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Composition of pelagic fish in commercial landings of the longline fishery in the Costa Rica Pacific during 2015-2021

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Longline fishing in the Pacific of Costa Rica targets multiple species of large pelagic fishes and faces challenges in assessment due to lack of data. This study analyzes landing data of pelagic fish in this fishery using unconventional statistical methods, to better understand the dynamics and provide recommendations for improving data collection and analysis. Landing data reported during 2015-2021 were examined. A descriptive and comparative analysis of landings was conducted using Spearman correlation tests and Non-Metric Multidimensional Scaling (NMDS) to visualize patterns in catch composition. Permutational Multivariate Analysis of Variance (PERMANOVA) and Similarity Percentage Analysis (SIMPER) were employed to identify significant differences between fleet types, landing ports, months, and years, as well as species contribution to these differences. The annual mean total landing of large pelagic fish was 7531.01 tons, with 39.14% corresponding to sharks, 24.34% to billfish (Istiophoridae and Xiphiidae), 18.05% to mahi-mahi, and 14.94% to tuna. Statistically significant differences were found between fleet types, landing ports, months, and years. Shark landings were the least correlated (rho=0.36) and had the greatest influence on variation by fleet type. An increase in the similarity of catch composition by port since 2015 was observed. In addition, a shift towards increasingly less selective fishing over the study period was evident. Our findings highlight the urgent need for advanced research methodologies to address gaps in data collection for commercial fisheries in Costa Rica. Improving these methods is crucial to ensure that management policies are based on accurate and comprehensive information. Results highlight the need for a comprehensive strategy involving diverse stakeholders to improve our understanding and ensure the sustainability of fisheries and the preservation of marine ecosystems in Costa Rica.

KEYWORDS

longline fishery, Pacific, Costa Rica, billfish, tunas, sharks, NMDS

1 Introduction

Longline fishing is a multispecies fishery targeting highly migratory large pelagic fish such as tuna, swordfish, and mahi-mahi. Alongside these target species, non-target species like marlins, sailfish, and cartilaginous fish are also frequently caught, often comprising a significant portion of the catch (Jordaan et al., 2020). Understanding the global dynamics of longline fisheries remains challenging due to their complexity and the lack of comprehensive data, which hampers efforts to assess and manage their environmental and economic impacts effectively.

In Costa Rica, most fishery catches are from the extensive Exclusive Economic Zone (EEZ), primarily in the Pacific Ocean, a region rich in nutrients and highly productive that has seen intensive use of fishery resources in recent decades (Alms and Wolff, 2019). Among the most productive fishing sectors is longline fishery. The Costa Rican longline fishery operating in the Eastern Pacific Ocean (EPO) is regulated by the Convention of the Inter-American Tropical Tuna Commission (IATTC) in the Costa Rica EEZ and international waters (Zamora-García et al., 2022), and the Costa Rican Fisheries and Aquaculture Law, Law 8436 (Incopesca, 2005), which in Chapter V, Article 62, defines longline as a “selective fishing gear using a mainline in which leaders with baited hooks are placed to catch pelagic and demersal species.”

In the country, artisanal longline vessels are categorized by their autonomy and size into medium and large scale (Valle-Esquivel et al., 2018). Previously, under Law 8436, commercial fishing was classified as medium scale fishing, carried out by natural or legal persons, aboard a vessel with autonomy to fish up to a maximum of forty nautical miles from the coast; and advanced commercial fishing, conducted by natural or legal persons, aboard a vessel with autonomy to fish beyond forty nautical miles, aimed at capturing pelagic species with longline, and other commercially important species, carried out by mechanical means. However, since 2022, the autonomy to fish for each fleet is established by the Costa Rican Institute of Fisheries and Aquaculture (Incopesca), as the executing fisheries authority according to Law 10155 (Incopesca, 2022).

The Costa Rican longline fleet currently consists of 336 vessels in the Pacific, with lengths ranging from 7.7 to 27.9 meters, although 83% are 16 meters or smaller, as reported by Incopesca. These vessels typically use surface longlines, setting monofilament motherlines and branch lines at shallow depths, no deeper than 60 meters (Andraka et al., 2013). Equipment length varies widely from 6 nautical miles (NM) for smaller vessels to 70 NM for larger ones, setting between 200 and 2,800 baited hooks per trip (Pacheco et al., 2020). The most used hooks are circular, sizes 13 to 16, although Japanese J tuna hooks and other J hooks are also occasionally used (Andraka et al., 2013). Bait usually consists of squid or small fish species, such as sardines and jack mackerel, with live bait being common, although prohibited within the first 30 NM from the coast. Most vessels have a gross tonnage below 42 metric tons, with an average fishing trip lasting around 22 days, although larger vessels may remain at sea for longer periods (Pacheco et al., 2020). Fish are typically preserved on ice for most of the fleet.

Longline fishing plays a significant environmental, social, and economic role in coastal communities and contributes to the processing and export industries (Herrera-Ulloa et al., 2011; Pons et al., 2017). Recognizing its importance, Costa Rica launched a Fishery Improvement Project (FIP) in 2018, aiming to enhance the sustainability of the yellowfin tuna, mahi-mahi, and swordfish fisheries (Incopesca, 2019). FIPs involve collaboration among multiple stakeholders—such as retailers, importers, processors, and other actors in the seafood supply chain—who contribute directly to policy formulation and fishery management (Cannon et al., 2018; Crona et al., 2019). The Costa Rican FIP focused on managing these primary species within established biological reference points while also addressing bycatch species, including sharks and billfish, which lack clear management frameworks. Despite its potential, the FIP is currently inactive due to insufficient funding and limited access to essential data.

A key challenge for Costa Rican longline fisheries is the limited availability and accessibility of detailed data on fishing areas, effort, and discards (Andraka et al., 2013). The only systematic information provided by Incopesca includes monthly total landings by port, which require some assumptions for analysis. These data offer valuable insights into long-term trends and inform management effectiveness (Heidrich et al., 2022; Saldaña-Ruiz et al., 2017; Zeller and Pauly, 2018). Effective fisheries management is crucial, as overfishing threatens global fish populations, biodiversity, ecosystem balance, food security, and the livelihoods of millions worldwide (Bradley et al., 2019). However, establishing robust management policies requires reliable, up-to-date data to understand fishery dynamics and inform decision-making.

In this context, the objective of this research is to characterize landings of pelagic fish by the commercial longline fleet operating in the Costa Rican Pacific during the period 2015-2021 through non-traditional statistical analyses. Results will contribute to our understanding of the dynamics of the fishery including spatial and temporal trends in fisheries landings, and allow for recommendations on improving the capabilities of data collection and fishery data analysis in Costa Rica.

2 Materials and methods

2.1 Study area

The marine richness found in the Exclusive Economic Zone (EEZ) of the Pacific of Costa Rica is influenced by three oceanographic and geomorphological elements: ocean currents that contribute to the distribution and dispersion of species, the Costa Rican Thermal Dome, which is one of the most important nutrient-rich upwellings in the Eastern Tropical Pacific, and the presence of the Cocos Submarine Volcanic Ridge, which is home to various commercially important pelagic fish species (Vega, 2012). Additionally, due to colder sea surface temperatures and high productivity levels, these areas serve as aggregation sites for large pelagics (Cubero-Pardo et al., 2023; Zevallos-Rosado et al., 2023) and are considered fishing opportunity zones for the medium and advanced scale longline fleet. This research focused on the Pacific coast of Costa Rica, specifically on the ports where longline vessels land: Cuajiniquil, Playas del Coco, Puntarenas, Quepos, and Golfito (Figure 1).

2.2 Landings

According to current regulations, Incopesca must inspect and record all commercial landings at national ports on landing forms completed by an inspector from the institution. This study analyzed monthly registered landings of various large pelagic fish species as recorded in landing forms from January 2015 to December 2021. From the group of tunas, yellowfin tuna (*Thunnus albacares*), bigeye tuna (*Thunnus obesus*), and skipjack tuna (*Katsuwonus pelamis*) were considered. All billfish were also included: blue marlin (*Makaira nigricans*), black marlin (*Istiompax indica*), striped marlin (*Kajikia audax*), sailfish (*Istiophorus platypterus*), and swordfish (*Xiphias gladius*), and the mahi-mahi, represented by a single species, *Coryphaena hippurus*. In the group of sharks, the thresher shark (*Alopias* spp.), silky shark (*Carcharinus falciformis*), blacktip reef shark (*Carcharinus melanopterus*), tiger shark (*Galeocerdo cuvier*), mako shark (*Isurus oxyrinchus*), blue shark (*Prionace glauca*), and hammerhead sharks (*Sphyrna* spp.) were included.

2.3 Data source

Data from Incopesca on landings by medium and large-scale longline fleets for the period 2015-2021 were publicly available. The databases were cleaned, and for each registered vessel, its registration and license status (active or inactive) were confirmed on the Incopesca website. Additionally, the registration number, license type (Medium or Large-scale), and length were added, information also obtained from data reported by Incopesca. For each species, its respective scientific name and conservation status according to the IUCN Red List of Threatened Species were included.

2.4 Data analysis

A descriptive and comparative exploratory analysis of landings was conducted for both the medium and large-scale fleets during the study period. To observe trends and patterns in the composition of pelagic fish landings, time series analyses were performed using monthly averages of landed tons from 2015 to 2021. To determine if the composition of landed species correlated with fleet type, Shapiro-Wilk tests for normality were conducted. Since the data did not follow a normal distribution, a non-parametric Spearman correlation analysis was used.

A Non-Metric Multidimensional Scaling (NMDS) analysis was conducted using the statistical software R (version 4.0.3) and the 'metaMDS' function from the 'vegan' package. A distance matrix based on Bray-Curtis similarity among landing samples was constructed. Subsequently, the NMDS algorithm was applied to

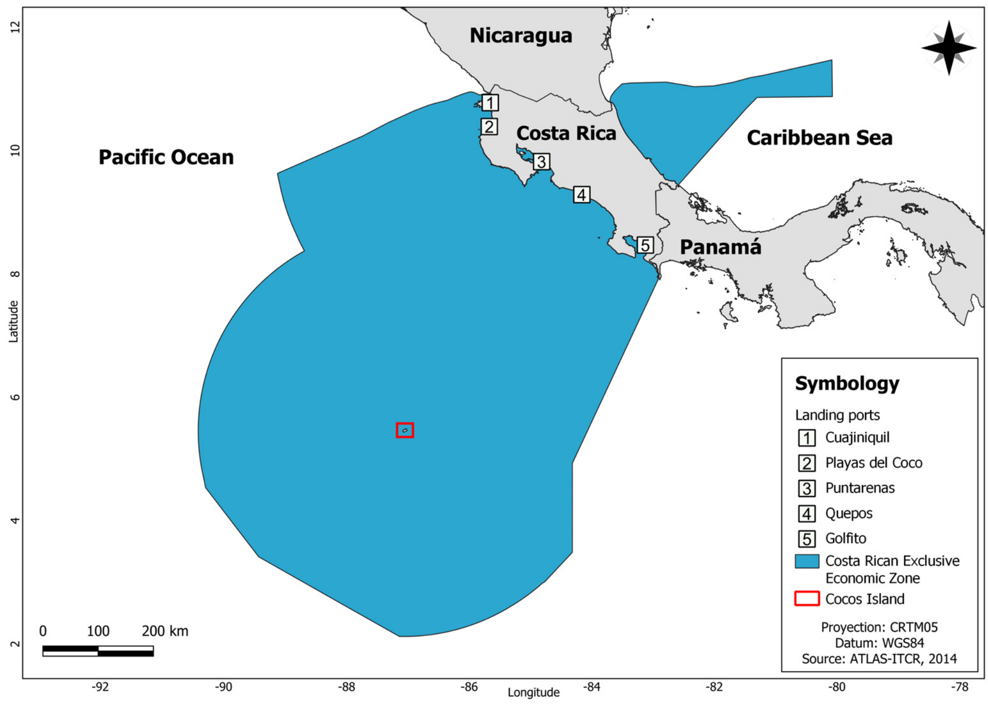

FIGURE 1
Landing ports in the Pacific of Costa Rica reported by Incopesca.

reduce the data dimensionality to two dimensions, preserving the original similarity structure as much as possible. NMDS results were interpreted by visualizing samples in a two-dimensional space, where proximity between points indicated similarity in landing characteristics.

To determine if there were statistically significant differences between fleet type, landing port, and year, a Permutational Multivariate Analysis of Variance (PERMANOVA) was conducted. In cases where differences were found, a Similarity Percentage (SIMPER) analysis was applied to identify species with the greatest influence on landing composition. Through exploratory analysis of landing data reported by Incopesca, significant information gaps relevant to fisheries research and regulation in Costa Rica were identified. Additionally, an extensive review of scientific articles and national and international technical documents was conducted to develop specific recommendations for improving the collection and systematization of fisheries data in the Costa Rican context.

3 Results

3.1 Landings trends

During the period 2015-2021, 310 active longline vessels were reported, comprising 117 advanced-scale fleet vessels and 193 medium-scale fleet vessels. The annual average of total landed catch of large pelagic fish was 7,531.01 metric tons, of which 53.65% corresponded to secondary species, sharks and billfish from the Istiophoridae family) and 46.35% were primary species (tunas, mahi-mahi, swordfish) (Figure 2).

3.1.1 Tuna

Yellowfin tuna was the predominant species in landings from 2015 to 2021, representing the vast majority of total tuna catches (98.39%), followed by bigeye and skipjack tuna (Figure 3). Peak landings for both fleet types occurred in 2020, with average catches exceeding 60 tons annually. Monthly trends showed variability, with September and October being particularly productive for the advanced fleet, and June and July for the medium fleet. Overall, tuna landings grew significantly from 2017 to 2020, with increases of 66.49% and 136.50% for the advanced and medium fleets, respectively, before declining by 25.93% in 2021.

3.1.2 Billfish

The advanced-scale and medium-scale fleets contributed nearly equally to the total landings of billfish species, with slight dominance by the advanced-scale fleet. This group primarily comprised swordfish, striped marlin, blue marlin, sailfish, and, to a much lesser extent, black marlin. The annual trends in landings varied across species, highlighting notable fluctuations over time (Figure 3).

For blue marlin (Figure 3), landings peaked in 2018 for both fleets, with July showing the highest averages. However, after 2018, a consistent decline was observed through 2021, although year-to-year variability persisted. Black marlin (Figure 3) had minimal landings, with no reports in 2020. The highest landings occurred in 2018, with notable peaks during May and June.

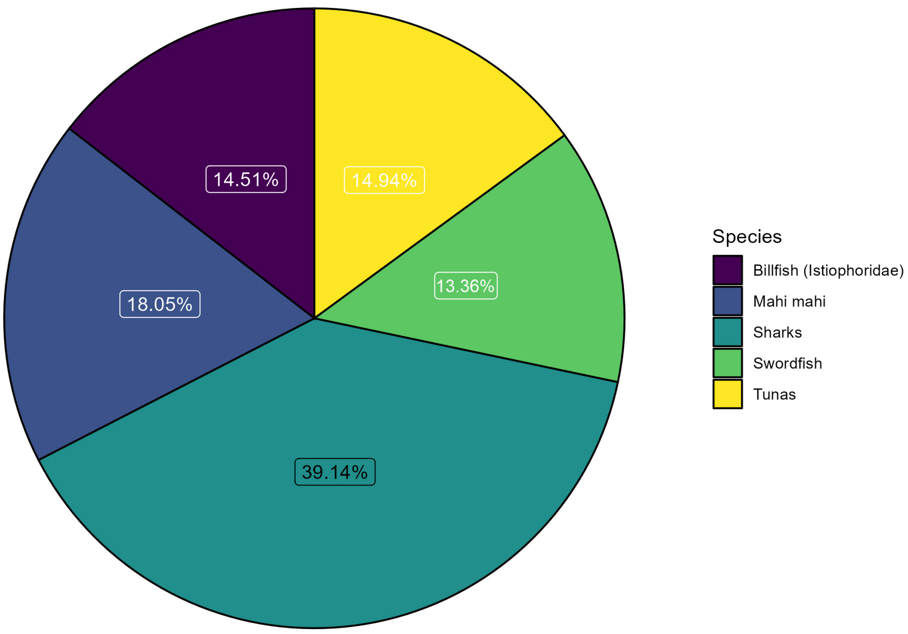

FIGURE 2
Percent composition of total average landings of large pelagic fish reported by the medium-scale and advanced commercial longline fleet in the Pacific of Costa Rica during the period 2015–2021.

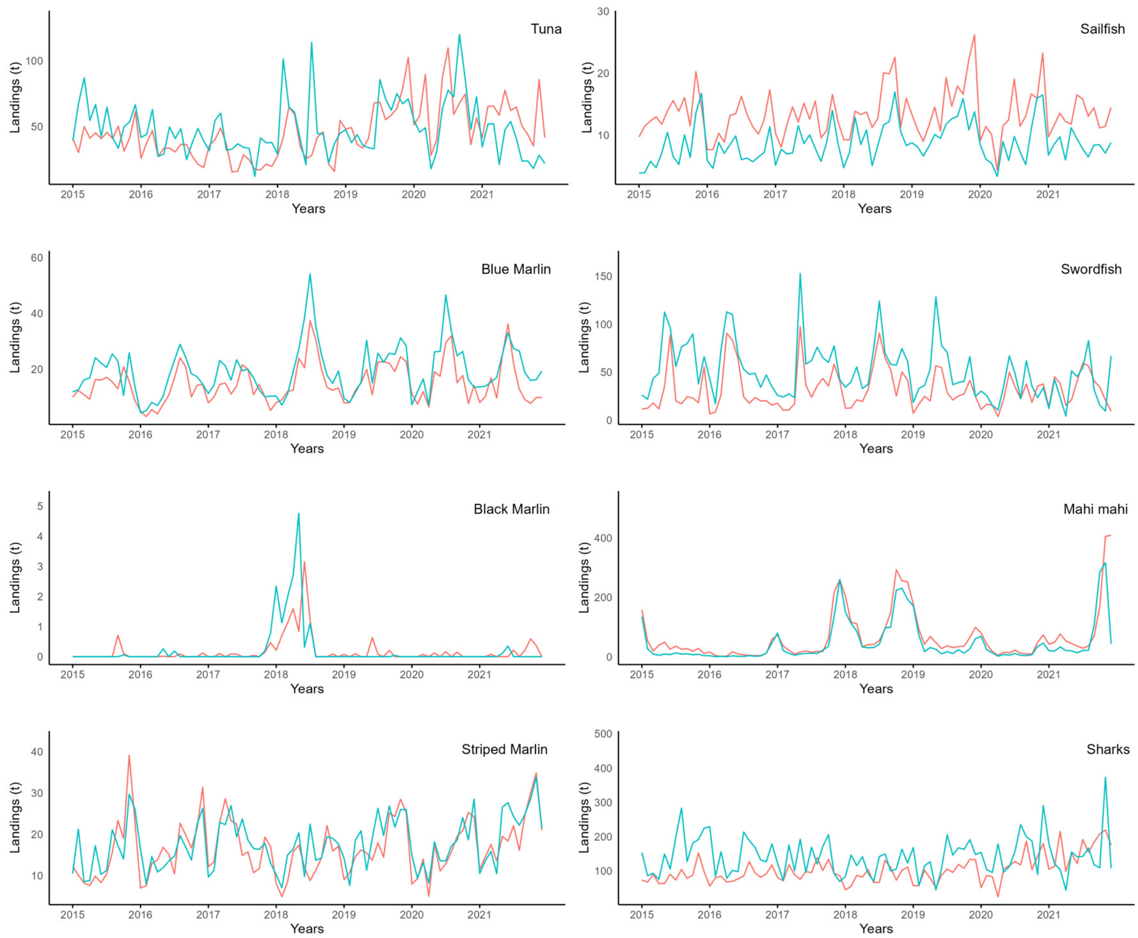

FIGURE 3
Time series of monthly landings of pelagic fish (tons) at ports in the Costa Rican Pacific during the period 2015–2021 by the advanced longline fleet (light blue line) and the medium-scale longline fleet (red line).

Striped marlin landings (Figure 3) showed a marked increase in 2021, particularly during May and November, where the medium-scale fleet consistently outperformed the advanced-scale fleet in several years. Sailfish (Figure 3) landings were dominated by the medium-scale fleet, showing a gradual increase from 2015 to 2019, followed by a slight decline in 2020 and 2021. The highest values were typically recorded in the last quarter of the year.

Swordfish (Figure 3) exhibited contrasting trends between fleets. The advanced-scale fleet recorded its highest landings in 2015, with a peak in May, while the medium-scale fleet peaked in 2018, particularly in July. Both fleets showed significant declines in swordfish landings after their respective peak years, although there were brief periods of recovery, such as a slight increase from 2020 to 2021.

3.1.3 Mahi-mahi

This group is composed of a single species, *Coryphaena hippurus*. Mahi-mahi landings exhibited variability, peaking in 2017, 2018, and 2021. The medium-scale fleet consistently outperformed the advanced-scale fleet, contributing 58.80% of total landings. October through January consistently saw the highest landings, with November 2021 marking a record high for the advanced-scale fleet and December 2021 for the medium-scale fleet.

3.1.4 Sharks

The landing records of sharks from the medium-scale fleet show a minimum in 2016, with 85.96 tons, and a maximum in 2021, with 161.49 tons (Figure 3). In contrast, for the advanced-scale fleet, the minimum value was 119.59 tons in 2018, while the maximum reached 158.43 tons in 2020. During the study period, there was a slight decrease of 5.85% in shark landings by the advanced-scale fleet, while the medium-scale fleet experienced an increase of 85.92%.

Regarding the months with the highest average landings, January, May, and November stand out for the advanced-scale fleet, while March, August, and November are the months with the highest landings for the medium-scale fleet across several years. Analysis of the records shows that the advanced-scale and medium-scale fleets contributed 57.92% and 42.08% of the total shark landings, respectively. The group of landed sharks is mostly composed of silky sharks (78.73%), followed by the thresher shark group (13.54%), blue shark (4.02%), hammerhead sharks (3.29%), blacktip shark (<1%), mako shark (<1%), whitenose shark (<1%), tiger shark (<1%), and others, which together account for 4%.

3.2 Characterization of landings

Highly positive correlations were observed between fleet types and total landings for mahi-mahi, blue marlin, and striped marlin, with correlation coefficients exceeding 0.75. In contrast, swordfish, sailfish, and tuna landings showed a weak correlation with fleet type. Black marlin and sharks exhibited very low or virtually negligible correlations between fleet types (Figure 4).

In the multivariate space (Figure 5), it is notable that Playas del Coco tends to be more associated with swordfish and mahi-mahi landings. Cuajiniquil shows a strong association with mahi-mahi in the early years (2015 and 2016), but as time progresses, there is a shift towards a closer proximity with swordfish, and subsequently with other billfish such as striped marlin and sailfish. On the other hand, Puntarenas, Golfito, and Quepos are closely clustered together in the multivariate space, suggesting similarity in the composition of species landed at these ports. Overall, in 2015, there is some overlap in landing composition among the different ports, and over the study period, there is a trend towards convergence in the multivariate space. By 2021, all groups show complete overlap, indicating a homogenization in the landing composition among the analyzed ports (Figure 5).

From the Permutational Multivariate Analysis of Variance (PERMANOVA), it was determined that there is a statistically significant difference at 99.9% between the landed species of large pelagic fish and the factors of license type (F=66.214, df=1, p=0.001), year of landing (F=7.534, df=6, p=0.001), months (F=5.560, df=11, p=0.001), and landing port (F=152.633, df=4, p<0.05) (Table 1).

It was determined that the species that significantly contributed to the variation between the advanced and medium-scale fleets were sharks and mahi-mahi (Table 2). The species' contribution to the variation between landing ports is represented in Table 3. The Striped marlin (*Istiompax indica*) was not included in Tables 2, 3 because in all combinations it contributed equal to or less than 0.1% of the species variation in landing ports.

4 Discussion

The longline fishery analysis in the Pacific of Costa Rica has revealed that most of the catches consist of secondary species such as sharks and billfish from the Istiophoridae family. In contrast, the target species for the fishery represent only a smaller percentage of the total (Figure 2). This distribution is related to the multispecies and non-selective nature of pelagic longline fisheries in tropical zones (Parra et al., 2023; Pons et al., 2020), which often result in a high rate of incidental catch or bycatch (Jiménez et al., 2020; Swimmer et al., 2020; Thorne et al., 2019), as well as the capture of individuals below sexual maturity sizes or ages, promoting discards (Fauconnet et al., 2019; Gilman et al., 2017; Jordaan et al., 2020). According to Gilman

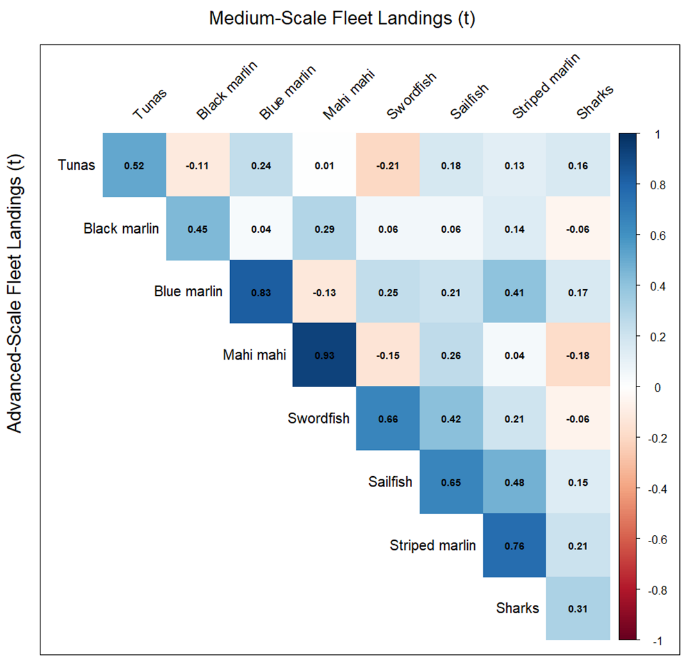

FIGURE 4
Spearman correlation analysis between the composition of landed species and the type of fleet (medium-scale and advanced). Values close to 1 represent a high positive correlation, values close to 0 indicate no correlation, and values close to -1 indicate a negative correlation.

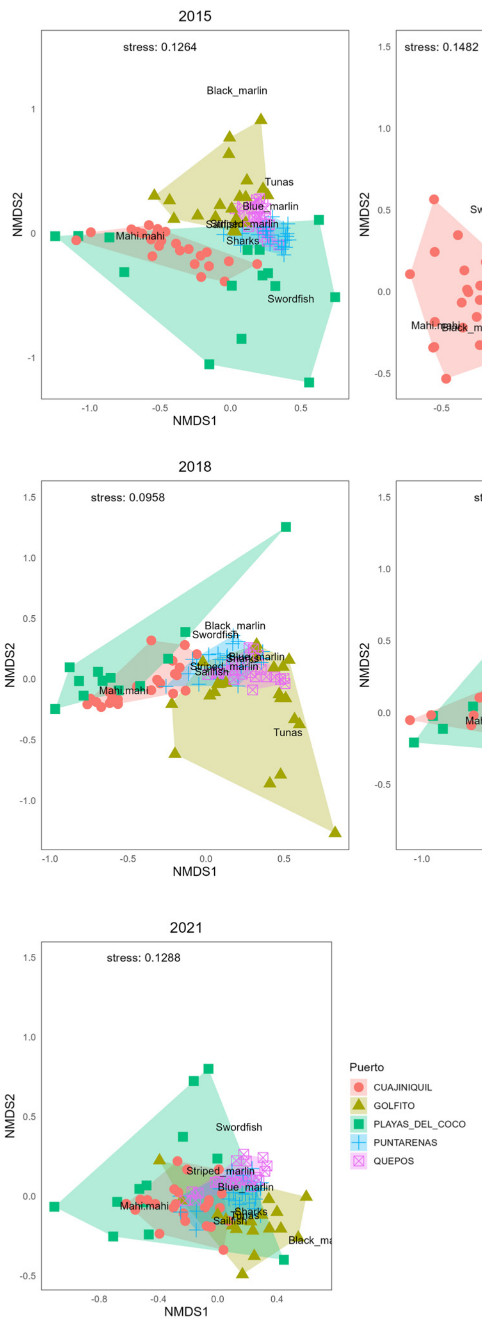

FIGURE 5
Non-Metric Multidimensional Scaling (NMDS) analysis of the composition of landings by port during the years 2015–2021. Each point represents a landing sample from a specific port, with different colors indicating different ports. The NMDS model stress suggests a representation of sample dissimilarities in two dimensions.

et al. (2017), globally, longline fisheries contribute nearly 64% of untargeted catches, followed by purse seine nets at 36%. In this case, the composition of the fishery diverges from what is expected according to the FIP (Incopesca, 2019).

4.1 Tunas

The predominance of yellowfin tuna among the tunas landed by the longline fleet could be linked to their wide distribution in the Eastern Tropical Pacific (Cubero-Pardo et al., 2021; Moore et al., 2020; Muñoz-Abril et al., 2022). The Costa Rican Exclusive Economic Zone (EEZ) is an aggregation area for different sexual maturity stages of yellowfin tuna (Muñoz-Abril et al., 2022; Orange, 1961; Schaefer and Fuller, 2022).

According to the Inter-American Tropical Tuna Commission (IATTC, 2023), in the Eastern Tropical Pacific, the catch per unit effort (CPUE) of the longline fishery targeting tuna has decreased since 2005, reaching historically low levels in the years 2017-2018. This coincided with the years of lowest landings by the Costa Rican

TABLE 1 Permutational Multivariate Analysis of Variance (PERMANOVA) for the pelagic fish community landed by fleet type (advanced or medium scale), years, months (specific months when landings occurred), and landing ports.

Factor	DF	Sum Sq	Mean Sq	Pseudo-F	Significant P-Value
Fleet Type	1	8.279	8.2793	66.214	0.001
Years	6	5.653	0.9421	7.534	0.001
Months	11	7.647	0.6952	5.560	0.001
Landing Ports	4	76.339	19.0848	152.633	0.001
Error	700	87.526	0.1250	–	–
Total	722	185.445	–	–	–

longline fleet during the period covered in this study (Figure 3). Moreover, in 2014, Decreto Ejecutivo N° 38681-MAG-MINAE, (2014) implemented fisheries management measures for the tuna fleet, prohibiting purse seine fishing within the first 45 nautical miles from the coast likely promoting higher biomasses in coastal areas of the Costa Rican Pacific. The IATTC (2023) evaluated various hypotheses to explain the increase in catches in 2020, including a possible spatial mixing of stocks in the Eastern Pacific; reference models showed similar trends in relative recruitment, suggesting a decrease in the availability of fish for fishing in all cases analyzed.

4.2 Billfish

In the Pacific Ocean, blue marlin is considered a single stock (Graves and McDowell, 2015; Williams et al., 2020). According to the most recent stock assessment conducted in 2021 by the Inter-American Tropical Tuna Commission (IATTC, 2023) and the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC), the biomass of blue marlin currently exceeds the level needed to achieve maximum sustainable yield by 13%, and the fishing mortality rate is 40% below the maximum sustainable fishing mortality level. This suggests that the blue marlin population is not being overfished and that the current level of fishing is sustainable. While there was a reduction in landings following the 2018 peak, the variability observed year-to-year suggests that there is no consistent declining trend over time.

TABLE 2 SIMPER Analysis showing the species contributing to 90% of the variation by fleet type.

SIMPER Species	Percentaje contribution (%)	Significant P-Value
Sharks	35.1	0.001
Mahi-mahi	22.4	0.001
Tunas	15.2	0.101
Swordfish	12.0	0.026
Blue Marlin	6.0	0.001
Striped Marlin	5.3	0.001
Sailfish	3.9	0.001

This aligns with the need for continued monitoring to better understand the local and regional factors influencing blue marlin landings, particularly considering broader catch trends reported for the Eastern Tropical Pacific during 2019–2021.

There are limitations in the stock assessments for black marlin, primarily due to the lack of reliable data (Zeller and Pauly, 2018). Additionally, the peculiarity of landings in this fishery, where specimens are unloaded without heads and fins, can complicate their correct identification (Pacheco et al., 2020). In the case of striped marlin, the IATTC recently assessed annual catches in the Pacific during the period from 2016 to 2021, where it was observed that these were approximately half of those recorded in 2010 (IATTC, 2023). On the other hand, according to the striped marlin assessment in the North Pacific conducted by the ISC (2023), a decrease in population biomass was recorded in 2020, and a downward trend in fishing mortality has been observed since 1998. Recent spawning biomass was 63% below the reference level, and current fishing mortality was 9% above the reference value, leading to the conclusion that the population is overexploited and subject to overfishing.

The sailfish has a well-documented distribution, showing greater presence in waters near the continent and islands of the Indo-Pacific compared to other billfish species (Ehrhardt and Fitchett, 2006; Pohlot and Ehrhardt, 2018). Maximum catches have been recorded along the Central American coast (Ehrhardt and Fitchett, 2016), being more abundant near the coast in response to changes in oceanographic conditions (Haulsee et al., 2022; Mondal et al., 2023). The first stock assessment was conducted in 2013, revealing a possible underestimation of catches (IATTC, 2023). Reported longline catches between 2016 and 2021 experienced a significant decrease compared to previous years; however, it is suggested that there are significant levels of unreported catches. In the waters of Costa Rica's EEZ, the medium-scale fleet registered higher landings than the advanced fleet, possibly due to the fishing areas closer to the coast frequented by this fleet, influenced by the specific characteristics of their vessels. Additionally, the medium-scale fleet is represented by nearly four times the number of vessels compared to the advanced fleet, representing a greater presence and spatial coverage of the coastal waters of the EEZ. This is based on the premise that the advanced fleet, due to its larger size and autonomy, has the capacity to venture into waters farther from the coast (Incopesca, 2005).

Regarding swordfish landings, they have shown a decreasing trend in recent years. For the Northern Hemisphere stock, the IATTC (2023) found that from 2017 to 2021, there was a decrease in

TABLE 3 SIMPER analysis showing the percentage contribution by species and significance for the variation by landing ports.

Landing Ports Combination	Percentage Contribution by Species and Significance (p-value)						
	Sharks	*Mahi-mahi*	*Tunas*	*Swordfish*	*Sailfish*	*Blue Marlin*	*Striped Marlin*
Cuajiniquil-Playas del Coco	25.2	53.9 ***	3.7	7.3	5.3***	1.7	2.9
Cuajiniquil-Puntarenas	40.9***	14.0	15.7***	17.2***	1.9	5.0	5.2***
Cuajiniquil-Quepos	26.2	24.3	18.5***	8.9	4.5***	10.4***	7.2***
Cuajiniquil-Golfito	27.2	40.6***	16.3*	4.9	4.6***	3.4	3.0
Playas del Coco-Puntarenas	42.5***	11.9	15.6***	17.0***	2.5	5.0**	5.4***
Playas del Coco-Quepos	32.8***	13.8	20.0***	9.0	6.0***	10.8***	8.0***
Playas del Coco-Golfito	32.3***	24.7***	23.4***	6.1	5.5***	4.7	3.3
Puntarenas-Quepos	42.4*	15.5	13.5	18.8***	1.6	3.8	4.3
Puntarenas-Golfito	41.8***	12.7	14.3*	18.7***	2.0	4.8	5.6***
Quepos-Golfito	30.8	13.5	18.2	11.3	5.7***	11.5***	9.0***

Asterisks represent the level of significance, where '***' represents significant with p-value < 0.001, '**' p-value < 0.01, '*' p-value < 0.05, '.' p-value < 0.1, and no asterisk represents p-value ≥ 0.1.

fishing effort toward this species. Despite the stock biomass being stable over the last decade (Pons et al., 2017), overall catches continue to decline. This decline could be partially explained by the fact that swordfish have a deeper distribution compared to other species (Su et al., 2020), requiring longlines to be set at greater depths. In contrast, shallower longlines tend to target other billfish species, as well as mahi-mahi and tuna.

4.3 Mahi-mahi

The mahi-mahi fishery in Costa Rica is primarily concentrated from November to February (Morgan and Martinez Tovar, 2020), coinciding with the peak landings observed in this study. In terms of catches, there has been a 50% increase over the last decade in the Eastern Pacific Ocean, with an average annual production of over 70,000 tons during the period from 2008 to 2012. In Costa Rica, catches peaked in 2011, exceeding 10,000 tons, and have since stabilized around 2,000 tons annually (Morgan and Martinez Tovar, 2020). The International Union for Conservation of Nature (IUCN) considers that there are no significant threats to mahi-mahi from commercial fishing (Collette et al., 2011), as preliminary analyses show variable but relatively stable trends in catch per unit effort. Additionally, the preliminary population assessment indicates that current fishing mortality rates represent 50% of the maximum sustainable yield, although there are levels of uncertainty in areas north of the equator. During the mahi-mahi season, fishers use a surface longline without a steel leader, while targeting other species throughout the rest of the year, they typically use a bottom longline with a steel leader, as in the case of shark-directed fishing (Valle-Esquivel et al., 2018). Similarly, there are variations in bait types and setting depth depending on the fleet and target species (Valle-Esquivel et al., 2018).

4.4 Sharks

Sharks accounted for 39.4% of the landings, despite being considered secondary species in this fishery. In recent decades, shark populations have faced increasing pressure due to pelagic fishing activities (Booth et al., 2022; Dapp et al., 2013; Zollett and Swimmer, 2019). This heightened mortality is mainly attributed to the inherent vulnerability of sharks, characterized by slow growth, late maturation, and low reproductive rates (Liu et al., 2021; Martínez-Candelas et al., 2020).

The silky shark, the dominant species in landings, is particularly found in regions where temperatures exceed 23°C (Compagno, 1984). Its habitat ranges from coastal to pelagic areas, with a latitudinal distribution limited between 20°N and 20°S (Clarke et al., 2011). This geographical range coincides with the main fishing grounds for tropical tuna species, leading to significant spatial overlap between silky sharks and commercial fishing activities, both purse seine and longline (Burns et al., 2023; Hutchinson et al., 2019). Despite the ecological concerns associated with silky shark catches, the data presented in this study (Figure 3) indicate that shark landings in Costa Rica's Pacific have remained relatively stable throughout the study period, without a clear declining trend. It is important to highlight that the stability observed in shark landings does not necessarily imply the sustainability of the fishery. Proving sustainability requires additional layers of data and analyses, including population assessments, fishing effort, and environmental factors. While this study does not provide sufficient evidence to conclude whether Costa Rican shark fisheries are sustainable, the results do suggest the need for continued monitoring and improved data collection, especially considering the variability in reporting during the COVID-19 pandemic and the lack of mandatory reporting of incidental catches (IATTC, 2023).

In 2021, the IATTC issued Resolution C-21-06, updating conservation measures for shark species, with a particular focus on silky sharks for the years 2022 and 2023. This resolution imposes restrictions on the surface longline fleet operating at depths less than 100 meters, limiting the catch of sharks under 100 cm in length to 20% of the total sharks caught during each trip. It also mandates inspections at the first landing point and prohibits the use of steel leaders for three consecutive months each year for those multispecies fisheries that catch more than 20% of silky sharks by annual weight. The resolution also establishes a long-term sampling program to improve data collection and identify silky shark nursery areas. Another relevant resolution is IATTC-C-11-10 from 2011, which prohibits various activities related to oceanic whitetip sharks. This measure bans the retention onboard, transshipment, landing, storage, sale, and offering for sale of oceanic whitetip shark carcasses, whether whole or in parts. It also requires the release of these sharks and accurate documentation of discards and releases through onboard observer programs, specifying whether the sharks were released alive or dead.

Recently, the government of Costa Rica prohibited the capture, retention onboard, transshipment, landing, storage, and commercialization of products and byproducts from the scalloped hammerhead shark (*Sphyrna lewini*), smooth hammerhead shark (*Sphyrna zygaena*), and great hammerhead shark (*Sphyrna mokarran)*, either in part or whole (Decreto Ejecutivo N° 43900-MAG-MINAE, 2023). These three species are listed as vulnerable on the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species.

4.5 Characterization of landings

The NMDS analysis results show a trend of convergence among landing ports, suggesting homogenization in the composition of landings. This observation aligns with the study by Villalobos-Rojas et al. (2014) on fishing activities in the Costa Rican North Pacific, where longline fishing activities were found to be concentrated primarily in Cuajiniquil and Playas del Coco. According to the fishers interviewed in that study, the most commonly caught species include mahi-mahi, silky shark, hammerhead shark, sailfish, swordfish, yellowfin tuna, and bigeye tuna. In Playas del Coco, where there are also several fish receivers, the longline fleet focuses mainly on catching mahi-mahi, yellowfin tuna, sailfish, and swordfish, sharing similar resources with fishers from Cuajiniquil. These findings are consistent with the landing results analyzed in this study for the years 2015-2021.

The prominence of billfish in landings at Quepos and Golfito, compared to other ports, indicates the high concentrations of these species in the central and southern Pacific regions, which align with key areas for tourism and sport fishing (Marrari et al., 2023). This also underscores the economic significance of these activities to the local economy (Cascante and Marín, 2019). Additionally, as is common in many parts of the world, there is ongoing conflict and overlap between commercial and recreational fishing fleets over access to fishery resources (Brown, 2016; MacKenzie and Cox, 2013; Martin et al., 2016).

This pattern could suggest a shift toward more opportunistic and less selective fishing practices, likely influenced by shared challenges such as fish availability, limited enforcement of management measures, captain decisions and other aspects related to fishing operations. Building on studies like Alglave et al. (2022) and Poulard and Léauté (2002), a more integrated approach combining spatial and temporal analyses of fisheries activities could provide deeper insights into the triggers influencing landings at various scales. Understanding how species and entire communities respond to different fishing pressure requires examining both spatial patterns and how they relate to broader ecological factors, such as ocean dynamics and population structures. For instance, the convergence in landing compositions among ports may reflect localized fishing practices and resource availability, influenced by the spatial distribution of fish stocks (Woźniacka et al., 2024).

The presented results indicate that the variation in species composition in Costa Rica's Pacific longline fishery is influenced by characteristics inherent to fishing activities, including the type of fleet, timing, and landing ports, and that species composition also responds to variations in fleet types. The fact that mahi-mahi, blue marlin, and striped marlin landings are highly correlated between fleet types suggests that when the advanced fleet increases its catches, the medium-scale fleet also does so, reflecting higher abundances of these species during those periods and the non-selective nature of longlines. The same pattern is observed with swordfish, sailfish, and tuna landings, though to a lesser extent. On the other hand, shark landings show the lowest correlations, which could be related to differences in fishing practices targeting this group, including fishing depth and equipment type, resulting in lower catches of other groups that are more efficiently caught at shallower depths and with different types of bait and technical specifications. The analyses identified sharks as the group that most influenced the differences observed between fleets. Interestingly, the increase in shark catches in the advanced fleet does not correspond to a proportional increase or decrease in the medium-scale fleet, and vice versa. This lack of proportionality suggests that the relationship between landings of target and bycatch species is more complex than previously assumed. Variations in fishing practices, such as depth, bait type, and technical specifications, most likely contribute to the observed disparities in shark catches.

This challenges the assumption that reduced fishing mortality on target species would uniformly result in a steady decline in shark landings across fleets and highlights the need for fleet-specific management measures. Recognizing the key species driving these variations is crucial for refining management and conservation strategies, especially given the secondary species status of sharks in this fishery.

Multispecies fisheries must be managed with species-specific regulations (Samoilys et al., 2017) and it is important to communicate these specific regulations to the appropriate user groups (Purcell et al., 2018). Fishing methods, gear types, autonomy, and trip frequency affect the magnitude and species composition of the catch and must be understood for management to be effective (Kittinger et al., 2015; Olopade et al., 2017). Gear types and fishing methods can also vary significantly between regions, even when catching the same species (Rahman et al., 2016). For example, the type of vessel will affect which ports can be accessed, and therefore, also the landing composition of the fishing area (Grazia Pennino et al., 2016).

Understanding the dynamics of the fishery and the species involved is fundamental to developing effective management strategies that promote sustainability and maximize benefits for coastal communities (Purcell et al., 2018). Although Costa Rica has established some regulations for longline fishing, the EEZ is extensive and monitoring is limited by the regulatory agencies capacity, resulting in sometimes under supervised operations and violations of existing regulations (Incopesca, 2005). The absence of a national onboard observers program despite CIAT requirements (CIAT, 2011) and insufficient funding to adopt technologies that would improve monitoring, may prevent the effective enforcement of the existing legal framework, which allows illegal and unsustainable activities to persist, negatively impacting marine resources and jeopardizing the sustainability of commercial and recreational fisheries (Alms and Wolff, 2019).

Longline fishery requires deeper study due to its interactions with other fisheries, high bycatch rates of secondary species, environmental impact, and economic importance. The use of monitoring devices, such as cameras, could be an alternative for onboard observers and improve *in situ* data collection, as well as species identification and bycatch quantification (Brown et al., 2021; Emery et al., 2019b, a). Additionally, these types of electronic monitoring systems would allow for traceability in fishery products, which could, in turn, provide access to premium markets that require such measures, thereby increasing the profitability of catches.

Other measures that could be implemented to advance the reduction of bycatch include continuing to promote the use of large circle hooks (Andraka et al., 2013; Saidi et al., 2020; Swimmer et al., 2011) and avoiding the use of steel leaders in shark-targeted fishing. Additionally, it has been demonstrated that the greenstick fishing method is selective and efficient in tuna capture (Marín Alpizar et al., 2019). Therefore, training fishers who are not yet using this method could improve the profitability of the catch while reducing the pressure on secondary species and reducing bycatch levels.

5 Conclusion

The analysis of landings by the longline fishery in Costa Rica revealed that secondary species such as sharks and billfish comprise the majority of the reported landed biomass, while the primary target species including tuna, mahi-mahi and swordfish represent a smaller fraction. Given the lack of more comprehensive data and being multispecies, the longline fishery in the Pacific of Costa Rica requires multivariate and non-traditional research approaches. The PERMANOVA analysis demonstrated that the type of fleet, port, and time of landing are significant factors in the variation of species caught, which helps to understand the dynamics of the fishery and make more informed decisions for fishery management. The SIMPER test identified sharks as the species most influencing the differences observed between fleets. Notably, the increase in shark catches by the advanced fleet does not correspond to a proportional change in the medium-scale fleet, and vice versa. Understanding the drivers of this disparity is essential for guiding management efforts and future assessments, particularly given the secondary status of sharks in the fishery. Future research should prioritize exploring the underlying causes of this non-proportional relationship, such as variations in fleet behavior, environmental factors, and species-specific vulnerabilities. These insights will be pivotal for designing targeted management strategies that promote the sustainability of both target and bycatch species.

The NMDS analysis showed that fishery landings during the study period became increasingly homogeneous among ports, suggesting a shift towards more opportunistic and less selective fishing. To address the difficulties of a lack of comprehensive data and challenging monitoring, a comprehensive strategy is required, including the prioritization of scientific research, data collection, the implementation of advanced technologies, and the development of a strategy to promote and incentivize sustainable fishing practices. It is essential to involve all stakeholders, including fishers, regulatory authorities, the scientific community, and non-governmental organizations, in a collaborative approach to ensure the long-term viability of fisheries and the preservation of marine ecosystems in the Pacific of Costa Rica.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.incopesca.go.cr/acerca_incopesca/transparencia_institucional/datos_abiertos.aspx.

Author contributions

AC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MM: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. FA: Conceptualization, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. AG: Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. MM: Conceptualization, Investigation, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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