Vol. 53: 295–326, 2024
https://doi.org/10.3354/esr01305

ENDANGERED SPECIES RESEARCH
Endang Species Res

Published March 14



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

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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-

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Publisher: Inter-Research · www.int-res.com

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 im-

portant 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.

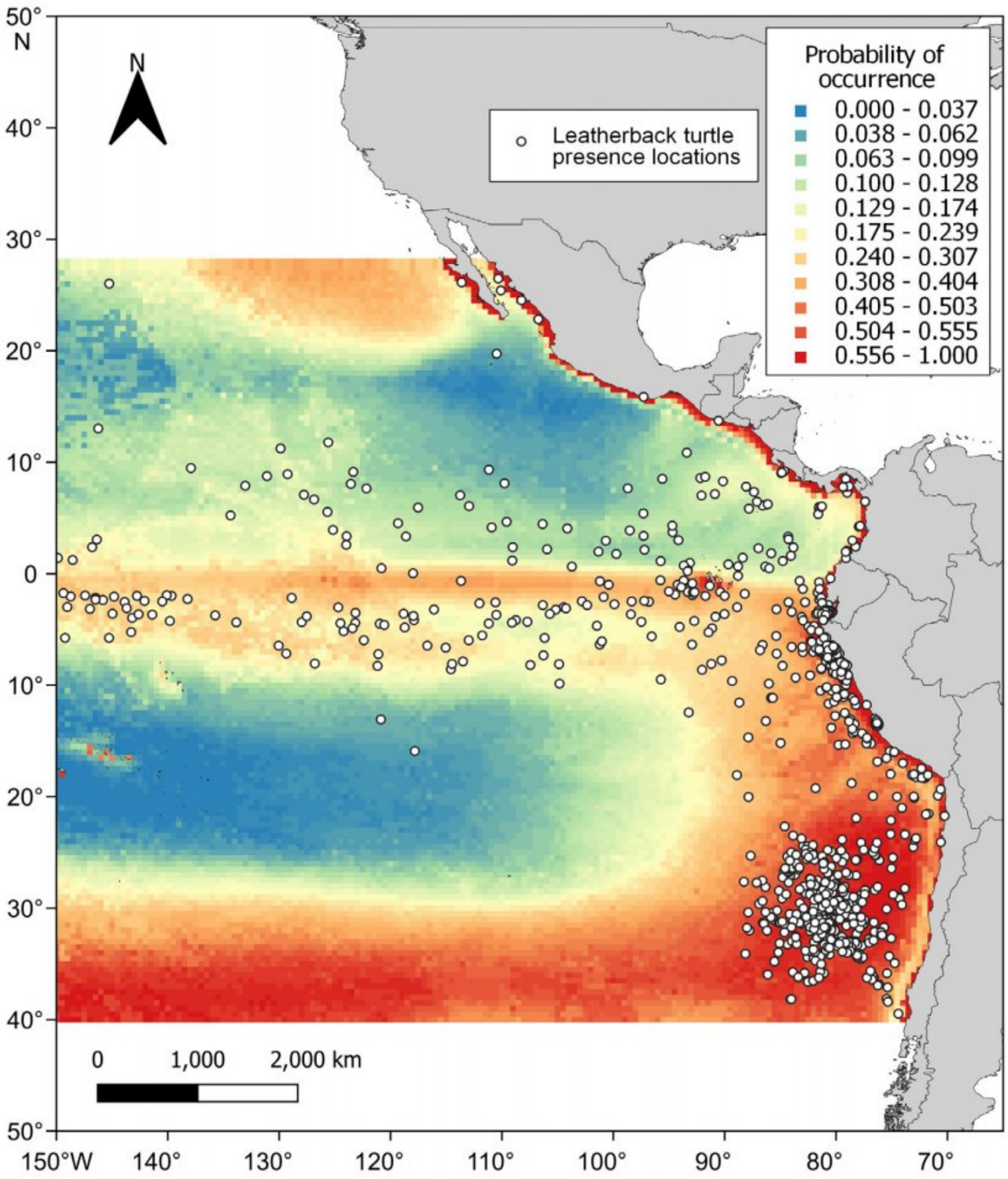


Fig. 1. Map showing the presence data (white circles) used to generate the predicted distribution of the East Pacific stock of leatherback turtles *Dermochelys coriacea* (shown using a probability-of-occupancy, ψ, threshold values of 0.2). To account for uncertainty in the model's predicted distribution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