pacific stock of leatherback turtles (Dermochelys coriacea) (dark colors indicate higher probability of occurrence). Set types for the purse 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).

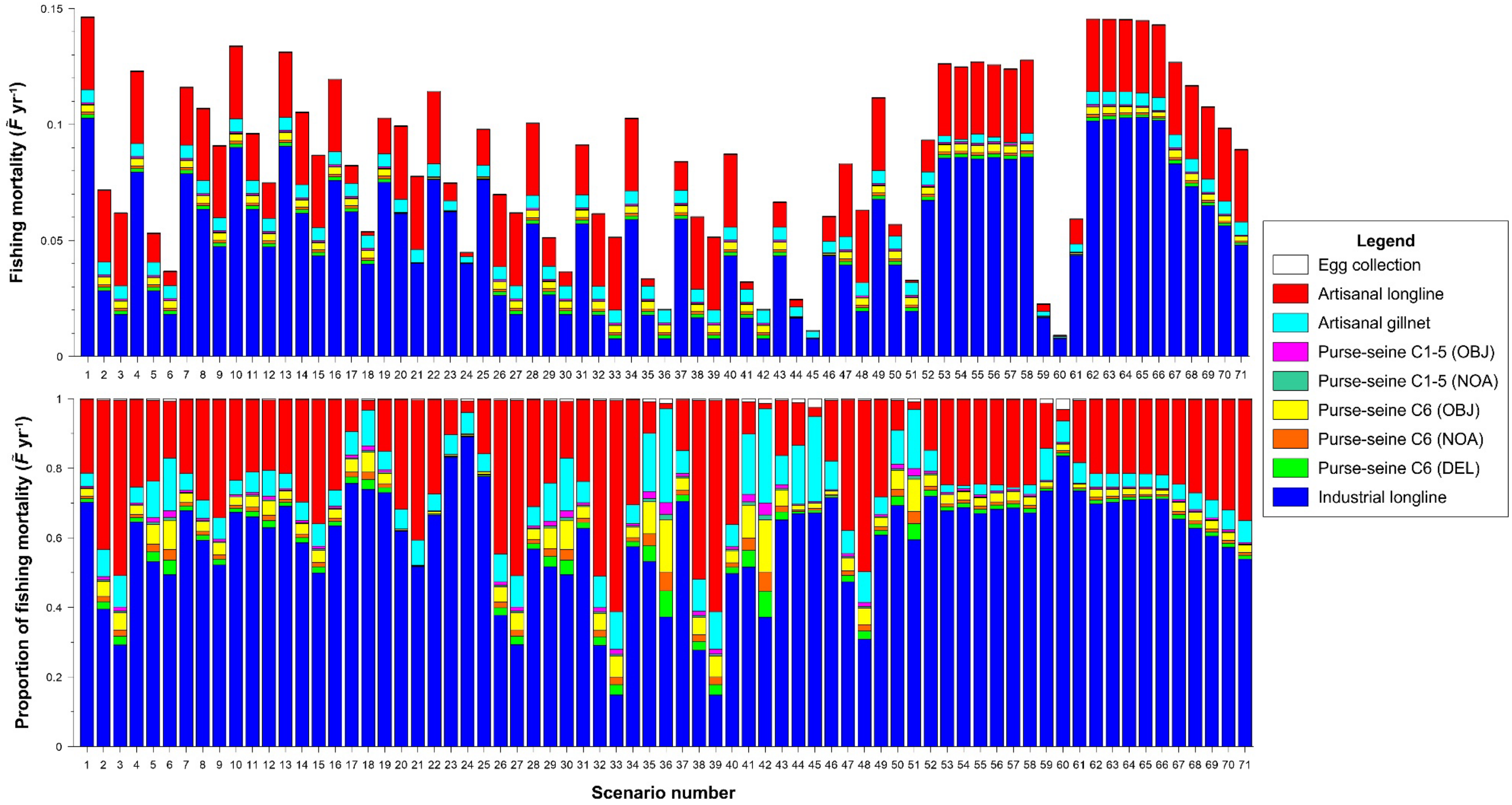

FIGURE 5. Mean values for the fishing mortality proxy ($\tilde{F}_{2019}$) for the East Pacific leatherback turtle (*Dermochelys coriacea*) stock estimated by EASI-Fish (top panel) and the proportion of total mortality $\tilde{F}_{2019}$ value (bottom panel) for each conservation and management scenario based on the effort regime for industrial and artisanal fisheries in 2019 in the eastern Pacific Ocean. Descriptions of each scenario number show in the x-axis are provided in Table 5 and Table S1.

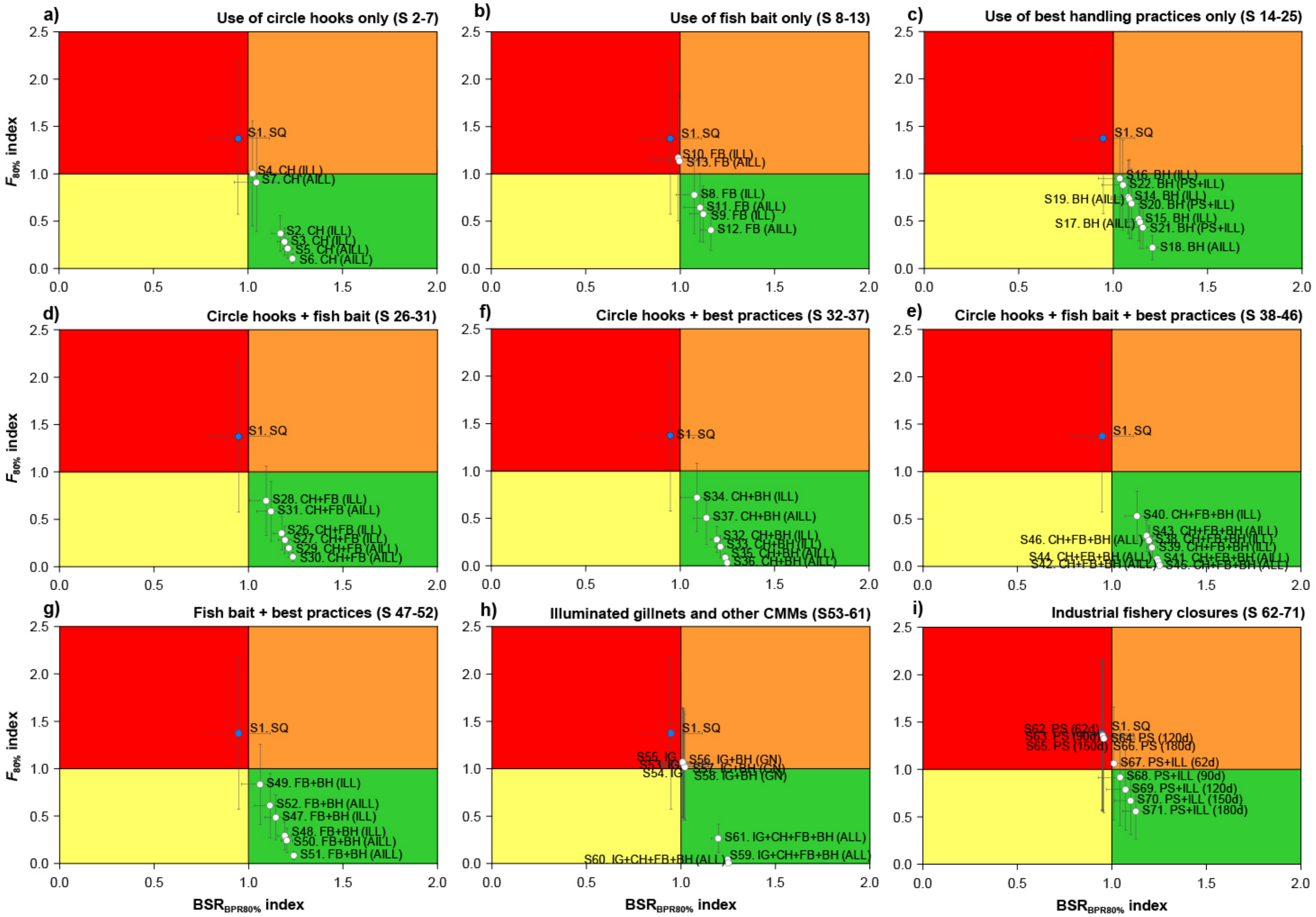

FIGURE 6. Vulnerability phase plots showing the vulnerability status of the East Pacific leatherback turtle (*Dermochelys coriacea*) stock estimated by EASI-Fish with respect to EPO industrial and artisanal pelagic fisheries represented by the mean (± standard deviation) biological reference points $\tilde{F}_{2019}/F_{80\%}$ and $BSR_{2019}/BSR_{80\%}$ for each hypothetical scenario. Note the blue symbol labelled "S1. SQ" in each plot shows the vulnerability status under the assumed *status quo* fishing effort and management scenario in 2019 to allow comparisons with other scenarios. Labels adjacent to symbols denote the scenario number detailed in Table 2 as well as an indication of the conservation measure addressed (CH = circle hooks, FB = finfish bait, BH = best handling practices, IG = illuminated gillnets) and the fisheries in which the measure was applied (ILL = industrial longline, AILL = artisanal and industrial longlines, PS = purse seine class 1-6, GN = gillnet, ALL = all fisheries). Numbers in parentheses in panel (i) show number of fishery closure days. Vulnerability status values for each of the 71 scenarios (and *status quo*) are provided in Table 7**.**

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 geo-referenced 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	2018	Monthly aggregates of number of hooks deployed at 5°x5° resolution (reports by CPCs); positional set data downscaled 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 5°x5° resolution to enable incorporation with LSTLFVs.	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 5°x5° resolution to enable incorporation with LSTLFVs.	Hernández and Valdez Flores (2016)*
Purse-seine (Class 6 - all set types)	IATTC Convention Area	2018	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	2018	Positional set data upscaled to 0.5°x0.5° resolution.	Unpublished data collected by TUNACONS observer program and IATTC staff at landing ports (logbooks).
Artisanal fisheries				
Surface-set gillnet	Chile (Northern and Central)	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); Martínez *et al*. (2017)*
	Chile (Southern)	2002	Positional set data upscaled to 1°x1° resolution.	Moreno *et al*. (2006)*
	Chile and Peru	2005–2010	Annual aggregates of number of sets at 1°x1° 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	Annual aggregates of number of sets at 1°x1° resolution.	Andraka *et al*. (2013)*
	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 downscaled to 0.5°x0.5° resolution.	Ayala *et al*. (2008)*; Alfaro-Shigueto *et al*. (2011)*
Egg collection	Costa Rica	1995–2006	Nest positions allocated to adjacent 0.5°x0.5° grid cells	La Red de la Conservación de la Tortuga Laúd del Océano Pacífico Oriental; Troëng *et al*. (2007)*
	Mexico	1982–2004	Nest positions allocated to adjacent 0.5°x0.5° grid cells	La Red de la Conservación de la Tortuga Laúd del Océano Pacífico Oriental; Sarti Martínez *et al*. (2007)*

TABLE 2. Summary of data used to develop a novel species distribution model for the EP leatherback stock. *The total number of presences incorporated in the model was 1,088 because some observation data were located outside the area of study.[1]IAC Party, [2]IATTC CPC, [3]party to both conventions.

Country	Gear	First year	Last year	Presence only	Abundance	Effort	No. Presences	No. individuals	No. total sets	% of presences	Source
Chile[1]	Purse-seine	2015	2019	No	No	-	3	3	4,396	0.07	Observers
Chile[1]	Industrial longline	2001	2018	No	Yes	Yes (No hooks)	327	365	13,828	2.36	Observers
Chile[1]	Artisanal longline	2002	2018	No	Yes	Yes (No hooks)	59	62	1,831	3.22	Observers
Chile[1]	Artisanal longline (espinel)	2010	2019	No	No (?)	Yes (No hooks)	2	2	564	0.35	Observers
Chile[1]	Artisanal gillnet	2007	2019	No	Yes	No	22	24	1,399	1.57	Observers
Colombia[2]	Gillnet	2017	2018	Yes	No	No	3	3	3	-	Observers
Colombia[2]	Longline	2018	2018	Yes	No	No	2	2	2	-	Observers
IATTC	Purse-seine	1995	2020	No	Yes	No	272	274	532,857	0.05	Observers
IATTC	Longline	2013	2020	No	Yes	No	67	67	24,005	0.28	Observers
Panama[3]	PS/LL/Gillnet	2018	2020	Yes	No	No	10	10	10	-	Observers
Peru[3] (ProDelphinus)	-	2001	2019	Yes	No	-	186	186	186	-	ProDelphinus
Ecuador[3]	Purse-seine	2019	2020	No	No (?)	-	3	3	2,746	0.11	Observers
Ecuador[3]	Longline (bottom)	2017	2020	No	No (?)	No	0	0	766	0.00	Observers
Ecuador[3]	Longline (surface)	2019	2020	No	No (?)	No	2	2	1,667	0.12	Observers
Peru[3]	Net	1997	2015	Yes	No	No	141	141	141	-	IMARPE/ACOREMA
Peru[3]	Driftnet/Gillnet	2013	2020	Yes	Yes	No	21	21	21	-	IMARPE (LAMBAYEQUE)
WWF (various)[3]	LL	2004	2009	No	Yes	Yes (Various)	20	20	7,539	0.27	WWF-IATTC
Costa Rica[3]	LL	2005	2012	No	Yes	Yes (No hooks)	5	5	2,602	0.19	WWF
-	**-**	**1995**	**2020**	**-**	**-**	**-**	**1145***	**1190**	**594563**	**0.19**	

TABLE 3. Baseline parameter values for EP leatherback vulnerability assessment in EASI-Fish. Length class susceptible to fishing mortality is in centimeters, curved carapace length. See Methods for more details about each parameter and estimated efficacy of each CMM.

Fishery	Duration of fishing season (Dx)	Seasonal availability (Axj)	Length class susceptible to fishing mortality (j)	Encounterability (Nxj)	Effective depth range	Contact selectivity (Cxj)	At-vessel mortality	Post-release mortality	Post-capture mortality (Pxj) (combination of at-vessel and post-release mortality)			References
									Preferred value	Low value	High value	
Industrial longlines	100%	100%	>90 cm	100%	0-200 m	100%	1%	30%	30%	10%	60%	Swimmer *et al.* (2017); Ryder *et al.* (2006); Swimmer and Gilman (2011); Gilman and Huang (2006); Watson *et al.* (2005); workgroup expert assessment
Purse seines	83%	100%	>90 cm	100%	0-200 m	100%	1%	5%	5%	1%	10%	IATTC unpublished data; workgroup expert assessment
Artisanal longlines	100%	100%	>90 cm	100%	0-200 m	100%	50%	10%	50%	20%	60%	Alfaro-Shigueto *et al.* (2011); Gilman *et al.* (2010); workgroup expert assessment
Artisanal drift gillnets	100%	100%	>90 cm	100%	0-200 m	100%	1%	25%	25%	10%	40%	Alfaro-Shigueto *et al.* (2011); Donoso and Dutton (2007); references for industrial longlines; workgroup expert assessment

TABLE 4. Biological parameters (and references) used in the EASI-Fish model for the EP leatherback stock.

	t_{max} (yrs)	L_{inf} (yr^{-1})	K (yr^{-1})	Length-weight *a*	Length-weight *b*	L_{50} (cm)	M (yr^{-1})
Parameter value(s)	48	147.6	0.286	0.0214	2.86	129.7	0.295–0.937
Data source	Jones *et al*. (2011)	Zug and Parham (1996)	Zug and Parham (1996)	Jones *et al*. (2011)	Jones *et al*. (2011)	Avens *et al*. (2020)	Santidrián Tomillo *et al*. (2017); Laúd OPO Network (2020)

Table 5. Estimated efficacy of CMMs included in EASI-Fish vulnerability assessment for EP leatherbacks. For estimated reductions in selectivity (*i.e.*, bycatch rates) and post-release mortality*, we included a preferred value and low and high efficacy values in the EASI-Fish scenarios to provide a range of potential results.

			Reduction in selectivity (bycatch rates)			Reduction in post-release mortality*			
Fishery	**Conservation management measures**	**Reduction in duration of fishing operations**	**Preferred value**	**Low value**	**High value**	**Preferred value**	**Low value**	**High value**	**References**
Industrial longlines	Large circle hooks		69%	20%	80%				Swimmer *et al.* (2017) US Pacific longline values, Parga (2012); Parga *et al.* (2015); Gilman and Huang (2016); Watson *et al.* (2005)
	Finfish bait		34%	10%	50%				(Watson *et al.* 2005); Swimmer *et al.* (2017), US Atlantic longline values; no change in post-release mortality assumed because no reduction in severity of injuries from hooking or from finfish bait
	Large circle hooks + finfish bait		71%	40%	80%				Swimmer *et al.* (2017), US Atlantic longline values.
	Best practices for safe handling and release					25%	10%	50%	Ryder *et al.* (2006); Swimmer and Gilman (2012); Workgroup expert assessment
	Spatio-temporal closures	60, 90 ,120, 150, 180 d							Expansion of existing IATTC CMMs
Industrial purse seines	Best practices for safe handling and release					90%	80%	95%	Workgroup expert assessment
	Spatio-temporal closures	60, 90 ,120, 150, 180 d							Expansion of existing IATTC CMMs
Artisanal longlines	Large circle hooks		59%	20%	80%				Parga (2012); Andraka *et al.* (2013); Parga *et al.* (2015); References for industrial longlines
	Finfish bait		34%	10%	50%				References for industrial longlines
	Large circle hooks + finfish bait		60%	30%	80%				References for industrial longlines
	Best practices for safe handling and release					75%	50%	95%	Workgroup expert assessment: Mariluz Parga, Sandra Andraka, Liliana Rendon, Jose Miguel Carvajal; Parga *et al.* (2015)
Artisanal drift gillnets	Net illumination		50%	30%	80%				Wang *et al.* (2010); Allman *et al.* (2020); Bielli *et al.* (2020); Senko *et al.* (2022)
	Best practices for safe handling and release					25%	10%	50%	Workgroup expert assessment

* no CMMs considered in this analysis would reduce the at-vessel component of post-capture mortality, so only reductions in post-release component are shown here

Table 6. Summary table of 71 hypothetical scenarios to evaluate the potential efficacy of implementing various CMMs on reducing EP leatherback vulnerability. EASI-Fish parameters marked with “X” or “XX” are those affected by one or two CMMs, respectively, in each scenario. See Methods for more details about each parameter and estimated efficacy of each CMM.

		Industrial longline				Purse seine				Small-scale longlines				Small-scale drift gillnets			
CMM SCENARIO	**Scenario number**	**Duration of fishing season (Dx)**	**contact selectivity (Cxj)**	**at-vessel mortality (AVM)**	**post-release mortality (PRM)**	**Duration of fishing season (Dx)**	**contact selectivity (Cxj)**	**at-vessel mortality (AVM)**	**post-release mortality (PRM)**	**Duration of fishing season (Dx)**	**contact selectivity (Cxj)**	**at-vessel mortality (AVM)**	**post-release mortality (PRM)**	**Duration of fishing season (Dx)**	**contact selectivity (Cxj)**	**at-vessel mortality (AVM)**	**post-release mortality (PRM)**
baseline EASI-Fish values	0																
STATUS QUO	1																
Circle hooks, industrial longlines	2-4		X														
Circle hooks, all longlines	5-7		X								X						
Finfish bait, industrial longlines	8-10		X														
Finfish bait, all longlines	11-13		X								X						
Best handling practices, industrial longlines	14-16				X												
Best handling practices, all longlines	17-19				X								X				
Best handling practices, all IATTC fisheries	20-22				X				X								
Best handling practices, all fisheries	23-25				X				X				X				X
Circle hooks + finfish bait, industrial longlines	26-28		XX														
Circle hooks + finfish bait, all longlines	29-31		XX								XX						
Circle hooks + best practices, industrial longlines	32-34		X		X												
Circle hooks + best practices, all longlines	35-37		X		X						X		X				
Circle hooks + finfish bait + best practices, industrial longlines	38-40		XX		X												
Circle hooks + finfish bait + best practices, all longlines	41-43		XX		X						XX		X				
Circle hooks + finfish bait + best practices, all fisheries	44-46		XX		X				X		XX		X				X
Finfish bait + best practices, industrial longlines	47-49		X		X												
Finfish bait + best practices, all longlines	50-52		X		X						X		X				
Illuminated gillnets	53-55														X		
Illuminated gillnets + best handling practices	56-58														X		X
Circle hooks + finfish bait + illuminated gillnets + best practices, all fisheries	59-61		XX		X				X		XX		X		X		X
Purse seine closures (62: 60d, 63: 90d, 64: 120d, 65: 150d, 66: 180d)	62-66					X											
Industrial fisheries closures (67: 60d, 68: 90d, 69: 120d, 70: 150d, 71: 180d)	67-71	X				X											

TABLE 7. Estimated mean (+/- standard deviation) values for proxy fishing mortality ($\tilde{F}_{2019}$), breeding stock biomass-per-recruit (BSR_{2019}) and biological reference points ($F_{80\%}$ and $BSR_{80\%}$) for the East Pacific leatherback turtle stock in 2019 under hypothetical conservation and management measures. Red and green colors indicate scenarios where the stock was classified as "most vulnerable" or "least vulnerable", respectively. Specific model parameter values used in each scenario are shown in Table 2.

Scenario description	Scenario	F_{2018}/ $F_{80\%}$	BSR_{2018}/ $BSR_{80\%}$
Absence of any conservation and management measures for all fisheries			
0 d EPO closure; all fisheries PRM 100%; L_c=90 cm	S0	16.43 (3.55)	0.05 (0.02)
Status quo (SQ) in 2019			
72 d PS EPO closure; Longline PRM 100%; L_c=90 cm	S1	1.37 (0.8)	0.95 (0.17)
Use of circle hooks (CH) only			
C = 0.3 in industrial LL only	S2	0.37 (0.19)	1.17 (0.05)
C = 0.2 in industrial LL only	S3	0.28 (0.15)	1.19 (0.04)
C = 0.8 in industrial LL only	S4	1 (0.55)	1.02 (0.13)
C = 0.3 in industrial LL; C = 0.4 in artisanal LL	S5	0.21 (0.1)	1.21 (0.03)
C = 0.2 in industrial LL; C = 0.2 in artisanal LL	S6	0.1 (0.05)	1.24 (0.01)
C = 0.8 in industrial LL; C = 0.8 in artisanal LL	S7	0.91 (0.52)	1.05 (0.12)
Use of finfish bait (FB) only			
C = 0.66 in industrial LL only	S8	0.78 (0.41)	1.08 (0.1)
C = 0.5 in industrial LL only	S9	0.58 (0.30)	1.12 (0.07)
C = 0.9 in industrial LL only	S10	1.17 (0.66)	0.99 (0.14)
C = 0.66 in industrial LL; C = 0.66 in artisanal LL	S11	0.65 (0.36)	1.11 (0.09)
C = 0.5 in industrial LL; C = 0.5 in artisanal LL	S12	0.41 (0.22)	1.16 (0.05)
C = 0.9 in industrial LL; C = 0.9 in artisanal LL	S13	1.14 (0.66)	1 (0.14)
Use of best handling and release practices (BP) only			
PRM = 0.225 in industrial LL only	S14	0.75 (0.39)	1.08 (0.09)
PRM = 0.15 in industrial LL only	S15	0.52 (0.23)	1.14 (0.06)
PRM = 0.27 in industrial LL only	S16	0.95 (0.5)	1.04 (0.11)
PRM = 0.225 in industrial LL; PRM = 0.063 in artisanal LL	S17	0.49 (0.28)	1.14 (0.07)
PRM = 0.15 in industrial LL; PRM = 0.013 in artisanal LL	S18	0.22 (0.13)	1.21 (0.03)
PRM = 0.27 in industrial LL; PRM = 0.125 in artisanal LL	S19	0.73 (0.42)	1.09 (0.1)
PRM = 0.225 in industrial LL; PRM = 0.005 in purse-seine	S20	0.68 (0.37)	1.1 (0.09)
PRM = 0.15 in industrial LL; PRM = 0.003 in purse-seine	S21	0.43 (0.23)	1.16 (0.06)
PRM = 0.27 in industrial LL; PRM = 0.01 in purse-seine	S22	0.88 (0.48)	1.05 (0.11)
PRM = 0.27/0.005/0.375/0.063 in ind. LL/PS/GN/art. LL	S23	0.42 (0.26)	1.16 (0.06)
PRM = 0.15/0.003/0.25/0.013 in ind. LL/PS/GN/art. LL	S24	0.16 (0.11)	1.22 (0.03)
PRM = 0.27/0.01/0.45/0.125 in ind. LL/PS/GN/art. LL	S25	0.68 (0.40)	1.1 (0.10)
Combination strategies - CH + FB			
C = 0.287 in industrial LL only	S26	0.35 (0.18)	1.18 (0.04)
C = 0.2 in industrial LL only	S27	0.28 (0.14)	1.19 (0.04)
C = 0.6 in industrial LL only	S28	0.7 (0.37)	1.09 (0.09)
C = 0.287 in industrial LL; C = 0.4 in artisanal LL	S29	0.2 (0.09)	1.21 (0.02)
C = 0.2 in industrial LL; C = 0.2 in artisanal LL	S30	0.1 (0.05)	1.24 (0.01)
C = 0.6 in industrial LL; C = 0.7 in artisanal LL	S31	0.59 (0.32)	1.12 (0.08)
Combination strategies - CH + BP			
C = 0.3, PRM = 0.225 in industrial LL only	S32	0.28 (0.14)	1.2 (0.04)
C = 0.2, PRM = 0.15 in industrial LL only	S33	0.2 (0.12)	1.21 (0.03)
C = 0.8, PRM = 0.27 in industrial LL only	S34	0.72 (0.36)	1.09 (0.09)
C = 0.308, PRM = 0.225 in ind. LL; C = 0.4, PRM = 0.063 in art.LL	S35	0.09 (0.04)	1.24 (0.01)
C = 0.2, PRM = 0.15 in ind. LL; C = 0.2, PRM = 0.013 in art.LL	S36	0.03 (0.01)	1.25 (0.01)
C = 0.8, PRM = 0.27 in ind. LL; C = 0.7, PRM = 0.125 in art.LL	S37	0.5 (0.28)	1.14 (0.07)

TABLE 7. continued

Scenario description	Scenario	F_{2018}/ $F_{80\%}$	BSR$_{2018}$/ BSR$_{80\%}$
Combination strategies - CH + FB + BP			
C = 0.287, PRM = 0.225 in industrial LL only	S38	0.27 (0.14)	1.2 (0.03)
C = 0.2, PRM = 0.15 in industrial LL only	S39	0.2 (0.11)	1.21 (0.03)
C = 0.6, PRM = 0.270 in industrial LL only	S40	0.53 (0.26)	1.13 (0.06)
C = 0.287, PRM = 0.225 in ind. LL; *C* = 0.4, PRM = 0.063 in artisanal LL	S41	0.08 (0.04)	1.24 (0.01)
C = 0.2, PRM = 0.15 in ind. LL; *C* = 0.2, PRM = 0.013 in artisanal LL	S42	0.03 (0.01)	1.25 (0.01)
C = 0.6, PRM = 0.27 in industrial LL; *C* = 0.7, PRM = 0.125 in artisanal LL	S43	0.32 (0.17)	1.18 (0.04)
C = 0.287/0.4 in ind. LL/art. LL; PRM = 0.225/0.005/0.375/0.063 in ind. LL/PS/GN/art. LL	S44	0.05 (0.03)	1.25 (0.01)
C = 0.2/0.2 in ind. LL/art. LL; PRM = 0.15/0.003/0.25/0.013 in ind. LL/PS/GN/art. LL	S45	0.01 (0.01)	1.25 (0.01)
C = 0.6/0.7 in ind. LL/art. LL; PRM = 0.27/0.01/0.45/0.125 in ind. LL/PS/GN/art. LL	S46	0.27 (0.15)	1.2 (0.04)
Combination strategies - FB + BP			
C = 0.66, PRM = 0.225 in industrial LL only	S47	0.49 (0.24)	1.14 (0.06)
C = 0.5, PRM = 0.15 in industrial LL only	S48	0.29 (0.15)	1.19 (0.04)
C = 0.9, PRM = 0.27 in industrial LL only	S49	0.83 (0.42)	1.06 (0.10)
C = 0.66, PRM = 0.225 in ind. LL; *C* = 0.66, PRM = 0.063 in art. LL	S50	0.24 (0.13)	1.2 (0.03)
C = 0.5, PRM = 0.15 in ind. LL; *C* = 0.5, PRM = 0.013 in art. LL	S51	0.08 (0.04)	1.24 (0.01)
C = 0.9, PRM = 0.27 in ind. LL; *C* = 0.9, PRM = 0.125 in art. LL	S52	0.61 (0.34)	1.11 (0.08)
Use of illuminated gillnets only and in combination with strategies CH + FB + BP			
C = 0.5 in gillnets only	S53	1.05 (0.58)	1.01 (0.13)
C = 0.2 in gillnets only	S54	1.03 (0.57)	1.02 (0.13)
C = 0.7 in gillnets only	S55	1.06 (0.58)	1.01 (0.13)
C = 0.5, PRM = 0.375 in gillnets only	S56	1.05 (0.57)	1.01 (0.13)
C = 0.2, PRM = 0.25 in gillnets only	S57	1.02 (0.56)	1.02 (0.13)
C = 0.7, PRM = 0.45 in gillnets only	S58	1.07 (0.58)	1.01 (0.13)
C = 0.287/0.5/0.4 in ind. LL/GN/art. LL; PRM = 0.225/0.005/0.375/0.063 in ind. LL/PS/GN/art. LL	S59	0.04 (0.02)	1.25 (0.01)
C = 0.2/0.2/0.2 in ind. LL/GN/art. LL; PRM = 0.15/0.003/0.25/0.013 in ind. LL/PS/GN/art. LL	S60	0.01 (0.01)	1.25 (0.01)
C = 0.6/0.7/0.7 in ind. LL/GN/art. LL; PRM = 0.27/0.01/0.45/0.125 in ind. LL/PS/GN/art. LL	S61	0.26 (0.15)	1.2 (0.04)
Implementation of EPO-wide closure of industrial fisheries			
62 d EPO closure for purse-seine fleet only	S62	1.36 (0.80)	0.95 (0.17)
90 d EPO closure for purse-seine fleet only	S63	1.36 (0.79)	0.95 (0.16)
120 d EPO closure for purse-seine fleet only	S64	1.36 (0.80)	0.95 (0.17)
150 d EPO closure for purse-seine fleet only	S65	1.36 (0.80)	0.95 (0.17)
180 d EPO closure for purse-seine fleet only	S66	1.32 (0.78)	0.96 (0.16)
62 d EPO closure for all purse-seine and industrial LL fleets	S67	1.06 (0.60)	1.01 (0.13)
90 d EPO closure for all purse-seine and industrial LL fleets	S68	0.92 (0.50)	1.04 (0.12)
120 d EPO closure for all purse-seine and industrial LL fleets	S69	0.79 (0.42)	1.07 (0.10)
150 d EPO closure for all purse-seine and industrial LL fleets	S70	0.67 (0.36)	1.1 (0.09)
180 d EPO closure for all purse-seine and industrial LL fleets	S71	0.56 (0.29)	1.13 (0.07)

d = days; EPO = eastern Pacific Ocean; PCM = post-capture mortality; PRM = post-release mortality, L_c = curved carapace length at first capture; *C* = contact selectivity; ind. LL = industrial longline; art. LL = artisanal longline; PS = purse-seine; GN = gillnet