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DESCRIPTIVE AND SPATIOTEMPORAL ANALYSIS OF THE TUNA PURSE SEINE FISHERY IN THE COLOMBIAN PACIFIC OCEAN

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Abstract: The tuna purse seine fishery is a large-scale fishery in the Colombian Pacific Ocean (CPO). This study aims to perform a descriptive and spatiotemporal analysis of the purse-seine tuna fishery in the CPO to provide new knowledge and alternatives for its domestic management. Georeferenced data (2000 – 2019) allowed the analysis by species, vessel carrying capacity, and fishing method. Yellowfin Tuna-YFT (*Thunnus albacares*) and Skipjack Tuna-SKJ (*Katsuwonus pelamis*) were the most captured species. The Not Associated method (NoAs) was mostly used in the first decade, while the method associated with Dolphins (DEL) was mainly used in the second. The natural floating objects method (NAT) was the least used method, while the fish aggregating device method (FAD) was the most used. There was no clear annual catch pattern with discrete peaks in May and October. The average number of sets per year was 1,230, and only 8.7% of the tuna was captured by the Colombian tuna fleet in the CPO. Capture per Unit Effort oscillated from 14.9 to 27.2 t/effective set/year. The spatiotemporal analysis showed four main fishing grounds; YFT was mainly fished in the northwestern zone and near the coast, while SKJ was captured in almost all CPO; the main fishing activity is performed by the largest vessels, showing significantly higher tuna catches. The DEL method is used mainly in the central area and towards the coast, while FAD is used in most of the CPO. It is important to work on the FAD regulation, small tuna discards, increase the fishing observer coverage, satellite, and on-the-field vessel monitoring, and characterize environmental conditions related to tuna fishing. Furthermore, tuna fishing should be considered in the initiatives to establish new protected areas in the CPO.

Keywords: Tuna purse seine fishery,

fishing methods, spatial-temporal analysis, Colombian Pacific Ocean.

INTRODUCTION

Industrial tuna purse seine fishing is carried out in the Eastern Pacific Ocean (EPO) in national and international jurisdictional waters. The Inter-American Tropical Tuna Commission (IATTC, https://www.iattc.org) and national regulations and provisions of each country belonging to the IATTC regulate this activity. In Colombia, 14 vessels whose lengths vary between 32.9 m and 78.3 m with carrying capacities between 227 and 1,367 metric tons are registered in the IATTC regional vessel registry (https://www.iattc.org/VesselRegister/VesselList.aspx?List=RegVessels&Lang=SPN#Colombia). These are authorized by the national maritime and fishing authorities to operate in national and international waters.

In addition, until 2019, 39 foreign flag vessels (mainly Ecuadorian) were duly affiliated with a Colombian company to operate in national jurisdictional waters of the Colombian Pacific Ocean (CPO). The procedure established for these vessels is that upon arrival at the port of San Andrés de Tumaco, they must process an authorization (a set sail) with the Harbor Master's Office (Maritime Authority). An observer gets on board (when available), and they then depart to fish in Colombian and/or international waters. At the end of their fishing trip, they return to this port and land some of the bycatch and the observer.

The dynamics of the purse seine tuna fleet in the EPO have been detailed by Sun et al. (2016), working on social and environmental factors for the spatiotemporal decision process of the purse seine fishery effort. As part of understanding the fisher behavior and the fisheries dynamics when establishing management regulations, Torres-Irineo et al. (2017) found that the Mexican purse seine fishery associated with dolphins decreased their time at ports, increased their fishing sets, and maintained the proportion of successful fishing sets in response to closed seasons. Zhang et al. (2021) analyzed the fishing behavior of tuna purse seine vessels spatially based on Automatic Identification System (AIS) data to identify the operating status of tuna purse seiners. The authors described the spatial characteristics of fishing intensity and the distribution of hot spots and analyzed the spatial attributes of vessels to describe their fishing behavior.

Detailed information and behavior of the tuna purse-seine fishery are little known for the CPO. Therefore, this study aims to perform a descriptive and spatiotemporal analysis of the purse-seine tuna fishery that operates in the CPO to provide new knowledge about this fishery and alternatives for its management at the national level.

MATERIAL AND METHODS

This study uses background data on the industrial tuna fishing activity with purse seine in the CPO during the last 20 years (2000-2019). The relevant data sources include the databases of the Fisheries Observers Pilot Program (FOPP) (INCODER database from 2009, 2010, and 2011) and the Colombian Fisheries Observer Program (CFOP) (AUNAP database from 2013, 2014, 2016, 2017, 2018, and 2019), a research project between AUNAP and Squalus Foundation (2015), and the database of the Inter-American Tropical Tuna Commission (IATTC) for the CPO jurisdictional waters between 2000 and 2019. The FOPP was carried out by INCODER, i.e., the national fisheries authority, until 2011. The CFOP was established in 2013 and has been carried out by the National Aquaculture and Fisheries Authority (AUNAP, for its acronym in Spanish), the current fisheries authority, since mid-2011. This program was operated for years by entities such as Conservation International Colombia, Fundación Fauna Caribe Colombiana, and Universidad del Magdalena.

A general descriptive analysis of the fishery and the spatiotemporal analysis of tuna catches by species, vessel carrying capacity (vessels of classes 2, 3, 4, 5, and 6 according to IATTC), and fishing method were carried out in the CPO. The fishing methods included tuna associated with Dolphins (DEL), tuna not Associated (NoAs, school sets), tuna on natural floating objects (NAT), and tuna captured on Fish Aggregating Devices (FAD).

The general effort was assessed in terms of sets performed per year. Capture per unit effort (CPUE) was estimated in tons per number of effective sets per year. Densities mapping by species, vessels, and fishing methods was represented as interpolations produced from XYZ coordinates data using the software Surfer 17™. The Point kriging method was implemented to create grid-based contour maps to estimate the values of the points at the grid nodes. Kriging predicts the value of a function at a given point generating a weighted average of the known values (Wojciech, 2018). The interpolation limits are the Colombian jurisdictional waters of the Pacific Ocean.

A simple periodogram analysis was applied to the entire tuna catch time-series data (aggregated for all species) from 2000 to 2019 to identify its seasonality structure. A Mann-Kendall test was employed to test its global trend. A hotspot analysis in QGis (Hotspot Analysis plugin for Local Indicators of Spatial Association LISA) was performed to detect fishing grounds using the Getis-Ord statistic of spatial association (Gi*) (Getis & Ord, 1992). This was done on a 0.05° x 0.05° grid where catch values were counted to calculate z and p-values from the G* statistic. These values were transformed into a shapefile and plotted to identify the statistically significant spatial clusters of high tuna catches and, thus, the tuna fishing grounds in the Colombian Pacific Ocean at 90, 95, and 99% statistical confidence levels.

RESULTS AND DISCUSSION

TARGET SPECIES

The targeted species for tuna purse seine fishery in the CPO are YFT (*Thunnus albacares*), SKJ) (*Katsuwonus pelamis*), and Bigeye tuna (BET) (*Thunnus obesus*). Other species, such as Black Skipjack tuna (BKJ) (*Euthynus lineatus*) and the Bullet tuna (FRZ) (*Auxis thazard*, *Auxis rochei*), are eventually captured. The catch percentage by species showed that the main species captured in the CPO was YFT, followed by SKJ. At the same time, the catch of other tuna species was considerably lower. The species with the highest catches oscillated over the years; the largest catches of YFT occurred in 2001, 2004, 2009, 2010, 2012, 2015, 2016, 2017, 2018, and 2019, and for the rest of the years, i.e., 2000, 2002, 2003, 2005, 2006, 2007, 2008, 2011, 2013, and 2014, SKJ registered the highest catches. These results suggest peak abundance alternation for these tuna species (Fig. 1A).

DESCRIPTIVE ANALYSIS OF THE TUNA PURSE SEINE FISHERY IN THE COLOMBIAN PACIFIC OCEAN

This study represents the most updated effort to describe the tuna purse seine fishery in the CPO with the most robust data set of catches in space and time so far. A total of 25,364 fishing sets were analyzed between 2000 and 2019. The data showed that an average of 17,000 t/year of tuna were caught in the CPO, with the highest catches occurring in 2000, 2005, 2014, 2015, and 2019 (25,900-31,200 t), and the lowest in 2004 and 2012 (6,800-9,300 t). Catch records exhibit three major periods of industrial purse seine tuna fishing in the CPO: i) one of decreasing catch (2000-2004), ii) one of catch stabilization around 15,000 t (2005-2013), and iii) one of increasing and stabilization catch at higher averages than 18,000 t (2014-2019) (Fig. 1B). This indicates the significant tuna production potential of the Colombian Pacific Ocean. It must be stressed that tuna has the highest catch of any fish species in the country, an issue that has been improving in recent years.

The catch analysis by vessel flag showed that foreign-flagged vessels had considerably higher catch participation (91.3%) than national-flagged vessels registering the remaining 8.7% catch participation in the CPO. The latter process their landings in national facilities (Cartagena). However, the former process only a small percentage of their catch in Colombian facilities (Barranquilla), and most tuna captured is processed abroad, not generating any socioeconomic benefits for the country. Polo et al. (2014) reported that the Colombian fleet carries out the most fishing activity (92.5% on average) on international waters.

The FOPP that operated between the end of 2009 and mid-2011 allowed analyzing 1,529 sets in detail, mainly from 2, 3, and 4 class vessels. All were foreign-flagged vessels, commonly with Ecuadorian flag, that departed and arrived at the Port of Tumaco with 100% coverage of observers on board. This fleet fished tuna in Colombian, Ecuadorian, or international waters, using mainly FAD or NoAs fishing methods and less NAT. They captured mainly YFT and SKJ in Colombian waters (Jimenez et al., 2012; Zambrano et al., 2014). Catches with DEL sets are not allowed to be used by most fleet vessels. Although this fleet showed a significant non-effective set (43.9% of zero captures), 56.1% of the sets (858 sets) were effective in catching or bycatching tuna, or both. Of these, 74% fished in Colombian jurisdictional waters, while the remaining 26% were in Ecuadorian or international waters. The tuna species predominantly caught in Colombian waters were YFT (44%) and SKJ (39%), while BET did not exceed 3% of the total catch. The remaining 14% belonged to other tuna species, such as BKJ and FRZ. On the other hand, an analysis of the catch records of the foreign fleet from IATTC data and the catch records from the Tumaco Port showed that this fleet had a significant catch percentage in Colombian waters from 2010 to 2019 (Table 1). This catch represents from 33% to 84% of the total recorded catch in the CPO.

Year	Catch (t) by foreign fleet (Tumaco Port)	Total catch (t) by foreign + national fleets	Catch percentage (%) by foreign fleet (Tumaco Port)
	Source: AUNAP	Source: IATTC	
2010	5,867	17,563	**33.4**
2011	6,303	18,448	**34.2**
2012	7,861	9,327	**84.3**
2013	9,277	16,040	**57.8**
2014	18,030	25,935	**69.5**
2015	12,635	21,920	**57.6**
2016	5,888	13,333	**44.2**
2017	9,819	18,242	**53.8**
2018	9,318	14,234	**65.5**
2019	15,762	19,614	**80.4**

Table 1. Tuna catch percentage of the foreign fleet in the Colombian Pacific Ocean as recorded by the Port of Tumaco from 2010 to 2019.

No clear annual tuna catch trend was identified because tuna is highly dependent on environmental sea conditions. The Mann-Kendall test showed no statistically significant trend in the tuna catch time series from 2000 to 2019. Further, a simple periodogram analysis showed that the only dominant frequency (higher spectrum) was 0.083, equivalent to 12 months. Hence, the tuna catch time series has a 12-month seasonality with conspicuous annual cycles. Although the statistical results showed higher catches between May and September (5 months), where catches are 300% higher on average compared to the rest of the year, May and October appear to be reference months for a higher catch. The fleet coming from Ecuador is more active during the second half of the year, and this may be one of the reasons for the higher catch registries in October in some years.

Navia and Maldonado (2019) analyzed 4,113 purse seine sets of class 6 vessels for the Integrated Management National District (IMND) Yuruparí-Malpelo. Although it shares some similarities with this study as finding the same species caught, i.e., YFT and SKJ, the main differences are related to the fact that their analyses were mainly focused on the IMND area and class 6 vessels. In contrast, this study analyzed fishing sets in the entire CPO, including sets of all vessel classes from national and foreign flags.

Tuna purse-seine fishery by fishing method

Although the fishing gear is purse seine, the fishing methods differ. Since sets on floating objects (OBJ) defined by IATTC were not NAT sets, they were treated as FAD sets for this study. This was confirmed by CFOP observers, where FAD and NAT are distinguishable from one another. Catch by fishing method showed that the NoAs sets were highly effective between 2000 and 2010 but gradually declined in the following decade (2010-2019). On the contrary, DEL sets were the less effective method during the first decade and began to increase towards the second decade. The highest catches with DEL occurred in 2013 (6,200 t) and 2016 (11,600 t). FAD was the most widely used method during the entire study period, still having the lowest catches in 2004 and 2016 (871 and 2,600 t, respectively). For the rest of the years, the catch with FAD was higher than other fishing methods, with peaks in 2000 (over 15,000 t) and 2014 (ca. 17,500 t). NAT sets were the least used method, with a peak of around 2,400 t in 2000, and did not surpass 1,000 t until 2007. After 2008, catches with NAT did not reach 400 t (Fig. 1 C). DEL and FAD sets obtained significant relevance, leading the fishery catches and showing a significant shift between decades.

The NoAs sets are usually used when it is possible to detect the tuna schools on the surface according to the different categories identified by Roman and Hall (2013) in vessels that may use FAD sets as well. In the CPO, NoAs and NAT sets may be used by the legal foreign-flagged vessels coming from Ecuador and maybe opportunistically by the national-flagged vessels.

Tuna purse-seine fishery by vessel type

The catch by vessel type results showed that class 6 vessels, i.e., the biggest, caught most of the tuna in the Colombian Pacific during the study period. The catch peaks were 15,400 t in 2000, more than 11,400 t in 2005, and around 12,800 t in 2016-2017, showing the largest vessels had significantly higher catches in the study period. Class 5 vessels were more important during the first decade, with the highest catches ranging from 1,200 to 4,600 t in 2000, 2005, 2007, and 2010. For the second decade, the largest catch for class 5 vessels occurred in 2014, with more than 6,200 t. For class 2, 3, and 4 vessels, i.e., small-medium sized vessels, catches in the first decade were generally lower, except in 2000, when those were even higher than for class 5 vessels. For the second decade, catches increased, reaching or exceeding the catches of class 5 vessels (Fig. 1D).

Although class 5 vessels are categorized as large vessels, they did not have a similar catch as class 6 vessels, and their catch was sometimes surpassed by smaller vessels. There were probably fewer 5 class vessels (national or foreign) than other class vessels (foreign vessels) fishing in the area during the studied period. The Colombian fleet has only one class 5 vessel, and the foreign fleet allowed to fish in the CPO registered fewer class 5 vessels.

Effort and Capture per Unit Effort (CPUE)

The general effort showed an average of 1,230 sets/year. It was exceptionally high in 2001 with 2,037 sets and dropped to 587 sets in 2004. Effective sets per year, i.e., sets with tuna catches, were always under the total effort previously described but always followed the same trend. However, there are many fishing sets with zero catches with an average of 365 sets/year.

Effective sets followed the same tuna catch trend (Fig. 1B) in the three main periods. However, higher catches did not coincide with higher efforts, except for the lowest effort that coincided with the lowest catch in 2004.

Capture per Unit Effort (CPUE) was estimated in tons per effective set per year for the first time in this study (Fig. 2). It showed the highest values in 2000, 2006, 2008, and 2011, with more than 26 t/effective set/year. Between 2001 and 2004, CPUE ranged from 15.9 to 20.1 t/set/year. From 2005 to 2012, CPUE oscillated between 15 and 28 t/effective set/year, and from 2013 to 2019, it became steadier, ranging again between 15 and 21 t/effective set/year, with an increasing trend in 2019.

As a preliminary indicator of abundance, it showed an average of 20 t/set ranging from 13.8 t/effective set/year to 27.6 t/effective set/year for the CPO between 2000 and 2019. these values showed an oscillating pattern from 2000 to 2009 and stabilized in 2010. Tuna catch (Fig. 1A) and CPUE values indicate a significant potential for tuna fishing in the CPO not reported previously.

SPATIOTEMPORAL ANALYSIS OF THE TUNA PURSE SEINE FISHERY IN THE COLOMBIAN PACIFIC OCEAN

Figure 3A shows the highest, medium, and lowest catch per set in 20 years, identifying preliminary four large fishing grounds. Two fishing grounds are offshore; the first is located between 4° and 5° N and between 82° and 84°W in the northwestern zone (Fig. 3A, a), including part of the IMND Yuruparí-Malpelo declared by Resolution 1908 of 2017. The second has the most extensive area and is located in the central-southern zone between 79.5° and 84° W and between the Ecuadorian border and 3.5°N (Fig. 3A,b). The other two fishing grounds are located toward the coast. One is between the Panamanian borders and off Malaga Bay (Fig. 3A, c), which may be overlapped with some artisanal tuna fishing grounds identified by Rodriguez et al. (2020). The other is between Buenaventura Bay and the Ecuadorian border off Cabo Manglares (Fig. 3A, d), which could be overlapped with the Mahi-Mahi (*Coryphaena hippurus*) season of some artisanal long-liners that may go offshore, and overlaps with the IMND Cabo Manglares, Bajo Mira and Frontera (declared by Resolution 2299 of 2017). The latter are presumably influenced by high primary productivity due to the rivers' discharge into the sea, bringing plenty of nutrients (Restrepo-Angel, 2008; Isaza et al., 2020).

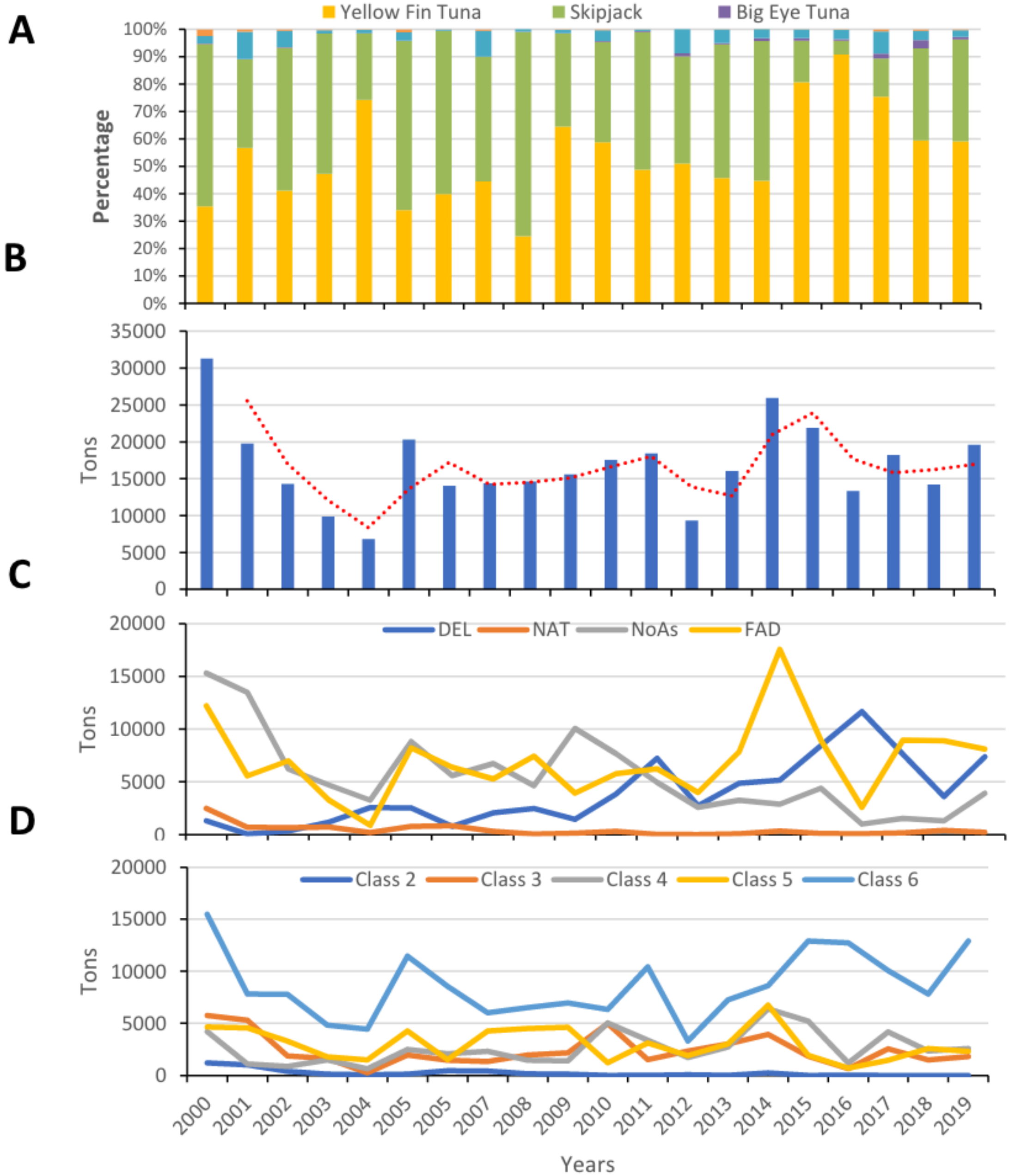

Figure 1. Tuna purse seine fishery in the Colombian Pacific Ocean between 2000 and 2019. **A**. Percentage of tuna catch per species, **B**. Total tuna catch (t), **C.** Tuna catch (t) per fishing method, and **D.** Tuna catch (t) per vessel class, according to the IATTC classification (classes 2, 3, 4, 5, and 6). DEL: Tuna associated with Dolphins; NoAs: Tuna not Associated; NAT: Tuna on Natural floating objects; FAD: Tuna catches on Fish Aggregating Devices.

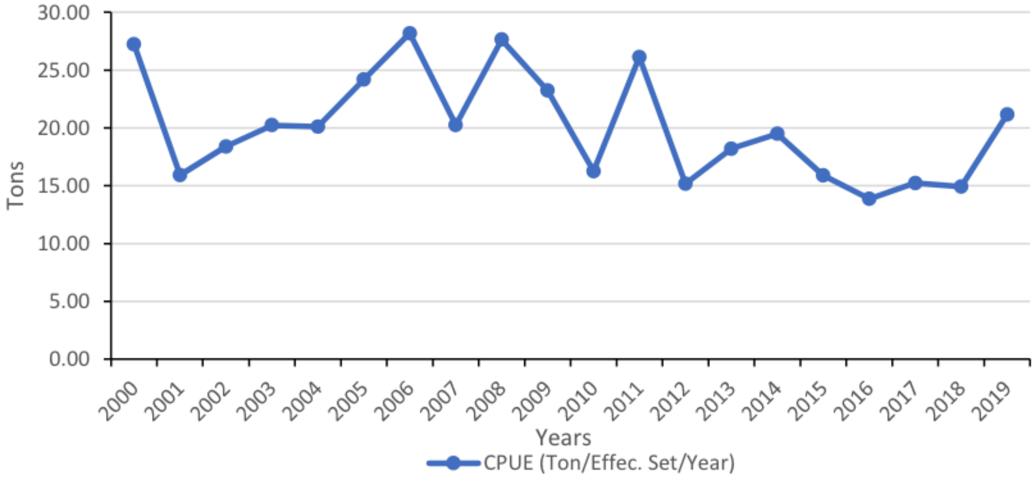

Figure 2. Capture per Unit Effort (CPUE) of tuna catches in the Colombian Pacific Ocean in tons per effective set per year.

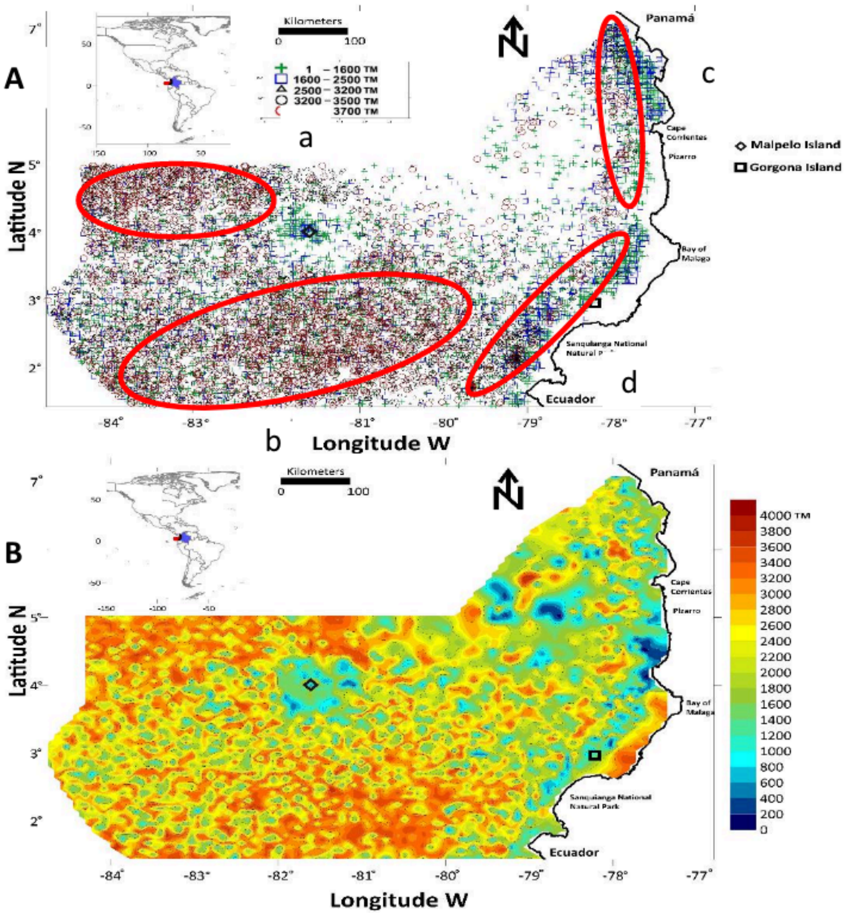

Figure 3. **A.** Identification of fishing grounds based on the highest tuna catches in the Colombian Pacific Ocean between 2000 and 2019 (a, b, c, d). **B.** Spatial analysis of average tuna catch density of industrial tuna purse seine fishing between 2000 and 2019.

The IMNDs mentioned are IUCN category VI protected areas allowing sustainable use. Their management plans are, however, under construction with some proposals, including no industrial fishing in Cabo Manglares, or allowing the NoAs fishing method for all class vessels, DEL fishing method for class 6 vessels, and a complete ban of the FAD fishing method (e.g., Yuruparí-Malpelo) (AUNAP-WWF, 2020a, b).

The general average catch density through a spatiotemporal analysis (Fig. 3B) confirms that purse seine tuna fishery is widespread throughout most of the CPO. High catch density areas are identified in the northern and central-southern offshore parts of the CPO. Some others are off Cabo Corrientes, off Pizarro, between Malaga Bay and Gorgona Island, and off Cape Manglares.

Statistical analysis identified seven tuna fishing grounds with statistical confidence equal to or higher than 99% for the study period. Most fishing grounds were located toward the Colombian Pacific coast, up to 150 km offshore from the north part near the Panamanian border up to Cape Corrientes, and from Malaga Bay heading south up to the border with Ecuador.

A fishing ground was statistically identified around Malpelo island, but this area is a Fauna and Flora Sanctuary (FFS) declared by Resolution 1292 of 1995, so this area is not currently a fishing ground. Other fishing grounds were statistically confirmed southwards from the Malpelo island and from east to west across the CPO with 90 and 95% statistical confidence levels. This spatial and statistical analysis establishes spatially four main fishing grounds for the tuna purse seine fishery in the CPO.

The results of the year-by-year spatiotemporal analysis (Fig. 4) with all effective fishing sets throughout the study period showed differences per year.

In 2000 (highest catch), fishing sets were concentrated in the southern part of the CPO towards coastal areas and around Malpelo Island. For 2001, the trend remained in Malpelo, and other sets were registered in the northern coastal areas of the CPO, evidencing illegal fishing in the protected area, especially during the first decade of the study period.

Between 2002 and 2003, sets were dispersed throughout the CPO. Between 2004 and 2009, they were again concentrated in coastal areas of the northern and southern CPO, gradually leaving the surroundings of Malpelo Island as a fishing place. Between 2010 and 2015, most of the sets were located along the southern coastal areas, and only a few were in the northern coastal areas, although more expanded offshore. Between 2015 and 2019, the set pattern was more uniform throughout the CPO, with almost no sets around Malpelo Island. The tuna fleet started to gradually abandon the surroundings of Malpelo Island in 2012, as control and surveillance at sea apparently improved. Furthermore, due to the expansion of this protected area in 2017 (declared by Resolution 1907 of 2017), it was barely visited by tuna purse seine vessels in the late 2010s (Fig. 4).

The year-by-year spatiotemporal analysis showed that catches concentrate in specific fishing grounds in some years but get dispersed during others. This fishery behavior may be caused by several factors such as 1) tuna behavior and abundance, 2) behavior of vessels belonging to the same company, and 3) sea conditions, e.g., sea surface temperature, primary productivity, and sea currents.

Isaza et al. (2020) analyzed the spatial distribution of the standardized catch effort associated with the foreign purse seine tuna fleet that operated in the eastern tropical sector of the Eastern Pacific Ocean between 2009 and 2015, as monitored by the FOPP (2009, 2010, 2011) and data from the CFOP

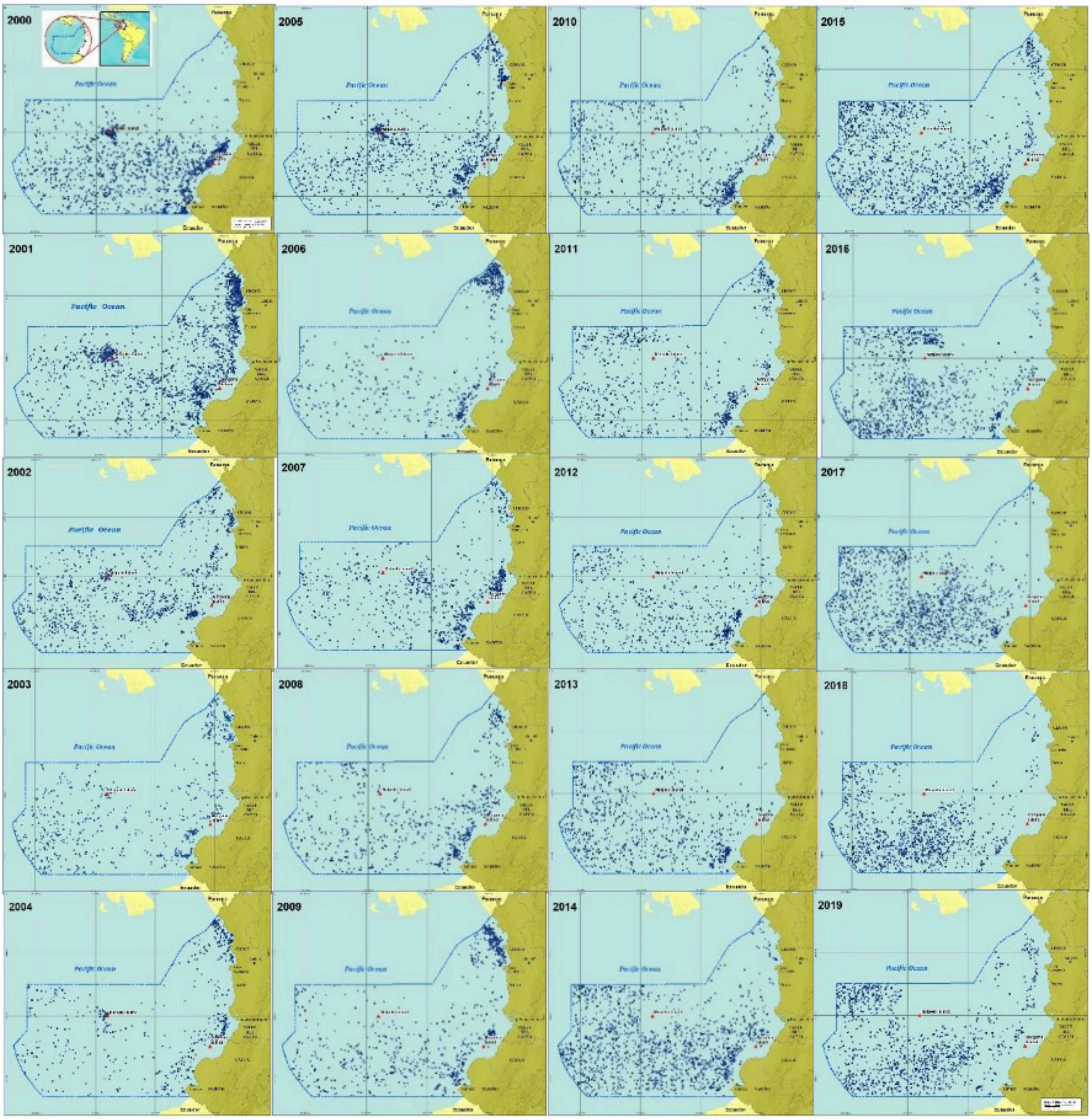

Figure 4. Spatiotemporal distribution of effective fishing sets of the industrial purse seine tuna fishery in the Colombian Pacific Ocean between 2000 and 2019.

(2013, 2014, 2015) for tuna vessels departing from and arriving at the Tumaco Port. Their research confirms the wide distribution pattern of the foreign fleet they monitored, finding that the highest concentration of fishing effort occurred between 2° and 4° N and from the coastline to 82° W, coinciding with the fishing grounds known as 'Banco Tumaco,' 'Pasacaballos,' and 'Banco Colombia' in the southeastern part of the CPO. It also showed that this purse seine foreign-flagged fleet mainly fishes towards the coast using NoAs and FAD. The spatiotemporal and statistical methods used in this study confirmed the fishing grounds reported by Isaza et al. (2020) and other fishing grounds that included a more extensive period and all fishing vessel classes and fishing methods.

The analysis of the average year-by-year catch density through a spatiotemporal showed no general trend of purse seine tuna fishing in the CPO during the study period, showing similar trends as in figure 4.

Spatiotemporal analysis by species

The spatiotemporal distribution of the average catch density performed by species (Fig. 5) showed tuna species with a wide distribution throughout the CPO. Figure 5A showed that YFT is captured offshore in a large area, especially from Malpelo Island heading northwest. It is also captured along the coast, usually beyond the slope of the continental shelf, except in the northern Pacific area, where the shelf is short and ends near the coast.

SKJ (Fig. 5B) is captured across most of the CPO. These captures are lower in the northern part of the Colombian waters or near the coast. BET (Fig. 5C) is the least captured of the three main species in the area. However, it is generally captured offshore around Malpelo Island and other central-southern areas towards the coast.

BKJ reported catch areas both offshore and in central-southern areas towards the coast, and FRZ is captured mainly offshore in the central-southern part and northwards near the border with Panama.

According to the review of Moorea et al. (2020), SKJ is distributed approximately up to 15° of latitude from the equator and east to about 145 °W, extending seasonally to around 30° N and 25° S offshore from the Americas in the eastern Pacific Ocean. However, SKJ biomass is registered within 10° of latitude from the equator. SKJ in Colombian waters appears to belong to the second group distributed from Panama to southern Chile.

YFT is broadly distributed in the Pacific Ocean, from tropical to temperate waters ranging from approximately 30° N to 30° S but extends seasonally to 40° in both hemispheres (Sund et al.,1981; Moorea et al., 2020). BET is distributed from around 40° N to 30° S in the EPO (Calkins, 1980; Moorea et al., 2020).

In the CPO, Salazar et al. (2021) worked on a spatiotemporal prediction for SKJ, establishing that one to three months of delayed-sea surface temperature effects were the primary drivers of CPUE throughout the intra-annual cycle across the Exclusive Economic Zone (EEZ). This study did not work on spatiotemporal predictions, including other parameters correlations, but showed how YFT seems to thrive in the northern part of the CPO and less in the south. Meanwhile, SKJ is registered almost everywhere and is the most captured tuna species. BET, BKJ, and FRZ are not abundant in Colombian waters, and according to the spatial distribution analysis, these species may be associated more with Islands (e.g., Malpelo Island), seamounts, or driven by environmental conditions.

Spatiotemporal analysis by fishing methods

The spatiotemporal distribution of the

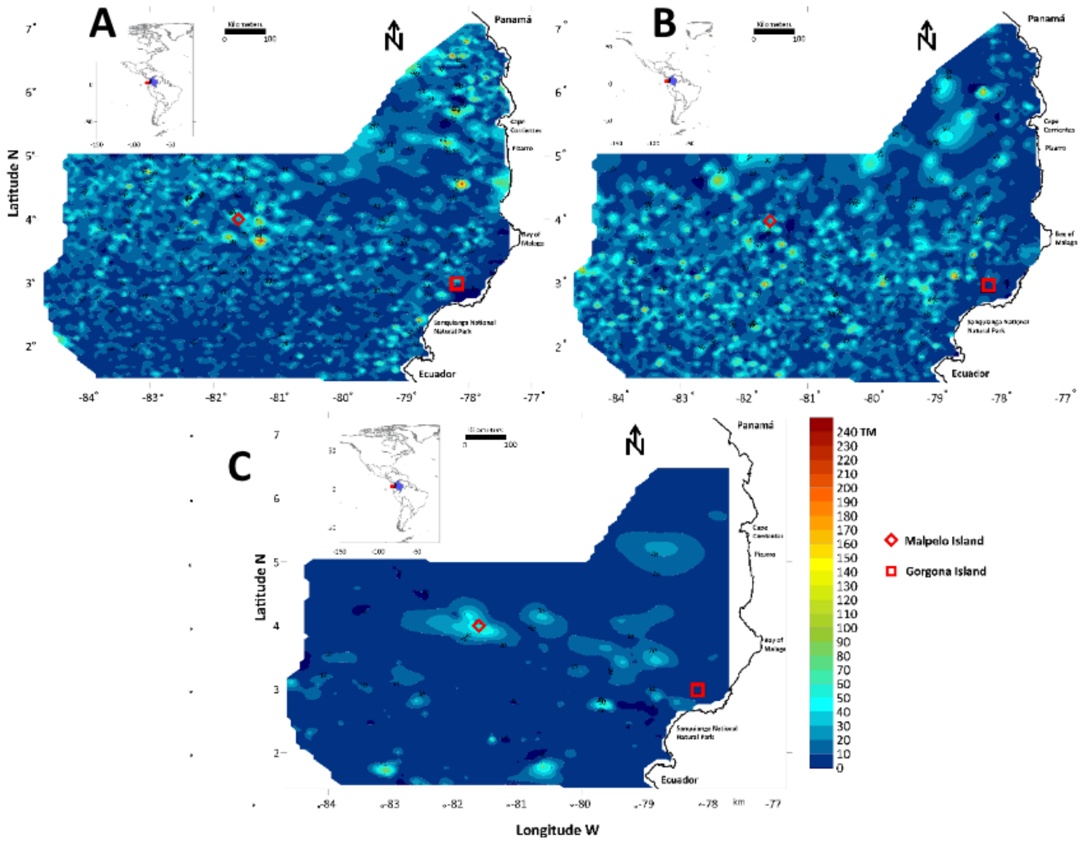

Figure 5. Spatial analysis for the average catch by species in the Colombian Pacific Ocean between 2000 and 2019. **A.** Yellowfin tuna (YFT) - *T. albacares*, **B.** Skipjack tuna (SKJ) - *K. pelamis*, and **C.** Bigeye tuna (BET) - *T. obesus*.

average catch density by fishing method (Fig. 6) allowed identifying different behavior patterns in tuna fishery according to the places with the highest density for each fishing method in the CPO. NAT sets (Fig. 6A) were performed in the central offshore area of the CPO, one spot in the northern Pacific, and another by the Ecuadorian border. The NoAs method is widespread throughout the CPO with a clear fishing ground around Malpelo Island, the northwest areas, some others in the southwest, and the northeast by the Panamanian border (Fig. 6B).

DEL sets showed higher fishing activity in offshore areas along the coast from south to north and in other areas offshore from south to north between 80° and 82° W before reaching Malpelo Island (Fig. 6C). FAD is spread throughout the CPO in offshore areas, but with poor fishing activity towards the coast (Fig. 6D), showing a trend for SKJ to be caught more with this fishing method and reporting a significant catch except in 2004 (Fig. 1B).

Isaza et al. (2020) reported standardized effort in using NoAs sets mainly in the southern coastal part of the CPO between 2009 and 2015 by foreign-flagged vessels. This study showed that NoAs sets are widely distributed primarily in the northern coastal area, offshore around Malpelo Island, and further west towards international waters, coinciding with the main spatial distribution of YFT and SKJ. This study considered a higher amount of fishing sets, a more exhaustive temporal analysis (20 years), and national and international fleets fishing in the CPO, showing similarities as well as other sites with this fishing method (Fig. 6B).

Tuna is associated with dolphins existing different hypotheses for this behavior (Scott et al., 2012). Most of the national fleet (class 6 vessels) use DEL sets, but there is a possibility that other authorized foreign-flagged vessels may use this method as well. Moreover, DEL sets coincide with YFT, SKJ, BET, and BKJ distribution, but there is a trend to get more YFT with DEL sets in Colombian waters as it is the trend in the EPO (Hall and Roman, 2013).

In the CPO, DEL set catches were upside down in the 2010's decade but increased from the previous decade between 8,000 and 21,000 t (2013-2019) (Fig 1C), performed by the biggest vessels and showed significant participation in the tuna fishery. The spatiotemporal distribution of the average catch density analysis showed time in the main areas of DEL sets, which may coincide with the cycle of Colombia and Panama currents flowing counter-clockwise in the CPO (Gutiérrez et al., 2014).

The FAD fishing trend in the CPO seems to be the same increasing trend as registered in the EPO, in which the spatial distribution of the overall purse-seine fishing effort was higher inshore (jurisdictional waters) than offshore (international waters) (Lennert-Cody et al., 2018). This was especially the case when the satellite buoys improved significantly, getting echo sounders that provide estimates of tuna aggregated below the FAD (Orue et al., 2019). So far, this analysis shows that there are FADs deployed in practically the entire area of the Colombian Pacific, except in nearby

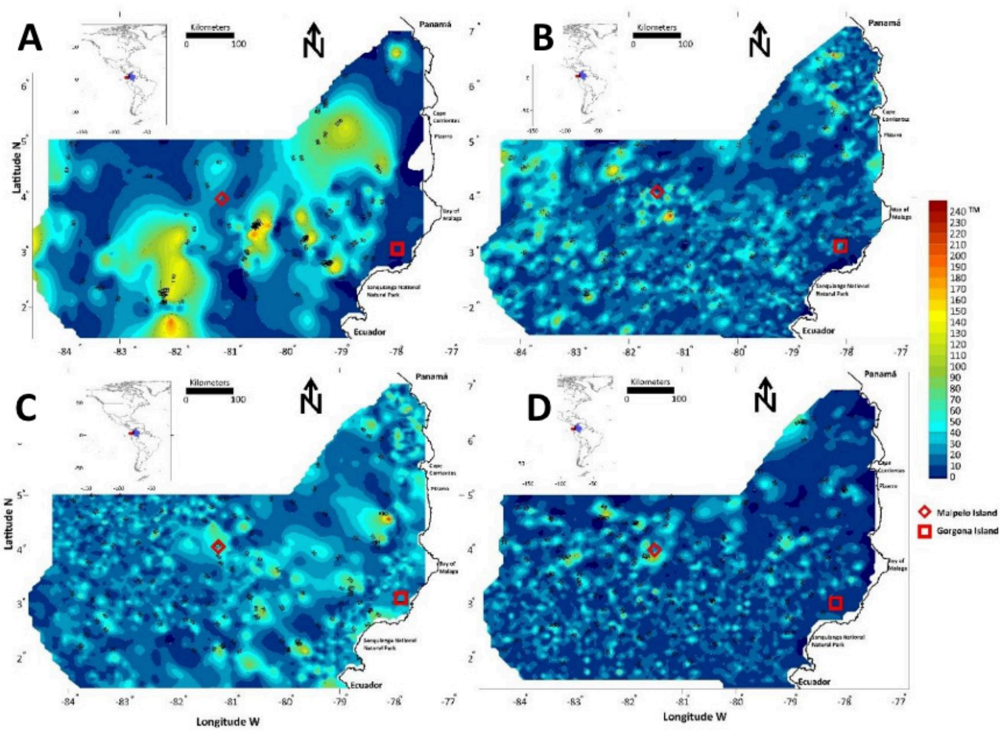

Figure 6. Spatial analysis by purse seine fishing method between 2000 and 2019. **A.** Natural floating objects (NAT), **B.** Non-Associated tuna (NoAs), **C.** Dolphin Associated (DEL), and **D.** Fish Aggregating Devices (FAD). Dark blue areas indicate no capture, and red zones indicate up to 250 t of capture.

coastal areas, being the predominant fishing method for tuna purse seine fishery (Fig. 6D).

However, it is relevant to start collecting FAD information in Colombian waters as is being carried out in other parts of the world, including knowledge on how far tuna are attracted to a particular FAD, if there are different species or size schools formed under a certain FAD, how long does tuna stay in a certain FAD, and why do they leave that FAD. Further, if there is a pattern in the drifting FAD throughout the year, it is important to learn more about this fishery behavior (Moreno et al., 2007).

Studies like those of Phillips et al. (2019) can serve as a reference to visualize the behavior of FADs in Colombian waters and confirm the hypothesis of tuna aggregated under FADs such as restructuring schools, indicators of productive water, and staying below FADs at night (Orue et al., 2019). It is still unknown if the fishing fleet in the CPO makes sets on FADs deployed by the same vessel or another vessel due to the mixed tuna fishing fleets (national and foreign-flagged vessels) belonging to different companies that may have different behaviors in FAD fishing.

On the other hand, it is crucial to analyze the tuna aggregation process in the FAD fishing in the CPO. This study confirmed that in addition to the satellite buoy, fishers attach a "bait barrel" filled with some small cut bycatch to the FAD. It is believed that with the "bait barrel," tuna aggregation is faster in the EPO (Hall & Roman, 2013). Fisheries Observers reported in foreign-flagged medium to small vessel sizes that an extra "bait bag" with pigskin is attached to the FAD, besides the "bait barrel." Fishers strongly believe that aggregation is even faster for the first FAD deployment with this bag. Faster aggregation may be possible since YFT can smell different things (Atema et al., 1980) and has a convenient system that enables the species to switch to a major food source while ignoring food sources of little abundance (Mana and Kawamura, 2014). Nonetheless, Hall and Roman (2013) believe that tuna aggregation may be at night so that there is no visual, shadow, or feeding stimulation. If tuna aggregation with the "bait barrel" is faster, possibly by the combining effect of natural tuna behavior to aggregate under floating objects and the aggregation behavior of its prey around the FAD due to the "bait barrel" or for any other reason, this may have implications on the fishing effort. This occurs because a vessel may visit more often the same FAD in a single fishing trip, making more effective tuna catch with FAD. FAD and DEL fishing methods showed significant catch in the CPO, so management efforts should focus on these fishing methods.

Spatiotemporal analysis by vessel class

The analysis shows that all vessel classes (carrying capacity size) have enough autonomy to fish around the entire CPO. Figure 7 shows the spatiotemporal distribution of catch average density by vessel class (class 2, 3, 4, 5, and 6, according to IATTC). Class 2 vessels fished the least and are not common in the CPO but showed autonomy to sail almost everywhere in the CPO, although with more presence in the central-southern area and some zones in the north (Fig. 7A). Class 3 and 4 vessels showed more places with higher catch intensities throughout the CPO but with higher catches in offshore areas with NoAs and FAD sets (Figs. 6 B, C). Class 5 and 6 vessels showed the most dispersed fishing pattern in all the study area, from spots relatively close to the coast to offshore spots (Fig. 6 D, E) using different fishing methods, especially FAD and DEL.

OTHER ASPECTS AND ALTERNATIVES

Local stock assessment for main tuna

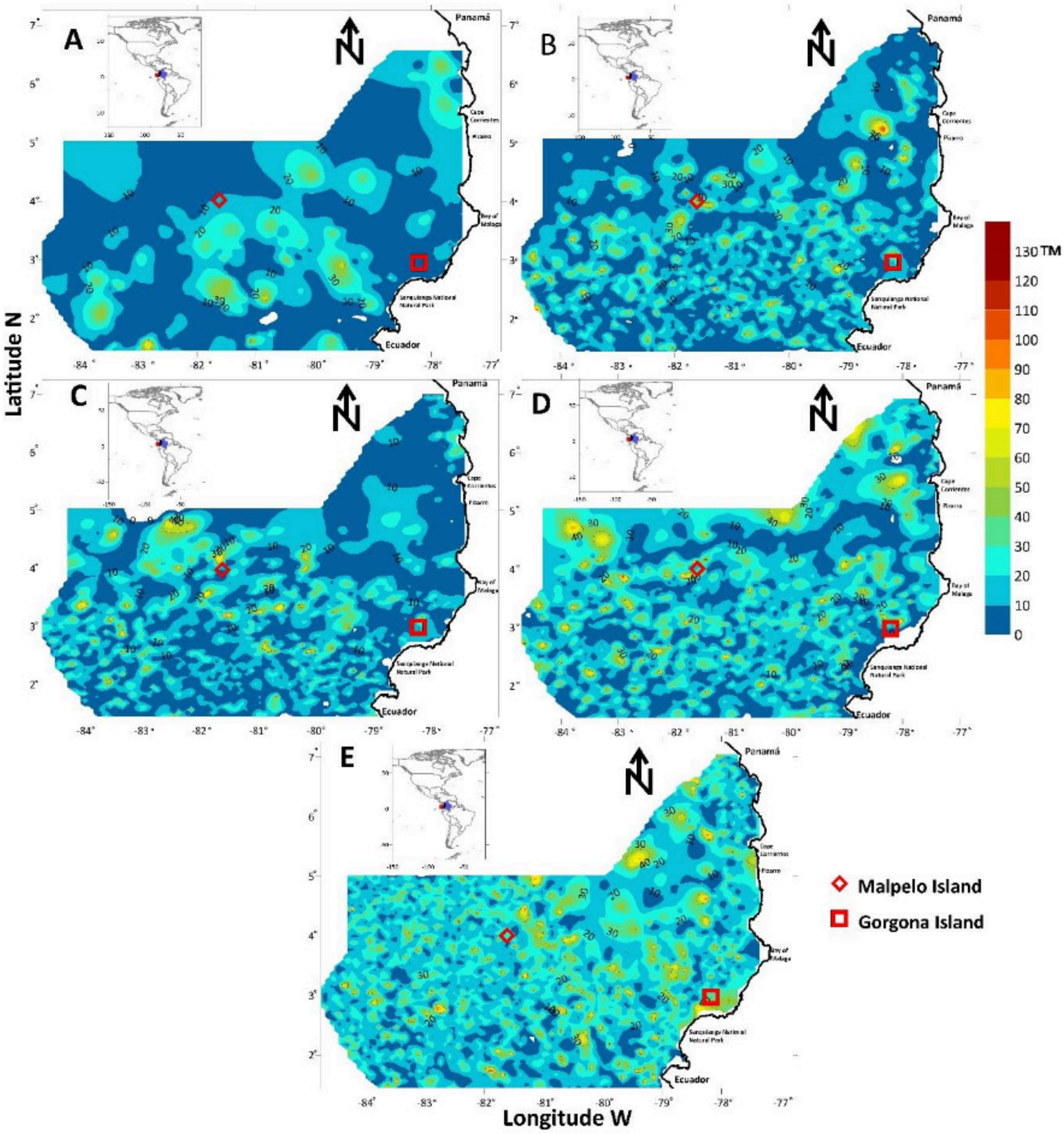

Figure 7. Spatial average tuna catches by vessel class in the Colombian Pacific Ocean between 2000 and 2019. **A.** Class 2, **B.** Class 3, **C.** Class 4, **D.** Class 5. **E.** Class 6.

species in the CPO shows that YFT and BET may be in a healthy condition, while SKJ starts to show overexploitation signs (Barreto, 2021). However, These tuna species are highly migratory, and we may be looking only at a part of these species' stocks. IATTC reported in 2020 that YFT is still in sustainable harvesting conditions (Minte-Vera et al., 2020), but BET shows signs of overexploitation (Xu et al., 2020). On the other hand, stock status indicators (IATTC, 2021) show increased fishing mortality in floating objects (FAD), and the average length for BET and SKJ was at historically low levels in 2020. These findings suggest that precautionary management measures are needed. This overall view suggests that it is possible to think of fisheries management measures in jurisdictional waters aligned with the regional management measures taken in the frame of IATTC, including spatiotemporal ones, as already proposed in other parts of the world (Kaplan et al., 2014).

Some local fisheries management regulations alternatives may include: i) Small size tuna bycatch discard regulation for all fishing methods (NAT, NoAs, DEL, and FAD). Tuna FAD fishing by class 2, 3, and 4 class vessels showed a significantly small size discard (845 t in 22 months, which is around 38 t/month on average), mainly in purse seine FAD fishing. ii) Complete (100%) observer coverage in all fleets and vessel sizes fishing in the CPO. Currently, there is no 100% coverage in tuna vessels departing and arriving at the port of Tumaco. iii) Regulation of FAD designs to use only those that avoid unwanted bycatch (Murua et al., 2017); the length and type of nets hanging from the FAD should be regulated as well. iv) Tuna vessels are monitored 24/7 via satellite and in the field during their fishing periods in the Colombian Pacific waters. v) Per-vessel FAD limits as an alternative to regulating this fishing method. This was already mentioned by Lennert-Cody et al. (2018). Colombia issued Resolution 0076 of January 20, 2022, in which FADs started to be regulated by a limit of FADs per vessel class. An "active" FAD (deployed and beginning to transmit its position with the satellite buoy attached) and a timeframe (between 60 and 90 days) were defined to send FAD positions to the IATTC secretariat. The resolution prohibits FAD deployments 15 days before the period established for fishing closure, the number of FADs to be recovered 15 days before the established closure must be equal to the number of FAD sets in the same 15 days, and no transshipments or landings of tuna and related species according to the measures established in this resolution are allowed. Colombia is one of the countries that have taken strong positions regarding FAD fishing in the Eastern Pacific Ocean in the frame of the IATTC negotiations.

It is also important for pelagic fisheries such as purse seine tuna fishery to characterize the environmental and oceanographic conditions related to the fishing in the CPO. Further analysis of the existing information may lead to knowing the tuna species and fishery behavior during climatic events such as El Niño or La Niña. No reports on the effects of climate change on tuna species were found for the eastern Pacific Ocean or even the Colombian waters, such as the models used for the Pacific Island waters and high sea areas (Sennina et al., 2018). There are possibilities that climate change modifies the sea conditions for worse or better for pelagic species. If sea surface temperature, primary productivity, and sea currents flow directions change, tuna species and their fishery will suffer changes. However, Senina et al. (2018) also reported that fishing pressure is expected to be the primary driver of tuna status rather than others related to climate change, at least until the mid-century in the western Pacific.

Finally, after COP 26 in Glasgow (Nov. 2021), Colombia's President announced expanding marine protected areas. In this sense, the Pacific offshore areas seem to be the most feasible to expand since there were no community consultations previously due to their distance from the coast. However, fishers may be affected by this decision. This means that the FFS Malpelo, the INMD Yuruparí-Malpelo, and new marine protected areas (MPAs) may be expanded or created. In that process, it is crucial to follow the route given by decree No. 2372 of 2010 (President and Ministry of Environment) and resolution No. 1125 of 2015 (Ministry of Environment) that analyzes the technical information for such expansion or the creation of MPAs, or both. In such a frame, fishers, the fishing grounds identified, and the potential development of sustainable fisheries evidenced in the CPO in this study must be considered.

CONCLUSIONS

Tuna purse-seine fishery targets six tuna species, from which the ones that are mostly captured are SKJ and YFT. SKJ is captured in almost all the CPO, while YFT is captured towards the coast and to the northwest of the CPO.

Tuna catches registered an average of 17,000 t/year showing three main catch periods, but no catch trend was found within a year. Catches were primarily carried out by foreign-flagged vessels.

FAD is the most used method throughout the CPO, followed by DEL and NoAs, while NAT is occasionally used. NoAs were used frequently around Malpelo Island and to the northwest, while DEL is mainly used towards the coast and the central part of the CPO, from north to south.

Most tuna is captured by the biggest vessels (class 6) almost everywhere in the CPO, while other vessels (Class 2, 3, 4, and 5) capture significantly less tuna, regardless of the fishing method, mainly in offshore areas.

The fishing effort showed an average of 1,230 sets/year with an average of 365 sets/year (29.7%) with zero tuna catches (regardless of the fishing method). Meanwhile, CPUE showed an average of 17,000 t/effective set/year, evidencing a significant tuna fishery potential in the CPO.

Four main tuna fishing grounds were identified in the CPO, two offshore and two toward the coast.

Over the years, the purse-seine tuna fleet performance showed different patterns that may be influenced by tuna behavior, movements of vessels belonging to the same company, and environmental sea conditions.

Possible management measures for the current tuna purse-seine fishery include: i) FAD regulations since it is the most effective fishing method in the CPO, including FAD design, number of FADs, and use of bait barrels, ii) small size SKJ discards, iii) Total (100%) observer coverage when required, and iii) satellite and in-the-field monitoring of tuna vessels in the CPO, regardless of the IATTC regulations issued.

It is crucial to consider the tuna fishery potential shown in this study to create or expand new protected areas.

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