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Descriptive and spatial analysis of bycatch in tuna purse-seine fishery in the colombian Pacific Ocean, with an elasmobranch approach

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ABSTRACT

Bycatch species are as important as target species in the challenge of comprehensive fishery management. This is especially the case for vulnerable species such as elasmobranchs in offshore areas of the Colombian Pacific Ocean (CPO), for which information is scarce and long-term databases are used. Therefore, this study aimed to characterize the bycatch in tuna purse-seine fishery with an elasmobranch species approach using fishery data from 2000 to 2019. A total of 59 bycatch species were identified, including 27 bony fishes, 22 elasmobranchs, two mollusks, four sea turtles, and four dolphins. The total bycatch percentage was 20.8%, with elasmobranchs accounting for less than 5%. Fish aggregating devices (FADs) and class 6 vessels recorded the highest percentage of bycatch. Bony fish bycatch was mainly obtained from the border of Ecuador until 4° N across the CPO. Elasmobranchs were captured throughout the CPO, showing differences by vessel class and fishing method. The silky shark *Carcharhinus falciformis* was the most caught species. Elasmobranch spatial abundance and capture hotspots showed the highest values towards the northern coast, in offshore areas of Gorgona Island, southwards in offshore areas, and around Malpelo Island. FADs captured the highest number of bycatch species compared with other fishing methods, such as Tuna Associated with Dolphins (DEL), Natural Floating Objects (NAT), and Tuna not Associated (NoAs). Management recommendations for bycatch species in this fishery are provided in the CPO.

Keywords: Tuna fishery, Colombian eastern pacific ocean, Fish aggregating device, Management alternatives, Colombia

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INTRODUCTION

Multiple approaches have differed slightly when defining the term “bycatch”. Alverson et al. (1994) defined it as non-target species retained and sold, as well as those discarded due to economic, size, legal, or personal reasons. Posteriorly, FAO (1997) established that “bycatch” should be used generically to refer to the non-target portion of a fishery’s catch. Years later, Cochrane and Garcia (2009) defined “bycatch” as anything in the fishing process that differs from the species and sizes of the targeted marine organisms.

The International Guidelines on Bycatch Management and Reduction of Discards, published by the FAO in 2011, stated that it was impossible to develop an internationally standardized definition of bycatch, as its nature is diverse worldwide and there are historical differences in bycatch definitions between countries. Furthermore, functional interpretations inevitably include unintentional catches by fishermen and multispecies fishing gear with low selectivity, in which most species are captured and used. In this sense, bycatch refers to that part of the catch that should not have been caught, regardless of ecological and economic consequences.

Hall and Roman (2013) defined bycatch as dead species that are discarded and separated from other non-tuna catch in the tuna purse-seine fishery. However, our study used the FAO (2011) definition of bycatch: non-target species, including small-sized target species that are usually discarded and whose capture cannot be avoided by the fishing gear used.

Knowledge of bycatch provides fisheries with elements to build assertive criteria for sustainable management in regional and national contexts at ecological, economic, social, and institutional levels. Therefore, tuna bycatch has been studied in different oceans at the regional level, especially by Regional Fisheries Management Organizations (RFMOs) or research institutions of countries that are members of these organizations. For example, Gillman (2011) stated that five RFMOs have achieved mixed results in knowledge of tuna fisheries, but significant information gaps remain in terms of ecological bycatch risks and management. Various authors have analyzed bycatch in Indian Ocean fisheries with low observer coverage, building and running simulations to monitor priority species (Amandè et al., 2012); others have compiled bycatch information from tropical tuna purse-seine fisheries worldwide (Hall and Roman, 2013). In recent years, a summary of bycatch issues in the tuna purse-seine fishery overall and at a regional scale for the scientific committee of the Western and Central Pacific Commission (WCPFC) was published by Restrepo et al. (2017) and Peatman et al. (2018), respectively. In the Eastern Pacific Ocean (EPO), the Inter-American Tropical Tuna Commission (IATTC) and other research entities have been working on tuna purse-seine bycatch assemblages (Lezama-Ochoa et al., 2017) to generate data and provide some management strategies for both tuna and bycatch, for example, improvement of the use and function of sorting grids for juvenile tuna and bycatch (TUNACONES et al., 2019), quantitative ecological risk assessment of the devil ray *Mobula mobular* to manage and reduce its bycatch (Griffiths et al., 2019), strategies to reduce shark bycatch (Ortuño-Crespo et al., 2022), and modeling of Fish Aggregating Device (FAD) trajectories in critical sea turtle habitats (Escalle et al., 2022).

In Colombia, a comprehensive review of bycatch in almost all fisheries was conducted only until 2011 (Puentes, 2011). The following year, Jiménez et al. (2012) listed the main tuna purse-seine bycatch species in the Colombian Pacific Ocean (CPO) from July 2009 to July 2010. However, a couple of years later, Puentes et al. (2014) stated that there was no specific definition of bycatch in Colombia due to the high diversity of fisheries, especially small-scale ones. Despite this, the same year, Gómez et al. (2014) identified the non-commercial fish capture in small-scale bottom long-line experimental sets in the Gorgona National Natural Park and its area of influence in the CPO.

Bycatch species in the tuna purse-seine fishery have gained importance from the ecosystem to the fishery management approach, as 66% of the CPO is under a marine protected area (MPA) category (RUNAP, 1983; RUNAP, 1987; CODECHOCO, 2014; National natural Parks, 2017; CODECHOCO, 2017; Minambiente, 2022a; 2022b; 2022c). These MPAs and fishery regulations, such as Resolution 1856 of 2004 (INCODER, 2004), establish that approximately 77% of the CPO area has total or partial restrictions on tuna purse-seine fishery. Thus, knowledge of bycatch in the area is crucial under the current circumstances. This study aimed to describe bycatch information by listing the most comprehensive range of bycatch species to date, stating differences with regional studies, describing their spatial distribution, emphasizing a detailed analysis of elasmobranchs as one of the most vulnerable marine fish groups worldwide (Dulvy et al., 2014), and providing bycatch management recommendations for this fishery in the CPO.

METHODS

Knowledge of bycatch in tuna purse-seine fishery in the CPO (Figure 1) was obtained by listing the bycatch species reported from 2000 to 2019 in different class-size vessels based on the IATTC vessel carrying capacity in metric tons (MT). This classification includes vessels of class 1: 0-45 MT; class 2: 46-91 MT; class 3: 92-181 MT; class 4: 182-272 MT; class 5: 273-363 MT; and class 6: >364 MT. Data sources are listed in Table 1.

Elasmobranch bycatch data were used to conduct spatial analyses by vessel class and all fishing methods, i.e., Tuna Associated with Dolphins (DEL), Tuna not Associated (NoAs), Tuna Associated with Natural Floating Objects (NAT), and Tuna Associated with FADs. General and elasmobranch bycatch percentages were estimated using the following equation:

Bycatch percentage (%) = (*Bycatch* * 100)/ *Total catch*

in which total catch includes targeted and bycatch species data in tons per fishing set. Total bycatch and total elasmobranch bycatch are given in tons per fishing set.

Table 1. Data sources for tuna purse-seine bycatch in the Colombian Pacific Ocean. Sources include the Inter-American Tropical Tuna Commission (IATTC), the Fisheries Observer Pilot Program (FOPP), the Colombian Fisheries Observer Program (CFOP) of the Colombian Aquaculture and Fisheries Authority (AUNAP for its acronym in Spanish), and AUNAP research information.

Source	Time frame	Vessel class	Coverage
IATTC	2000-2019	5 and 6	100%
FOPP	2009-2011	2, 3, and 4	100%
CFOP	2013, 2014, 2017, 2018, and 2019	2, 3, and 4	5-12 fishing trips/year
AUNAP	2015	3 and 4	8 fishing trips

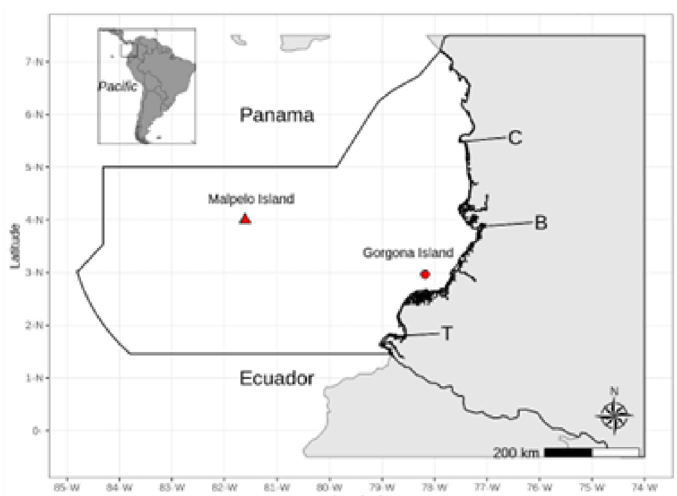


Figure 1. Colombian Pacific Ocean (Exclusive Economic Zone, EEZ) and its location in South America. Colombian reference points from north to south include Cabo Corrientes (C), Malpelo Island (red triangle), Buenaventura (B), Gorgona Island (red circle), and Tumaco (T).

A spatial analysis of bycatch was carried out using distribution maps created in R software version 4.2 (R Core Team, 2022), using different libraries, such as cowplot (Wilke 2020), ggplot2 (Wickham, 2016), ggpubr (Kassambara, 2020), ggrepel (Slowikowski, 2021), ggspatial (Dunnington, 2021), raster (Hijmans, 2022), rgdal (Bivand et al., 2022), sf (Pebesma, 2018), and tmaptools (Tennekes, 2021).

A specialized hotspot analysis focused on elasmobranch data was performed to identify spatial patterns of pronounced clustering for these species. This analysis aims to pinpoint statistically significant concentrations or depletions of species occurrences within specific geographical locations. Furthermore, it allows for an understanding of whether certain areas show discernible patterns of aggregation or dispersion of organisms beyond what could reasonably be attributed to chance (Schröter and Remme 2016; Li et al. 2017).

A prominent method for conducting hotspot analysis is facilitated by the Gi* statistic, originally formulated by Getis and Ord (1992). This statistical approach is derived from a set of values associated with spatial units (points, lines, or polygons) and is used to assess whether attribute values of high or low magnitude manifest as clustered entities or are randomly distributed. The Gi* computation produces a z-score with an associated p-value. The z-score acts as a metric to quantify the amount by which the data point value deviates from the mean value of its neighboring data points. It reveals whether a specific geographical location has a significantly higher or lower value when compared to its surrounding locations. A positive z-score indicates a hotspot (a value higher than anticipated), a negative z-score indicates a coldspot (a value lower than anticipated), and a z-score close to zero denotes a lack of significant clustering (Manepalli; Bham & Kandada, 2011; Boubekraoui et al., 2023).

The specialized elasmobranch hotspot analysis procedure involved three primary steps: 1) Cell size optimization; 2) Delineation and characterization of clustered zones; and 3) Hotspot refinement. The first step is very important to determine the most appropriate cell size for hotspot detection, as excessively small or large cells may result in underestimation or overestimation of areas of significant clustering. Such discrepancies can subsequently lead to an inflation of false negative or false positive rates, a circumstance to be avoided for effective natural resource management. To address this issue, cell size optimization was conducted iteratively, spanning the study area from 1 x 1 km to 300 x 300 km. This involved generating z-scores and p-values for each iteration. Ultimately, a cell size of 10 x 10 km was determined to maximize z-scores while minimizing p-values. Consequently, this dimension was the optimal choice for performing the final hotspot analysis. The data used for cell size optimization and final hotspot identification included the cumulative number of elasmobranch specimens captured from 2000 to 2019 within each cell. The second step was delineating and characterizing the clustered zones, starting with the creation of a 10 x 10 km grid covering the entire study area. The number of statistically significant hotspots and coldspots was determined using a neighborhood-based approach, in which focal units (cells) were juxtaposed with their neighbors within a predetermined radius or distance. Lastly, the third step of hotspot refinement consisted of omitting all coldspots and hotspots characterized by a statistical confidence level below 95% within the study area. Consequently, only those hotspots with a statistical confidence of 95% or higher were recognized as candidates for higher elasmobranch occurrence. The entire suite of procedures was performed using ArcGIS Pro.

RESULTS

Bycatch species in the tuna purse-seine fishery in the CPO

Fifty-nine bycatch species were identified in the CPO, including 27 teleost fish, 22 elasmobranchs (16 sharks and six mantas and rays), four sea turtles, two mollusks (one squid and one paper nautilus), and four marine mammals (dolphins) (Table S1). The largest bycatch fish species reported were *Mobula* spp., *Mola mola*, *Rhincodon typus*, and seven species of Billfish. Medium size bycatch included *Acanthocybium solandri*, *Caranx sexfasciatus*, *Coryphaena* spp., and *Decapterus macarellus*. Smaller bycatch included *Balistes polylepis*, *Canthidermis maculata*, *Elagatis bipinnulata*, *Kyphosus* spp., *Lobotes pacifica*, *Naucrates ductor*, and others. Regardless of size, some bycatch species are of commercial interest, while others may be discarded or used as part of the crew's diet, among other uses.

No differences in bycatch species composition were found between medium (classes 2, 3, and 4) and large vessels (classes 5 and 6). Sea turtles and dolphins were considered bycatch, but were mainly released alive, and squid were occasionally caught. Figure 2 shows some bycatch species.

Percentage of bycatch

A total of 26,625 fishing sets with bycatch records were obtained during 3,640 fishing trips in all vessel classes, with information available across the CPO. No class 1 vessels were recorded in this study. The total catch weight for target catch and bycatch was recorded for 451 fishing sets, with 20.8% of the total bycatch coming from large class vessels (5 and 6). Conversely, small and medium class vessels (2, 3, and 4) had lower bycatch, with 1,529 fishing sets analyzed, of which 1.6% corresponded to bycatch. Thus, small-medium and large vessel classes have a high difference in bycatch percentage. The discard rate of small tuna was 7.2% for small and medium class vessels, and the rate of elasmobranch bycatch was lower, less than 5% in all cases (Table 2).

Figure 2. Some bycatch species captured in the tuna purse-seine fishery in the Colombian Pacific Ocean (CPO). **A**. *Balistes polylepis*, **B**. *Coryphaena equiselis*, **C**. *Canthidermis maculata*, **D**. *Lobotes pacifica*, **E**. *Kyphosus elegans*, **F**. *Kyphosus ocyurus*. **G**. *Dosidicus gigas*, **H**. *Lepidochelys olivacea*, and **I**. *Argonauta* sp. (without shell). Photographs: E. A. Angulo ©, CFOP.

The percentage of teleost bycatch by fishing method showed that FAD sets captured most of the bycatch (80%). The most common species caught with FADs included *Coryphaena* spp. (83.2%), *A. solandri* (89%), *E. bipinnulata* (79.6%), and several fish groups, including Triggerfish (85.2%), Chubs (88.4%), Jacks and Mackerels (81.6%), and in a lower percentage, Billfish (57.3%). No teleost bycatch was reported for class 2 vessels, while the percentage of bycatch by class 3, 4, and 5 vessels remained low (Table 3). Only class 6 vessels had high teleost bycatch percentages, ranging from 77 to 88%.

Table 2. Catch and bycatch in tons and percentage in class 2, 3, and 4 vessels (data source: Fisheries Observer Pilot Program – FOPP), and class 5 and 6 tuna purse-seine vessels (data source: Inter-American Tropical Tuna Commission IATTC) in the Colombian Pacific Ocean.

Catch type	Catch in tons (%) 1,529 fishing sets Class 2 to 4 vessels Source: FOPP	Catch in tons (%) 451 fishing sets Class 5 to 6 vessels Source: IATTC
Total catch	11,811.4 (100)	18,328.5 (100)
Tuna catch	11,621.7 (98.4)	14,507.5 (79.2)
Total bycatch	189.7 (1.6)	3,821 (20.8)
Elasmobranch bycatch	51.8 (0.4)	894 (4.9)

Table 3. Teleost bycatch percentage (%) in tuna purse-seine fishery in the Colombian Pacific Ocean by fishing method and vessel class (IATTC categories). Fishing methods include DEL = Tuna Associated with Dolphins, NAT = Tuna under Natural Floating Objects, NoAs = Tuna Not Associated (school sets), and FADs = Fish Aggregating Devices. Sources: IATTC, FOPP, and CFOP.

Species or fish group (FG)	Fishing method				Vessel class			
	DEL	NAT	NoAs	FAD	Class 3	Class 4	Class 5	Class 6
Coryphaena spp.	0.9	10.3	5.6	83.2	5.8	13.6	3.2	77.4
Acanthocybium solandri	0.2	9.3	1.5	89.0	2.2	7.3	4.1	86.4
Elagatis bipinnulata	0	16.0	4.4	79.6	5.6	3.1	3.8	87.5
Lobotes pacifica	0	13.6	1.8	84.6	5.7	13.0	2.5	78.8
Billfish (FG)	17.5	8.2	17.0	57.3	1.7	7.4	2.9	88.0
Triggerfish (FG)	0.2	12.9	1.7	85.2	5.2	14.6	3.1	77.1
Chubs (FG)	0	8.3	3.3	88.4	5.2	18.3	5.2	71.3
Jacks-Mackerels (FG)	0	15.6	2.8	81.6	5.1	11.2	5.4	78.3

SPATIAL ANALYSIS OF TELEOST FISH BYCATCH SPECIES

The most commonly captured large pelagic bycatch species among bony fish were Billfish *(Istiompax indica, Istiophorus platypterus, Kajikia audax, Makaira nigricans, Tetrapturus angustirostris,* and *Xiphias gladius*). Among medium-sized species, the most commonly caught were Mahi-Mahi (*Coryphaena* spp.) and Wahoo (*A. solandri*). Smaller fish such as Cortez Sea Chub (*Kyphosus elagans*), Blue Striped Chub *(Kyphosus ocyurus*), Rainbow Runner (*E. bipinnulata*), Unicorn Leatherjacket Filefish (*Aluterus monoceros*), and Pacific Tripletail (*L. pacifica*), were reported in lower percentages of bycatch. Conversely, other smaller fish, such as the Spotted Oceanic Triggerfish (*C. maculata*), Bigeye Trevally (*C. sexfasciatus*), and Mackerel Scad (*D. macarellus*), were recorded in higher percentages. Figure 3 shows the bycatch percentages of the main teleost species and fish groups. In addition, Figure 4 shows a spatial analysis of bycatch in the CPO, in which overlapping fishing sets (black dots) represent multiple occurrences of a species in the same location (Figure 4).

The spatial analysis (Figure 4) showed that some bycatch was caught mainly in the Colombian border with Ecuador up to 4° N from east to west. This trend was observed for the Tripletail fish (Figure 4A), Jacks and Mackerels (Figure 4C), Wahoo (Figure 4D), Rainbow Runner (Figure 4E), and Chubs (Figure 4F). Other species, such as Mahi-Mahi (Figure 4B), Triggerfish (Figure 4G), and Billfish (Figure 4H), were captured throughout the CPO, from north to south and from east to west, except in an area between 4° and 5° N and between 79° and 80° W. In coastal areas, Mahi-Mahi and Billfish were captured to the north. The Rainbow Runner and Triggerfish had low catch rates; other species had a low or null catch rate . The Shortbill Spearfish *T. angustirostris* was recorded only once and had not been previously reported in the CPO.

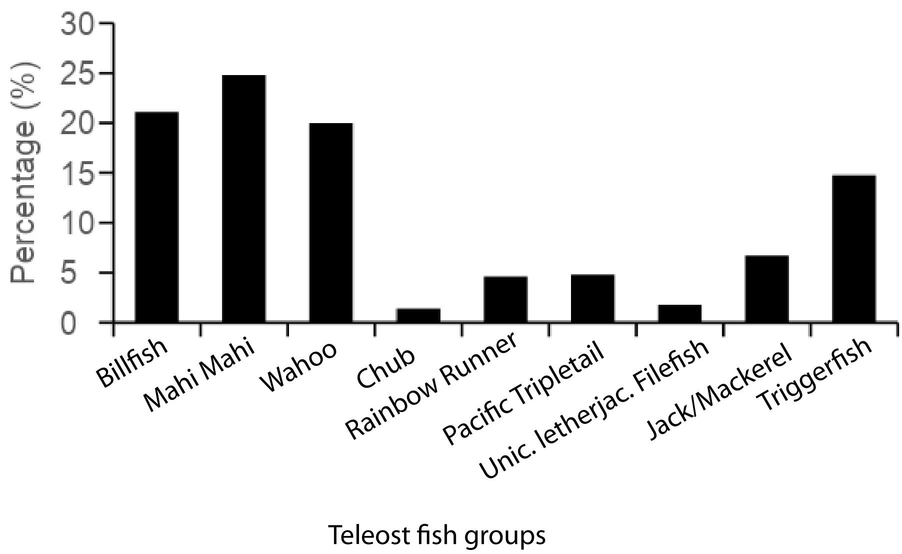


Figure 3. Teleost bycatch percentage of the main species and fish groups caught in tuna purse-seine fishery in the Colombian Pacific Ocean.

Descriptive and spatial analyses of elasmobranch bycatch

The overall elasmobranch bycatch percentage recorded in the CPO during the study period (Figure 5) confirmed that the Silky shark *Carcharhinus falciformis* was the elasmobranch bycatch species most commonly captured with FADs and, to a lesser extent, with other fishing methods. Thresher sharks *Alopias* spp. were also common bycatch with FADs and DEL. Other *Carcharhinus* species were caught less frequently with all or specific fishing methods, but were sometimes captured with FADs, DEL, and NoAs. Hammerhead sharks *Sphyrna* spp. were caught frequently, but in lower numbers. Mantas were mainly captured with FADs and NoAs, while the pelagic ray *Pteroplatytrygon violacea* was caught mainly with DEL. Four shark species (*Alopias vulpinus*, *Carcharhinus brachyurus, Carcharhinus longimanus*, and *Rhizoprionodon longurio*) were reported only once during the 20-year study period (Table S2).

Class 3 vessels reported catches from the Buenaventura Bay to the western border and south to the Ecuadorian border (Figure 6A). Class 4 vessels reported elasmobranch bycatch throughout the CPO (Figure 6B), and little bycatch was reported by class 5 vessels (Figure 6C). Elasmobranchs were captured mainly by class 6 vessels throughout the CPO (Figure 6D).

Spatial analysis of elasmobranchs by fishing method showed that DEL and FAD sets were the most common fishing methods with elasmobranch bycatch throughout the CPO (Figure 7A, 7D). DEL sets were mainly distributed in coastal areas and the northwestern upper edge of the CPO (Figure 7A). NAT sets were distributed randomly (Figure 7B), and NoA sets were distributed randomly offshore, but more frequent towards the coast from north to south (Figure 7C). FAD sets captured elasmobranchs across the CPO, except in an area off Cabo Corrientes (Figure 7D).

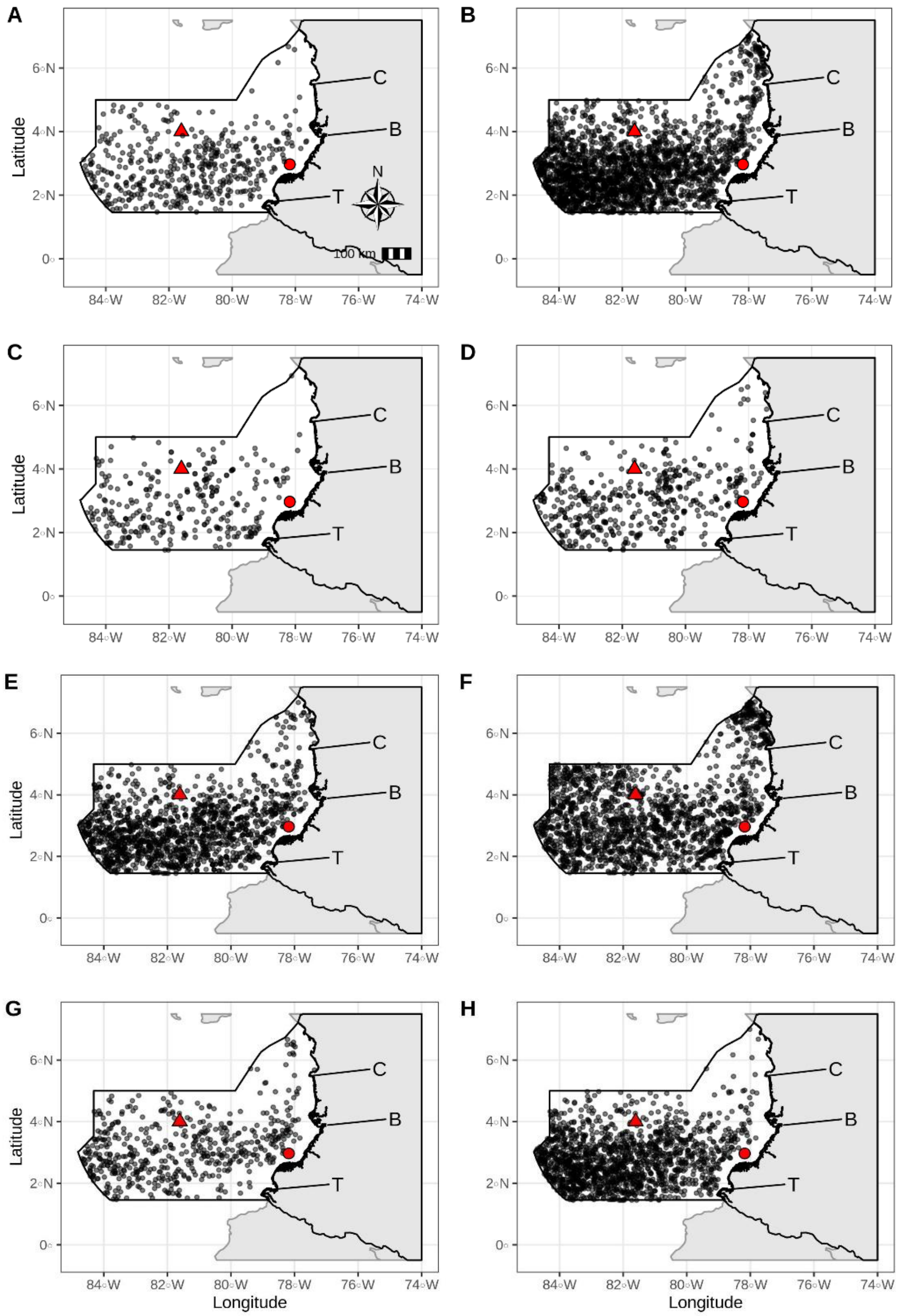


Figure 4. Spatial distribution of the main teleost fish bycatch in tuna purse-seine fishery in the Colombian Pacific Ocean from 2000 to 2019. **A**. Tripletail; **B**. Mahi-Mahi; **C**. Jacks-Mackerels; **D**. Wahoo; **E**. Rainbow runners; **F**. Chubs; **G**. Triggerfish; and **H**. Billfish. Colombian reference sites from north to south include Cabo Corrientes (C), Malpelo Island (red triangle), Buenaventura (B), Gorgona Island (red circle), and Tumaco (T). Gray dots indicate georeferenced fishing sets with the presence of the species. Black dots indicate overlapping fishing sets.

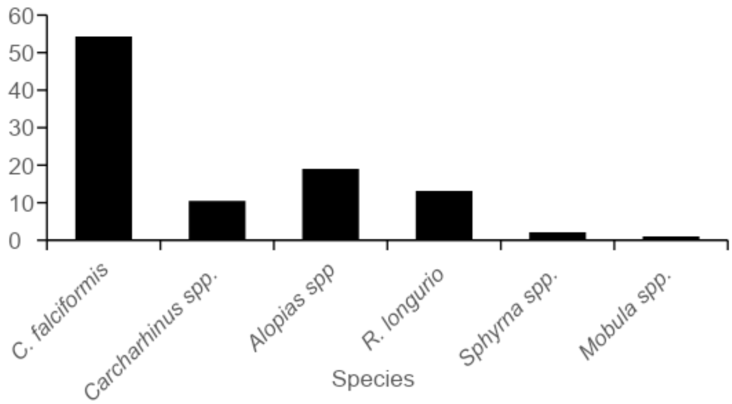


Figure 5. Elasmobranch bycatch percentages of the main species and genus caught in tuna purse-seine fishery in the Colombian Pacific Ocean.

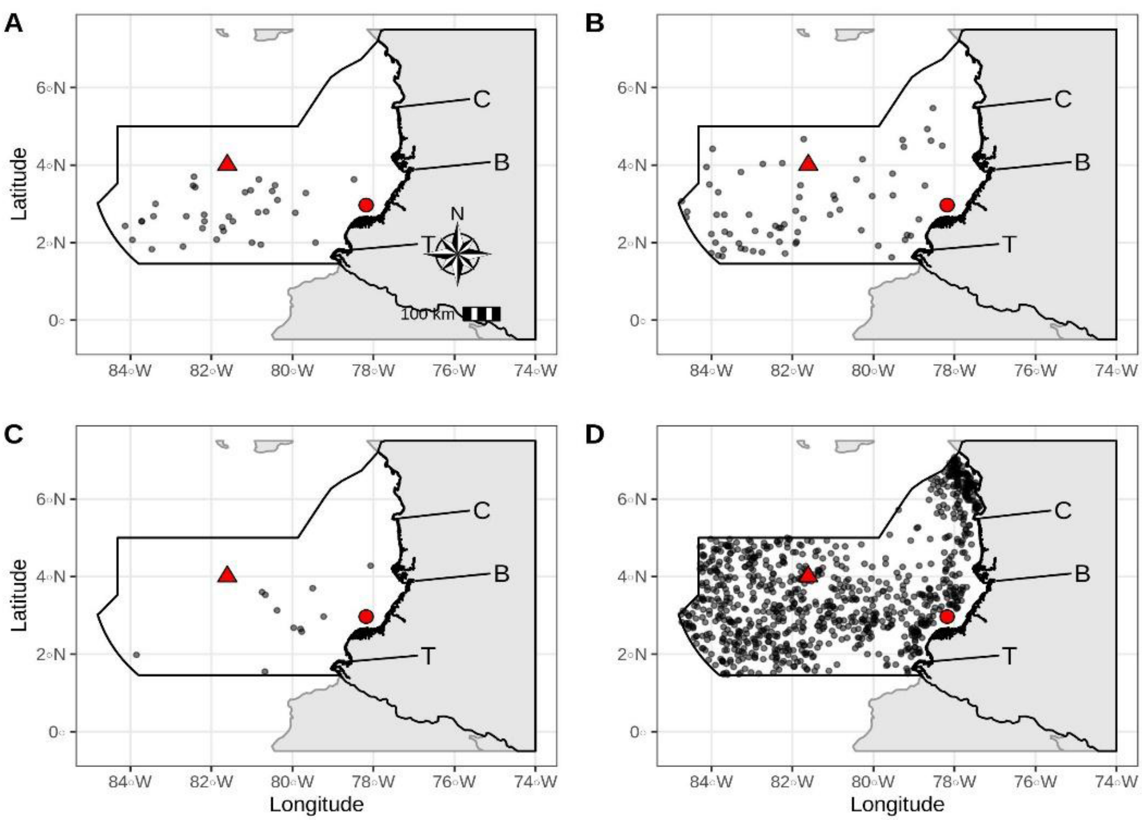


Figure 6. Spatial analysis of elasmobranch purse-seine bycatch in the Colombian Pacific Ocean by vessel class from 2000 to 2019. **A**. Class 3; **B**. Class 4; **C**. Class 5; and **D**. Class 6. Colombian reference sites from north to south include Cabo Corrientes (C), Malpelo Island (red triangle), Buenaventura (B), Gorgona Island (red circle), and Tumaco (T). Gray dots indicate georeferenced fishing sets with the presence of elasmobranchs. Black dots indicate overlapping fishing sets.

Figure 8A shows the spatial elasmobranch bycatch rates (number of elasmobranchs per set). In this figure, the main cells are highlighted for visual purposes, and cell frames do not correspond to the specimens found in each cell. The highest spatial elasmobranch bycatch rates (number of elasmobranchs per set) showed 17 cells around 4° N and 83° W near Malpelo Island, and at 2° N and 81-82° W, an area around 2-3° N and 80-81° W, other zones towards the coast, north of Cabo Corrientes, off Buenaventura Bay and west of Gorgona Island.

The statistical hotspot analysis (Figure 8B) identified 22 significant spatial hotspots for elasmobranchs, 15 at 99% statistical confidence and seven at 95%. Three hotspots were identified towards the coast around Buenaventura Bay, eight in an area at 1-2° N and 80-84° W in the southern CPO, and six from 2-3° N to 81-84° W. Other four hotspots were found at 3-4° N and 80-81° W, and another at 4° N and 83° W.

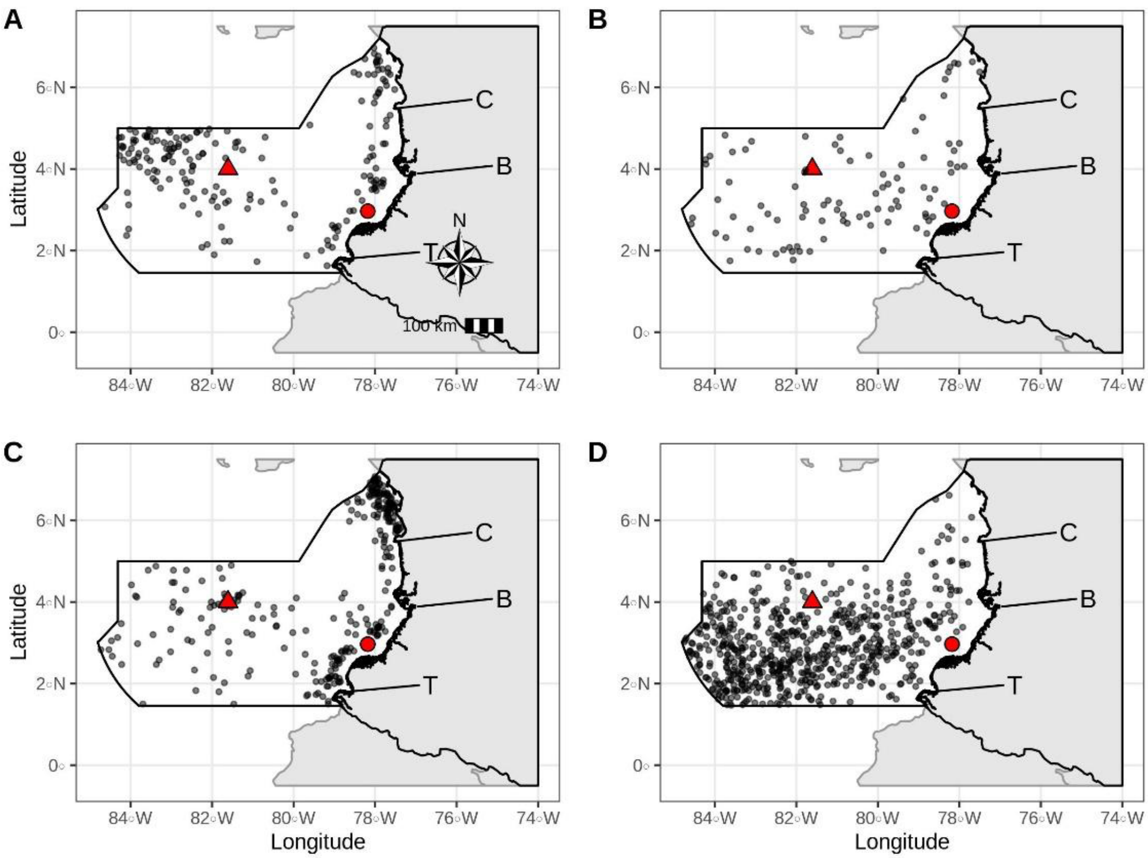
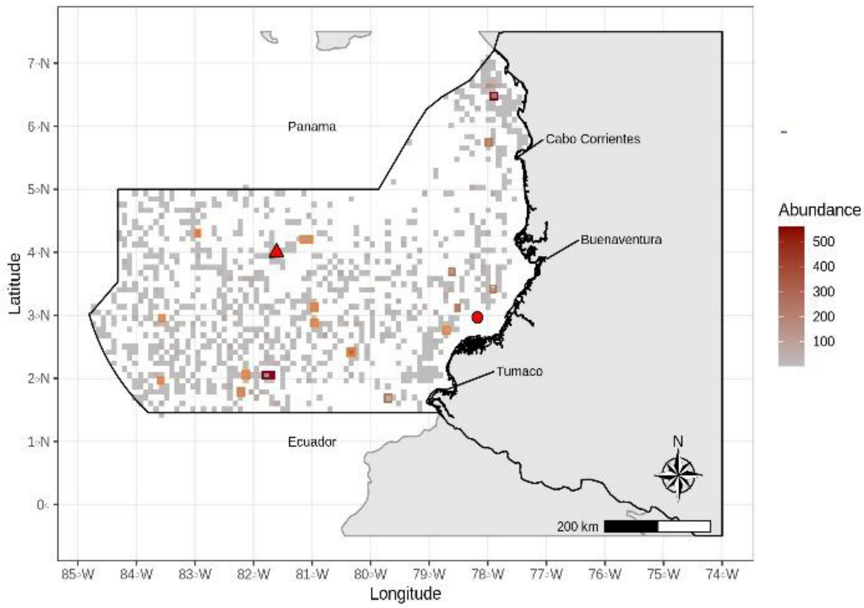


Figure 7. Spatial analysis of elasmobranch purse-seine bycatch in the Colombian Pacific Ocean by fishing method from 2000 to 2019. **A**. Tuna Associated with Dolphins (DEL); **B**. Tuna under Natural Floating Objects (NAT); **C**. Tuna not Associated (NoAs); and **D**. Fish Aggregating Devices (FAD). Colombian reference sites from north to south include Cabo Corrientes (C), Malpelo Island (red triangle), Buenaventura (B), Gorgona Island (red circle), and Tumaco (T). Grey dots indicate georeferenced fishing sets with the presence of elasmobranchs. Black dots indicate overlapping fishing sets.



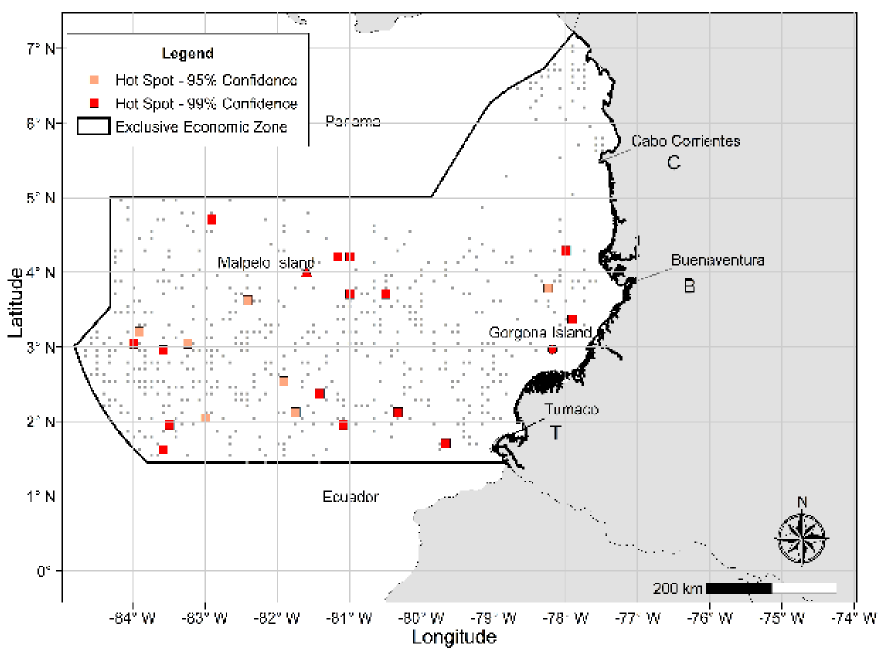


Figure 8. **A**. Higher spatial elasmobranch bycatch rates by number of elasmobranchs per set in the Colombian Pacific Ocean from 2000 to 2019. The main cells were frame--highlighted for visual purposes. **B**. Hotspot analysis of elasmobranch occurrence per cell area at 95% and 99% statistical significance. Colombian reference sites from north to south include Cabo Corrientes (C), Malpelo Island (red triangle), Buenaventura (B), Gorgona Island (red circle), and Tumaco (T).

DISCUSSION

Tuna purse-seine bycatch species were identified for Colombia's Exclusive Economic Zone (EEZ) in the Pacific Ocean in a 20-year timeframe from 2000 to 2019 and had not been analyzed before. In general, bycatch was low in terms of weight for all vessel sizes. Small and medium vessels had lower bycatch than larger vessels, and fewer bycatch species were reported in the CPO than in the EPO (Hall and Roman, 2013). However, larger vessels had higher bycatch (20.8%) in the CPO than in the EPO (9.6%) for the most commonly used fishing methods, i.e., DEL, FADs, and NoAs (Hall and Roman, 2013).

Bycatch rates may be higher in the EEZs of tropical countries due to physicochemical and biological conditions or oceanographic conditions that affect capture in the CPO and international waters of the EPO, which may reflect differences in bycatch rates between the two areas. For instance, temperature and chlorophyll appear to be the best predictors to describe the diversity of target species and bycatch assemblages in the EPO (Lezama-Ochoa et al., 2017; Salazar et al., 2021). Conversely, the CPO is a typical tropical ocean with no influence of the Humboldt Current and only a few small upwelling events throughout the year (Pineda, 1995; Villegas Bolaños, 1997a; 1997b; 2003) that bring cold water and high productivity to tropical areas.

Bycatch species

Although Jiménez et al. (2012) described the main bycatch species for medium-sized tuna purse-seine vessels in the CPO, the current study included a longer time period and all vessel sizes with bycatch records, revealing a broader list of bycatch species for the CPO. The 59 bycatch species reported here were captured with all fishing methods. However, FADs had the highest number of bycatch species. This tendency for more bycatch species to be captured with FADs has been reported in the EPO and the eastern Atlantic Ocean. In the first area, 68 bycatch species were captured with FADs compared to 56 caught with NoAs (Lezama-Ochoa et al., 2017), and in the second area 87 bycatch species were captured with FADs compared to 61 caught with NoAs (Torres-Irineo et al., 2014).

Lezama-Ochoa et al. (2017) reported several species across the EPO that were not found for the CPO in the current study, even though they have been reported in Colombian Pacific waters (e.g., *Caranx caballus, Selar crumenophthalmus, Exocoetus volitans, Urapsis helvola, Sphyraena* spp.) (Robertson and Allen, 2015). *Tarectes rubescens* is a rare species in the CPO in deep waters (Puentes et al., 2001), but has been reported as bycatch in the EPO. Differences in bycatch between these two areas may be due to observers not reporting the species, misidentifying them, or simply not catching them with tuna purse-seine fishing methods in the CPO. *Lobotes pacifica* has been reported in the CPO, and *Lobotes* cf. *surinamensis* has been recorded in the EPO. However, molecular differences are clear and these species are well separated (Tavera et al., 2012); the former inhabits the Pacific Ocean and the latter inhabits the Atlantic Ocean, with no evidence of ocean translocation. Therefore, the species reported as bycatch in the CPO and EPO is *L. pacifica*.

The spatial analyses showed that *A. solandri, E. bipinnulata*, *L. pacifica, C. sexfasciatus,* and *N. ductor* were the most common teleost bycatch species captured across the CPO, from the Ecuadorian border to 4° N. Conversely, species captured throughout the CPO include *Coryphaena* spp., *Kyphosus* spp., Billfish, and Triggerfish. These catch patterns may be influenced by fishing methods, species migration patterns, prey availability in certain areas and times, and productivity patterns related not only to upwelling events, but also to the influence of larger rivers flowing into the CPO in the central-southern Colombian Pacific coast (Cantera and Contreras, 1993; Díaz, 2002).

Four marine mammal bycatch species were reported, specifically four different dolphin species (*Delphinus delphis, Stenella attenuata, Stenella longirostris,* and *Steno bredanensis*). These animals must be released alive according to the protocols established by the IATTC (Resolution C-07-03–IATTC) and the International Dolphin Conservation Program (AIDCP). Four sea turtle species (*Caretta caretta, Chelonia mydas, Eretmochelis imbricata,* and *Lepidochelys olivacea*) were also registered, with no record of *Dermochelys coriacea*, which has not been reported in the CPO since 1999 (Ramirez-Gallego and Barrientos-Muñóz, 2015; Rivera-Gomez et al., 2016). Regarding mollusks, *Dosidicus gigas* was reported as seasonal bycatch, and a malacologist expert (J. Guerrero-Kommritz, Pers. Comm.) identified *Argonauta* sp. based on photographs (e.g., Figure 2I), a possible new report for Colombian marine biodiversity.

Bycatch by vessel size and fishing method

Differences in bycatch were detected according to vessel class, with small vessels expected to obtain less bycatch than medium or large vessels. Indeed, classes 3 to 6 had the highest bycatch reports, with most records found in class 6 vessels. However, class 5 vessels reported less bycatch due to their low presence in the CPO (Figure 6C).

Regarding the fishing method, this study showed that FADs had the highest bycatch species rate. *Coryphaena* spp., *D. macarellus, L. pacifica*, *Seriola* spp., and Triggerfish were mainly captured under or around floating objects (NAT and mostly FADs), while Billfish were caught mostly with DEL. In the EPO, bycatch species can be captured with all fishing methods (e.g., Silky shark), while other species may vary depending on the fishing method (Hall and Roman, 2013). Lezama-Ochoa et al. (2017) reported that *Coryphaena* spp. was the species most commonly caught with FADs, while *C. sexfasciatus* was the species most commonly captured with NoAs. *Mobula* spp. and Billfish were primarily caught with DEL, but *Coryphaena* spp. and *A. solandri* were rarely caught with this fishing method. Billfish were absent in FAD and NAT sets. In the western Indian Ocean, FADs had the highest bycatch, with *A. solandri, C. maculata*, *Coryphaena* spp., *E. bipinnulata,* and sharks being the main bycatch species (Taquet et al., 2007). The reasons why some species are captured more frequently with a particular fishing method than others may be related to their behavior and other factors influencing their occurrence at a certain time and in a particular area. For instance, the association of tuna and dolphins with DEL sets are observed mainly in the EPO, and several unverified hypotheses suggest that it may occur due to feeding, protection, resting, or other reasons (Ballance; Pitman & Fiedler, 2006; Scott et al., 2012).

Regardless, among the different fishing methods used in tuna purse-seine fishery in the CPO, FADs have been identified as the most used and effective (Puentes et al., 2022a), with technology that allows for the estimation of fish biomass even from long distances (Orue et al., 2019). In addition, many vessel captains believe that using different types of "bait" in FADs promotes faster aggregation under these devices, fostering their use in the region. However, no studies support this theory. Hall and Román (2013) reported the use of attractants ("bait containers") attached to the FADs in the EPO, describing them as being used "to attract tuna." Jiménez et al. (2012) described "bait containers" as one of the components of the FADs used in medium fleets in the CPO. These containers have small holes and are filled with pieces of non-commercial bycatch. In the CPO, and according to our data, the CFOP reported an additional "bait bag" filled with pork skin due to its slow decomposition rate and attached to a FAD deployed in a new area or for the first time with the bait container (Figure 9). If the bait induces faster fish aggregation, it increases the fishing effort on FADs, with vessels visiting the same FAD several times on the same fishing trip once fish aggregation is confirmed.

The percentage of Elasmobranch bycatch was low in the CPO (4.8% for sharks and 0.03% for rays), but higher than that reported in other areas worldwide. For instance, Restrepo et al. (2017) reported elasmobranch bycatch of less than 0.5% of the weight of bycatch in the tropical tuna purse-seine fishery across the Atlantic, Indian, and Pacific oceans. These differences may be related to elasmobranch migration routes, which occur specifically in the EPO between oceanic islands and seamounts (e.g., Nalesso et al., 2019; Lara-Lizardi et al., 2020), while the CPO appears to be important for sharks in reproductive (e.g., Quintanilla et al., 2015) and feeding areas (represented for several potential prey items; e.g., Vélez et al., 2019), increasing their abundance in the CPO.

Elasmobranch data reported large specimens of *Alopias* spp. and juvenile Silky sharks *C. falciformis*. The scalloped hammerhead shark *Sphyrna lewini* was frequent, with large and few specimens, and *Mobula* spp. was rare. These findings are partially consistent with those reported for the EPO, where shark species such as *C. falciformis* (75-85%), *C. longimanus* (4-10%), and *S. lewini* (1-4%) were recorded as bycatch (Hall and Román, 2013). Similarly, Restrepo et al. (2017) reported *C. falciformis* and *C. longimanus* as the main shark bycatch in the EPO. Therefore, Resolution C-21-06 (IATTC, 2021b) should be strictly enforced to release elasmobranchs alive and avoid areas recognized as having high shark presence whenever possible (see Figure 8B).

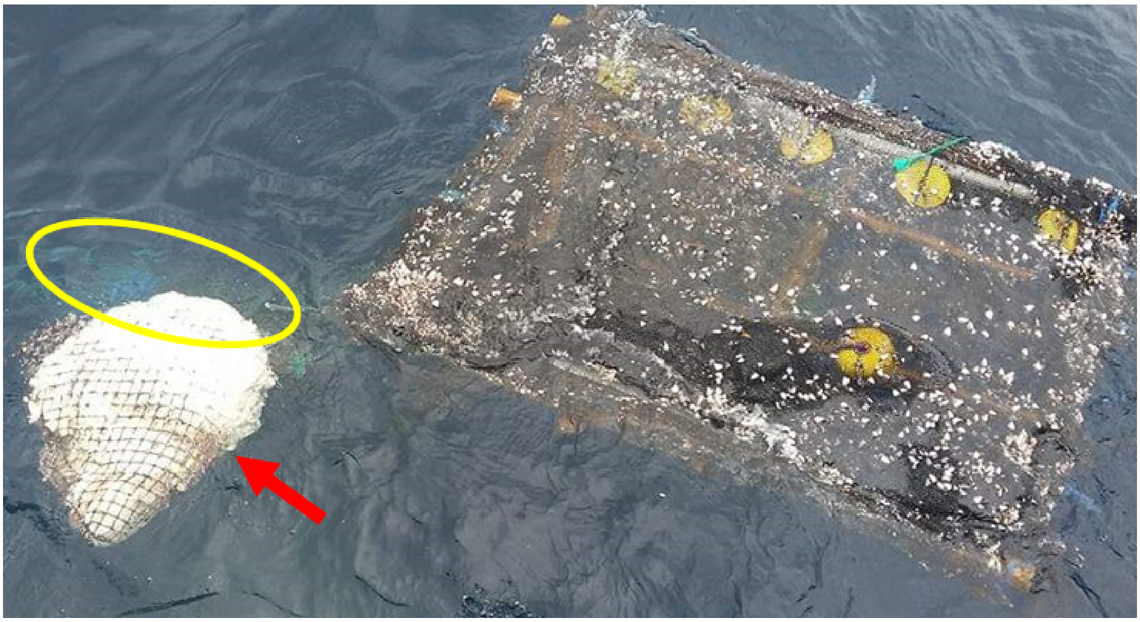


Figure 9. Drifting fish aggregating device (FAD) deployed in the Colombian Pacific Ocean. The yellow oval shows a blue submerged "bait container," and the red arrow shows an additional "bait bag." Photo: E. A. Angulo ©, CFOP.

The Common Tresher Shark *A. vulpinus* and the Shortbill Spearfish *T. angustirostris* were reported by observers in this study. Although they have been previously reported in bycatch assemblages in Fish Aggregating Devices (FADs) and School Sets in the EPO (Lezama-Ochoa et al., 2017), photographic evidence or vouchered specimens are needed to properly confirm the presence of these two species in the CPO. Other species reported in this area (e.g., *Carcharhinus altimus, Carcharhinus plumbeus, Isurus oxyrynchus, Isurus paucus*, and *Sphyrna media*) were not included in this study due to their coastal demersal and subtropical distribution associated with islands (e.g., Galapagos Islands) or due to the fact that they are common in tuna long-line fishery but not in tuna purse-seine fishery (Bonanomi et al., 2017; Compagno, 1984; Grove and Lavenberg, 1997; Hall and Roman 2013; Lezama-Ochoa et al., 2017).

Elasmobranch bycatch was common throughout the CPO for all fishing methods and vessel sizes. However, species such as *Alopias* spp., *C. falciformis*, *Carcharhinus limbatus*, *Carcharhinus obscurus*, and *R. longurio* were more commonly caught with FADs and rarely caught with other fishing methods. Devil and pelagic rays were more commonly caught with DEL and NoAs. Similarly, in the western Indian Ocean, the highest elasmobranch bycatch was recorded for FADs (>40%) compared to NoAs (<17%), varying by species (Clavareau et al., 2020).

The highest spatial elasmobranch bycatch rates indicate the sites where most of these fish were captured (Figure 8A), and these were confirmed by the hotspot analysis in most areas with higher bycatch occurrence (Figure 8B). Although counting high numbers of bycatch specimens by a single observer in a set can be difficult, and observers may tend to make estimates, areas of higher elasmobranch bycatch occurrence were identified in the CPO. Higher occurrences in these places may be due to the reasons mentioned above, i.e., fishing methods, prey availability, migration routes, and high productivity areas, among others (Cantera and Contreras, 1993; Díaz, 2002; Nalesso et al., 2019; Lara-Lizardi et al., 2020).

Bycatch management

Elasmobranchs are important to prioritize for bycatch management in tuna purse-seine fishery, particularly *Alopias* spp. and *C. falciformis*, which are the most captured and vulnerable species in the CPO (Puentes et al., 2022b).

Further annual bycatch analyses are needed to identify high intra-annual bycatch seasons and areas to enforce additional management measures for elasmobranchs and other species. An Ecological Risk Assessment (ERA) and a Productivity-Susceptibility Analysis (PSA) in the EPO for DEL, FADs, and NoAs showed that the most vulnerable species are elasmobranchs (*Alopias* spp., *C. faciformis*, *Mobula* spp., and *Sphyrna* spp.). Other species, such as Tuna and Billfish, were classified as moderately vulnerable, and other bony fishes were the least vulnerable (Duffy et al., 2019).

Alternatives for bycatch reduction and management include: i) installing excluder devices in purse-seine nets; ii) removing FADs from the net before it is completely closed; iii) releasing elasmobranchs alive as far as possible from the net or onboard; iv) avoiding sets on small tuna (e.g., <10 t); v) changing the effort on NoAs and FADs, as well as FAD time setting; vi) using non-entangling FADs; vii) using cargo nets and stretchers to release bycatch species from the vessel (e.g., devil rays); viii) using deterrents or attractants to remove bycatch species; ix) using capture data to search for FAD spatiotemporal patterns and identify places and seasons to avoid higher bycatch; x) 100% observer coverage on board in all vessel classes; and xi) fishing closures (Kondel and Rusin, 2007; Hall and Roman, 2013; Bonanomi et al., 2017; Restrepo et al., 2019; Torres-Irineo et al., 2019; Grande et al., 2019). Some alternatives can be implemented by the Colombian Aquaculture and Fisheries Authority (AUNAP for its acronym in Spanish) within the National Committee for Bycatch Management via Resolution No. 1970 of 2018 (AUNAP, 2018), while others depend on regional IATTC negotiations.

Marine Protected Areas (MPAs) may help regulate fishing efforts. However, if fishing efforts are significantly increased, the MPAs declared or expanded in the CPO will affect the sustainable fishing potential already identified in the CPO (Puentes et al., 2022a). The spillover effect may be diluted when MPAs are so large that the spillover effect is not noticeable, or when migratory species leave the MPA without reaching sexual maturity and become part of the bycatch in fishing areas.

Dynamic spatial closures (e.g., Hazen et al., 2018; Pons et al., 2022) may be possible in the CPO, but the IATTC has already established an extended closure of 72 days for purse-seine vessels (IATTC, 2021a), which Colombia has implemented. Nevertheless, further studies on target and bycatch species are needed to implement such a closure. For instance, the high bycatch of FADs needs to be regulated in the CPO by including a limited number of FADs per vessel (Isaza-Toro et al., 2021; AUNAP, 2022), regulating FAD attractants to control effort, continuing to enforce strict release bycatch protocols when possible, and implementing alternatives to reduce FAD bycatch.

For elasmobranchs, live release of bycatch is the most feasible alternative to reduce bycatch impacts while maintaining fishing activity. Grande et al. (2019) reported that release protocols improved the live release of mantas, rays, and whale sharks by 100%, turtles by more than 95%, Hammerhead sharks by 80%, and other shark species by more than 50%. Nevertheless, Colombia may need to review all bycatch release protocols and work towards FAD management to reduce bycatch.

The situation of the CPO in 2023, with around 77% of its area under partial or total restrictions for tuna purse-seine fishery, requires future detailed studies on species and groups of species to provide crucial information that may allow for other effective management measures.

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AUTHOR CONTRIBUTIONS

V. P.: Conceptualization; Investigation; Writing – original draft; Writing – review & editing.

D. C. B., K. B. A.: Methodology; Formal Analysis; Software; Writing – review & editing.

F. D. E., L. A. Z., J. T.: Investigation; Formal analysis; Writing – review & editing.

E. Z., J. A.: Data curation; Writing – review & editing.

C. G. B., A. S. M., C. J. P., I. F. B.: Formal analysis; Writing - review & editing.

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