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Facultad de Ciencias Exactas y Naturales  
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**Informe Escrito Final  
(Artículo Científico)**

**Composición de peces pelágicos en los desembarques de la pesquería de  
palangre comercial en el Pacífico costarricense durante 2015-2021**

**Trabajo Final de Graduación para optar al grado de Licenciatura en  
Biología Marina**

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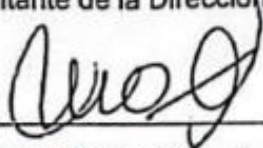
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## Abreviaturas

CIAT	Comisión Interamericana del Atún Tropical
CPUE	Catch per unit effort
EEZ	Exclusive Economic Zone
ENSO	El Niño-Southern Oscillation
EPO	Eastern Pacific Ocean
FIP	Fishery Improvement Project
IATTC	Convention of the Inter-American Tropical Tuna Commission
INCOPESCA	Costa Rican Institute of Fisheries and Aquaculture
ISC	International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean
IUCN	International Union for Conservation of Nature
NMDS	Non-Metric Multidimensional Scaling
PERMANOVA	Permutational Multivariate Analysis of Variance
SIMPER	Similarity Percentage Analysis

## Resumen

La pesca de palangre en el Pacífico de Costa Rica se dirige a múltiples especies de grandes pelágicos y enfrenta desafíos en su evaluación debido a la falta de datos. Este estudio analiza datos de desembarques de peces pelágicos en esta pesquería utilizando métodos estadísticos no convencionales, con el objetivo de comprender mejor las dinámicas y ofrecer recomendaciones para mejorar la recolección y el análisis de datos. Se examinaron los datos de desembarques reportados entre 2015 y 2021. Se realizó un análisis descriptivo y comparativo de los desembarques utilizando pruebas de correlación de Spearman y Escalamiento Multidimensional No Métrico (NMDS) para visualizar patrones en la composición de la captura. Se emplearon Análisis de Varianza Multivariado Permutacional (PERMANOVA) y Análisis de Porcentaje de Similitud (SIMPER) para identificar diferencias significativas entre tipos de flotas, puertos de desembarque, meses y años, así como la contribución de las especies a estas diferencias. El promedio anual de desembarques totales de peces pelágicos grandes fue de 7 531,01 toneladas, con un 39,14 % correspondiente a tiburones, 24,34 % a peces de pico (Istiophoridae y Xiphiidae), 18,05 % a dorado y 14,94 % a atún. Se encontraron diferencias estadísticamente significativas entre tipos de flotas, puertos de desembarque, meses y años. Los desembarques de tiburones fueron los menos correlacionados ( $\rho=0,36$ ) y tuvieron la mayor influencia en la variación por tipo de flota. Desde 2015, se observó un aumento en la similitud de la composición de la captura por puerto. Además, se evidenció una tendencia hacia una pesca cada vez menos selectiva a lo largo del período de estudio. Nuestros hallazgos resaltan la necesidad urgente de metodologías de investigación avanzadas para abordar las brechas en la recolección de datos de las pesquerías comerciales en Costa Rica. Mejorar estos métodos es crucial para asegurar que las políticas de gestión se basen en información precisa y completa. Los resultados subrayan la necesidad de una estrategia integral que involucre a diversos actores para mejorar nuestra comprensión y garantizar la sostenibilidad de las pesquerías y la preservación de los ecosistemas marinos en Costa Rica.

**Palabras claves:** palangre, Pacífico, Costa Rica, peces picudos, atunes, tiburones, NMDS.

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

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**Keywords:** Longline fishery, Pacific, Costa Rica, billfish, tunas, sharks, NMDS.

## Abstract

Longline fishing in the Pacific of Costa Rica targets multiple species of large pelagics and faces challenges in assessment due to lack of data. This study analyses 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.

## Introduction

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 & 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 (Incopescas, 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, 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 (Incopescas), as the executing fisheries authority according to Law 10155 (Incopescas, 2022).

Longline fishing plays a crucial role in environmental, social, and economic aspects in coastal communities, as well as in processing and export industries (Herrera-Ulloa et al., 2011; Pons et al., 2017). Additionally, the commercial longline fishing sector is one of the most relevant fishing sectors in the country for international markets. Longline fishing is a multispecies fishery in which highly migratory large pelagic fish are captured, such as tuna, swordfish, and mahi-mahi, which are target species, as well as other species like marlins, sailfish, and cartilaginous fish (Jordaan et al., 2020), which, despite not being target species, represent the highest percentage of catches.

One of the main threats to marine ecosystems and fishery management worldwide is the incidental mortality of non-target species (bycatch) during fishing activities (Andraka et al., 2013; Gilman et al., 2022; Lucas & Berggren, 2023). In Costa Rica, there is evidence that longline fishing in the Pacific has significantly impacted some species, particularly species important for tourism and sport fishing, such as sailfish and marlin species (Dapp et al., 2013; Marrari et al., 2023; Villalobos-Rojas et al., 2014). These species are highly valued by recreational fishermen due to their size, beauty, and challenge in their capture, and their fishing has generated significant tourism activity, sustaining approximately 33,000 jobs in coastal areas of the country, and generating 520 million dollars annually (Cascante & Marín, 2019). The mortality of pelagic fish resulting from longline incidental capture reduces the abundance of the population and negatively affects catch rates in recreational fisheries (Pohlot, 2019; Pons et al., 2017). Moreover, this commercial fishery can also affect the balance of marine ecosystems by removing top predators such as sharks, from the orders Carcharhiniformes and Lamniformes (Hutchinson et al., 2019). Sharks play an important role in the ecosystem by controlling pathogens and maintaining population balances in the food chain, making them ecosystem bioindicators (Dulvy et al., 2014; Liu et al., 2021). Due to their slow growth, late maturity, and low fecundity, they are particularly vulnerable to overfishing (Dulvy et al., 2014; Martínez-Candelas et al., 2020).

One of the efforts to improve the longline fishery was the adoption of a Fishery Improvement Project (FIP) in 2018 (Incopescas, 2019). FIPs are projects that involve multiple stakeholders, including retailers, importers, processors, and other actors in seafood supply chains, directly in the formulation of policies and the management of fisheries (Cannon et al., 2018; Crona et al., 2019). In Costa Rica, the objective of the FIP was to improve the fishery for yellowfin tuna, mahi-mahi, and swordfish caught with surface longlines. This initiative considers these three species as the most important for the fishery, designating them as primary species, and manages

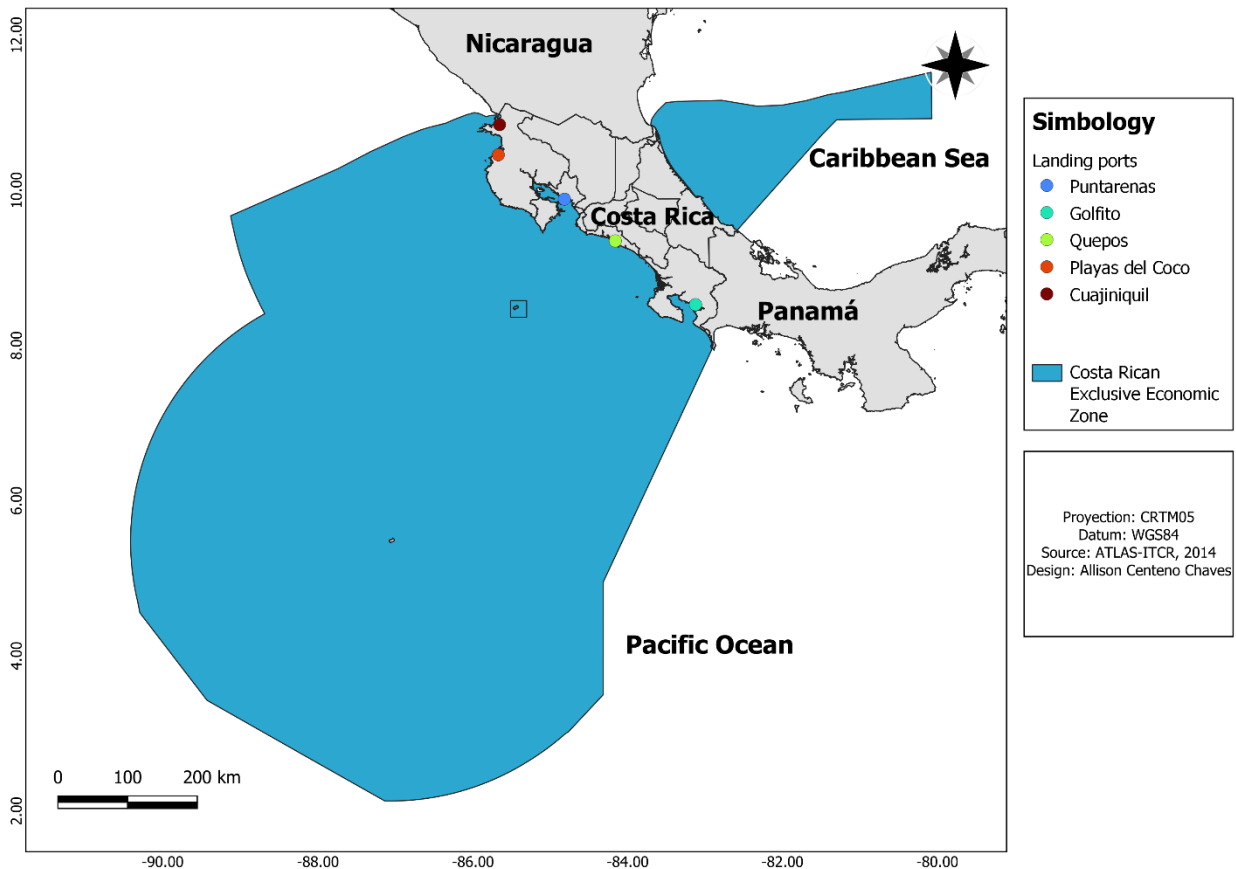
them through measures aimed at maintaining biomass levels within their established biological reference points. On the other hand, secondary species, which include sharks and billfish, do not have management schemes with clear objectives and reference points, although many are not classified as endangered, threatened, or protected species. Despite the potential of this initiative, it is currently inactive due to a lack of funding and access to necessary information for the FIP evaluation.

There is an interest in understanding and evaluating the effects of fishing on marine ecosystems, but in most cases, there is a lack of information, leading to poor and uncertain assessments (Andraka et al., 2013). The management of the longline fishery in the Costa Rican Pacific has been affected by the lack of available and accessible information regarding fishing areas, catch effort, and discards. The only systematic and publicly accessible information reported by Inopesca are monthly data on total landings by port, which require interpolations and strong assumptions; however, it is historical information that can provide a reasonable approximation of changes in fisheries over time, helping to evaluate the effectiveness of current management (Heidrich et al., 2022; Saldaña-Ruiz et al., 2017; Zeller & Pauly, 2018). Achieving effective fisheries management is important, as overfishing threatens fish populations worldwide, reduces biodiversity, alters ecosystem functioning, and endangers food security, as well as the livelihoods of millions of people around the world (Bradley et al., 2019). Fisheries management is a complex socio-political process; however, access to reliable data on the characteristics and functioning of a fishery and how it has changed over time is essential for establishing efficient management based on updated and trustworthy data.

In this context, the objective of this research is to analyze the characteristics of pelagic fish landings by the commercial longline fleet operating in the Costa Rican Pacific during the period 2015-2021 through non-traditional statistical analyses. This will contribute to the understanding of the dynamics of this fishery and allow for recommendations on improving the capabilities of fishery data collection and analysis in the country.

## **Materials and methods**

**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 its sea surface temperature conditions and high productivity levels, these areas are 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 (Fig. 1).



**Figure 1.** Landing ports in the Pacific of Costa Rica reported by Incopescas.

**Landing Data:** According to current regulations, Incopescas must inspect and record all commercial landings at national ports on landing forms completed by an inspector from the institution. In this study, all landings of different large pelagic fish species reported in the landing forms between January 2015 and December 2021 were analyzed. 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.

**Data Source:** Data Source: Data from Incopescas on landings by medium and large-scale longline fleets for the period 2015-2021 were used, which are publicly available. The databases were cleaned, and for each registered vessel, its registration and license status (active or inactive) were confirmed on the Incopescas 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.

**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, non-parametric Spearman correlation analysis was used.

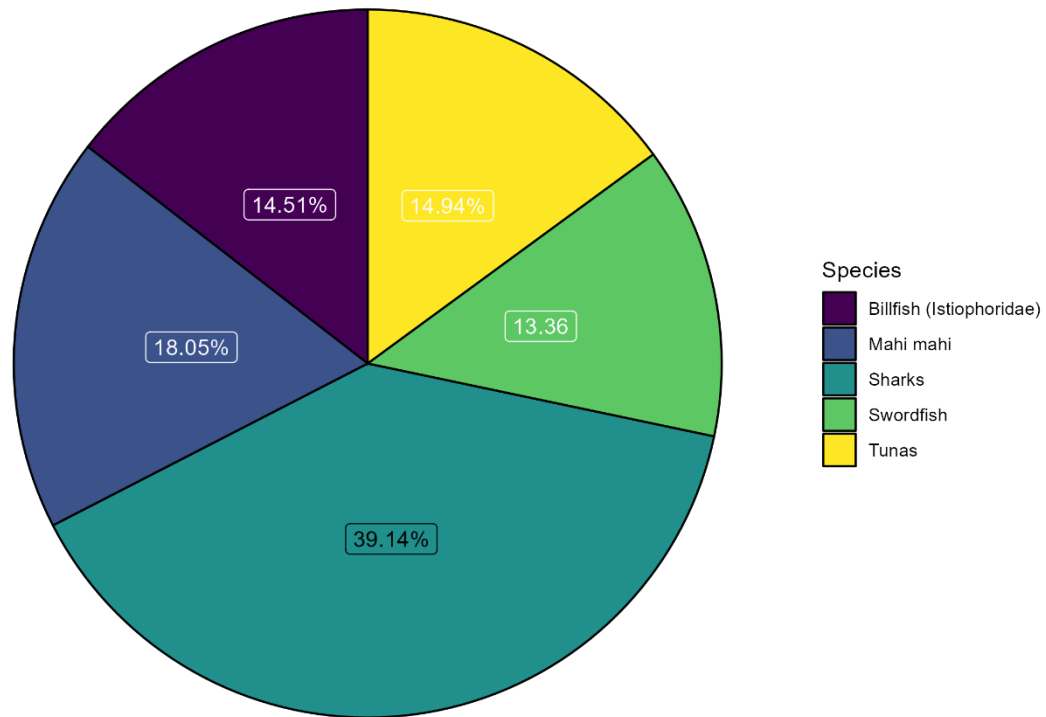
A Non-Metric Multidimensional Scaling (NMDS) analysis was conducted using statistical software R (version 4.0.3) and the 'metaMDS' function from the 'vegan' package. A distance matrix based on Bray-Curtis similarity among landing samples was constructed. Subsequently, the NMDS algorithm was applied to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

## **Results**

### **1. Landings trends**

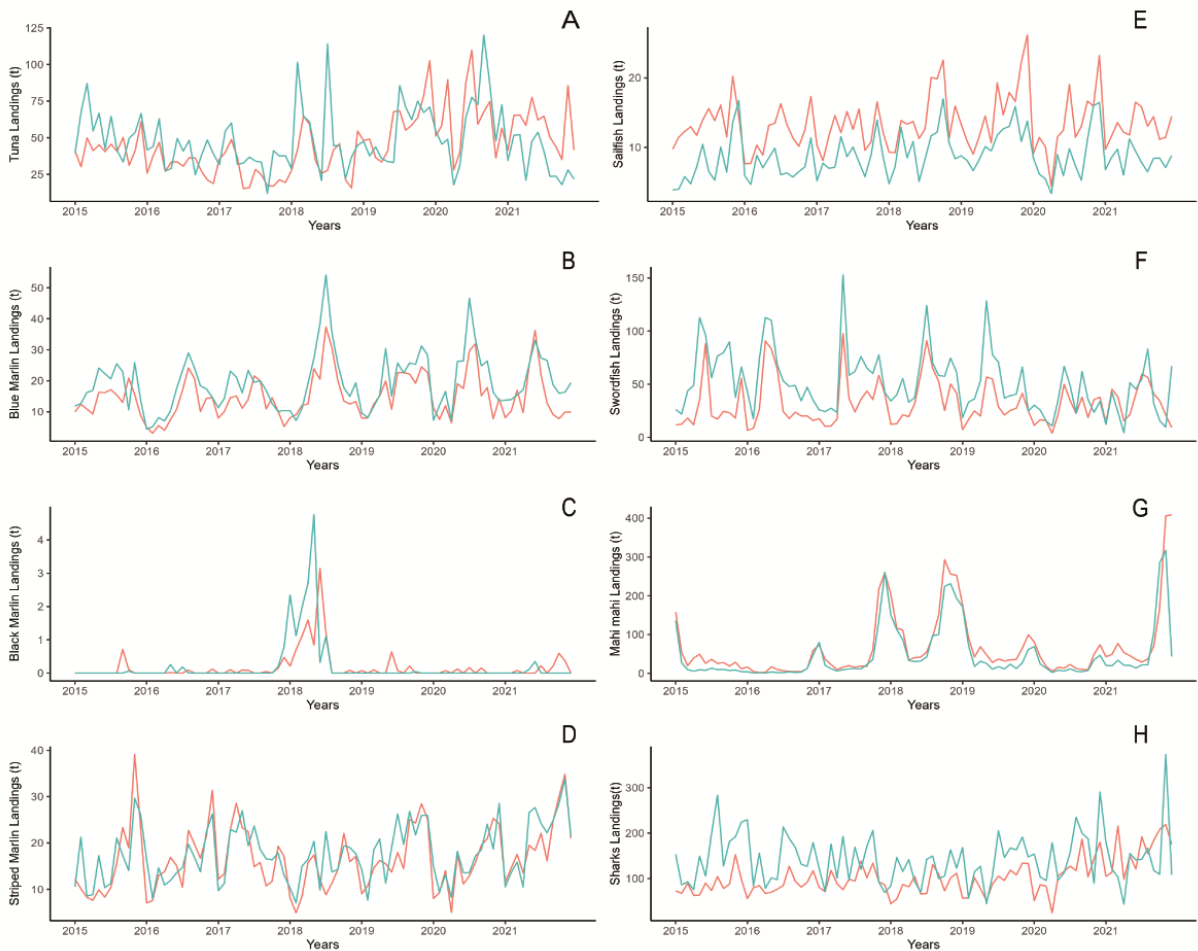
During the period 2015-2021, 310 active longline vessels were reported, comprising 117 advanced-scale fleet vessels and 193 medium-scale fleet vessels. The annual average of total landed catch of large pelagic fish was 7,531.01 metric tons, of which 39.14% corresponded to sharks, 24.34% to billfish (Istiophoridae and Xiphiidae), 18.05% to mahi-mahi, and 14.94% to tunas (Fig. 2).



**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.

### ***1.1 Tuna***

Yellowfin tuna dominated the landed tuna species during the period 2015-2021, accounting for 98.39% of the total. This was followed by bigeye tuna, at 1.23%, and skipjack tuna, at 0.38%. In 2020, both the medium-scale and large-scale fleets reached their peak tuna landings, with annual averages of 63.22 tons and 61.55 tons respectively (Fig. 3a). The standout months for the large-scale fleet in terms of production were September (120.08 tons) and October (86.40 tons), which recorded the highest values compared to other months of the year. For the medium-scale fleet, June and July of 2020 were the most productive months with averages of 109.83 tons and 87.31 tons, respectively. Overall, the medium-scale fleet reported lower landings compared to the large-scale fleet. The percentage growth in tuna landings between 2017 and 2020 was 66.49% for the large-scale fleet and 136.50% for the medium-scale fleet. However, there was variability, with a decrease in landings from 2020 to 2021 by 25.93%.



**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).

## 1.2 Billfish

The advanced-scale and medium-scale fleets contributed 53.26% and 46.74%, respectively, to the total landings of billfish species. This group of species was mainly composed of swordfish (47.92%), striped marlin (19.60%), blue marlin (19.59%), sailfish (12.68%), and black marlin (0.21%). The annual trend of landings for each species varied over the period, showing differences between species (Fig. 3).

For blue marlin (Fig. 3b), the highest monthly landings for both fleets were in 2018, reaching 17.79 tons for the advanced-scale fleet and 23.37 tons for the medium-scale fleet. Specifically, July stood out with the highest average for both fleets, reaching 54.17 tons and 37.39 tons, respectively. Blue marlin landings showed a growth trend of 28.62% for the advanced-scale fleet and 25.44% for the medium-scale fleet between 2015 and 2018. From 2018 onwards, a

decreasing trend was observed until 2021, with year-to-year variability resulting in decreases of 16.85% and 13.39%, respectively. Regarding black marlin (Fig. 3c), there were few landings observed, with none even reported in 2020. Among the years analyzed, 2018 stood out as the period with the highest records, reaching a peak average in May of 4.76 tons for the advanced-scale fleet and in June of 3.15 tons for the medium-scale fleet. As for striped marlin (Fig. 3d), landings peaked in 2021 with a monthly average of total tons landed of 21.65 tons and 20.32 tons for the advanced-scale and medium-scale fleets, respectively. The medium-scale fleet consistently had higher averages in several years in the months of May and November.

Sailfish landings were dominated by the medium-scale fleet, accounting for 60.58%, (Fig. 3e). There was a progressive increase from 2015 to 2019, with a rise of 36.68% for the advanced-scale fleet and 14.02% for the medium-scale fleet, followed by a slight decline in the years 2020 and 2021. The highest monthly averages for sailfish landings for both fleets were recorded in 2019, reaching 10.77 tons for the advanced-scale fleet and 15.56 tons for the medium-scale fleet. Consistently high values were observed in the months of October, November, and December over the years.

Regarding swordfish (Fig. 3f), the year with the highest landings for the advanced-scale fleet was 2015, with an annual average of 62.99 tons; May of that year recorded the highest landing at 112.69 tons. For the medium-scale fleet, the year with the highest landings was 2018, averaging 40.23 tons; July stood out with the maximum landing of 90.83 tons. Swordfish landings decreased by approximately 42.27% (advanced-scale fleet) and 36.55% (medium-scale fleet) from 2018 to 2020. Although the overall trend is downward, there are intermittent periods of growth, such as the slight increase of 7.39% between 2020 and 2021 following the pronounced decrease in the previous year.

### **1.3 Mahi-mahi**

This group is composed of a single species, *Coryphaena hippurus*. Mahi-mahi landings have shown variability, with three significant peaks during the study period: in 2017 (Advanced: 51.45 tons; Medium: 64.06 tons), the largest peaks were recorded in 2018 (Advanced: 111.15 tons; Medium: 137.41 tons), and in 2021 (Advanced: 77.03 tons; Medium: 118.73 tons) (Fig. 3g), where the medium-scale fleet had the highest averages. From October to January, consistently high landings are observed across the years compared to other months, with November 2021 being the highest total landing for the advanced-scale fleet at 317.18 tons, while for the medium-scale fleet it was December 2021 with 409.08 tons. On average, the medium and advanced-scale fleets landed 58.80% and 41.20%, respectively.

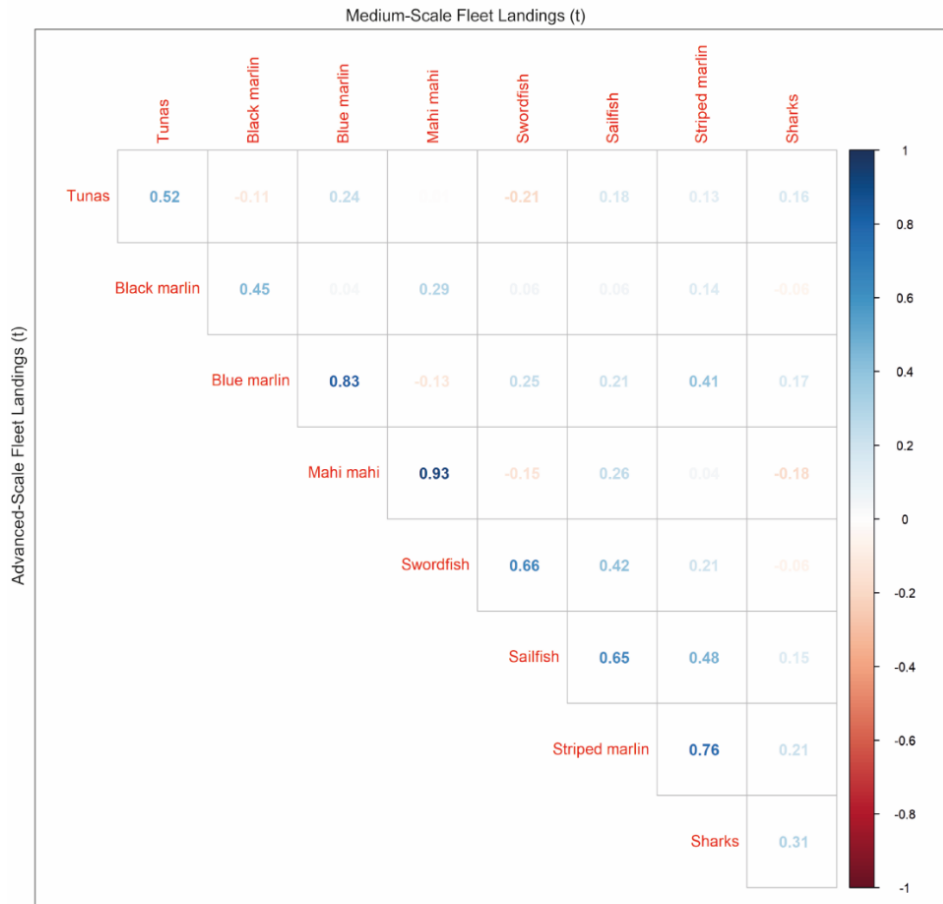
### **1.4 Sharks**

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 (Fig. 3h). 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%.

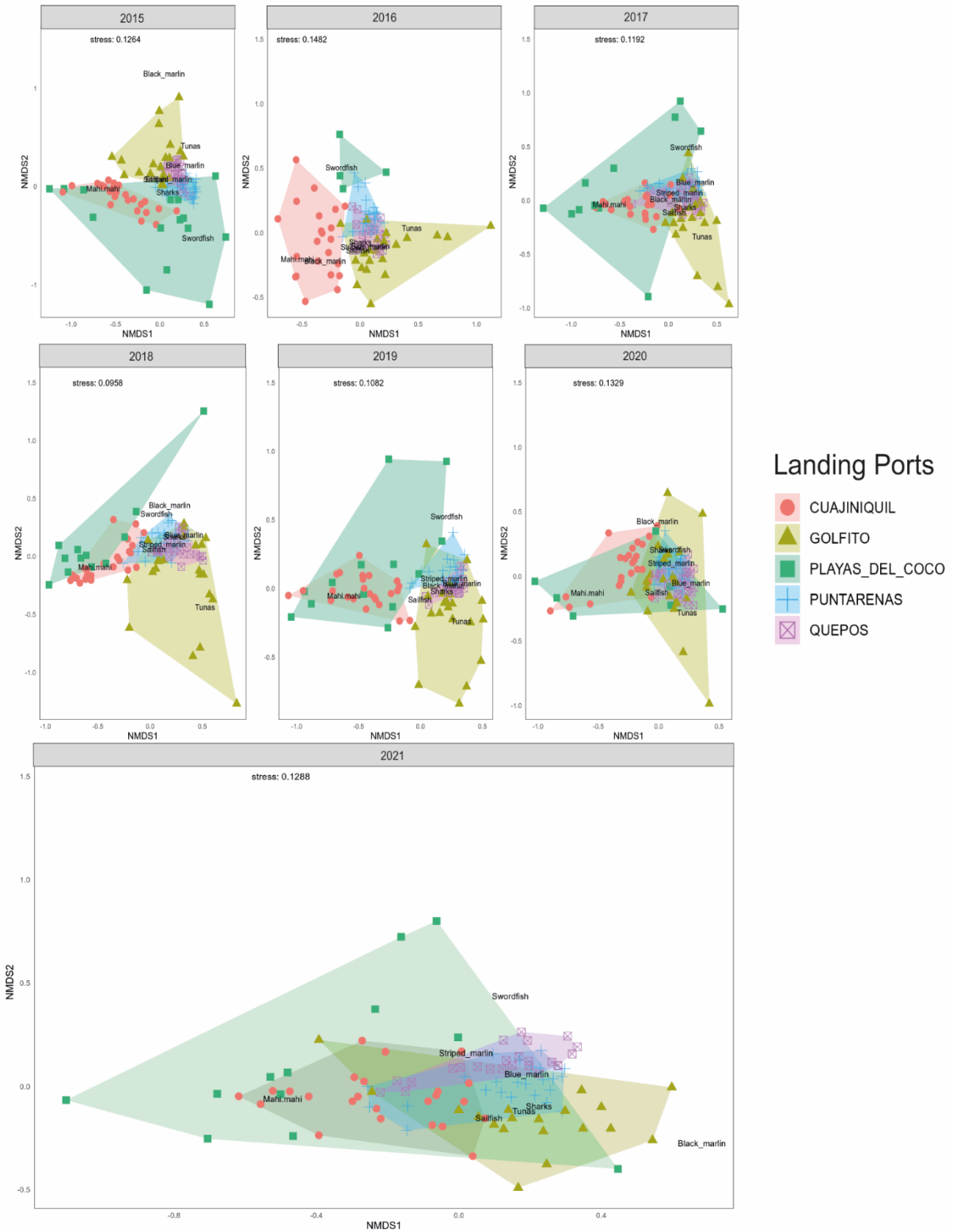
## 2. Characterization of landings

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 (Fig. 4).



**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.

In the multivariate space (Fig. 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 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 landing 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 (Fig. 5).



**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.

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).

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. 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  $\geq 0.1$ .

Factor	DF	Sum Sq	Mean Sq	Pseudo-F	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	-	-	-

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 and 3 because in all combinations it contributed equal to or less than 0.1% of the species variation in landing ports.

Table 2. SIMPER Analysis shows the species contributing to 90% of the variation by fleet type. 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  $\geq 0.1$ .

SIMPER Species	Percentage Contribution (%)	P-Value
Sharks	35.1	0.001****
Mahi-mahi	22.4	0.001****

<b>Tunas</b>	15.2	0.101
<b>Swordfish</b>	12	0.026*
<b>Blue Marlin</b>	6	0.001***
<b>Striped Marlin</b>	5.3	0.001***
<b>Sailfish</b>	3.9	0.001***

Table 3. SIMPER Analysis shows the percentage contribution by species and significance for the variation by landing ports. 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.

Landing Ports Combination	Percentage Contribution by Species and Significance (p-value)						
	<i>Sharks</i>	<i>Mahi-mahi</i>	<i>Tunas</i>	<i>Swordfish</i>	<i>Sailfish</i>	<i>Blue Marlin</i>	<i>Striped Marlin</i>
<i>Cuajiniquil-Playas del Coco</i>	25.2	53.9 ***	3.7	7.3	5.3***	1.7	2.9
<i>Cuajiniquil-Puntarenas</i>	40.9***	14	15.7***	17.2***	1.9	5	5.2***
<i>Cuajiniquil-Quepos</i>	26.2	24.3 .	18.5***	8.9	4.5***	10.4***	7.2***
<i>Cuajiniquil-Golfito</i>	27.2	40.6***	16.3*	4.9	4.6***	3.4	3
<i>Playas del Coco-Puntarenas</i>	42.5***	11.9	15.6***	17***	2.5	5**	5.4***
<i>Playas del Coco-Quepos</i>	32.8***	13.8	20***	9	6***	10.8***	8***
<i>Playas del Coco-Golfito</i>	32.3***	24.7***	23.4***	6.1	5.5***	4.7	3.3
<i>Puntarenas-Quepos</i>	42.4*	15.5	13.5	18.8***	1.6	3.8	4.3
<i>Puntarenas-Golfito</i>	41.8***	12.7	14.3*	18.7***	2	4.8	5.6***
<i>Quepos-Golfito</i>	30.8	13.5	18.2	11.3	5.7***	11.5***	9***

## **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 (Fig. 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 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 (Incopescas, 2019).

### ***1.1 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 & 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 longline fleet during the period covered in this study (Fig. 3a). In 2020, relatively high monthly averages were observed for both fleets, which could have been influenced by regulations due to the COVID-19 pandemic, reducing fishing effort globally (He et al., 2021), possibly decreasing competition with foreign industrial fleets operating with purse seines within the Costa Rican EEZ. Moreover, in 2014, Executive Decree No. 38681-MAG-MINAE 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.

### ***1.2 Billfish***

In the Pacific Ocean, Blue marlin is considered a single stock (Graves & 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), it was found that 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. However, it is important to note that the results presented here indicate a declining catch pattern in Costa Rica's Pacific, which coincides with the catch trend for the entire Eastern Tropical Pacific during the period from 2019 to 2021.

There are limitations in the stock assessments for black marlin, primarily due to the lack of reliable data (Zeller & 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 & Fitchett, 2006; Pohlot & Ehrhardt, 2018). Maximum catches have been recorded along the Central American coast (Ehrhardt & 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 carried out in 2013, revealing a possible underestimation of catches (IATTC, 2023). Reported 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 a higher tonnage of 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 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 dorado and tuna.

### ***1.3 Mahi-mahi***

The mahi-mahi fishery in Costa Rica is primarily concentrated from November to February (Morgan & 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 & Martínez 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, fishermen use a surface longline without a steel leader, while for 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, variations in bait types and setting depth vary depending on the fleet and target species (Valle-Esquivel et al., 2018).

#### ***1.4 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 & 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). Considering that data reporting for the Tropical Pacific may have been affected due to the COVID-19 pandemic and the lack of mandatory reporting of incidental catches, there is significant variability in shark landing data; however, trends indicate a decrease in shark catches in some fisheries (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 (Executive Decree 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.

### ***1.5 Influence of climate oscillations and oceanographic variability on landings***

Climate oscillations and their associated anomalies profoundly influence marine ecosystems, particularly regarding the migration and population dynamics of top predators such as tuna and marlin (Lehodey et al., 2011). These fluctuations, especially during the warm phase of the El Niño-Southern Oscillation (ENSO), are associated with a relaxation of the trade winds that blow from east to west, resulting in the accumulation of warm waters along the eastern Pacific coast and a general increase in temperature. This has significant implications for multiple aspects of pelagic environment ecology (Domokos, 2023; Williams & Reid, 2018), including changes in water column stratification, oxygen and nutrient availability, and ocean productivity. ENSO is the main source of variability in the oceanographic conditions of the Eastern Tropical Pacific, with substantial impacts on ecosystem function, fishery resources, and carbon capture.

From November 2018 to April 2019, Costa Rica's Pacific coast experienced the effects of the El Niño phenomenon (Instituto Meteorológico Nacional, 2019), which may have affected the dynamics of species in this fishery. High landings for most of the studied species were reported during these years (Figure 3). According to Mondal et al. (2023), the distribution and presence of blue marlin and sailfish in the Eastern Tropical Pacific are hypothesized to be related to physical and oceanographic variables such as sea surface temperature, ocean currents, eddies, and current velocity. Seasonal changes in blue marlin distribution have been linked to changes in sea surface temperature, mixed layer depth, and chlorophyll-a concentrations. These environmental conditions can directly affect the physiology of blue marlin and sailfish and may also be indirectly related to the distribution of their prey, such as small tuna and squid, which are influenced by oceanic climate oscillations like ENSO.

In the case of tuna, Domokos (2023) demonstrated that during the warm phase of ENSO and in subsequent periods, longline catches increased, suggesting that these effects could be related to changes in preferred habitat distribution as well as changes in fishing behavior. However, interpreting these results is complicated by various factors that influence catch per unit effort and whose effects are not well understood, including changes in the fishery and environment, as well as the long-distance migration of tuna (Minte-Vera et al., 2020; Xu et al., 2020).

### ***1.6 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 and colleagues (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 fishermen 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 fishermen 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 (Cascañe & 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 & Cox, 2013; Martin et al., 2016)

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 also respond to variations between 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 the 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.

Multispecies fisheries must be managed with species-specific regulations (Samoilys et al., 2017), and it is also 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 species 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, their implementation is considerably limited, resulting in poorly supervised operations and frequent violations of existing regulations (Incopescas, 2005). The shortage of specialized personnel, such as inspectors, statisticians, and scientists, combined with Incopesca's reliance on the National Coast Guard Service for offshore surveillance, the absence of an onboard observer program despite CIAT requirements (CIAT, 2011), a lack of funding to adopt technologies that would improve control over fishing activities, and insufficiently trained personnel to monitor port landings, have hindered the effective enforcement of the existing legal framework. This lack of effective implementation has allowed illegal and unsustainable

activities to persist, which degrade marine resources and jeopardize the sustainability of the fishery (Alms & Wolff, 2019).

There is limited independent information available to validate landing records. As a result, assessments of endangered, threatened, and protected species may not be representative of all fleets and geographic areas, potentially leading to biased data (Mendenhall et al., 2020). Additionally, there is uncertainty about the amount of discarded catch, the accuracy of reported catch locations in logbooks, and the quantity of catch transshipped at sea. Insufficient information on catches is hindering the sustainable management of the fishery and could compromise the management of populations that are rapidly adapting their distributions in response to a changing climate (Brown et al., 2021).

The 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 oversight and improve *in situ* data collection, as well as species identification and bycatch quantification (Brown et al., 2021; Emery et al., 2019b, 2019a). 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.

Moreover, there are various measures that must be implemented to advance the reduction of bycatch. For example, 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 are essential. Additionally, it has been demonstrated that the greenstick fishing method is selective and efficient in tuna capture (Marín Alpizar et al., 2019). Therefore, training fishermen who are not yet using this method could improve the profitability of the catch while reducing the pressure on secondary species in the longline fishery, as well as reducing bycatch levels to focus on better-studied target species.

## **Conclusion**

The longline fishery in the Pacific of Costa Rica, being multispecies, requires multivariate and non-traditional research approaches due to the lack of data for more comprehensive assessments. 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 improvement plans. The SIMPER test identified sharks as the species that most influence the differences observed between fleets, highlighting that the increase in shark catches in the advanced fleet does not imply a proportional increase in the medium-scale fleet, and vice versa. Recognizing the key species in this variation is crucial for focusing management efforts and future assessments, especially when these species are considered secondary.

The NMDS analysis showed that fishery landings by port during the study period became increasingly homogeneous, suggesting a shift towards more opportunistic and less selective

fishing. The analysis of the composition and landing patterns of the Costa Rican longline fleet, together with a review of the implementation of management and conservation measures, reveals information gaps and deficiencies in controls and implementation. To address these challenges, 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 fishermen, 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.

### **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.*

### **Author Contributions**

Allison Centeno led data analysis and manuscript writing. Marina Marrari contributed to data analysis and manuscript writing. Fausto Arias and Moisés Mug provided expertise on fisheries in Costa Rica and assisted with manuscript review. Andrea García contributed to manuscript writing and review. All authors contributed to the study and approved the final version of the manuscript.

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### **Data Availability Statement**

The datasets analyzed for this study can be found in the "Transparency" section of the Costa Rican Institute of Fisheries and Aquaculture (Incopesca) website: [https://www.incopesca.go.cr/acerca\\_incopesca/transparencia\\_institucional/datos\\_abiertos.aspx](https://www.incopesca.go.cr/acerca_incopesca/transparencia_institucional/datos_abiertos.aspx)

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## Conclusiones

La pesca de palangre en el Pacífico de Costa Rica es una actividad multiespecífica que requiere enfoques de investigación multivariados y no convencionales debido a la insuficiencia de datos para realizar evaluaciones más completas. Los resultados del análisis PERMANOVA evidenciaron que el tipo de flota, el puerto y el momento de desembarque son factores significativos que explican la variabilidad en las especies capturadas. Esto proporciona información clave para comprender la dinámica de la pesquería y fundamentar futuras acciones para mejorar la sostenibilidad de la actividad.

Por otro lado, la prueba SIMPER identificó que los tiburones son la especie que más influye en las diferencias observadas entre las flotas. Sin embargo, el incremento en la captura de tiburones en la flota avanzada no se traduce en un patrón similar en la flota de mediana escala, lo que subraya la importancia de identificar especies clave en estos patrones para orientar mejor las estrategias de gestión pesquera.

El análisis NMDS reveló una tendencia hacia la homogeneización de los desembarques pesqueros en los puertos durante el período de estudio, lo que sugiere un cambio hacia una pesca más oportunista y menos selectiva. Además, la revisión de patrones de desembarque y el análisis de medidas de manejo actuales expusieron vacíos críticos en la información y deficiencias en los controles y regulaciones. Estos resultados ponen en evidencia la necesidad de abordar estos vacíos mediante un enfoque más sistemático y coordinado.

## **Recomendaciones**

Para enfrentar los desafíos identificados, es fundamental implementar una estrategia integral que priorice la investigación científica, facilite la recopilación de datos a través de la incorporación de tecnologías avanzadas y promueva prácticas de pesca sostenible. Esta estrategia debe involucrar una colaboración activa entre todos los actores relevantes: pescadores, autoridades regulatorias, la comunidad científica y organizaciones no gubernamentales.

Además, se recomienda enfocar los esfuerzos de manejo en las especies clave identificadas en el análisis, especialmente aquellas consideradas secundarias, con el objetivo de mitigar las variaciones observadas en las capturas y mejorar la sostenibilidad de la actividad pesquera. La implementación de políticas efectivas que permitan mejorar la regulación y el cumplimiento de las normas en el área es esencial para la conservación de los ecosistemas marinos y para asegurar la viabilidad a largo plazo de la pesca en el Pacífico de Costa Rica.

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### **Conflicto de Interés**

La investigación se realizó sin ningún vínculo comercial o financiero que pudiera interpretarse como un conflicto de interés potencial.