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Vulnerability of the Critically Endangered leatherback turtle to fisheries bycatch in the eastern Pacific Ocean. II. Assessment of mitigation measures

Shane P. Griffiths[1,*,#], Bryan P. Wallace[2,3,4,#], Verónica Cáceres[2], Luz Helena Rodríguez[2], Jon Lopez[1], Marino Abrego[5], Joanna Alfaro-Shigueto[6,7,8], Sandra Andraka[9], María José Brito[10], Leslie Camila Bustos[11], Ilia Cari[12], José Miguel Carvajal[13], Ljubitza Clavijo[12], Luis Cocas[11], Nelly de Paz[14], Marco Herrera[10], Ann Marie Lauritsen[15], Jeffrey C. Mangel[7,8], Miguel Pérez-Huaripata[16], Rotney Piedra[17], Javier Antonio Quiñones Dávila[16], Liliana Rendón[9], Juan M. Rguez-Baron[18,19], Heriberto Santana[20], Brian Stacy[21], Jenifer Suárez[22], Yonat Swimmer[23], Callie Veelenturf[24], Rodrigo Vega[12], Patricia Zárate[12]

[1]Inter-American Tropical Tuna Commission, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA

Full author addresses are given in the Appendix

ABSTRACT: Industrial tuna and artisanal fisheries targeting multiple species in the eastern Pacific Ocean (EPO) interact with the Critically Endangered East Pacific (EP) leatherback turtle *Dermochelys coriacea*. In 2021, a revised Inter-American Tropical Tuna Commission (IATTC) resolution on sea turtles aimed to reduce sea turtle bycatch in EPO industrial tuna fisheries and ensure their safe handling and release. A new ecological risk assessment approach — Ecological Assessment for the Sustainable Impacts of Fisheries (EASI-Fish) — was used to assess vulnerability status and to better understand the potential efficacy of 70 scenarios that compared simulated conservation and management measures (CMMs) for EPO industrial (purse-seine and longline) and artisanal (longline and gillnet) fisheries to the status quo in 2019. In 2019, a fishing mortality proxy ($\tilde{F}_{2019}$) and the breeding stock biomass per recruit (BSR_{2019}) exceeded precautionary biological reference points ($F_{80\%}$ and $BSR_{80\%}$), classifying the stock as 'most vulnerable'. Industrial and artisanal longline fisheries had the highest impacts because they had the highest areal overlap with the modelled EP leatherback distribution. Of the 70 CMM scenarios, 42 resulted in significant improvements in vulnerability status (i.e. to 'least vulnerable'). The use of large circle hooks, finfish bait, and best handling and release practices each decreased vulnerability; however, the most effective scenarios involved using these 3 measures in concert. The benefits predicted from EASI-Fish for CMM scenarios assume full compliance and attaining the modelled levels of efficacy, our modelling provides stakeholders with evidence-based recommendations to address key threats to EP leatherback turtles to improve their conservation status by reducing fishing impacts.

KEY WORDS: Ecological risk assessment · Longline · Artisanal fisheries · Tuna · Sea turtle · *Dermochelys coriacea* · Fisheries bycatch

1. 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. This has been a particularly im-

*Corresponding author: sgriffiths@iattc.org
#Joint lead authors

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portant evolution in the management of industrial tuna fisheries that target high trophic level predators but also inadvertently interact with a range of non-target species (i.e. 'bycatch') representing various species groups such as teleosts, elasmobranchs, marine mammals, seabirds, and sea turtles. Together, impacts by these fisheries can have negative impacts on not only individual species but also on the structure and dynamics of the broader ecosystem (Ward & Myers 2005, Polovina et al. 2009, Griffiths et al. 2019a). The Inter-American Tropical Tuna Commission (IATTC) is one of the world's 5 tuna Regional Tuna Fisheries Management Organisations (tRFMO) and is mandated under its Antigua Convention (IATTC 2003) to be responsible for the management of tuna and tuna-like species in the eastern Pacific Ocean (EPO), defined as the region from the coast of the Americas to 150° W between 50° S and 50° N. The Antigua Convention has also formalised an ecosystem-based approach to the management of EPO tuna fisheries. For example, Article VII 1(f) of the Convention (p. 4) 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 infeasible. To address this problem, ecological risk assessment (ERA) has been a popular alternative to prioritise the relative vulnerability of data-poor bycatch species (Stobutzki et al. 2001, Hobday et al. 2006, Zhou & Griffiths 2008). A major limitation with these methods is that they generally do not provide reliable and biologically meaningful measures of vulnerability and instead provide a measure of vulnerability that is relative to other species being assessed. Consequently, they are generally incapable of assessing the cumulative impacts of multiple fisheries. These shortcomings provided the impetus for Griffiths et al. (2019b) to develop a flexible spatially explicit quantitative ERA approach — Ecological Assessment of Sustainable Impacts of Fisheries (EASI-Fish) — to quantify the cumulative impacts of multiple fisheries for data-limited bycatch species. The approach has recently been applied in the EPO to prioritise the vulnerability of various bycatch species groups caught in industrial tuna fisheries (Griffiths et al. 2019b), and shark species caught in industrial and artisanal fisheries (Griffiths et al. 2022), and to explore the efficacy of potential conservation and management measures (CMMs) for the spinetail devil ray *Mobula mobular* (Griffiths & Lezama-Ochoa 2021).

Industrial tuna fisheries in the EPO 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, including sea turtles, are unavoidable and unintentional bycatch that present significant conservation issues. Despite the low frequency of turtle interactions in EPO fisheries (Hall & 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 turtle populations particularly sensitive to unsustainably high anthropogenic sources of mortality. This makes sea turtle bycatch a significant conservation issue for EPO tuna fisheries, which performed at least 33 125 purse-seine sets and deployed 147 million longline hooks in 2019 (IATTC 2020). Sea turtle species face a range of anthropogenic threats throughout their worldwide distribution (Wallace et al. 2011) such as vessel strikes (Schoeman et al. 2020), mining impacts, and pollution (Lutcavage et al. 1997), but the most significant threat is bycatch in industrial and artisanal fisheries (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.

Conservation measures have been developed by some tRFMOs, specifically to reduce the bycatch of sea turtles in longline and purse-seine fisheries. In the EPO, for example, IATTC Resolution C-19-04, which entered 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 Organisation of the United Nations (FAO 2009). In addition to requiring use of best handling and release practices, the resolution 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. 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 North, Central, and South America 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 was updated in 2022 to Resolution CIT-COP10-2020-R6. It requests IAC Parties to make efforts to reduce the bycatch of leatherbacks in the EPO using recommendations from IAC Resolution CIT-COP10-2022-R7 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. A collaborative project was established to better understand the extent to which these measures previously implemented by the IATTC and other potential measures might decrease the vulnerability of sea turtles to fishing and facilitate effective implementation of IATTC Resolution C-19-04 and IAC Resolution CIT-COP10-2020-R6. This study describes results of this collaborative effort by the IAC and IATTC ad hoc working group.

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 yr (Jones et al. 2011), exhibits low fecundity (~65 eggs per clutch, ~5 clutches per season, nests every 3–4 yr, average hatching success <50%; Laúd OPO Network 2020), and female age of maturity is approximately 12–20 yr (Avens et al. 2009, 2020). For the East Pacific (EP) leatherback turtle population, in particular, a combination of this low productivity and high susceptibility to anthropogenic threats — principally fisheries bycatch and human consumption of eggs — has 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 (Laúd OPO Network 2020). A recent population viability analysis of the EP stock predicted that the population, currently estimated to be fewer than 1000 adult females, may be extirpated in the region within 60 yr under current conservation and environmental conditions (Laúd OPO Network 2020). In contrast, the analysis predicted that the population could eventually stabilise 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.

Based on recent reports, EP leatherback turtle bycatch in industrial purse-seine and longline fisheries in the EPO is relatively infrequent (Hall & Roman 2013, Griffiths & Duffy 2017, Lezama-Ochoa et al. 2017, Lezama-Ochoa et al. 2019), which is likely due to some combination of depleted population abundance, improved implementation of conservation measures (e.g. IATTC resolutions 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 in most fleets (e.g. ~5% or less in the high seas and EPO coastal nation longline fleets). Because reported leatherback encounter rates at the regional scale 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 study was to identify potentially effective conservation and management measures (CMMs) that may — individually or in unison — be implemented in the major pelagic fisheries in the EPO to improve the conservation status of the EP leatherback turtle population. To accomplish this goal, we sought to evaluate the potential efficacy of various CMMs — mainly those required by IATTC Resolution C-19-04 — in reducing impacts of fisheries on the EP leatherback population. Specifically, we developed hypothetical scenarios that incorporated different CMMs to understand the potential improvements in vulnerability status of the EP leatherback turtle stock due to (1) implementing the use of large circle hooks and/or finfish bait to reduce the interaction rate and fishing mortality due to hooking injuries, (2) decreasing post-release mortality (PRM) on specific size classes of turtles through improved handling and release practices, (3) increasing the duration of the existing EPO-wide fishing closure for the industrial purse-seine fishery, (4) using illumination to reduce interactions with artisanal gillnets, and (5) using combinations of the aforementioned CMMs simultaneously. This study is a first important step to quantify the current impacts of EPO fisheries bycatch on leatherbacks and the potential efficacy of conservation measures intended to decrease fisheries-related mortality.

2. MATERIALS AND METHODS

2.1. Data compilation

EASI-Fish requires 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.

We compiled fishing effort information from 18 different fisheries (7 industrial fisheries and 11 national or artisanal fisheries) that target tunas as well as other species (Table S1; www.int-res.com/articles/suppl/n053p295_supp.pdf). Using this effort information, we developed novel, region-wide maps of leatherback occurrence over a nearly 20 yr 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 and in the electronic supplement.

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

General overview. 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 characterises 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, Tapilatu et al. 2013) and electronic tags (Benson et al. 2011, Shillinger et al. 2011, Schick et al. 2013), 2 distinct stocks of leatherback turtles occur in the EPO (Laúd OPO Network 2020). Such evidence was used by Wallace et al. (2023) in the development of 2 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 & Dutton 2010, Shillinger et al. 2011, Bailey et al. 2012) and in continental shelf and shelf break 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 (unpubl. IATTC observer data), 105 (94%) occurred within the EP stock boundary defined by Wallace et al. (2023). 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 S1.

Industrial fisheries. The industrial fisheries included large-scale tuna longline fishing vessels (LSTLFVs) (herein called the 'industrial longline fishery') and 2 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, collected by on-board scientific observers or submitted to the IATTC by its Members under IATTC resolutions C-03-05 and C-19-08. Specifically, the industrial longline fishery data were derived from vessels >24 m length overall (LOA) included in the IATTC Regional Vessel Register that are authorised to fish for tuna and tuna-like species, which provide monthly reports of catch and fishing effort at a resolution of at least 5° × 5°, and from national scientific observer programs that monitor at least 5% of the fishing effort by LSTLFVs over 20 m LOA. Although this fishery has 2 distinct set types — shallow sets (generally characterised as <100 m) targeting swordfish and deep sets (>100 m) targeting bigeye tuna — the current data provision requirements under IATTC Resolution C-03-05 does not require the submission of operational-level data that would allow for these 2 set types to be separated into distinct fisheries.

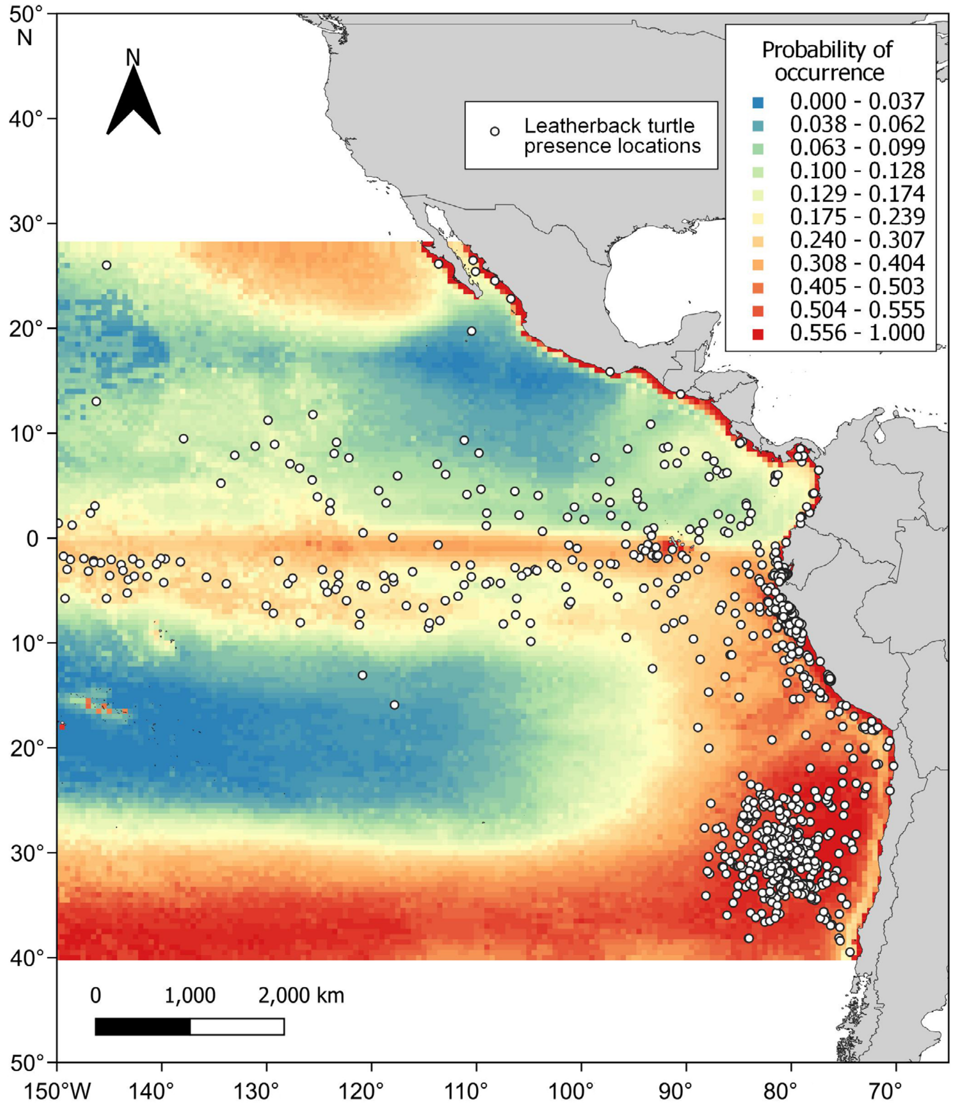

Fig. 1. Map showing the presence data (white circles) used to generate the predicted distribution of the East Pacific stock of leatherback turtles *Dermochelys coriacea* (shown using a probability-of-occupancy, ψ, threshold values of 0.2). To account for uncertainty in the model's predicted distribution of the species, the Ecological Assessment for the Sustainable Impacts of Fisheries model was run using ψ values of 0.1, 0.2, and 0.3

Consequently, all longline sets were assumed to fish the full depth range of shallow and deep sets combined, that is, 0–300 m.

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 3 fisheries based on set type: (1) sets associated with floating objects (OBJ), (2) sets associated with dolphins (DEL), and (3) 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 a voluntary basis aboard Ecuadorian vessels since 2018, with coverage being 12% of the total number of trips reported for this fleet component in 2019 (IATTC unpubl. 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 ummarizing 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° × 0.5° grid cell to define each fishery.

It should be noted that entanglement in netting materials used on fish aggregating devices (FADs) deployed by the Class 6 and Class 1–5 purse-seine fleets can be an additional mortality source of mortality in sea turtles (see Blasi et al. 2016) but was not explicitly considered in the modelling process due to a lack of information. However, the IATTC and other tRFMOs (see Escalle et al. 2023) have been trialing non-entangling and biodegradable FADs in an attempt to reduce the risk of entanglement of sea turtles and other marine fauna.

Artisanal fisheries. In contrast to the industrial purse seine and longline fisheries in the EPO, the numerous artisanal fleets (here defined as vessels <24 m LOA; larger vessels are subject to IATTC resolutions) that operate mainly within the exclusive economic zones (EEZs) of countries in the EPO generally have very low (if any) observer coverage and are poorly documented in general (Griffiths et al. 2019b). However, adult and juvenile leatherback turtles — as well as most other species of sea turtles — have been shown to be impacted by coastal, artisanal gillnet and longline fisheries, particularly in foraging areas, but also in migratory and reproduction areas (Donoso & Dutton 2010, Alfaro-Shigueto et al. 2011, 2018, Ortiz-Álvarez et al. 2020). Therefore, it was especially important to collate and include in this assessment available fishing effort data sources for artisanal fisheries.

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). However, significant spatial gaps throughout the EPO in catch and/or effort data exist, including unregulated, unreported artisanal fisheries (e.g. Doherty et al. 2014). Filling these gaps and creating more comprehensive fishing effort maps was a key aim of this project. 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 for several artisanal fisheries operating in territorial waters of 5 countries in the EPO (Table S1). These maps were digitised and georeferenced and fishing effort allocated to grid cells of appropriate resolution — usually 0.5° × 0.5° — in QGIS software (QGIS 2022). We augmented these maps 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 2 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 (~111 km) of latitude and/or longitude to reach their preferred fishing grounds, and 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, elasmobranchs, and dorado on a seasonal basis (Martínez-Ortiz et al. 2015, Siu & Aires-da-Silva 2016). Further, fishing fleets from South American countries have different characteristics from those of Mesoamerican countries, such as materials used in fishing gears, gear configurations, and socio-political traits of fishing communities; details that have 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; for example, longline vessels offloading in Costa Rica are routinely inspected (Siu & 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 at least one set in any 0.5° grid cell — 5° × 5° for the industrial longline fishery — was considered presence of effort.

Other anthropogenic threats to leatherbacks. Human consumption of leatherback turtle eggs on nesting beaches in the EPO has been a major source of mortality for the EP leatherback turtle stock (Santidrián Tomillo et al. 2008). Therefore, this was included in the EASI-Fish model as the egg collection 'fishery', i.e. another anthropogenic impact on EP leatherbacks. Specifically, nesting locations provided by La Red Para 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 (http://seamap.env.duke.edu/swot) and reported in IAC Annual Reports (www.iacseaturtle.org/informes-eng.htm) were allocated to the nearest 0.5° × 0.5° grid cell to define the spatial extent of the egg collection 'fishery,' and mortality estimates were applied to these cells based on a recent population assessment (Laúd OPO Network 2020).

It is important to note that there are several other fishery and anthropogenic activities in the EPO that may pose a threat to the sustainability of the EPO leatherback turtle stock. For example, there are several small-scale fisheries that operate within the jurisdictions of coastal states, such as purse-seine, shrimp trawl, hook and line, harpoon and aquaculture, and a small number of industrial fisheries that operate in areas beyond national jurisdictions that mainly target deep water fishes associated with seamounts, ridges and plateaus in the southern Pacific Ocean using demersal and midwater trawling and squids using jigging. These fisheries were considered to either pose a negligible threat to leatherback turtles (e.g. deep water trawling) and/or no effort data were available to include them. There are also several potential non-fishery anthropogenic mortality sources that may impact leatherback turtles (Wallace et al. 2011), such as strikes from freight, commercial, artisanal and recreational vessels (Schoeman et al. 2020), mining impacts, and pollution such as chemical spills and plastics that cause mortality by ingestion or entanglement (Lutcavage et al. 1997). Quantitative data on the number and spatial distribution of these impacts on EP leatherback turtles were not available for all potential mortality sources, and since the focus of the work was to explore the relative efficacy of CMMs under IATTC Resolution C-19-04, they were not included in the model.

2.1.2. EP leatherback species distribution model

To estimate the degree to which fisheries interact with the leatherback stock, it is necessary to use a reliable species distribution model (SDM) on which the effort by each fishery can be overlaid. A concurrent project by Lopez et al. (2024) used a machine learning algorithm with boosted regression trees (BRT) to develop a SDM using 1088 leatherback turtle observed presences from bycatch interactions and sightings from fishery operations made between 1995 and 2020 from 18 different fisheries operating in the EEZ of at least 8 countries, as well as areas beyond national jurisdiction. In addition to these presences, nearly 500 000 fishing sets where leatherback turtles were not recorded served as 'absence' data. A detailed description of the SDM development is provided in Lopez et al. (2024). We used the SDM outputs to develop a map of occurrence predictions for the species (Fig. 1) for determining the volumetric overlap with each fishery within the EASI-Fish modeling framework.

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

2.2.1. Susceptibility parameters

Vulnerability status was estimated for each scenario based on data from 2019, using the EASI-Fish approach. A comprehensive description of EASI-Fish and its parameterisation for the EP leatherback stock is provided in the Supplement and by Griffiths et al.

(2019b). In brief, EASI-Fish is similar to other ecological risk assessment approaches in that it is comprised of separate susceptibility (Table 1) and productivity (Table 2) components. The susceptibility component in EASI-Fish is used to estimate a proxy for the instantaneous fishing mortality rate ($\tilde{F}$) by quantifying 6 ecological and fishery attributes that influence the susceptibility of the species to interacting with each fishery specified in the model, including:

(1) geographic distribution (*G*) of leatherback turtles, which is defined using the species distribution model of Lopez et al. (2024) to predict the presence or absence of animals in each grid cell (0.5° × 0.5°) in the EPO;

(2) 'fishery duration' (*D*), which describes the proportion of the year that a fishery operates in the EPO;

(3) 'availability' of the stock to EPO fisheries expressed as the proportion of a year the species is present in EPO;

(4) 'encounterability' (*N*), which characterises the proportion of the vertical distribution of the species that overlaps with the depth range of the fishing gear when the species is available in the EPO;

(5) 'contact selectivity' (*C*), which is the probability that an animal within a specific size class that encounters the gear will be retained; and

(6) 'post-capture mortality' (PCM) (*P*), which describes the proportion of animals retained by the gear that incur fishery-induced mortality soon after release by a fishery.

The estimate of $\tilde{F}$ derived from the susceptibility component that is then compared to biological reference points (BRPs) used in the productivity component, specifically length-structured yield and breeding biomass per-recruit models (see Text S1 for details).

2.2.2. 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

Table 1. Baseline parameter values for East Pacific leatherback vulnerability assessment in Ecological Assessment for the Sustainable Impacts of Fisheries. Length class susceptible to fishing mortality is in cm, curved carapace length. See Section 2 'Methods and materials' for more details about each parameter and estimated efficacy of each conservation and management measure. D_x: duration of fishing season; A_{xj}: seasonal availability; *j*: length class susceptible to fishing mortality; N_{xj}: encounterability; C_{xj}: contact selectivity; P_{xj}: post-capture mortality (combination of at-vessel and post-release mortality)

Fishery	D_x	A_{xj}	*j* (cm)	N_{xj}	Effective depth range	C_{xj}	At-vessel mortality	Post-release mortality	P_{xj} Preferred value	Low value	High value	References
Industrial longlines	1.0	1.0	>90	1.0	0–200 m	1.0	0.01	0.30	0.30	0.10	0.60	Swimmer et al. (2017), Ryder et al. (2006), Swimmer & Gilman (2012), Gilman & Huang (2017), Watson (2005), Workgroup expert assessment
Purse seines	0.83	1.0	>90	1.0	0–200 m	1.0	0.01	0.05	0.05	0.01	0.10	IATTC unpubl. data, Hall & Roman (2013), Workgroup expert assessment
Artisanal drift gillnets	1.0	1.0	>90	1.0	0–200 m	1.0	0.50	0.10	0.50	0.20	0.60	Alfaro-Shigueto et al. (2011), Gilman et al. (2010), Workgroup expert assessment
Artisanal longlines	1.0	1.0	>90	1.0	0–200 m	1.0	0.01	0.25	0.25	0.10	0.40	Alfaro-Shigueto et al. (2011), Donoso & Dutton (2010), References for industrial longlines, Workgroup expert assessment

Table 2. Biological parameters (and references) used in the Ecological Assessment for the Sustainable Impacts of Fisheries model for the East Pacific leatherback stock. t_{max}: maximum recorded age; L_∞: mean asymptotic length of an animal in the von Bertalanffy growth function; K: intrinsic growth rate; length−weight relationship parameters a and b of the exponential function; L_{50}: mean length at which 50% of the population is mature; M: instantaneous natural mortality rate

	t_{max} (yr)	L_∞ (cm)	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 & Parham (1996)	Zug & Parham (1996)	Jones et al. (2011)	Jones et al. (2011)	Avens et al. (2020)	Santidrián Tomillo et al. (2017), Laúd OPO Network (2020)

PCM estimates for sea turtles in longlines ranged between 0 to ~0.9, with most values centering around 0.3 (Swimmer & 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).

2.2.3. 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 & Dutton 2010). Further, Alfaro-Shigueto et al. (2011) reported zero at-vessel mortality of leatherback turtles in the Peruvian artisanal longline fishery. However, because the extent to which safe handling and release practices are implemented in artisanal fisheries is unquantified but likely limited, 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 vs. 6 km) and deployment of more hooks per set (average ~2500 vs. <1000) (Alfaro-Shigueto et al. 2010, IATTC unpubl. observer data for the industrial longline fleet in 2017). 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).

2.2.4. Artisanal drift gillnet fisheries

Artisanal drift gillnets in the EPO region, particularly Ecuador, Peru, and Chile, are characterised by long soak times approximately equivalent to the artisanal longline fishery, and mesh sizes used are typically for targeting large pelagic teleosts 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).

2.2.5. 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 unpubl. 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

Table 3. Estimated efficacy of conservation and management measures (CMMs) included in the Ecological Assessment for the Sustainable Impacts of Fisheries (EASI-Fish) vulnerability assessment for East Pacific 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. IATTC: Inter-American Tropical Tuna Commission

Fishery	CMM	Reduction in duration of fishing operations (d)	Reduction in selectivity (bycatch rates)			Reduction in post-release mortality[a]			References
			Preferred value	Low value	High value	Preferred value	Low value	High value	
Industrial longlines	Large circle hooks		0.69	0.20	0.80				Swimmer et al. (2017) US Pacific longline values Parga (2012), Parga et al. (2015), Gilman & Huang (2017), Watson et al. (2005)
	Finfish bait		0.34	0.10	0.50				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		0.71	0.40	0.80				Swimmer et al. (2017), US Atlantic longline values
	Best practices for safe handling and release					0.25	0.10	0.50	Ryder et al. (2006), Swimmer & Gilman (2012), Workgroup expert assessment
	Spatio–temporal closures	60, 90, 120, 150, 180							Expansion of existing IATTC CMMs
Industrial purse seines	Best practices for safe handling and release					0.90	0.80	0.95	Workgroup expert assessment
	Spatio–temporal closures	60, 90, 120, 150, 180							Expansion of existing IATTC CMMs
Artisanal longlines	Large circle hooks		0.59	0.20	0.80				Parga (2012), Andraka et al. (2013), Parga et al. (2015), References for industrial longlines
	Finfish bait		0.34	0.10	0.50				References for industrial longlines
	Large circle hooks + finfish bait		0.60	0.30	0.80				References for industrial longlines
	Best practices for safe handling and release					0.75	0.50	0.95	Workgroup expert assessment (M. Parga, S. Andraka, L. Rendon, J. M. Carvajal), Parga et al. (2015)
Artisanal drift gillnets	Net illumination		0.50	0.30	0.80				Wang et al. (2010), Allman et al. (2021), Bielli et al. (2020), Senko et al. (2022)
	Best practices for safe handling and release					0.25	0.10	0.50	Workgroup expert assessment

[a]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

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.

Across all fisheries included in the model the PCM values used assume that current implementation of CMMs (e.g. large circle hooks in longlines, safe handling and release practices) is negligible. In contrast, scenarios that include such measures assume full implementation throughout each relevant fishery. We recognise 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.

2.3. Biological reference points (BRP)

Depending on the life history of a species, various BRPs have been used in fisheries 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 emphasise 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. Yield per recruit (YPR) models assume that recruitment is constant and independent of stock size — equivalent to a steepness (h) value of 1 (Gabriel & Mace 1999). Therefore, use of an F value at which yield is maximised (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. 2019b), which had been generally regarded as precautionary for most marine finfish stocks (see Ralston 2002). However, recent work by Cortés & Brooks (2018) suggests that for slow-growing and long-lived species 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 $\tilde{F}_{2019}$ value divided by the BSR where $F = 0$. The corresponding $BSR_{80\%}$ 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 $BSR_{80\%}$ values and displayed on a 4-quadrant 'vulnerability phase plot' (Fig. 2). 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'.

Given the uncertainty in model parameter values owing to the lack of reliable biological catch/interaction and fishing effort data and that per-recruit models do not have a stock–recruitment relationship, EASI-Fish cannot provide a reliable estimate of stock status, as would be derived from data-rich conven-

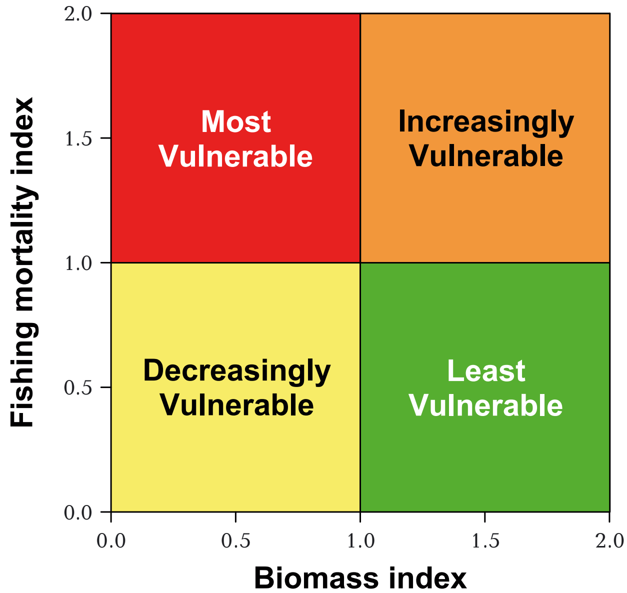

Fig. 2. Phase plot illustrating how vulnerability status was defined for the East Pacific leatherback turtle stock assessed using $F_{80\%}$ (fishing mortality value corresponding to 80% of the breeding potential ratio) and $BSR_{80\%}$ (breeding stock biomass per recruit value at $F_{80\%}$) from the Ecological Assessment for the Sustainable Impacts of Fisheries model as a reference point on the x and y axis, respectively. Vulnerability was defined by its position within 1 of 4 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. $\tilde{F}_{2019}$: $\tilde{F}$ in 2019

tional stock assessments; hence, this is why we provide a measure of vulnerability relative to the BRPs. As a result, the IATTC has not yet developed a resolution for a set of BRPs from EASI-Fish for particular bycatch species groups (e.g. teleosts, elasmobranchs, sea turtles) that may elicit specific management responses. However, in the context of this work, we consider $F_{80\%}$ and $BSR_{80\%}$ to represent trigger reference points that can guide fishery managers to consider CMMs that are predicted to reduce vulnerability, until such times as more data become available to undertake assessments to determine stock status.

2.4. Implementation of the model

The EASI-Fish 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, SD, SE, and 95% confidence intervals (95% CI) were derived for the BRPs $\tilde{F}_{2019}$, $F_{80\%}$, BSR_{2019}, and $BSR_{80\%}$.

2.5. Hypothetical conservation and management scenarios

2.5.1. Definitions of hypothetical conservation and management measures

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, other existing IATTC CMMs (e.g. 72 d EPO-wide closure) as well as the inclusion of a recent mitigation approach for gillnets, we compared the status quo scenario with 70 hypothetical CMMs (Table S2):

(1) use of large circle hooks in industrial and/or artisanal longline fisheries;

(2) use of finfish bait in industrial and/or artisanal longline fisheries;

(3) improved handling and release practices in each fishery;

(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 IATTC Resolution C-19-04. However, we included artisanal fisheries in addition to IATTC industrial fisheries 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.

2.5.2. Estimated efficacy of conservation and management measures

General overview. For each category of CMMs, specific scenario values were compared to the 'status quo' fishery situation for 2019 (Scen1), which was an EPO-wide closure of 72 d, a 30 d 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 longlines, purse-seines, artisanal gillnets, artisanal longline, and egg collection, respectively. The Scen1 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, though their effects on leatherback vulnerability were not explicitly calculable. 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 71 scenarios (i.e. the status quo and 70 alternative CMM 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 or alternative parameter values produced from alternative approaches, such as meta-analyses. For all scenarios in which CMMs were expected to reduce selectivity or PCM, we applied 3 values of estimated reduction that corresponded to low, intermediate, and high efficacy. In this way, we were able to analyse the variation in potential effect size for each CMM as well as the uncertainty around the efficacy estimates in status quo and CMM scenarios. Susceptibility values used in each scenario are given in Table S3. 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.

Status quo scenario. We attempted to estimate status quo values for both components of PCM for all fisheries (Table 1) 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 'menu of options' in IATTC Resolution C-19-04 included the use of large circle hooks and/or finfish bait in shallow longline sets — where the deepest hook is generally less than depths of 100 m — to allow flexibility in applying CMMs to reduce impacts on sea turtles. Large 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 & Gilman 2012, Andraka et al. 2013, Parga et al. 2015), which should improve post-release survivorship of 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 large circle hooks, finfish bait, or both together by between ~30 and ~70% (range 10 to 80%, depending on the combination) (Table 3). Although IATTC Resolution C-19-04 only requires these measures to be applied to shallow longline sets, the IATTC does not receive operational data from the longline fishery to enable the separation of shallow versus deep sets. Therefore, in exercising the precautionary approach required under the IATTC's Antigua Convention, we applied this measure to all longline sets. We also note that the IATTC has yet to explicitly define the specifications for 'large' circle hooks to be used in compliance with the resolution; future evaluations of circle hook efficacy could be adjusted when required circle hook size is established by IATTC.

Illuminated gillnets. Drift gillnets in nearshore, national waters in the EPO are considered a primary source of leatherback mortality (Alfaro-Shigueto et al. 2011, 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). Further, in the eastern Atlantic Ocean, researchers documented reductions in leatherback bycatch between 50 and 80% in small-scale gillnets in Ghana across years (Allman et al. 2021). Although gillnet illumination was not a specific mitigation measure in IATTC Resolution C-19-04, we felt that it was important to compare the potential efficacy of this mitigation measures alongside the other CMMs in the Resolution that focus primarily on industrial fisheries. Given results of the aforementioned research, we introduced scenarios that applied net illumination with an estimated efficacy of leatherback bycatch reduction between 30 and 80% (Table 3).

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 (IATTC Resolution C-07-03) and current (IATTC Resolution C-19-04) and (IAC Resolution CIT-COP10-2020-R7) 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 incurring significant changes to normal fishing gear configuration and operations. 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 & 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 & Gilman 2012).

Considering the available information, we 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 3). We relied on available estimates of post-release mortality in industrial longlines when best practices are implemented (e.g. Swimmer & 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 from gillnets. 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 (Hall & Roman 2013), we estimated 90% efficacy (range 80–95%) for best practices implemented in those operations. It should be noted that entanglement in netting materials used on FADs deployed by the purse-seine fishery can be an additional mortality source of mortality in sea turtles (see Blasi et al. 2016) but was not explicitly considered in the modelling process due to a lack of information. However, the IATTC and other tRFMOs (see Escalle et al. 2023) have been trialing non-entangling and biodegradable FADs in an attempt to reduce the risk of entanglement of sea turtles and other marine fauna.

3. RESULTS

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

The extent of areal overlap of fisheries with the EPO leatherback species distribution (Fig. 3) had a significant influence on potential effects on leatherback vulnerability (Fig. 4). Based on the preferred SDM for leatherback turtles (ψ = 0.2) in the status quo scenario (Scen1), 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. 3). 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. 3).

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. 3). 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 mo closure in Mexican waters. Each purse-seine fishery fished for 81% of the year due to the 72 d EPO-wide closure and the 30 d closure of the 'corralito'.

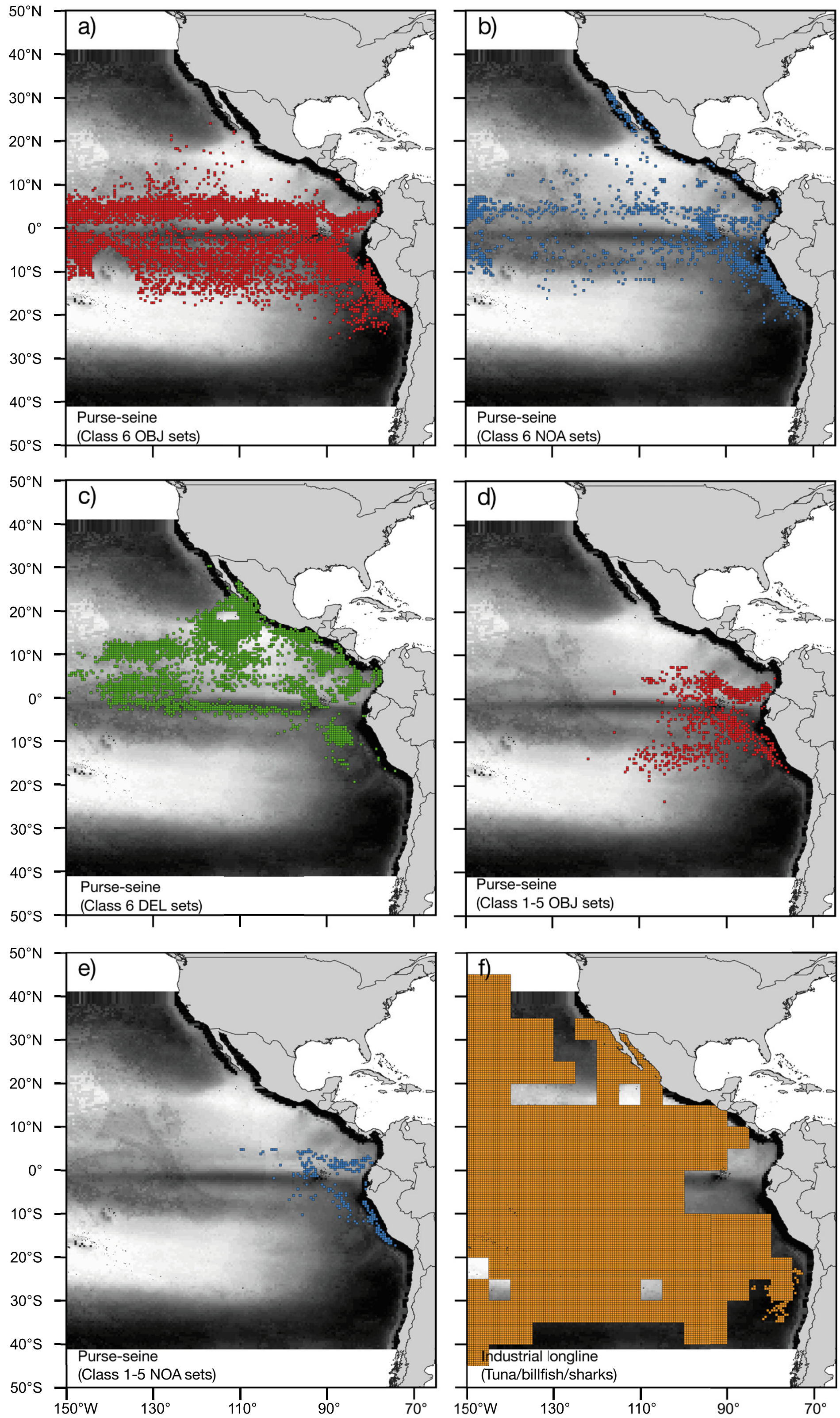

Fig. 3 continued on next page

Fig. 3. Distribution of fishing effort (at 0.5° × 0.5° resolution) by 9 fisheries in the eastern Pacific Ocean in 2019 overlaid on the probability of occurrence of the East Pacific stock of leatherback turtles *Dermochelys coriacea*. (a–c) Class 6 purse seine; (d–e) Classes 1–5 purse seine; (f) industrial longline; (g) artisanal gillnet; (h) artisanal longline; (i) egg collection. Darker shading indicates higher probability of turtle occurrence. Set types for the purse seine fisheries are sets associated with floating objects (OBJ), sets on unassociated schools of tuna (NOA), and sets associated with dolphins (DEL)

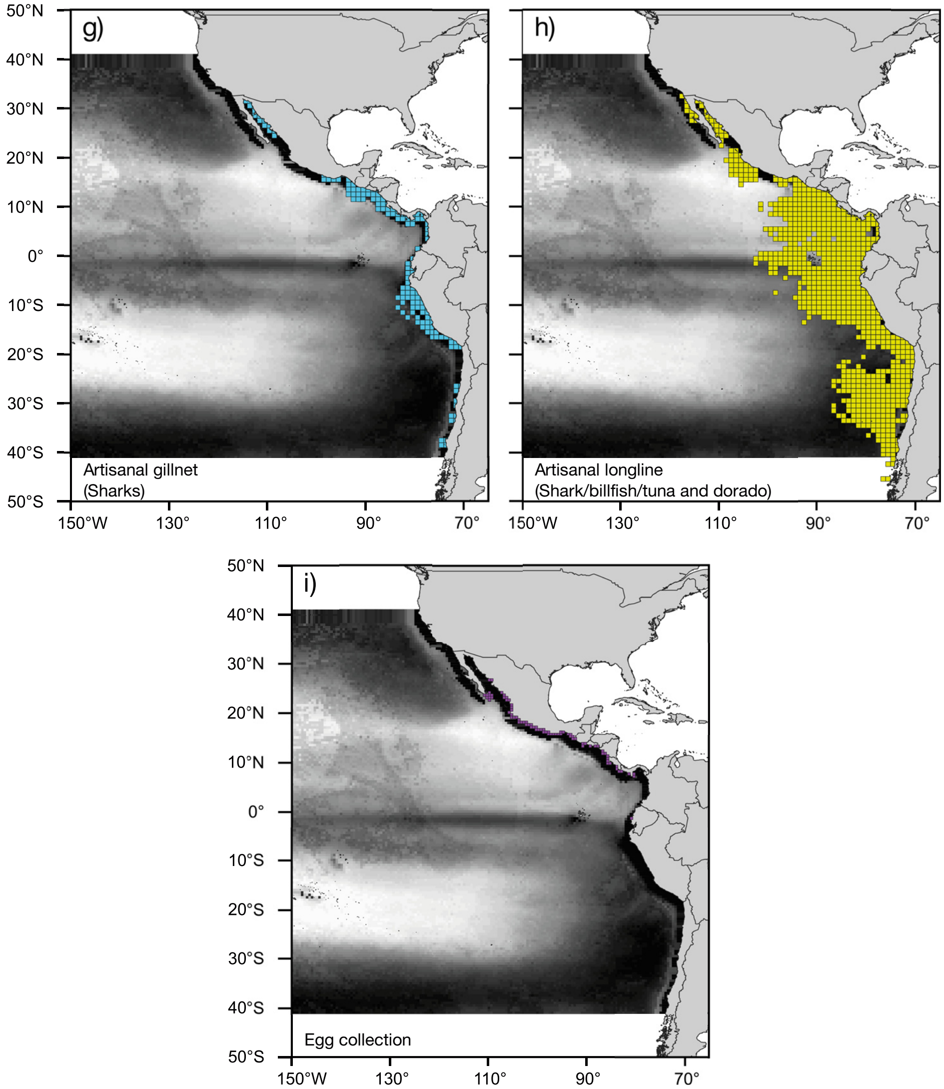

Fig. 3. (continued)

Electronic tagging studies of the EP leatherback turtle stock confirm year-round presence of leatherback turtles within the IATTC Convention Area (e.g. Benson et al. 2011, Shillinger et al. 2011, Bailey et al. 2012, Schick et al. 2013); leatherbacks were therefore considered to be available to all fisheries year-round (A_{xj} = 1.0). Encounterability was fully realised (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 remove only 4% of the total leatherback turtle nests within the EP stock boundaries (Laúd OPO Network 2020).

Contact selectivity was fully realised (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 (Scen1) in 2019, the industrial longline fishery imposed the highest fishing mortality ($\tilde{F}_{2019}$= 0.103 yr^{-1}) (Fig. 4), mainly due to its high volumetric overlap with the stock (Fig. 3). The artisanal longline fishery had the second highest volumetric overlap and second highest fishing mortality (0.031 yr^{-1}) (Fig. 4), despite its overlap with the stock being approximately half that of industrial longlines (Fig. 3). The artisanal gillnet fishery had a comparatively low fishing mortality (0.006 yr^{-1}) (Fig. 4), owing to a very low (4.1%) areal overlap with the stock (Fig. 3). The remaining fisheries (purse-seine and egg collection) each contributed a fishing mortality of less than 0.007 yr^{-1} (Fig. 4). In the purse-seine fisheries, this is attributed to a very low PCM rate (5%), despite relatively high volumetric over-

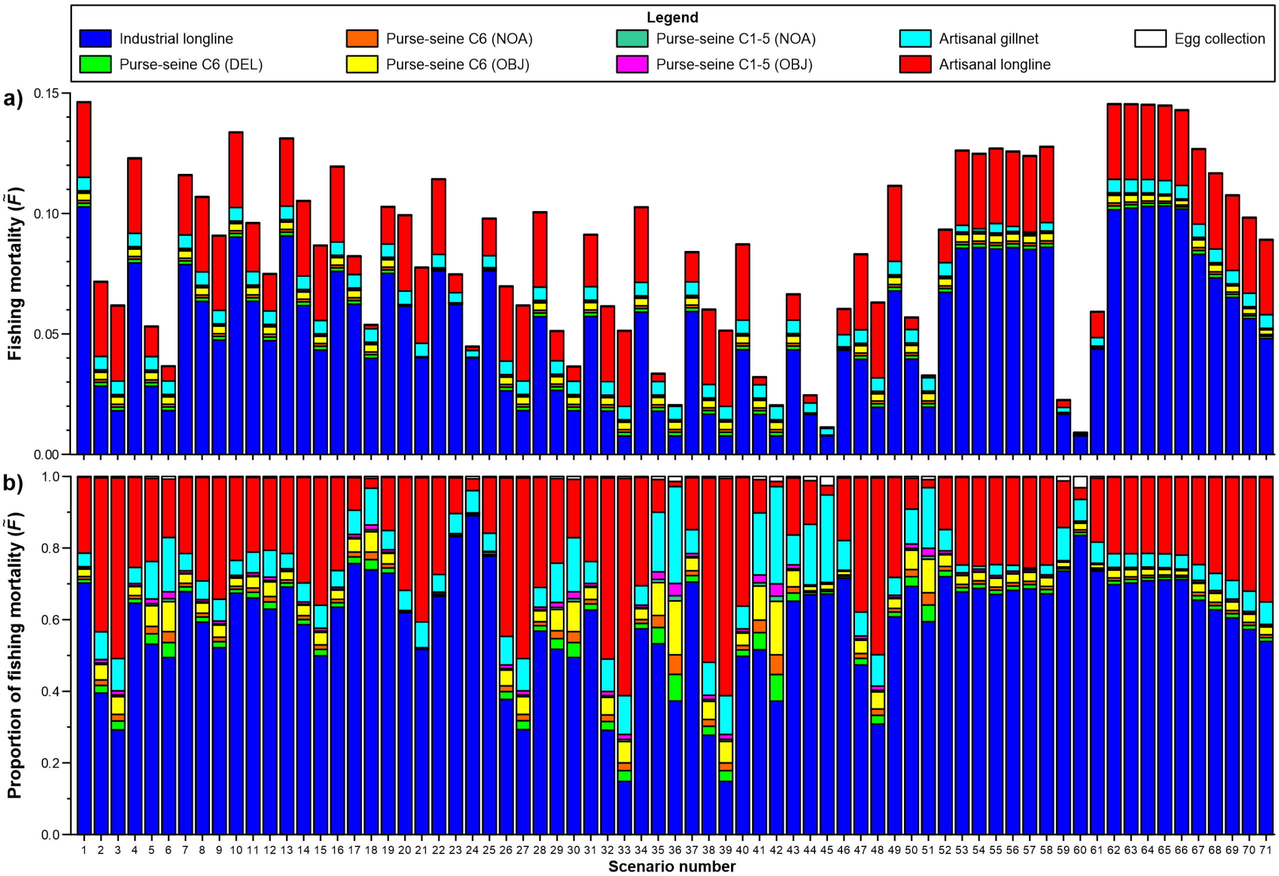

Fig. 4. Mean values for (a) the fishing mortality proxy ($\tilde{F}_{2019}$) for the East Pacific leatherback turtle *Dermochelys coriacea* stock estimated by the Ecological Assessment for the Sustainable Impacts of Fisheries model and (b) the proportion of total mortality $\tilde{F}_{2019}$ value for 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 shown in the *x*-axis are provided in Tables 2 & S1. DEL: sets associated with dolphins; NOA: sets on unassociated schools of tuna; OBJ: sets associated with floating objects

lap with the stock (up to 20%) (Fig. 3), 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 Fig. 4a, while Fig. 4b 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.

3.2. 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 2, while EASI-Fish estimates of the $F_{80\%}$ and $BSR_{80\%}$ BRPs for each scenario are provided in Table 4.

Under Scen1 characterising 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. 5a, Table 4). 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 Scen1 would be classified as 'least vulnerable' is low.

3.2.1. 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 (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 2) resulted

Table 4. Estimated mean (±SD) 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. Asterisks (*) indicate scenarios where the stock was classified as 'most vulnerable' (otherwise they are 'least vulnerable'). Specific model parameter values used in each scenario (Scen) are shown in Table S2. EPO: eastern Pacific Ocean; PRM: post-release mortality, L_c: curved carapace length at first capture; PS: purse-seine; *C*: contact selectivity; ind. LL: industrial longline; art. LL: artisanal longline; GN: gillnet

Scenario description	Scenario	$F_{2019}/F_{80\%}$	$BSR_{2019}/BSR_{80\%}$
Absence of any conservation and management measures for all fisheries 0 d EPO closure; all fisheries PRM 100%; L_c = 90 cm	Scen0*	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	Scen1*	1.37 (0.8)	0.95 (0.17)
Use of circle hooks (CH) only			
C = 0.3 in ind. LL only	Scen2	0.37 (0.19)	1.17 (0.05)
C = 0.2 in ind. LL only	Scen3	0.28 (0.15)	1.19 (0.04)
C = 0.8 in ind. LL only	Scen4*	1 (0.55)	1.02 (0.13)
C = 0.3 in ind. LL; *C* = 0.4 in art. LL	Scen5	0.21 (0.1)	1.21 (0.03)
C = 0.2 in ind. LL; *C* = 0.2 in art. LL	Scen6	0.1 (0.05)	1.24 (0.01)
C = 0.8 in ind. LL; *C* = 0.8 in art. LL	Scen7*	0.91 (0.52)	1.05 (0.12)
Use of finfish bait (FB) only			
C = 0.66 in ind. LL only	Scen8*	0.78 (0.41)	1.08 (0.1)
C = 0.5 in ind. LL only	Scen9	0.58 (0.30)	1.12 (0.07)
C = 0.9 in ind. LL only	Scen10*	1.17 (0.66)	0.99 (0.14)
C = 0.66 in ind. LL; *C* = 0.66 in art. LL	Scen11	0.65 (0.36)	1.11 (0.09)
C = 0.5 in ind. LL; *C* = 0.5 in art. LL	Scen12	0.41 (0.22)	1.16 (0.05)
C = 0.9 in ind. LL; *C* = 0.9 in art. LL	Scen13*	1.14 (0.66)	1 (0.14)
Use of best handling and release practices (BP) only			
PRM = 0.225 in ind. LL only	Scen14*	0.75 (0.39)	1.08 (0.09)
PRM = 0.15 in ind. LL only	Scen15	0.52 (0.23)	1.14 (0.06)
PRM = 0.27 in ind. LL only	Scen16*	0.95 (0.5)	1.04 (0.11)
PRM = 0.225 in ind. LL; PRM = 0.063 in art. LL	Scen17	0.49 (0.28)	1.14 (0.07)
PRM = 0.15 in ind. LL; PRM = 0.013 in art. LL	Scen18	0.22 (0.13)	1.21 (0.03)
PRM = 0.27 in ind. LL; PRM = 0.125 in art. LL	Scen19*	0.73 (0.42)	1.09 (0.1)
PRM = 0.225 in ind. LL; PRM = 0.005 in purse-seine	Scen20*	0.68 (0.37)	1.1 (0.09)
PRM = 0.15 in ind. LL; PRM = 0.003 in purse-seine	Scen21	0.43 (0.23)	1.16 (0.06)
PRM = 0.27 in ind. LL; PRM = 0.01 in purse-seine	Scen22*	0.88 (0.48)	1.05 (0.11)
PRM = 0.27/0.005/0.375/0.063 in ind. LL/PS/GN/art. LL	Scen23	0.42 (0.26)	1.16 (0.06)
PRM = 0.15/0.003/0.25/0.013 in ind. LL/PS/GN/art. LL	Scen24	0.16 (0.11)	1.22 (0.03)
PRM = 0.27/0.01/0.45/0.125 in ind. LL/PS/GN/art. LL	Scen25*	0.68 (0.40)	1.1 (0.10)
Combination strategies: CH + FB			
C = 0.287 in ind. LL only	Scen26	0.35 (0.18)	1.18 (0.04)
C = 0.2 in ind. LL only	Scen27	0.28 (0.14)	1.19 (0.04)
C = 0.6 in ind. LL only	Scen28*	0.7 (0.37)	1.09 (0.09)
C = 0.287 in ind. LL; *C* = 0.4 in art. LL	Scen29	0.2 (0.09)	1.21 (0.02)
C = 0.2 in ind. LL; *C* = 0.2 in art. LL	Scen30	0.1 (0.05)	1.24 (0.01)
C = 0.6 in ind. LL; *C* = 0.7 in art. LL	Scen31	0.59 (0.32)	1.12 (0.08)
C = 0.3, PRM = 0.225 in ind. LL only	Scen32	0.28 (0.14)	1.2 (0.04)
C = 0.2, PRM = 0.15 in ind. LL only	Scen33	0.2 (0.12)	1.21 (0.03)
C = 0.8, PRM = 0.27 in ind. LL only	Scen34*	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	Scen35	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	Scen36	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	Scen37	0.5 (0.28)	1.14 (0.07)
Combination strategies: CH + FB + BP			
C = 0.287, PRM = 0.225 in ind. LL only	Scen38	0.27 (0.14)	1.2 (0.03)
C = 0.2, PRM = 0.15 in ind. LL only	Scen39	0.2 (0.11)	1.21 (0.03)
C = 0.6, PRM = 0.270 in ind. LL only	Scen40	0.53 (0.26)	1.13 (0.06)
C = 0.287, PRM = 0.225 in ind. LL; *C* = 0.4, PRM = 0.063 in art. LL	Scen41	0.08 (0.04)	1.24 (0.01)
C = 0.2, PRM = 0.15 in ind. LL; *C* = 0.2, PRM = 0.013 in art. LL	Scen42	0.03 (0.01)	1.25 (0.01)
C = 0.6, PRM = 0.27 in ind. LL; *C* = 0.7, PRM = 0.125 in art. LL	Scen43	0.32 (0.17)	1.18 (0.04)

Table 4 continued on next page

Table 4. (continued)

Scenario description	Scenario	$F_{2019}/F_{80\%}$	$BSR_{2019}/BSR_{80\%}$
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	Scen44	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	Scen45	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	Scen46	0.27 (0.15)	1.2 (0.04)
Combination strategies: FB + BP			
C = 0.66, PRM = 0.225 in ind. LL only	Scen47	0.49 (0.24)	1.14 (0.06)
C = 0.5, PRM = 0.15 in ind. LL only	Scen48	0.29 (0.15)	1.19 (0.04)
C = 0.9, PRM = 0.27 in ind. LL only	Scen49*	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	Scen50	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	Scen51	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	Scen52	0.61 (0.34)	1.11 (0.08)
Use of illuminated GN only and in combination with strategies CH + FB + BP			
C = 0.5 in GN only	Scen53*	1.05 (0.58)	1.01 (0.13)
C = 0.2 in GN only	Scen54*	1.03 (0.57)	1.02 (0.13)
C = 0.7 in GN only	Scen55*	1.06 (0.58)	1.01 (0.13)
C = 0.5, PRM = 0.375 in GN only	Scen56*	1.05 (0.57)	1.01 (0.13)
C = 0.2, PRM = 0.25 in GN only	Scen57*	1.02 (0.56)	1.02 (0.13)
C = 0.7, PRM = 0.45 in GN only	Scen58*	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	Scen59	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	Scen60	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	Scen61	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	Scen62	1.36 (0.80)	0.95 (0.17)
90 d EPO closure for purse-seine fleet only	Scen63	1.36 (0.79)	0.95 (0.16)
120 d EPO closure for purse-seine fleet only	Scen64	1.36 (0.80)	0.95 (0.17)
150 d EPO closure for purse-seine fleet only	Scen65	1.36 (0.80)	0.95 (0.17)
180 d EPO closure for purse-seine fleet only	Scen66	1.32 (0.78)	0.96 (0.16)
62 d EPO closure for all purse-seine and ind. LL fleets	Scen67	1.06 (0.60)	1.01 (0.13)
90 d EPO closure for all purse-seine and ind. LL fleets	Scen68	0.92 (0.50)	1.04 (0.12)
120 d EPO closure for all purse-seine and ind. LL fleets	Scen69	0.79 (0.42)	1.07 (0.10)
150 d EPO closure for all purse-seine and ind. LL fleets	Scen70	0.67 (0.36)	1.1 (0.09)
180 d EPO closure for all purse-seine and ind. LL fleets	Scen71	0.56 (0.29)	1.13 (0.07)

in the stock's vulnerability status changing markedly from 'most vulnerable' (red quadrant) to 'least vulnerable' (green quadrant) (Fig. 5a, Table 4). 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. 5a).

3.2.2. Use of finfish bait in longline fisheries

Like circle hooks, the hypothetical introduction of finfish bait to longline fisheries (Scen8–13) was assumed to reduce contact selectivity. When applied to the industrial longline fishery (Scen8–10) and all longline fisheries (Scen11–13) the low and intermediate selectivity values (i.e. maximum [50% reduction] and intermediate [34%] potential efficacy values; Table 3) resulted in the stock's vulnerability status improving to 'least vulnerable' (Fig. 5b, Table 4). However, the use of the highest selectivity value (i.e. lowest estimate efficacy [10% reduction]) did not change the status from 'most vulnerable' (Fig. 5b).

3.2.3. Use of best handling and release practices

The hypothetical use of best handling and release practices (Scen14–25) were assumed to reduce PCM

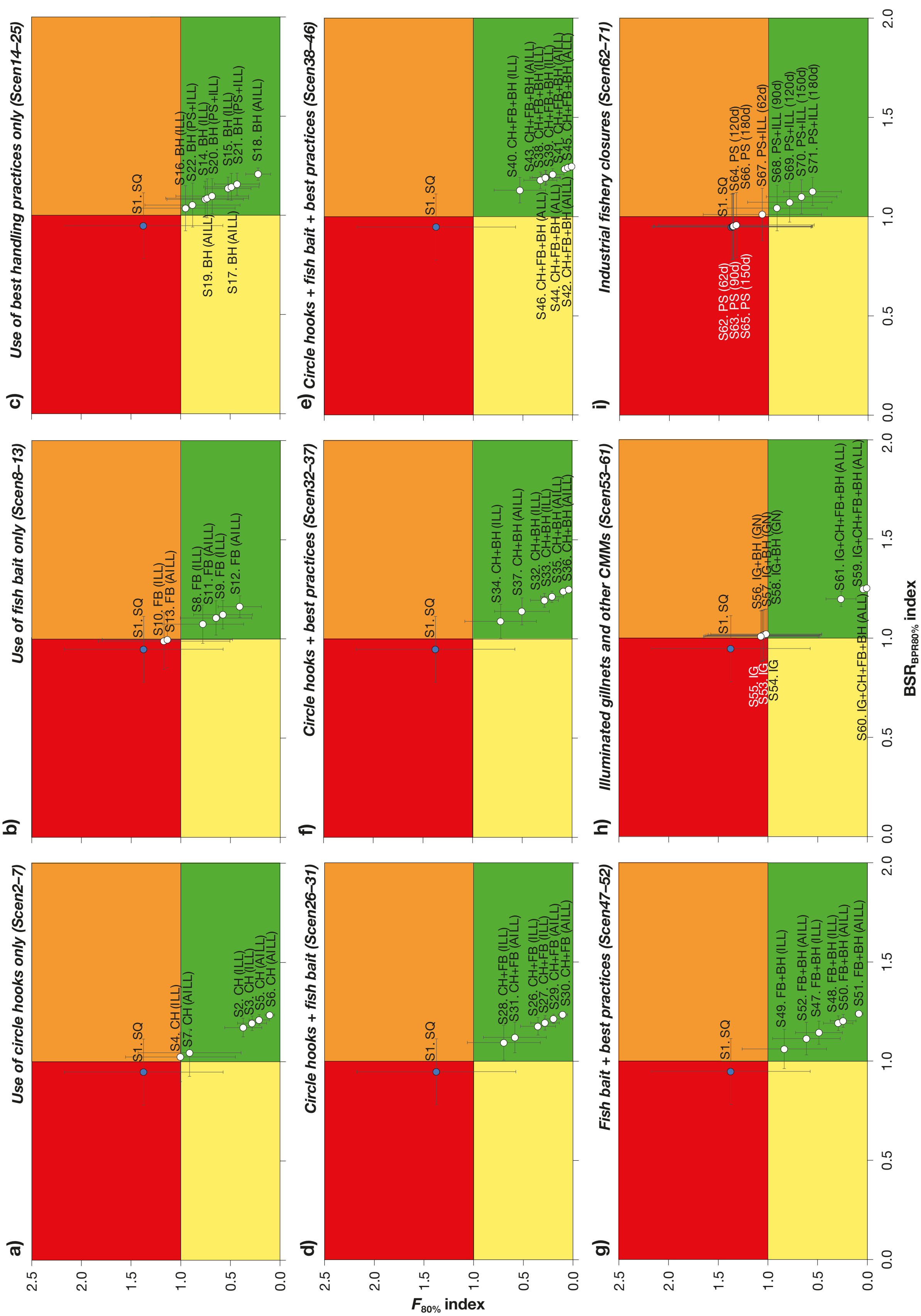

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Fig. 5. Vulnerability phase plots showing the vulnerability status of the East Pacific leatherback turtle *Dermochelys coriacea* stock estimated by the Ecological Assessment for the Sustainable Impacts of Fisheries model with respect to the eastern Pacific Ocean industrial and artisanal fisheries represented by the mean (±SD) biological reference points $\tilde{F}_{2019}/F_{80\%}$ and $BSR_{2019}/BSR_{80\%}$ for each hypothetical scenario (Scen). 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 ('S' for brevity here) detailed in Table 4 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 4. $F_{80\%}$: fishing mortality value corresponding to 80% of the breeding potential ratio; $BSR_{BPR80\%}$: breeding stock biomass per recruit at $F_{80\%}$; CMM: conservation and management measure

by varying degrees in each fishery (Table 2). When applied to industrial longline only (Scen14–16), all longline fisheries (Scen17–19), or all industrial fisheries (S20–22), only scenarios with low and intermediate PCM (i.e. maximum and intermediate efficacy; Table 2) resulted in the status changing to 'least vulnerable' (Fig. 5c, Table 4). However, when best practices were applied to all fisheries (Scen23–25), status changed to 'least vulnerable' for low, intermediate, and high values of reduced PCM (Fig. 5c, Table 4).

3.2.4. Use of a combination of CMMs

Combining the assumed benefits of using large circle hooks in the industrial longline fishery or in all longline fisheries with the use of finfish bait (Scen26–31), or with best handling and release practices (Scen32–37), or with both finfish bait in all longline fisheries and best handling and release practices in all fisheries (Scen38–46) significantly decreased vulnerability (Fig. 5d,e, Table 4). Apart from Scen28 and Scen34, which had the highest selectivity values, all other scenarios resulted in a status change to 'least vulnerable' (Fig. 5d,e).

Similarly, combining the use of finfish bait with best handling and release practices (Scen47–52) resulted in significant reductions in vulnerability. With the exception of Scen49, all scenarios resulted in a change in status to 'least vulnerable' (Fig. 5g, Table 4).

3.2.5. Use of illuminated gillnets

Although gear illumination was not one of the CMMs listed in IATTC Resolution C-19-04, it was investigated in isolation (Scen53–55) and in combination with best handling and release practices (Scen56–58) (Table S2) 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 (Scen59–61). Neither illuminated gillnets alone nor in combination with best handling and release practices in gillnets were sufficient to change leatherback vulnerability status from 'most vulnerable' (Fig. 5h, Table 4). However, when combined with the use of the full suite of CMMs applied to other fisheries (Scen59–61) vulnerability decreased dramatically to 'least vulnerable', including the most effective scenario (Scen60; Fig. 5h, Table 4).

3.2.6. Temporal closures for industrial fishing fleets

The EPO purse-seine fishery has had a long history in the effective use of temporal fishing closures to reduce the fishing mortality on target tuna species. Scenarios were developed to further extend the existing 72 d closure period to 90, 120, 150 and 180 d for the purse-seine fishery alone (Scen62–66) and for both the purse-seine and longline fisheries, respectively (Scen67–71). Extending the closure period for the purse-seine fishery resulted in a negligible change in vulnerability status (Fig. 5i). 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 d (Fig. 5i, Table 4).

3.2.7. Most effective scenarios for reducing EP leatherback vulnerability in EPO fisheries

Scenarios with the largest reduction in proxy fishing mortality values (i.e $\tilde{F}_{2019} < 0.1$; Scen35–36, Scen41–42, Scen44–45, Scen51, and Scen59–60; Table 4) all included moderate to high estimated reductions in both contact selectivity and PCM in multiple fisheries (Fig. 4). 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 $\tilde{F}_{2019}$ values an order of magnitude higher (Fig. 5, Table 4).

4. DISCUSSION

4.1. EASI-Fish demonstrates the potential efficacy of several CMMs

ERA is a suite of tools that are commonly applied in fisheries to assess the vulnerability of data-limited species and/or fisheries. These methods have the advantage of being rapidly and cost-effectively implemented to identify species most vulnerable to fishing impacts, allowing fisheries managers identify and mitigate specific risks, or develop data collection programs to allow conventional stock assessment to be undertaken (Hobday et al. 2011). There have been at least 3 ERAs undertaken in the EPO (Griffiths et al. 2017, 2018, Duffy et al. 2019), one of which included leatherback turtles, that indicated this species is among the most vulnerable species impacted by tuna fisheries (Griffiths et al. 2018).

However, this study 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 large 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 called for in IATTC Resolution C-19-04 and IAC Resolution CIT-COP10-2020-R6 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.

4.2. 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 CMMs to implement that may achieve desirable conservation benefits to leatherbacks. Considering the full and complex suite of scenarios, we can draw some general conclusions to guide further discussions about how to implement IATTC Resolution C-19-04. The following statements describe scenarios that significantly improved EP leatherback vulnerability status (Figs. 4 & 5, Tables 4 & S3):

- The best-performing scenarios (i.e. $\tilde{F}_{2019}/F_{80\%} <$ 0.1; Scen35–36, Scen41–42, Scen44–45, Scen51, and Scen59–60) 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 (Scen2–13);
- 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. Scen15), or;
- Post-capture mortality must be reduced by at least 25% in industrial longlines and 75% in artisanal longlines (e.g. Scen17) (even 10 and 50% reductions, respectively, were insufficient);
- Minimum estimated reductions in post-capture mortality values (e.g. Scen16, Scen19, Scen22, Scen25) were only sufficient if combined with at least 2 other CMMs and implemented in multiple fisheries (e.g. Scen31, Scen37, Scen43, Scen52, Scen61);
- EPO-wide closures of both industrial longline and purse seine fisheries must be implemented and extend 150 d or more to effectively reduce leatherback vulnerability beyond the current 72 d 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 2). 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, large 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.

Although IATTC resolutions — and the fishing authorities of several coastal states in the EPO — have explicitly mandated the use of specific measures to reduce the catch and maximise post-release survival of non-target species such as sharks and turtles, for several fisheries it is unknown to what extent these measures are adopted by fishers in the majority of these fisheries due to low observer coverage. The industrial purse-seine fleet of Class 6 vessels has 100% observer coverage, but interaction and mortality rates of leatherback turtles is extremely low. From 1993–2022 a total of 117 interactions have occurred (about around 4 turtles yr^{-1}), of which only 1 mortality has been recorded (IATTC, 2023). In contrast, this study showed the industrial longline fishery to potentially have the highest fishing mortality on leatherback turtles but is required under IATTC Resolution C-19-08 to provide only 5% observer coverage for vessels >24 m LOA that fish for tuna and tuna-like species in the EPO. A total of 10 leatherback turtle interactions (3 mortalities) were recorded in this fishery in 2020, while none were recorded in 2022, possibly indicating variable interaction and/or reporting rates. Since 2016, the IATTC scientific staff has annually made a recommendation to its Members to increase observer coverage to at least 20% in the longline fishery, but unfortunately there has no consensus among IATTC Members to adopt this recommendation. There have been recent efforts by the IATTC to increase coverage and reduce costs of observer coverage through electronic monitoring, which would likely be an effective monitoring tool for leatherback turtles both in industrial and artisanal pelagic fisheries within the EPO (Bartholomew et al. 2018, Brown et al. 2021).

Therefore, 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. 5, Table 4). 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 sufficient capacity to 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. 5) 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. At the same time, management strategies should account for tradeoffs with target catch and consideration of important logistical and socio-economic factors related to CMM implementation that could affect the fishing industry — and fishermen in particular.

4.3. Conservation measures and their potential benefits to EP leatherback conservation

Our results demonstrate that effective, comprehensive implementation of best handling and release practices — when combined with other measures in IATTC Resolution C-19-04 — has significant potential for contributing to reductions in EP leatherback vulnerability to fisheries bycatch (Figs. 4 & 5, Table 4).

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) and in 2020 (IAC Resolution CIT-COP10-2020-R7), 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 for an initial phase — 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 (p. 2) 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 FAO (2009). There are, however, added challenges to reducing PCM from small-scale vessels that should be considered, since animal handling may be more difficult and resources and available equipment are more limited (Parga 2012).

Nonetheless, the level of fishing mortality exerted on leatherback turtles (and other vulnerable, non-target species) may be significantly reduced by relatively simple and low-cost modifications to hook size and appropriate handling and release practices that is expected to minimise PCM — coupled with existing turtle and bycatch conservation measures. Of course, uncertainties persist in PCM estimates both under current practices and projected reductions of PCMs with CMMs and the predicted level of mortality reduction can only be achieved if fishers appropriately exercise handling and release procedures as prescribed by researchers. From a practicality viewpoint, focusing on reducing mortality through hook size increases and improving release and handling practices is likely to be more effective than spatio–temporal closures at small spatial scales (e.g. neritic areas adjacent to nesting beaches) that require a high level of on-site compliance, which many developing coastal states in the EPO may not have the resources to implement.

4.4. 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 (e.g. Pacific Leatherback Conservation Area, US National Marine Fisheries Service, Federal Register 2001). 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 d in 2002–2003 to 72 d in 2018–2020. In addition, from 2002 the IATTC has also implemented an annual 30 d closure of the 'corralito' in the central equatorial Pacific in an attempt to further reduce fishing mortality on juvenile bigeye tuna *Thunnus obesus* 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 *T. albacares* and skipjack *Katsuwonus pelamis* (IATTC 2021). Although spatial–temporal closures of the 'corralito' and other tuna catch 'hotspots' were predicted by Harley & Suter (2007) to reduce the catch of bigeye tuna by up to 24%, they were insufficient for reducing fishing mortality to biologically sustainable levels. As an alternative, increasing the area and duration of closures or exploring dynamic management measures has been recommended (Harley & Suter 2007, Pons et al. 2022).

Although spatial–temporal closures are not specified in IATTC Resolution C-19-04, a range of spatial–temporal closures — applied to fisheries individually and in concert — were explored in the present study because it is a measure that (1) has already been implemented by the IATTC for tuna conservation for several years, (2) is easily monitored for compliance purposes, and (3) has not previously been applied to the industrial longline fishery (see IATTC Resolution C-21-04 for closure measures for 2022–2024), which was shown in the present study to potentially have the highest fishing mortality on leatherback turtles. Our simulations of various spatial—temporal closures complemented the results of Harley & Suter (2007) in that the duration of recent EPO-wide closures (i.e. 72 d) 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). This was mainly due to the relative proportion of fisheries overlap with the stock in coastal areas was negligible compared to the high overlap that occurred on the high seas by industrial fisheries, especially industrial longline. Extending the EPO-wide closure duration reduced the species' vulnerability, primarily as a result of reduced mortality by the industrial longline fishery, 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 d yr^{-1} (Fig. 5i, Table 4). 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 analysed 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.

5. RECOMMENDATIONS FOR FUTURE WORK

This study 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.

5.1. 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 industrial longline fleet in the EPO has often failed to reach the 5% requirement under IATTC 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 industrial longline fleet — 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 or re-analyzing data from 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 recognise 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. In addition, best handling practices are currently required in these fisheries, so a logical goal of sea turtle conservation efforts is to implement and maintain adequate training to ensure compliance. Current practices and the effects of outreach and education should be evaluated to improve our understanding of the efficacy of this CMM.

5.2. 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. 2009, Smith et al. 2009), Central America (Swimmer et al. 2011, Whoriskey et al. 2011), and South America (Alfaro-Shigueto et al. 2007, 2018, Martínez-Ortiz et al. 2015, Ortíz-Álvarez et al. 2020, Quiñones et al. 2021) — often in far higher numbers per unit effort 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 1000 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 (Hays-Brown & Brown 1982, Alfaro-Shigueto et al. 2007, Quiñones et al. 2017, 2021).

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, 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 (Siu & Aires-da-Silva 2016, Oliveros-Ramos et al. 2019) with plans to expand sampling to include Mexico, Ecuador, and Peru in 2022, which should provide further data on catches and fishing effort of these small coastal fisheries. Also, the IAC EP leatherback Resolution requires IAC Parties to provide information on the bycatch of the species in their Annual Report. 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.

5.3. 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 costs and benefits to industrial tuna fisheries as well as artisanal 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 different fisheries throughout the region. 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.

5.4. 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 suite 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 explicitly 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, Parque Marino Mar Juan Fernández) 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) and types of material used in longlines and gillnets are associated with different levels of entanglement risk and severity for sea turtles (Gilman et al. 2010). 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 & Roman 2013). Importantly, potential effects on leatherback vulnerability of illegal, unregulated, and unreported fisheries as well as derelict or unattended fishing gear (e.g. 'ghost' nets, artificial fish aggregation devices) and other threats 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.

6. CONCLUSIONS

The initial impetus for the development of EASI-Fish was to provide a quantitative means by which the relative vulnerability of data-limited non-target species can be assessed to allow the identification of species that may be at risk of becoming unsustainable under existing fishing regimes. Depending on the perceived severity of fishing-related threats, these vulnerable species can be subjected to immediate management intervention or further data collection through research and or/fishery dependent monitoring of catches for subsequent reassessment using EASI-Fish, or more sophisticated conventional stock assessment models. 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, 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 IATTC Resolution 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 modeling 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, the CMMs must be tailored appropriately to different fisheries to achieve the potential benefits, and 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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Appendix. Authors and affiliations

Shane P. Griffiths[1,*], Bryan P. Wallace[2,3,4], Verónica Cáceres[2], Luz Helena Rodríguez[2], Jon Lopez[1], Marino Abrego[5], Joanna Alfaro-Shigueto[6,7,8], Sandra Andraka[9], María José Brito[10], Leslie Camila Bustos[11], Ilia Cari[12], José Miguel Carvajal[13], Ljubitza Clavijo[12], Luis Cocas[11], Nelly de Paz[14], Marco Herrera[10], Ann Marie Lauritsen[15], Jeffrey C. Mangel[7,8], Miguel Pérez-Huaripata[16], Rotney Piedra[17], Javier Antonio Quiñones Dávila[16], Liliana Rendón[9], Juan M. Rguez-Baron[18,19], Heriberto Santana[20], Brian Stacy[21], Jenifer Suárez[22], Yonat Swimmer[23], Callie Veelenturf[24], Rodrigo Vega[12], Patricia Zárate[12]

[1]Inter-American Tropical Tuna Commission, 8901 La Jolla Shores Drive, La Jolla, CA 92037, USA
[2]Inter-American Convention for the Protection and Conservation of Sea Turtles, Fairfax, VA 22046, USA
[3]Ecolibrium, Inc, Boulder, CO 80303, USA
[4]Department of Ecology and Evolutionary Biology, University of Colorado Boulder, Boulder, CO 80310, USA
[5]Ministerio de Ambiente, Panama City, C-0843-00793 Panamá
[6]Carrera de Biologia Marina, Universidad Cientifica del Sur, Lima, 15067 Perú
[7]ProDelphinus, Jose Galvez 780E, Lima, 10680 Perú
[8]School of Biosciences, University of Exeter, Cornwall Campus, Penryn, Cornwall TR10 9EZ, UK
[9]EcoPacifico+, San José, 11801 Costa Rica
[10]Instituto Público de Investigación de Acuicultura y Pesca, Guayaquil, 090314 Ecuador
[11]Subsecretaria de Pesca y Agricultura, Valparaiso, 2340000 Chile
[12]Instituto del Fomento Pesquera, Valparaiso, 2340000 Chile
[13]Instituto Nacional Costarricense de Pesca y Acuicultura, Puntarenas, 60101 Costa Rica
[14]Áreas Costeras y Recursos Marinos, Pisco, 11600 Perú
[15]US Fish and Wildlife Service, Fairfax, VA 22046, USA
[16]Instituto del Mar del Perú, Callao, 07021 Peru
[17]Sistema Nacional de Áreas de Conservación, Nicoya, 50201 Costa Rica
[18]JUSTSEA Foundation, Bogotá, 1100111 Colombia
[19]University of North Carolina Wilmington, Wilmington, NC 28403, USA
[20]Instituto National de Pesca y Acuacultura, Manzanillo, Colima, 28200 Mexico
[21]Office of Protected Resources, National Oceanic and Atmospheric Administration, Gainesville, FL 32611, USA
[22]Parque Nacional Galápagos, Puerto Ayora, Galápagos Islands, 200101 Ecuador
[23]Pacific Islands Fisheries Science Center, National Oceanic and Atmospheric Administration, Honolulu, HI 96818, USA
[24]The Leatherback Project, Norfolk, MA 02056, USA

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