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**Mapping blue shark (*Prionace glauca*) distribution:
Assessing fishing pressures in the Eastern Tropical Pacific**



UNIVERSIDADE DO ALGARVE

Faculdade de Ciências e Tecnologia

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**Mapping blue shark (*Prionace glauca*) distribution:
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Professional Master in Biodiversity, Fisheries, and Conservation

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Declaration of authorship of work

Mapping blue shark (*Prionace glauca*) distribution: Assessing fishing pressures in the Eastern Tropical Pacific

I declare I am the author of this work, which is original and unpublished. The sources consulted have been duly cited in the text and included in the list of references.

(Ángela P. Palomino Gaviria)

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Sumário

Os tubarões oceânicos, particularmente o *Prionace glauca* (tubarão-azul), enfrentam ameaças crescentes de sobre-exploração, principalmente devido às pescarias pelágicas de palangre, que os capturam tanto de forma direta como acidental (bycatch). Neste contexto, as Áreas Marinhas Protegidas (AMPs) são amplamente reconhecidas como uma forma eficaz de conservar espécies e habitats marinhos. Embora as AMPs possam reduzir os impactos humanos, como a sobrepesca, a proteção de espécies marinhas altamente móveis dentro delas continua a ser um desafio. AMPs individuais podem oferecer uma proteção limitada se não abrangerem uma parte significativa dos habitats críticos das espécies. A criação de uma Rede de Áreas Marinhas Protegidas (RAMP) poderia aumentar a proteção, ligando habitats vitais e servindo como uma ferramenta mais eficaz na gestão de espécies móveis, como o tubarão-azul.

Este estudo integra dados dos registos de desembarque da pescaria artesanal de palangre do Equador, do Projeto Tubarão-Azul das Galápagos e de bases de dados online para avaliar a distribuição potencial do tubarão-azul no Pacífico Tropical Oriental (PTO) e sobrepor essas áreas com as atividades de pesca. Os resultados revelaram que o tubarão-azul é uma das espécies de elasmobrânquios mais frequentemente capturadas e desembarcadas, representando 25% do total de capturas. Através dos Modelos de Distribuição de Espécies (SDMs), foram identificados habitats altamente adequados para o tubarão-azul em torno da Reserva Marinha das Galápagos, particularmente a sudeste da Ilha Isabela. O estudo também avaliou a sobreposição entre esses habitats potenciais e as zonas de pesca ativas, mostrando que cerca de 20% dos habitats adequados estão sob pressão da pesca. Estes resultados mostram a necessidade de estratégias de conservação mais abrangentes, incluindo a expansão da RAMP, para melhor proteger os tubarões-azuis e mitigar os impactos da pesca que podem somar-se às mudanças ambientais e comprometer ainda mais a sobrevivência da espécie na região.

Abstract

Oceanic sharks, particularly *Prionace glauca* (blue shark), face growing threats from overexploitation, primarily due to pelagic longline fisheries that target them both directly and as bycatch. In this context, Marine Protected Areas (MPAs) are broadly acknowledged as an effective way of conserving marine species and habitats. Although MPAs can reduce human impacts such as overfishing, protecting highly mobile marine species within them remains a challenge. Single MPAs may offer limited protection if they do not encompass a significant portion of the specie's critical habitats. Establishing a Marine Protected Area Network (MPAn) could enhance protection, connecting vital habitats and serving as a better tool for managing mobile species like blue sharks.

This study integrates data from Ecuador's artisanal longline fishery landing records, the Galapagos Blue Shark Project, and online databases to assess the potential distribution of the blue shark in the Eastern Tropical Pacific (ETP) and overlaying areas with fishing activities. The results revealed that the blue shark is one of the most frequently captured and landed elasmobranch species, accounting for 25% of the total catch. Using Species Distribution Models (SDMs), blue shark's suitable habitat was identified around the Galapagos Marine Reserve, particularly southeast of Isabela Island. The study also assessed the overlap between these potential habitats and active fishing zones, showing that around 20% of the suitable habitats face fishing pressures. These findings emphasize the need for more comprehensive conservation strategies, including the expansion of MPAn, to better protect blue sharks and mitigate the impacts of fishing which may combine with environmental changes and further exacerbate the threat to the species' survival in the region.

Keywords: *Prionace glauca*, blue sharks, marine protected areas (MPA), spatial ecology, species distribution modelling (SDM), fisheries overlap.

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Keywords: *Prionace glauca*, blue sharks, marine protected areas (MPA), spatial ecology, species distribution modelling (SDM), fisheries overlap.

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List of Abbreviations, Acronyms and Symbols

ABNJ	Areas Beyond National Jurisdiction	NEC	North Equatorial Current
AFE	Apparent Fishing Effort	NECC	North Equatorial Counter-Current
ARGOS	Advanced Global Observing and Research Satellite System	NOAA	National Oceanic and Atmospheric Administration
BMMA	Bicentennial Marine Management Area	MPAs	Marine Protected Areas
CBD	Convention on Biological Diversity	MPAn	Marine Protected Area network
CMS	Convention on the Conservation of Migratory Species of Wild Animals	NT	Near Threatened
CINP	Cocos Island National Park	OBIS	Ocean Biogeographic Information System
CRTD	Costa Rica Thermal Dome	OECMs	Other Effective area-based Conservation Measures
EEZ	Exclusive Economic Zones	PC	Panama Current
ENSO	El Niño-Southern Oscillation	PCL	Pre-Caudal Length
ETP	Eastern Tropical Pacific	SEC	South Equatorial Current
FAO	Food and Agriculture Organization	SDM	Species Distribution Model
FL	Fork length	SPOT	Smart Position and Temperature Transmitting Tag
GBIF	Global Biodiversity Information Facility	SRP-VMAP	Secretary of Fisheries Resources, Vice Ministry of Aquaculture and Fisheries
GFW	Global Fishing Watch	SST	Sea Surface Temperature
GMR	Galapagos Marine Reserve	TL	Total Length
HMR	Hermandad Marine Reserve	UICN	International Union for Conservation of Nature
ISC	International Scientific Committee	UNEP	United Nations Environment Programme
IUU	Illegal, Unreported, and Unregulated	UNESCO	United Nations Educational, Scientific and Cultural Organization
KDE	Kernel Density Estimation	WC-DAP	Wildlife Computers Data Analysis Programs
LC	Location Codes		

1. Introduction

Oceanic sharks are facing rising overexploitation due to the growing impact and intensity of global fishing pressures (Pacoureau *et al.*, 2021), particularly from pelagic longline fisheries (Oliver *et al.*, 2015) as a target species or as bycatch (Worm *et al.*, 2013; Dulvy *et al.*, 2014b). This activity is a major factor in the decline of oceanic shark populations (Pacoureau *et al.*, 2021), which are particularly vulnerable due to their low resilience to exploitation (Stevens *et al.*, 2000). According to the Food and Agriculture Organization (FAO), global fishery production of sharks, rays, and chimaeras peaked at 868,190 tonnes in 2000. However, over the following two decades, it declined by nearly 2%, reaching 679,978 tonnes by 2018 (FAO, 2021k).

In addition to overfishing, climate change has intensified extreme weather events, leading to a rise in the frequency of anomalous events in the world's oceans (Henson *et al.*, 2017). These changes have contributed to the loss and degradation of habitats (Dulvy *et al.*, 2021), destabilising food chains and marine communities (Doney *et al.*, 2012) causing shifts in their distribution (Lezama-Ochoa *et al.*, 2016). Although climate change is not considered as significant a threat to shark populations as fishing mortality and habitat loss (Dulvy *et al.*, 2021), extreme weather events can still have meaningful impacts in the population dynamic. For example, a cold snap in the Florida Everglades led to the mortality of a substantial portion of the juvenile bull sharks (*Carcharhinus leucas*). However, the population recovered over time, demonstrating the resilience these animals can show in response to isolated events (Matich *et al.*, 2020).

The establishment of Marine Protected Areas (MPAs) is widely recognized as an effective tool for conserving marine habitats and species (Allison *et al.*, 1998; Lubchenco *et al.*, 2003; Balbar & Metaxas, 2019; Bucaram & Cárdenas, 2020). MPAs help mitigate human pressures and activities, such as overfishing (Carr *et al.*, 2017). However, ensuring the effectiveness of MPAs in safeguarding highly mobile marine species is challenging. Individual MPAs may provide limited protection or be insufficient if they do not cover a significant portion of the

species' key habitats (Klein *et al.*, 2015). A practical strategy would be to establish a Marine Protected Area Network (MPAn), which offers significantly broader protection for marine ecosystems compared to a single reserve (Lubchenco *et al.*, 2003). A MPAn would link essential habitats for highly mobile species, allowing these species to act as indicator species to assess the effectiveness of MPAs management and planning (Hooker & Gerber, 2004; Carr *et al.*, 2017).

In alignment with international biodiversity goals, Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets outlined by the Convention on Biological Diversity (CBD, 2010), there has been a global increase in the number of protected areas and other effective area-based conservation measures (OECMs) worldwide (Carr *et al.*, 2020). This trend is evident in the Eastern Tropical Pacific (ETP), where recent initiatives have led to the establishment and expansion of several MPAs and OECMs, including Costa Rica's Cocos Island National Park (CINP), the Bicentennial Marine Management Area (BMMA), Ecuador's Hermandad Marine Reserve (HMR), and the Galapagos Marine Reserve (GMR).

The ETP is a dynamic and diverse region where warm and cold ocean currents converge (Palacios, 2004; Kessler, 2006), (see **Figure 1**), leading to numerous upwelling zones that create unique oceanographic, biological, and ecological conditions (Heylings *et al.*, 2002). Oceanic islands like the Galapagos and Cocos are geologically linked by the Cocos Sea Ridge and its surrounding seamounts, which interact with ocean circulation patterns to enhance productivity, biomass, and biodiversity in the region (Lavelle & Mohn, 2010). These geological structures serve as habitat hotspots for numerous marine species, forming potential migration corridors between the open ocean with coastal areas (Lara-Lizardi *et al.*, 2020). This region is particularly significant for highly migratory species like the blue shark, which is the primary focus of this study.

Prionace glauca (Linnaeus, 1758), (Nakano & Seki, 2003), commonly known as the blue shark, is a large, oceanic-epipelagic species known for its extensive migratory behaviour, inhabiting both coastal and open ocean waters. Blue sharks may occasionally inhabit depths,

sometimes exceeding 1000 meters. The deepest recorded dive reached 1706 m (Queiroz *et al.*, 2017). It has one of the widest geographic distributions and temperature tolerances among sharks, ranging from 60°N to 50°S latitudes (Nykänen *et al.*, 2018). Despite their ecological role, this species is globally assessed as Near Threatened (NT) on the IUCN Red List (Rigby *et al.*, 2019), and included in Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals (CMS), (UNEP, 2017). Globally, blue shark catches increased from the 1950s to 2014, reaching a peak in 2013. However, production has declined in recent years (Da Silva *et al.*, 2021; FAO, 2021k). Since 2014, the ISC Shark Working Group has identified two distinct blue shark stocks in the Pacific Ocean—one in the North Pacific and one in the South Pacific—based on biological and fishery data (ISC, 2013). Although some genetic exchange between the two regions is expected, it is recommended for both populations to be managed independently as a precautionary measure (Tagachi *et al.*, 2015). Moreover, tagging data so far does not support the idea of panmixia in the Pacific. No tagging data has shown movement across the equator, suggesting that both subpopulations are likely separated by the equator (ISC, 2016).

Population estimates are primarily based on catch data, but reliable information on population trends remains scarce (Queiroz *et al.*, 2016). Studies show that the abundance of the blue shark is lower in equatorial waters (Jolly *et al.*, 2013), however, it remains one of the most common species in landings in Peru (González-Pestana *et al.*, 2016) and Ecuador (Martínez-Ortiz *et al.*, 2011). In the southeastern tropical Pacific, there are no published studies on the spatial ecology and distribution of the blue shark (Elliott *et al.*, 2022). This lack of data presents a major challenge for the development of sustainable management plans and hinders our understanding of the population structure and dynamics of the species (Martínez-Ortiz *et al.*, 2015).

The present study assessed the potential distribution of the blue shark (*Prionace glauca*) by integrating data from Ecuador's artisanal longline fishery landing records (2008-2012), the Galapagos Blue Shark Project (2019-2024) and online databases. Species Distribution Models (SDMs) were employed to identify potential distribution in the study area and evaluate the

effectiveness of the Marine Protected Areas network (MPAn) in the Eastern Tropical Pacific (ETP) for protecting this species. Additionally, the model was used to assess the overlap between blue shark's potential habitats and fishing activities within the study area.

2. General objectives

To assess the potential distribution of the blue shark (*Prionace glauca*) in the Eastern Tropical Pacific (ETP) by integrating data from Ecuador's artisanal longline fishery records, the Galapagos Blue Shark Project, online databases and to evaluate the effectiveness of the Marine Protected Areas network (MPAn) in the ETP.

2.1. Specific objectives

- 1) To explore temporal catches of elasmobranch species.
- 2) To identify seasonal catch trends of *P. glauca* in landing records of the Ecuadorian artisanal longline fishery between 2008 and 2012.
- 3) To model the potential distribution of *P. glauca* across the Galapagos Marine Reserve and its surrounding waters in the Eastern tropical Pacific using a machine learning framework tuned with predictor variables and occurrence records.
- 4) To quantify the contribution of climatic variables to the potential distribution of *P. glauca*.
- 5) To estimate the overlapping areas between fishing activities and the potential distribution of blue sharks.

3. Material and methods

3.1. Study area

Positioned on the equator within the ETP, the Galapagos archipelago spans approximately 1,000 km west of mainland Ecuador (Bustamante *et al.*, 2000). The archipelago's relative isolation, influenced by one of the world's most dynamic ocean circulation systems (Kessler, 2006), has resulted in the creation of three main biogeographic zones (Spalding *et al.*, 2007) fostering a remarkable degree of endemism (Edgar *et al.*, 2008).

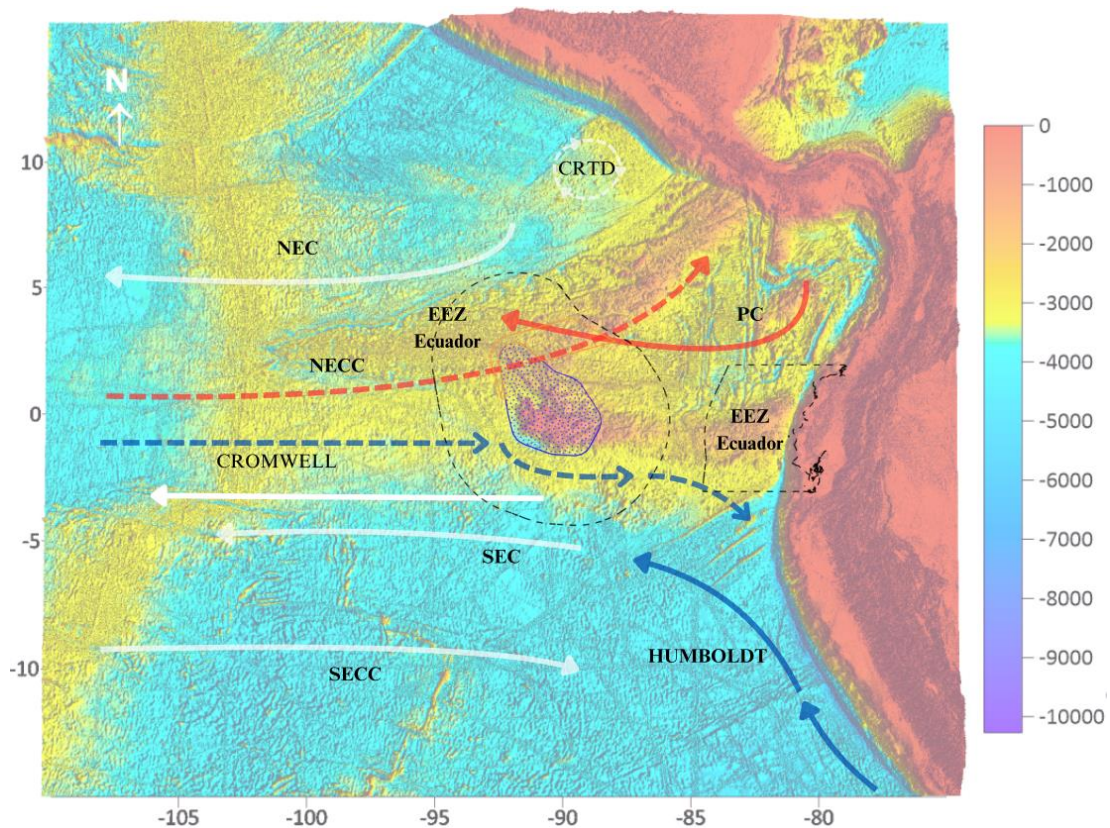


Figure 1. Schematic diagram of bathymetry and main currents around Galapagos Archipelago at ETP; **CRTD**: Costa Rica Thermal Dome, **NEC**: North Equatorial Current, **NECC**: North Equatorial Counter-Current, **PC**: Panama Current, **CROMWELL**: or

Equatorial Subsurface Current, **SEC**: South Equatorial Current, **HUMBOLT**: or Peru Coastal Current (GEBCO, 2023; Wyrki, 1967; Fiedler *et al.*, 1991; Fiedler *et al.*, 2013).

Three major ocean currents primarily influence the environmental conditions in this region. The eastward Equatorial Undercurrent, or Cromwell Current, flows west to east, colliding with the Galapagos platform and generating an upwelling zone (Pak & Zaneveld, 1974). This upwelling brings nutrient-rich waters to the surface, increasing productivity, particularly to the west of Isabela Island, and extends eastward across the GMR (Steger *et al.*, 1998). The Panama Current, which flows from Central America, brings warm conditions from December to May, with sea surface temperatures (SST) > 25 °C (Banks, 2002; Liu *et al.*, 2014). In contrast, the Humboldt Current, along with the South Equatorial Current, two cold currents flowing from South America, brings cooler conditions from June to November with SST ranging from 18-20 °C (Banks, 2002; Liu *et al.*, 2014).

The El Niño-Southern Oscillation (ENSO) significantly impacts the region by causing interannual fluctuations in sea temperature, resulting in warmer or cooler conditions than average (Wang & Fiedler, 2006). These temperature changes alter the depth of the thermocline, affecting primary productivity (Lavín *et al.*, 2006), and, consequently, marine life across various trophic levels (Watters *et al.*, 2003). ENSO is therefore a key factor in climate variability, with considerable ecological and economic effects (Adams & Flores, 2016; Holbrook *et al.*, 2020; FAO, 2024).

3.2. Occurrence records

3.2.1. Electronic tracking data

The final dataset comes from the Galapagos Blue Shark Project, initiated in 2019 to collect the first electronic tracking data for blue sharks within the GMR. A total of nine Smart Position and Temperature Transmitting Tags (SPOTs) were deployed on blue sharks during the warm

and rainy seasons of 2019 and 2022. In the cold and dry season of 2024, two additional SPOT tag were affixed.

All collected SPOTs tracks were pre-processed using Wildlife Computers Data Analysis Programs (WC-DAP) v.3.0 processor software (<https://wildlifecomputers.com/>) to remove duplicates. Subsequently, the set of tracks from 11 individuals ($n = 11$) were analysed using RStudio® v.4.1.2. Initially, highly inaccurate positions (LC Z) were excluded. Following this, improbable Argos locations were filtered out using the ‘argosfilter’ package (Freitas, 2022). Specifically, all locations that would require sharks to move faster than 3.0 ms^{-1} between consecutive positions were removed (Fontes *et al.*, 2018). A total of 990 observations were obtained for further analysis.

3.2.2. Satellite tagging methods

Shark capture operations were carried out during fishing expeditions aboard *F/V Yualka*. In February 2019, researchers tagged five blue sharks near the platform break southeast of Isabela Island. The tagged sharks included four adult males and one adult female. These individuals were caught using longlines equipped with 70-80 circle hooks (size 15/0) baited with a mix of Galapagos mullet (*Mugil galapagensis*), Thoburn's mullet (*Xenomugil thoburni*), and common dolphinfish (*Coryphaena hippurus*). Two fiberglass skiffs, or ‘fibras’, operated simultaneously during the fishing operations to increase efficiency and productivity.

Continuing this initiative, further efforts were conducted in March 2022, as well as in May and June 2024, to enhance the tracking of blue sharks in the waters surrounding the GMR. The fishing methodology in 2022 and 2024 remained largely the same, with circle hooks now baited with White salema (*Xenichthys agassizi*) and Skipjack tuna (*Katsuwonus pelamis*). During the 2022 tagging, three adult females and one sub-adult female were tagged in the northern and northeastern sectors of San Cristóbal Island, near two seamounts. In 2024, two adult males were tagged, the first was tagged northeast of Genovesa Island within the

boundaries of the GMR, and the other individual was tagged on a seamount outside the GMR but within the newly established HMR boundaries (as shown in **Figure 2**).

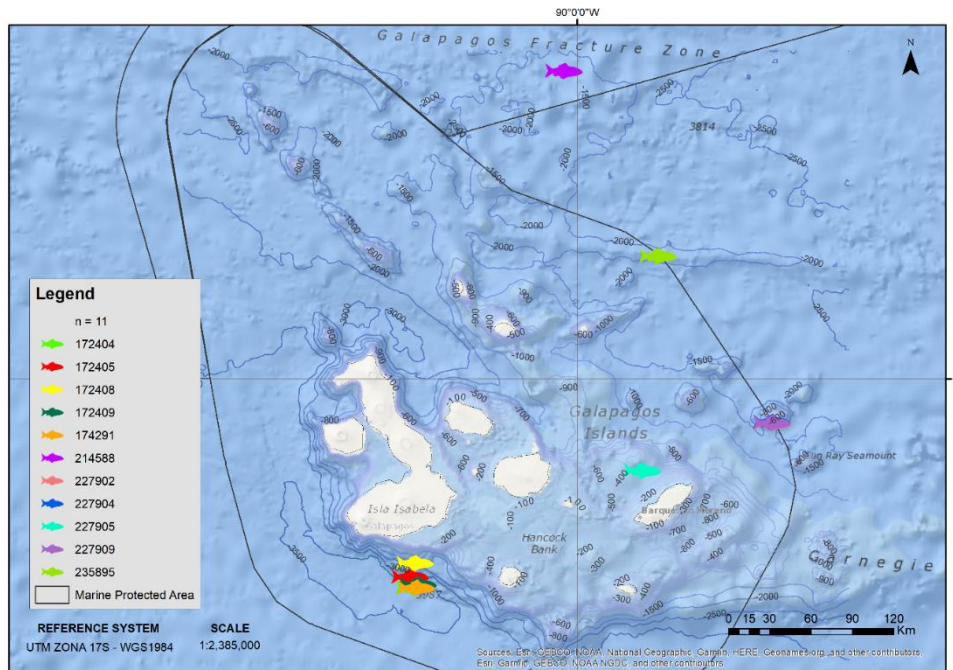


Figure 2. Tagging sites for blue sharks include areas south of Isabela Island, north and northeast of San Cristobal Island, northeast of Genovesa Island, and within the Galapagos Fracture Zone in the HMR.

In 2019, the longlines were soaked for approximately 5 hours and captured sharks were brought alongside the vessel and immobilized with a tail rope and an additional rope behind the pectoral fins to keep the shark close to the boat. By 2022 and 2024, sharks were instead brought on board, where a water pump ensured a constant flow of water through their gills. The longline were monitored regularly intervals due to the potential presence of smooth hammerhead sharks (*Sphyrna zygaena*) in the area. Given the heightened sensitivity of hammerhead sharks to fishing stress, as documented by Martínez-Ortiz *et al.* (2015) and Wells *et al.* (2018), the crew took extra precautions to minimize mortality risks. Non-target species were promptly released.

SPOT tags were attached to the first dorsal fin of each blue shark using a custom clip for a single point of attachment or by drilling 3-4 small holes and securing the tag with stainless steel bolts, neoprene washers, steel washers, and steel screw-lock nuts. Each tagged shark was measured for total length (TL), fork length (FL), pre-caudal length (PCL), maximum girth, maturity stage, gender, tagging location, and handling time. A fin clip or tissue sample was also collected for genetic analysis. All animal handling procedures were approved by institutional review committees and carried out by licensed, trained, and experienced professionals. The entire procedure usually takes no more than 10 minutes on average.

3.2.3. Tag programming

The Smart Position and Temperature Transmitting Tags, (SPOT; model SPOT6, Wildlife Computers, Redmond, WA, USA) send short signals to the National Oceanic and Atmospheric Administration's (NOAA) Advanced Global Observing and Research Satellite System (ARGOS). These transmissions are processed through the Argos-CLS website, which provides key data, including date, time, and positions for each tagged animal detection.

Programmed to transmit location and ambient temperature data whenever the tagged shark's dorsal fin breaches the surface, SPOT tags offer the advantage of near real-time, high-resolution tracking (Hammerschlag *et al.*, 2011). This makes them particularly suitable for shark species like blue sharks that frequently surface (Stevens *et al.*, 2010).

The accuracy of the geographic locations of satellite-tagged sharks, determined through Doppler-shift calculations, depends on the number of signals received by ARGOS satellites (Calich *et al.*, 2018; <https://www.argos-system.org>). The wet/dry sensor within the tag activates transmission upon exposure to air, subsequently relaying signals to satellites for reception (Doyle *et al.*, 2015). Data transmission includes tag identification and location accuracy, classified by Argos into seven location codes (LC): 3, 2, 1, 0, A, B, and Z. These codes represent the estimated error in location, with LC 3 being the most accurate (< 250 meters) and LC 0 being less accurate (up to 1500 meters). Locations coded as A and B have

an accuracy range of 2-3 kilometres. LC Z denotes invalid positions due to high inaccuracies (Boyd & Brightsmith, 2013).

3.3. Artisanal longline fishing data

Between 2008 and 2012, the Secretary of Fisheries Resources, operating under the Vice Ministry of Aquaculture and Fisheries (SRP-VMAP) in Ecuador, launched a program aimed at controlling and monitoring the landings of large pelagic species by the artisanal longline fleet at main ports throughout the country. This program covered fishing activities and fishing efforts of Ecuador's artisanal longline fishing fleet within Ecuador's Exclusive Economic Zone (EEZ) as well as in Areas Beyond National Jurisdiction (ABNJ). This data was compiled from Martínez-Ortiz *et al.* (2015). For the purposes of this study, data on *P. glauca* occurrences in the ETP from 2008 to 2012 were filtered for further analysis.

3.3.1. Artisanal data analysis

The data obtained from the landing records of the Ecuadorian artisanal longline fleets were filtered to remove any observations lacking longitude or latitude position. After this, further types of analyses were conducted. First, the dataset containing only blue shark occurrences was filtered, which consisted of 4,160 observations with a sample size of 15,009 individuals ($n = 15,009$). This filtered dataset was then used in subsequent analyses in conjunction with the rest of the occurrence data.

Second, the complete database, with 61,452 observations, was used to calculate total catch per elasmobranch species, categorized by month and year, as well as catch percentages and fishing effort. In addition, catch percentages for elasmobranchs were specifically calculated. Rays and skates were excluded from the graphs in this analysis due to the limited number of records.

3.3.2. Statistical analyses

Additional analyses were conducted with the total number of species landed as the variable of interest, categorized by year, month, date, and species. Initially, data normality was assessed using the Shapiro-Wilk test. Subsequently, further statistical tests, including the non-parametric Kruskal-Wallis test followed by the post-hoc Dunn test, were performed.

3.4. Online Data Bases

To verify the tracking of blue shark within Galapagos region, the geographical coordinates were accessed from three online biodiversity databases: GBIF (Global Biodiversity Information Facility; gbif.org), OBIS (Ocean Biogeographic Information System; obis.org), and iNaturalist (inaturalist.org). These databases provided spatial information on the global species' distribution.

Data was filtered and cleaned before pooling all occurrences to create the SDM. All estimated ground locations, duplicate locations, and observations missing longitude and latitude values were removed, resulting in a total of 19,369 observations available for further analysis.

3.5. Fishing data

In addition to data on artisanal longline fisheries in Ecuador, spatial data on fishing vessels operating within Ecuador's Exclusive Economic Zone (EEZ), neighbouring countries' EEZs (Costa Rica, Peru, Panama, and Colombia), and ABNJ were obtained from the Global Fishing Watch (GFW) platform (<https://globalfishingwatch.org/map>) for the period between 2019 to 2023. The data was downloaded at a resolution of 0.1 degrees, using information from the International Scientific Committee (ISC, 2022). The dataset included various types of fishing

gear, such as drifting longlines, gillnets, static gears, purse seines (including both other purse seines and tuna purse seines), trawlers, and trollers.

3.5.1. Potential overlap with fisheries using raster analysis

Data obtained from the Ecuadorian artisanal longline fleet and GFW was used to calculate the AFE in the study area. A standardized raster map with a 0.1-degree resolution was created (**Figure S1**), which was then overlaid with a species distribution model (SDM) estimating the distribution of blue sharks in the ETP. This approach enabled the assessment of the risk associated with the fishing gear that contributes to blue shark catches in the Pacific Ocean, as detailed in section 3.3.

3.6. Kernel analysis

Using georeferenced data from the databases mentioned above (see section 3.2), a kernel density estimation (KDE) analysis was conducted with the spatial analysis tool in ArcMap® software version 10.8 (<http://www.esri.com/>). This non-parametric method estimates density functions, allowing to visualize relative densities and identification of residential areas. The KDE function was specifically utilized to represent the general and seasonal home ranges of *P. glauca* within the study area.

3.7. Species distribution modelling

The occurrence records were gathered from three online biodiversity databases: GBIF, OBIS, and iNaturalist. Additionally, points provided from field survey were also included as occurrence records in the models.

Seven environmental data for modelling were downloaded from Bio-ORACLE v3.0 (Assis *et al.*, 2024) at a 0.05° resolution (approx. 5 km at the equator) for present-day conditions (decade 2000–2020), namely surface temperatures (long-term average of monthly maximum and minimum), primary production, dissolved oxygen, chlorophyll, seawater speed and slope. These layers were selected based on their biological significance for *Prionace glauca*. Since the models depend on species occurrence records, pseudo-absences were randomly assigned to regions lacking reported occurrences. All steps were performed according to the methodology described by Gouvêa *et al.*, (2024).

The BRT algorithm modelled occurrence records against predictor variables using a Bernoulli distribution. Hyperparameter tuning, an essential step in machine learning, was conducted through 10-fold spatial block cross-validation to minimize overfitting (Roberts *et al.*, 2016; Valavi *et al.*, 2018; Gouvêa *et al.*, 2022). This step used the “grid search” method to test all hyperparameter combinations of the number of trees ranging between 50 and 1000 (step 50) of tree complexity between 1 and 6 (step 1), learning rate between 0.001 and 0.1 (step 0.005) and n.minobsinnode between 1 and 10 (step 1). Positive or negative monotonic responses (Hofner *et al.*, 2011) were enforced to mitigate overfitting based on expected species distribution patterns. The negative effects on species were hypothesized for maximum temperature, while minimum temperatures, oxygen, productivity, terrain slope, seawater speed, and chlorophyll were thought to positively affect species occurrence. Pearson’s correlation coefficient (r) and Variance Inflation Factor (VIF) were calculated for predictor pairs. The model’s performance was through Boyce index, receiver operating characteristic curve (AUC) and true skills statistic (TSS) (Gouvêa *et al.*, 2024).

Species distribution modelling, fishery overlay area calculations and final maps were produced in R (R Development Core Team, 2024).

4. Results

4.1. Tracking data

The data collected from various databases indicate that blue shark inhabit both coastal and oceanic regions (*Figure S2*).

Tracking data from 11 sharks provided insights into movement patterns, speed, and habitat use (*Table 1*). Sharks were monitored for periods ranging from 6 to 101 days, covering total distances between 291 and 8066 km. Notably, Shark A2 (female, 264 cm) travelled the longest total distance, covering 8066 km, and exhibited the highest average daily movement, covering 175.34 km/day over 46 days, with a maximum velocity of 1.25 ms⁻¹. Shark A8 (female, 160 cm) displayed the highest maximum speed of 2.54 ms⁻¹ and covered 2519 km over 31 days.

Shark A10 (male, 223 cm) was monitored for up to 101 days, travelling a total of 2212 km. On average, sharks travelled between 10.06 and 175.34 km per day, with the mean distance from the coast ranging from 35.90 km to 437.09 km. These findings provide valuable data on shark mobility, speed, and spatial behaviour in relation to coastal areas.

Tagging efforts were primarily concentrated during the warm season, with nine sharks tagged between February and March. However, the last two sharks tagged during the cold season provided substantial tracking data, reducing seasonal bias, and enhancing the overall analysis of the species' behaviour in the study area.

*Table 1. Characteristics of tagged blue shark (*Prionace glauca*) within Galapagos Blue Shark Project, with information on Shark identification (ID), tag number, tagging date, sex, total length (TL), days tracked, distance travelled (km), average daily distance (km/day), velocity max (m/s) and mean distance to the coast.*

Shark ID	Tag Number	Tagging date (m/d/y)	Sex	TL (cm)	Days Tracked	Distance travelled (km)	Average daily distance (km/day)	Velocity max. (m/s)	Mean distance to the coast (km)
A1	172405	02/10/19	M	230	27	497	18.40	0.55	58.41
A2	172408	02/11/19	F	264	46	8066	175.34	1.25	50.76
A3	172409	02/12/19	M	220	18	874	48.55	0.76	169.74
A4	174291	02/12/19	M	233	29	292	10.06	0.75	35.90
A5	172404	02/12/19	M	244	29	1152	39.72	1.09	94.43
A6	227902	03/03/22	F	218	71	3434	48.36	0.93	332.72
A7	227904	03/04/22	F	195	6	608	101.42	2.03	162.73
A8	227909	03/04/22	F	160	31	2519	81.25	2.54	361.54
A9	227905	03/05/22	F	173	32	1448	45.24	1.23	136.47
A10	235895	05/26/24	M	223	101	2212	21.90	0.71	174.53
A11	214588	06/05/24	M	216	82	3228	39.37	0.81	437.09

4.2. Artisanal data

Records from the database of landings of the Ecuadorian artisanal longline fleets shows that the blue shark is one of the most frequently captured and landed elasmobranch species (**Figure 3; Table S1. Percentage of elasmobranch species captures (%) based on data from the landings of Ecuadorian artisanal longline fleets between 2008 and 2012.**). Between 2008 and 2012, a total of 15,009 blue sharks were caught, accounting for 2.5% of the total catch (**Table 2**) and 24.4% of the elasmobranch catch (**Table S1. Percentage of elasmobranch species captures (%) based on data from the landings of Ecuadorian artisanal longline fleets between 2008 and 2012.**). The highest recorded number of blue shark catches occurred in 2010, 2011 and 2012, with a maximum of 5,256 individuals. Two notable peaks in catch numbers can be observed in 2011 and 2012, during the warm season from March to May (**Figure 4. Seasonal captures of *Prionace glauca* based on data from the landings of Ecuadorian artisanal longline fleets between 2008 and 2012. Figure 4.**).

Table 2. Percentage of *Prionace glauca* captures (%) based on data from the landings of Ecuadorian artisanal longline fleets between 2008 and 2012.

Scientific Name: <i>Prionace glauca</i>		
Year	Total individuals	Percentage
2008	674	0.112
2009	996	0.166
2010	4958	0.824
2011	5256	0.874
2012	3125	0.520
Total	15009	2.496

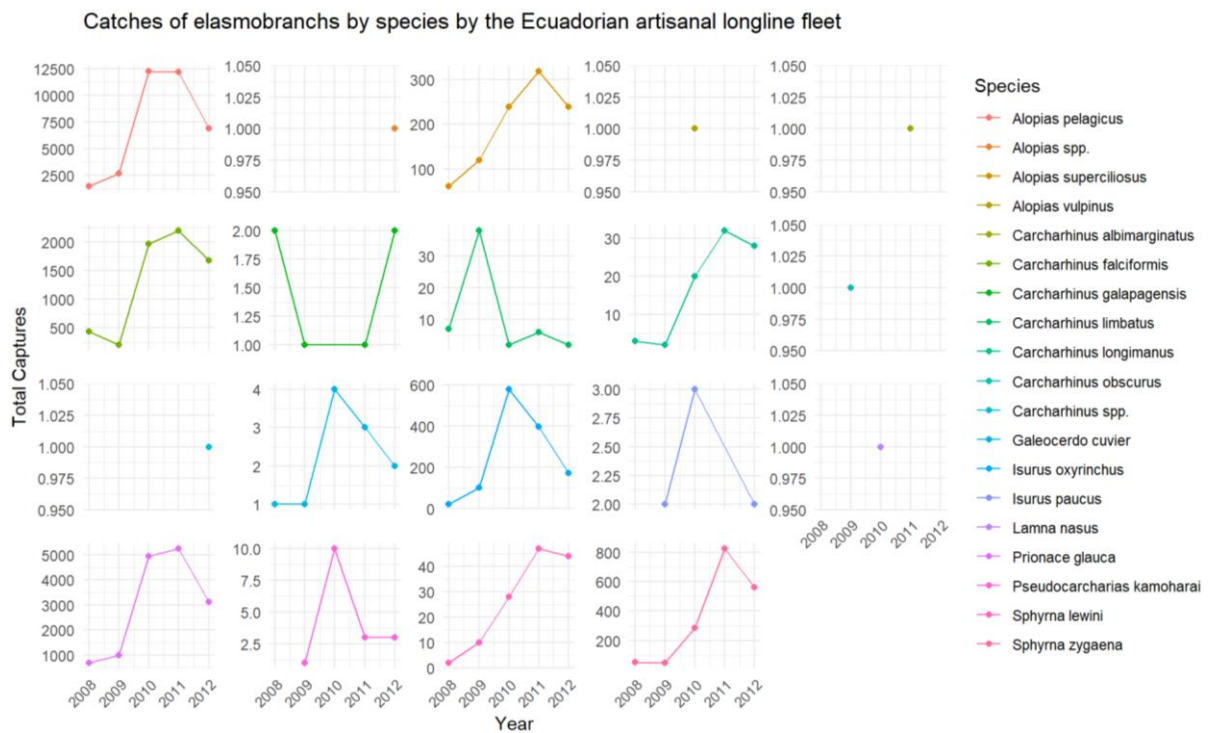


Figure 3. Total captures of elasmobranch species based on data from the landings of Ecuadorian artisanal longline fleets between 2008 and 2012.

Regarding the caught elasmobranch species during this period included the pelagic thresher (*Alopias pelagicus*), the silky shark (*Carcharhinus falciformis*) and the smooth hammerhead (*Sphyrna zygaena*), comprising 57.66%, 10.55%, and 2.87% of the elasmobranch catch, respectively (**Table S1**) with peaks in 2010 and 2011 (**Figure 4**). These species are known for their oceanic, highly migratory behaviour and account for 71% of the total catch.

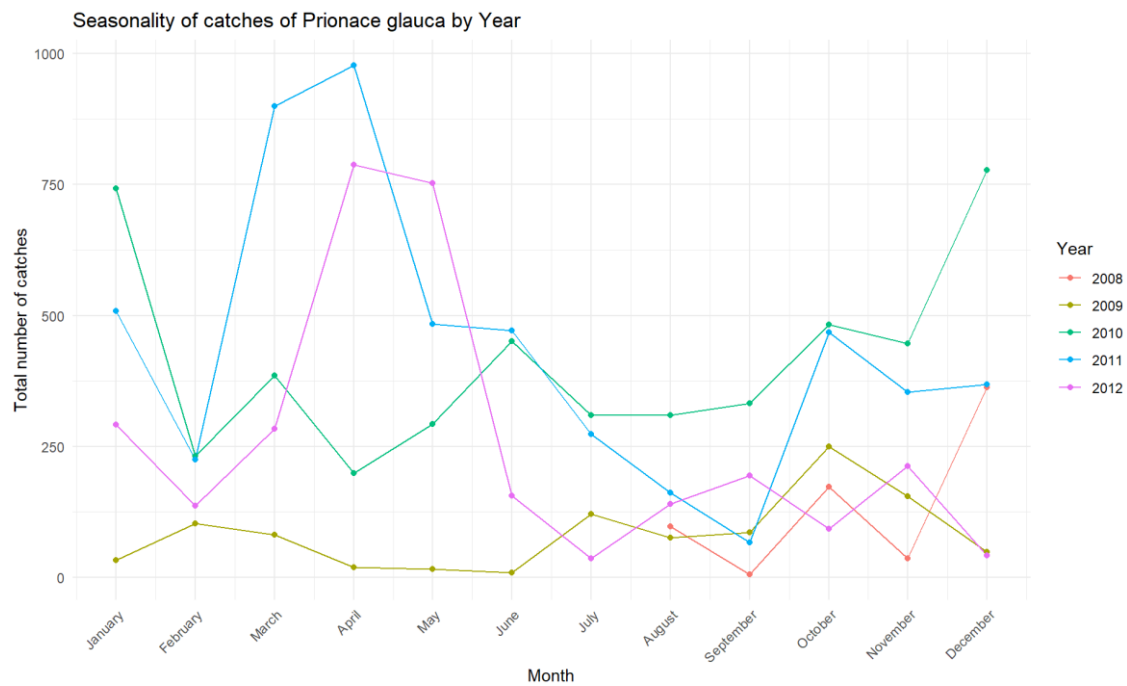


Figure 4. Seasonal captures of *Prionace glauca* based on data from the landings of Ecuadorian artisanal longline fleets between 2008 and 2012.

4.2.1. Statistical analyses

The results indicated that the null hypothesis of normality was rejected ($p < 0.05$), meaning the data do not follow a normal distribution. Consequently, a non-parametric Kruskal-Wallis test was performed for elasmobranch artisanal captures ($p < 0.05$), (**Table S2**). This suggests

statistically significant differences in the total number of species landed across the grouping variables.

To further explore these differences, a post-hoc Dunn test with Bonferroni correction was applied to identify which specific group pairs differed significantly. Notably, significant differences were observed between 2010 and the other years (2008, 2009, 2011, 2012), while no significant differences were found between the other pairs of years (*Table S3*). Similarly, statistically significant differences were found across multiple months, suggesting a potential seasonal, climatic, or event-specific influence on the number of species landed during certain months (*Table S4*).

4.3. Kernel density

Through data from occurrence data in the study area kernel density estimation reveals areas of varying shark densities, highlighting core areas of occupancy in red, while lower density areas degrading colours up to green tones. Blue shark's occurrences give insight into their use of the GMR and surrounding waters.

In this study, the distribution range of the blue shark spans both Ecuador's EEZ and ABNJ. One of the areas with the highest blue shark density is around the GMR, particularly southeast of Isabela Island, close to the breakwater platform within the Ecuadorian EEZ (*Figure 5*). Another key zone for blue sharks is observed along the Carnegie Ridge and around some seamounts in the region. These areas are potentially important for this species in both cold and warm seasons. This highlights the need to strengthen the preservation of seamounts due to their ecological importance, further justifying greater protection of these key biodiversity habitats.

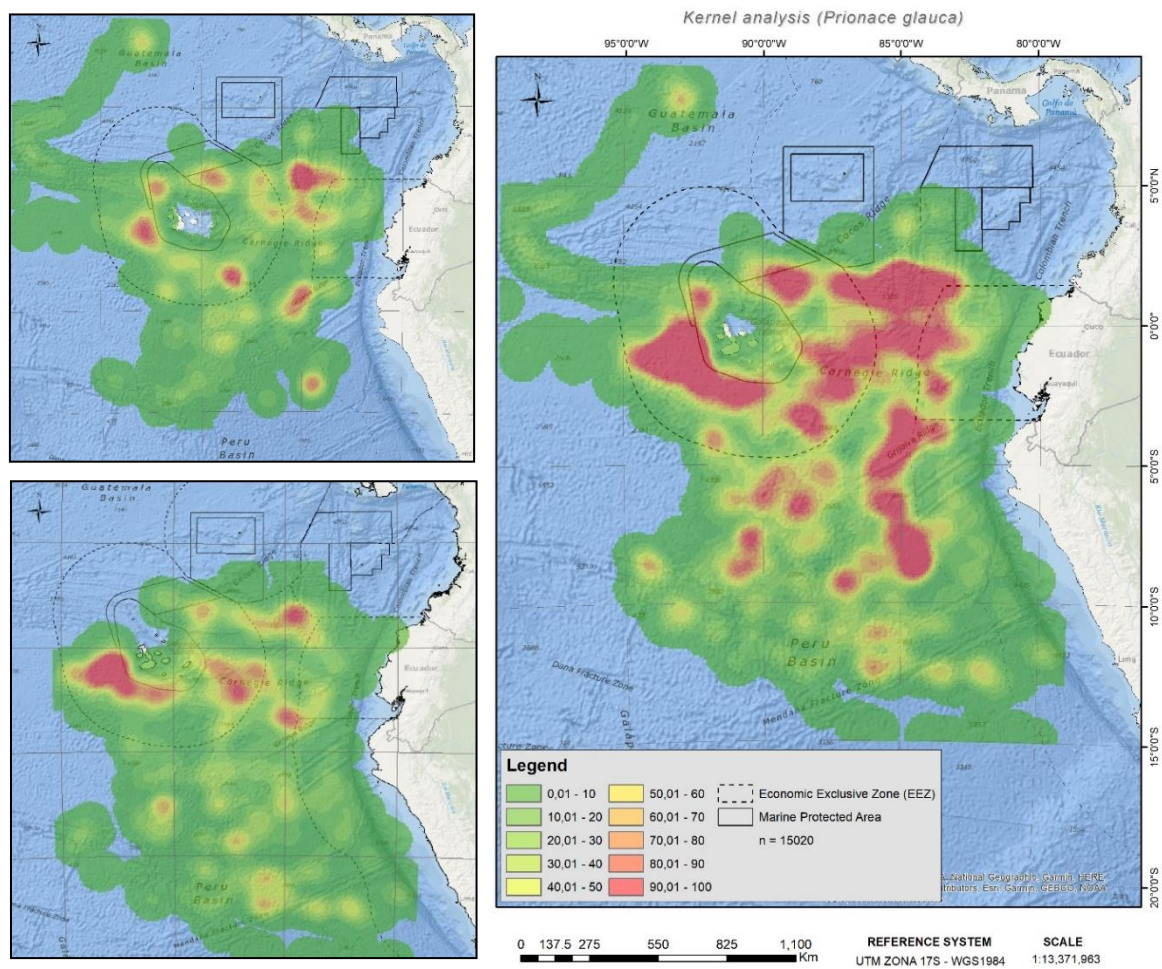


Figure 5. Kernel density estimation plot within the study area. The red tones represent a greater probability of spatial occurrence of the monitored species.

4.4. Species Distribution modelling

The distribution model retrieved high predictive performance (final prediction Boyce index: 0.99; final prediction AUC: 0.97, sensitivity of 0.94) and matched the known distribution of blue shark for such region, as detailed in additional studies (Druon *et al.*, 2022).

Productivity and maximum temperature largely explained the occurrence of *P. glauca* (combined relative contribution of 77.9%), followed by seawater speed and oxygen (relative contributions of 12.1% and 7.9%; **Table 3**).

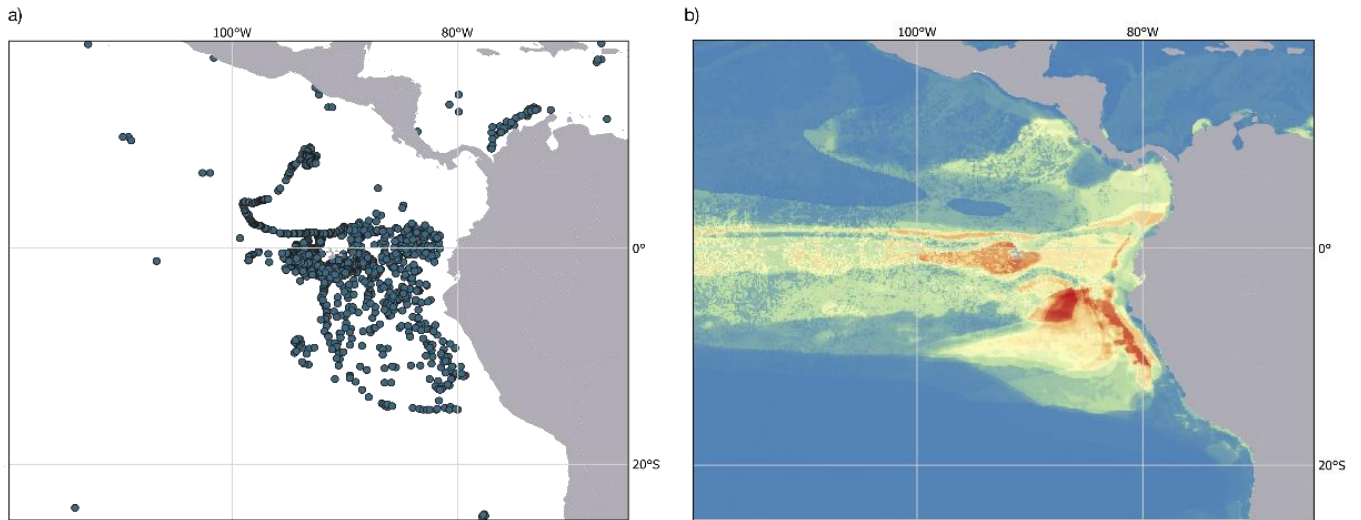


Figure 6. (a) Occurrence records of *Prionace glauca* (blue circles) gathered from field surveys and online databases (GBIF, OBIS and INaturalist) and (b) Potential distribution of *P. glauca* predicted for present-day conditions. Potential global distribution is shown on a yellow (low suitability) to red (high suitability) scale.

Table 3. Relative contribution (%) of predictor variables used in distribution modelling of *P. glauca*.

Predictor	Contribution (%)
Maximum temperature	48.7
Productivity	29.2
Seawater speed	12.1
Oxygen	7.9
Chlorophyll	4.8
Slope	3.6
Minimum temperature	1.6

4.4.1. Spatial overlay of SDM with apparent fishing effort (AFE)

Integrating data on the relative distribution patterns of highly mobile species with potential overlaps in fishing effort provides valuable insights into the impacts of fishing, particularly in the high seas where management is often limited (Queiroz *et al.*, 2019). This study presents a preliminary assessment, constrained by the lack of comprehensive spatial and temporal data on blue shark distribution and fishing pressure in the region. Despite these limitations, the analysis is critical for evaluating human impacts on pelagic shark populations.

Overlaying fishery data with the distribution predicted for the present, revealed that ~20% of blue shark suitable habitats are currently subject to fishing activities. The region with the greatest overlap is around the GMR, especially southeast of Isabela Island, near the breakwater platform within Ecuador's EEZ (*Figure 7*).

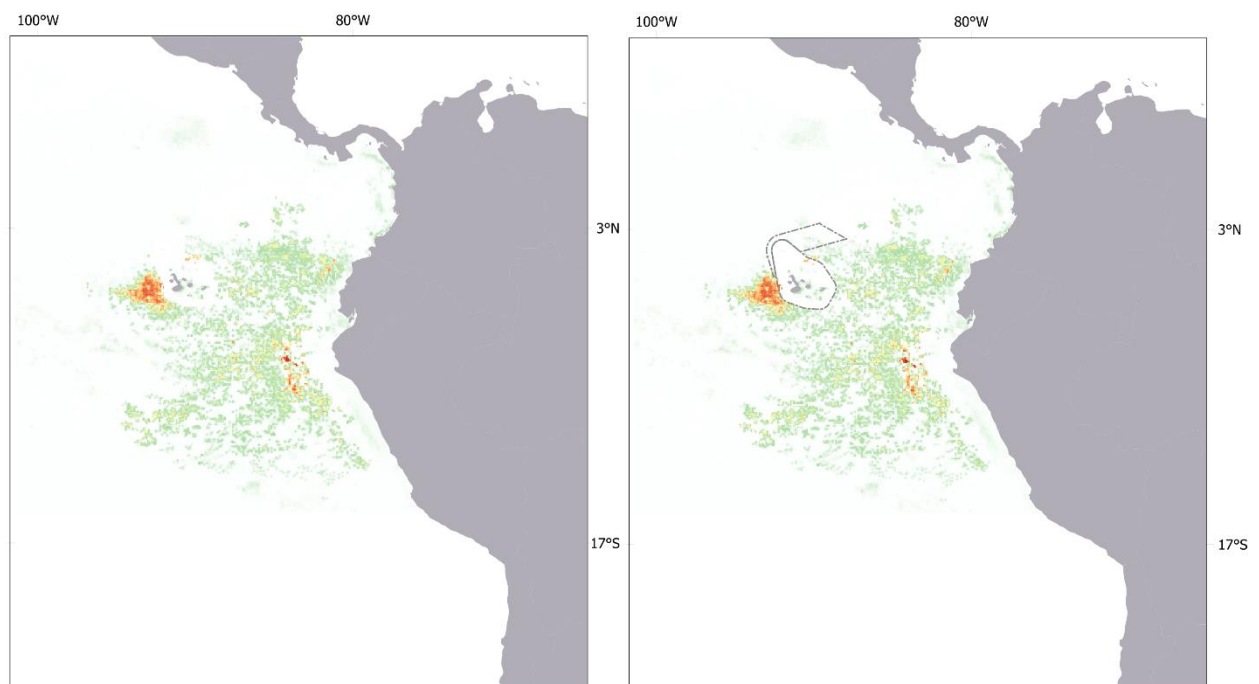


Figure 7. Overlaying the fishery areas with the predicted current distribution. Regions of overlap are highlighted in red. The large MPAs in Ecuador are shown on the left with dashed lines.

5. Discussion

This study identified key habitat areas for blue sharks and provides insights into the spatial and temporal movement patterns of this highly migratory species in the southeastern Pacific. The results revealed that the blue shark is one of the most frequently captured and landed elasmobranch species, accounting for 25% of the total catch. Analysing fishing data alongside predicted blue shark distribution shows that ~20% of their suitable habitats coincide with areas of fishing activities. These findings enhance the regional understanding of blue shark behaviour, providing crucial data for the effective management and conservation of their populations. In particular, the results underscore the importance of MPAs in safeguarding critical habitats for this highly migratory species. By identifying key areas where blue sharks are most vulnerable to fishing pressure, especially in regions where their habitats overlap with fishing zones, such as near the GMR and within Ecuador's EEZ (**Figure 7**), this study highlights the pivotal role MPAs can play in reducing bycatch, promoting sustainable fisheries, and ensuring the long-term survival of blue shark populations. These insights are essential to assess MPA design, enforcement, and expansion strategies to enhance blue shark conservation efforts on both regional and global scales.

Data from the Ecuadorian artisanal longline fishery between 2010 and 2012, revealed frequent catches of elasmobranchs, with blue sharks being one of the most frequently landed species, especially in 2010 and 2011. Blue shark landings were found to peak during the warm season, with notable increases from December 2010 to January 2011 and from March to May in both 2011 and 2012 a trend also reported in previous studies (Martínez, 2007; Doherty *et al.*, 2014; Martínez *et al.*, 2015), which identified a clear seasonality in blue shark landings. Overall, the composition of landings was influenced by the oceanographic dynamics of the region. During some seasons, high commercial value species dominated the catch, while in others, a more diverse range of species was observed, including elasmobranchs (Martínez *et al.*, 2015). Blue shark catches were concentrated in the study area, located east of the northeast flow of the Humboldt Current system, where the species density was highest (**Figure 5**, **Figure 6b**, **Figure 7**). Analysing fishing data alongside with the predicted blue shark

distribution shows that 20% of their suitable habitats coincide with current fishing activities (**Figure 7**). Such localized and intense pressures, acting in synergy with ongoing and projected climate changes, are likely to compromise the survival of blue shark in Galapagos islands, since long lasting or irreversible impacts have already been observed in previously dredged regions, on the scale of years (Cerutti-Pereyra *et al.*, 2014).

This overlap with fishing activity underscores the increased risk of blue sharks being exposed to fishing pressures both within Ecuadorian jurisdictional waters and in adjacent international waters.

The model predicted for present-day conditions matched the known distribution of *P. glauca* (Druon *et al.*, 2022). This modelled patterns of *P. glauca* distribution were mostly explained by productivity and temperature. The blue shark (*Prionace glauca*) is the most abundant epipelagic shark, found worldwide in tropical and temperate waters. It is also the most frequently caught shark species globally (Okes & Sant, 2019). While *P. glauca* is predominantly an oceanic species, it is occasionally found near coastal areas where the continental shelf is narrow (Nakano and Seki, 2003). Adult individuals usually move in open oceans around highly productivity areas (Queiroz *et al.*, 2012; Queiroz *et al.*, 2016). These high-productivity areas can fluctuate seasonally due to changing oceanographic conditions, prompting species inhabiting these regions to migrate or travel long distances (Block *et al.*, 2001). Oceanic islands like the Galapagos and Cocos are geologically linked by the Cocos Sea Ridge and its surrounding seamounts, which interact with ocean circulation patterns to enhance productivity, biomass, and biodiversity in the region (Lavelle & Mohn, 2010).

Despite the efficient methodology used to monitor sharks in the field project, the main limitation was that some signals were emitted for a shorter duration than expected, based on the SPOT tags' capacity. It is possible that the tags detached prematurely or due to interactions with fisheries. During the project, signals were received from tags on land, and in some cases, fishermen reported finding the devices. This highlights the risk that these migratory animals face from being caught in unprotected areas. Also, although our models have achieved high

performance, it is important to recognize certain limitations inherent of the approach like additional predictors important to occurrence of blue sharks (e.g., seamounts).

Globally, conservation efforts have been focusing on implementing stricter fishing regulations, establishing MPAs, and improving bycatch mitigation techniques (FAO, 2022). MPAs serve as crucial tools for conservation and fisheries management. Their effectiveness is often associated with a reduction in the mortality rates of non-target and endangered species (Rigby *et al.*, 2019). The home range of migratory species extends beyond political boundaries, making it crucial to establish strong conservation policies that foster collaboration between neighbouring MPAs in the region (Heupel *et al.*, 2015; Daly *et al.*, 2018).

Established over 20 years ago, the GMR has been the focus of numerous studies evaluating its effectiveness, particularly regarding semi-oceanic and iconic shark species like the scalloped hammerhead (*Sphyrna lewini*). The GMR protects a diverse range of habitats critical for various shark species throughout different life stages including, *Sphyrna lewini* (Boerder *et al.*, 2019). However, it offers only partial protection for the blue shark by limiting fishing activities within its boundaries. This species has home ranges that extend beyond the ETP region, meaning it is only protected during specific periods of its life when it inhabits the reserve's waters (Rigby *et al.*, 2019).

As many South American nations, Ecuador faces challenges in controlling and enforcing fishing regulations, particularly those concerning sharks. Illegal, unreported, and unregulated (IUU) fishing remains a concern, within the EEZ and MPA, by both Ecuadorian and foreign fisheries (Rentería *et al.*, 2019) due to the lack of monitoring in their waters, enhanced enforcement is needed to ensure long-term protection.

In this context, this study contributes on the ongoing conservation initiatives by identifying key habitats and migration patterns of blue sharks, particularly areas where their movement overlaps with fishing zones. By providing data on the spatial and temporal distribution of blue sharks, the study supports the creation of more targeted conservation strategies, such as

expanding MPA boundaries, improving regulations around fishing gear, and informing policy decisions to safeguard these critical areas from overfishing. These findings can help to strengthen both local and global conservation efforts, promoting the sustainable management of blue shark populations in the Galápagos and beyond.

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8. Appendixes

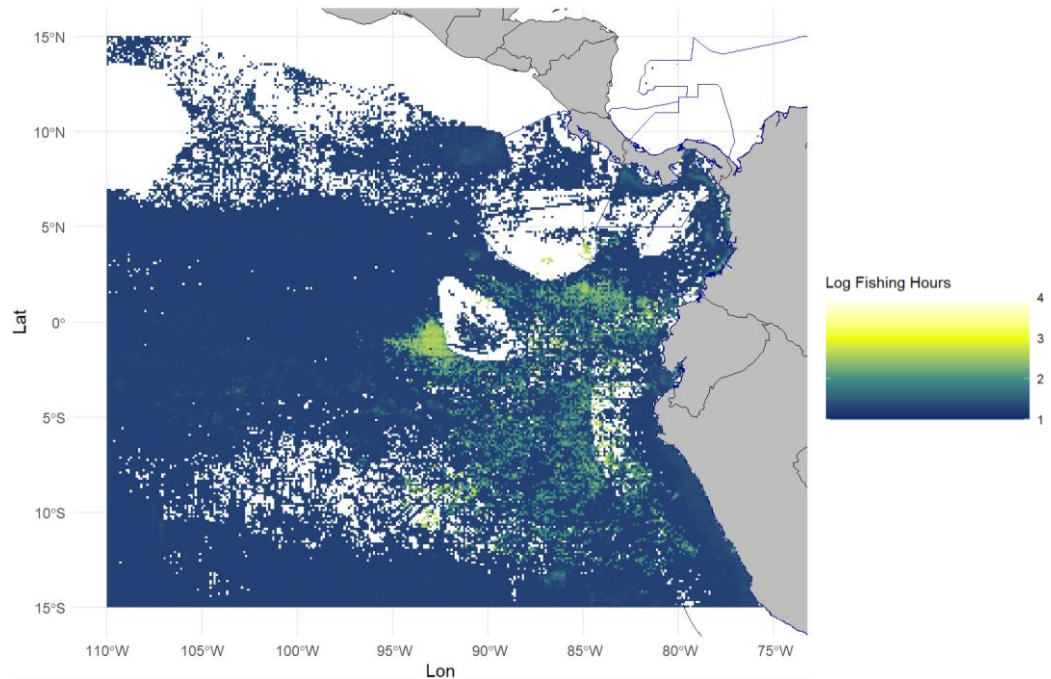


Figure S1. Standardized 0.1-degree raster map showing the apparent fishing effort (AFE) in hours, based on data from Global Fishing Watch (GFW) and Ecuador's artisanal longline fleet, within the study area.

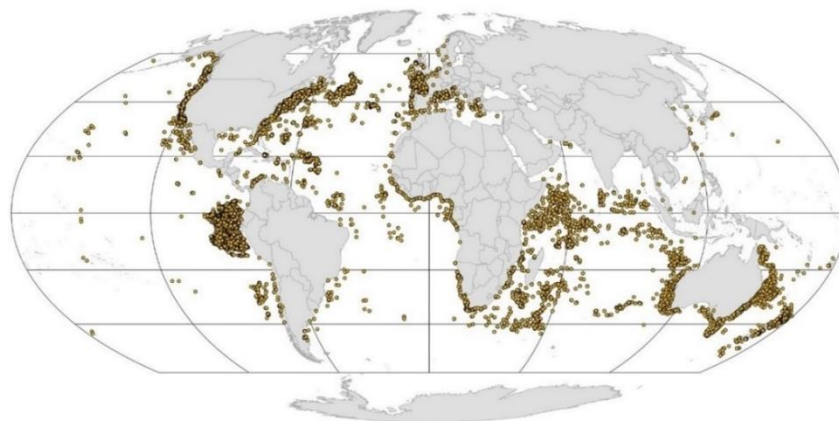


Figure S2. Blue shark's occurrences, including data from the Ecuador's artisanal longline fishery landing records (2008-2012), Galapagos Blue Shark Project (2019-2024) and online databases (GBIF, OBIS and INaturalist).

Table S1. Percentage of elasmobranch species captures (%) based on data from the landings of Ecuadorian artisanal longline fleets between 2008 and 2012.

Scientific Name	Total	Percentage
<i>Alopias pelagicus</i>	35454	57.6619
<i>Prionace glauca</i>	15009	24.4104
<i>Carcharhinus falciformis</i>	6490	10.5552
<i>Sphyrna zygaena</i>	1768	2.8755
<i>Isurus oxyrinchus</i>	1275	2.0736
<i>Alopias superciliosus</i>	977	1.5890
<i>Pteroplatytrygon violacea</i>	135	0.2196
<i>Sphyrna lewini</i>	131	0.2131
<i>Carcharhinus longimanus</i>	85	0.1382
<i>Carcharhinus limbatus</i>	55	0.0895
<i>Mobula spp.</i>	40	0.0651
<i>Pseudocarcharias kamoharai</i>	17	0.0276
<i>Galeocerdo cuvier</i>	11	0.0179
<i>Mobula munkiana</i>	10	0.0163
<i>Isurus paucus</i>	7	0.0114
<i>Carcharhinus galapagensis</i>	6	0.0098
<i>Dasyatidae</i>	4	0.0065
<i>Mobula japonica</i>	3	0.0049
<i>Alopias spp.</i>	1	0.0016
<i>Alopias vulpinus</i>	1	0.0016
<i>Carcharhinus albimarginatus</i>	1	0.0016
<i>Carcharhinus obscurus</i>	1	0.0016
<i>Carcharhinus spp.</i>	1	0.0016
<i>Dasyatis longa</i>	1	0.0016
<i>Lamna nasus</i>	1	0.0016
<i>Manta birostris</i>	1	0.0016
<i>Mobula thurstoni</i>	1	0.0016
Total	61486	100

Table S2. Results of the Kruskal-Wallis Test used to assess whether there are significant differences between the distributions of the variables under study between the groups species by year, species by month and species by year and month.

Kruskal-Wallis tests			
Data	chi-squared	df	p-value
Species by Year	145.87	4	< 2.2e-16
Species by Month	3498	11	< 2.2e-16
Species by Year and month	8677.9	1289	< 2.2e-16

Table S3. Results of Dunn's test for multiple post-hoc comparisons between years.

Comparison (year)	Z	P.unadj	P.adj
2008 - 2009	2.37984125	0.0173201	0.17320098
2008 - 2010	6.46015907	1.05E-10	1.05E-09
2009 - 2010	5.91711543	3.28E-09	3.28E-08
2008 - 2011	2.26911111	0.02326157	0.2326157
2009 - 2011	-0.6112913	0.54100674	1
2010 - 2011	-10.193645	2.12E-24	2.12E-23
2008 - 2012	2.1242308	0.03365085	0.33650849
2009 - 2012	-0.7260087	0.46783342	1
2010 - 2012	-9.2961211	1.46E-20	1.46E-19
2011 - 2012	-0.2169677	0.82823354	1

Table S4. Results of Dunn's test for multiple post-hoc comparisons between months.

Comparison (months)	Z	P.unadj	P.adj
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1 - 10	3.12702035	0.00176588	0.11654788
1 - 11	-10.595582	3.12E-26	2.06E-24
10 - 11	-15.328163	4.96E-53	3.27E-51
1 - 12	-4.102733	4.08E-05	0.00269477
10 - 12	-8.0364005	9.25E-16	6.11E-14
11 - 12	7.04397862	1.87E-12	1.23E-10
1 - 2	12.2124107	2.67E-34	1.76E-32
10 - 2	10.4535254	1.41E-25	9.32E-24
11 - 2	23.0138411	3.39E-117	2.24E-115
12 - 2	16.8944235	4.95E-64	3.26E-62
1 - 3	24.1288626	1.24E-128	8.22E-127
10 - 3	23.9371372	1.26E-126	8.30E-125
11 - 3	38.0623595	0	0
12 - 3	30.9100938	8.74E-210	5.77E-208
2 - 3	9.43994034	3.73E-21	2.46E-19
1 - 4	22.3612741	9.38E-111	6.19E-109
10 - 4	21.8536653	7.17E-106	4.73E-104
11 - 4	35.7146127	2.35E-279	1.55E-277
12 - 4	28.7460184	1.02E-181	6.70E-180
2 - 4	8.10895391	5.11E-16	3.37E-14
3 - 4	-1.3420315	0.17958578	1
1 - 5	21.0087056	5.46E-98	3.60E-96
10 - 5	20.30714	1.11E-91	7.34E-90
11 - 5	34.1331936	2.37E-255	1.57E-253
12 - 5	27.2128218	4.58E-163	3.02E-161
2 - 5	6.92384813	4.40E-12	2.90E-10
3 - 5	-2.6756453	0.00745855	0.49226454
4 - 5	-1.30739	0.1910803	1
1 - 6	18.3129767	6.52E-75	4.30E-73
10 - 6	17.2548256	1.03E-66	6.79E-65
11 - 6	31.1317404	8.96E-213	5.91E-211
12 - 6	24.2418228	8.06E-130	5.32E-128
2 - 6	4.44291745	8.87E-06	0.00058573
3 - 6	-5.5528617	2.81E-08	1.85E-06
4 - 6	-4.1138162	3.89E-05	0.00256853

5 - 6	-2.7922144	0.00523487	0.34550117
1 - 7	20.2997915	1.29E-91	8.52E-90
10 - 7	19.447638	3.05E-84	2.01E-82
11 - 7	32.8330784	1.99E-236	1.31E-234
12 - 7	26.1584926	7.89E-151	5.21E-149
2 - 7	6.69052618	2.22E-11	1.47E-09
3 - 7	-2.6042367	0.00920791	0.6077223
4 - 7	-1.293172	0.19595157	1
5 - 7	-0.0355796	0.9716176	1
6 - 7	2.65299704	0.00797806	0.52655177
1 - 8	16.5182048	2.71E-61	1.79E-59
10 - 8	15.1925019	3.96E-52	2.62E-50
11 - 8	28.0934981	1.18E-173	7.76E-172
12 - 8	21.7363707	9.30E-105	6.14E-103
2 - 8	3.67571433	0.00023718	0.0156542
3 - 8	-5.6256807	1.85E-08	1.22E-06
4 - 8	-4.3163685	1.59E-05	0.00104687
5 - 8	-3.1038617	0.00191013	0.12606832
6 - 8	-0.53653	0.59159228	1
7 - 8	-2.9729899	0.00294914	0.19464334
1 - 9	18.8970596	1.21E-79	7.96E-78
10 - 9	17.8081457	6.11E-71	4.03E-69
11 - 9	30.3211439	6.04E-202	3.98E-200
12 - 9	24.123083	1.43E-128	9.45E-127
2 - 9	6.21780672	5.04E-10	3.33E-08
3 - 9	-2.4786208	0.01318914	0.87048342
4 - 9	-1.275316	0.20219743	1
5 - 9	-0.1131177	0.9099372	1
6 - 9	2.37602752	0.01750016	1
7 - 9	-0.0777907	0.93799453	1
8 - 9	2.70693685	0.00679072	0.44818735