Spatio-temporal Distribution of Catch and Population Structure of Blue shark, *Prionace glauca* and Silky shark, *Carcharhinus falciformis*, caught by longlines in Kenya's Exclusive Economic Zone

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Abstract

The Kenya exclusive economic zone (EEZ) and the entire Western Indian Ocean (WIO) forms a region that is characterized with a high degree of fishing pressure, which has resulted to increased bycatches especially of sharks (Kiilu *et al.,* 2019). The Blue shark *Prionace glauca* (Linnaeus, 1758) and Silky shark *Carcharhinus falciformis* are considered as the most salient pelagic shark species in the Kenyan EEZ with high incidental catches across various fishery types (Kiilu *et al.,* 2023). The risk of increased bycatch continues to raise alarm on inevitable extinction of several shark species and various ecosystem structure and functions through elimination of these apex predators (Zhang *et al.,* 2024). This study aimed to assess their catches in a spatio-temporal distribution perspective by employing combined approach for longline industrial fishing catch logbooks, fishery-independent data from the national observer scheme and environmental variables of seawater potential temperature and mass concentration of chlorophyll -a from Mercator Ocean International. The output showed unique spatial and temporal patterns of distribution for both species whereby, cool and high productive waters had high catches for the Blue shark coupled with considerable seasonal migrations noted towards equatorial regions during the cooler South Easterly Monsoon winds and warmer North Easterly Monsoon winds seasons. On the other hand, warmer waters revealed high concentration of catches for Silky sharks that had a seamless distribution across the Kenyan EEZ all year round. The spatial and temporal distribution of catches for both species was determined as significant hotspots that tend to overlap with regions of high fishing and exploitation. Therefore, such overlaps highlights a vital opportunity for targeted conservation measure to control risks of over-exploitation. The study emphasizes that in the development of effective conservation and management measures it is paramount to associate distribution of catches and population structure of Blue sharks and Silky shark at both spatio-temporal scale and environmental factors.

Keywords: Sharks, Spatial, Temporal, Distribution, Catch, Bycatch, Conservation

Introduction

The conservation and management of oceanic sharks are a critical subject as far as sustainable fisheries is concerned. The current global trend of continuous rise in exploitation of marine fisheries resources has left stocks of oceanic sharks at high risk of recuperation due to over-exploitation (Wu *et al.,* 2020). This worldwide threat to sharks has been assessed to be about one-third the species risk to extinction whereby, majorities of the dangers result from fishing undertakings (Kiilu *et al.,* 2023). In addition, this scenario has been worsened by the nature of oceanic shark's reproductive biology that is characterized by gradual growth rate, delayed sexual maturity and low-level fecundity (Wu *et al.,* 2020, Kiilu *et al.,* 2019; GoK-NPOA, 2023). Therefore, the stocks of oceanic sharks have reduced globally with estimations of approximately 70% with shark species in the Western Indian Ocean (WIO) being the most adversely affected (Kiilu *et al.,* 2023). There is an all-inclusive range of fishing pressure with the small-scale artisanal fisheries undertaking perennial fishing coupled with minimal degrees of surveillance (Kiilu *et al.,* 2023). In addition, recent reports have indicated that bycatch has become a fundamental outcome in the management and development of global fisheries (Cosandey-Godin and Morgan, 2024; Kiilu and Ndegwa, 2013).

Oceanic sharks are integral components of the marine ecosystem with significant roles to ensure stability and sustain the marine biodiversity. They have unique attributes like prominent sizes, pelagic, distribution and migratory nature across large expanses (Zhang *et al.,* 2024). A major key characteristic is that the sharks are apex predators in diverse marine ecosystems around the world oceans (Kaunda-Arara *et al.,* 2022). Therefore, population decline of pelagic sharks would pose a severe ecological outcome including but not limited to activation of the descent of trophic interactions and consequently, this effect would culminate to collapse of the fishery (Kiilu and Ndegwa, 2013; Zhang *et al.,* 2024). Thus, the management of oceanic sharks is of paramount significance from an ecological understanding in order to safeguard the structure of marine ecosystems.

A wide range of literature has highlighted that anthropogenic activity particularly overfishing as the main drivers to sharks' stocks decline including numerous shark species being listed in the International Union for the Conservation of Nature (IUCN) Red List of threatened species. Similarly, authors have argued that the knowledge base of pelagic sharks is limited given to their dynamic spatial structure, very few targeted species in fishing and inadequate data due to constraints of low fisheries governance (Wu *et al.,* 2020; Zhang *et al.,* 2024; Kiilu *et al.,* 2019). Previous assessments undertaken in Kenya like the ecological risk assessment (ERA) and Productivity and Susceptibility Analysis (PSA) in 2023 have employed counterbalance approaches to the situation of data scarcity with a guide to rank various scales of data-quality applied in the administration of fisheries resources (Kiilu *et al.,* 2023).

The recent Kenya Marine Frame Survey Report (2022) showed that approximately 3,174 small-scale artisanal fishing crafts are active in the Kenyan nearshore waters and are responsible for substantial landings of shark species, which are targeted in the artisanal fisheries. However, in the semi-industrial prawn-trawl and industrial longline fishery, oceanic sharks are usually caught as bycatch (Kiilu *et al.,* 2023; Fulanda *et al.,* 2011; Munga *et al.,* 2014). The PSA model in Kenya attempted to document proportions of possible vulnerabilities of oceanic sharks to fishing activities (Patrick *et al*., 2010) and identified that the longline commercial fishery had the second ranking estimates of vulnerable species whereby shark species had 46% of high vulnerability (Kiilu *et al.,* 2023). In addition, several Vulnerable (VU) sharks species that are captured in the IUCN Red List like the Silky shark (*Carcharhinus falciformis*) were determined to have medium vulnerability score (Phillips *et al*., 2015) in the small-scale artisanal and prawn trawl fisheries (Kiilu *et al.,* 2023). However, for the same species *C. falciformis* and Vulnerable listed Blue shark (*Prionace glauca*) were evaluated to have high proportions of vulnerability in longline commercial fishery, which meant that the two species were at high threat of interaction with the fishery (Kiilu *et al.,* 2023). Therefore, further investigation require priority consideration to understand why Blue sharks and Silky sharks have an increasing vulnerability in order to properly guide management approaches that focus on conserving their depleting populations.

Blue shark *P. glauca*

Blue sharks *P. glauca* are one of the most commonly found oceanic sharks in the globe (Zhu *et al.,* 2011; Zhang *et al.,* 2024; Nikolic *et al.,* 2020) and to a higher degree abundant, distributed, productive and with fast maturity (Druon *et al.,* 2022). Although these characteristics make it a reasonably resilient species, Blue sharks contribute to the most intensely fished bycatch in the world with an extent of 10.74 million year^{-1} (individuals) of fishing mortality every year (Hung *et al.,* 2024; Druon *et al.,* 2022; Clarke *et al.,* 2006). Similarly, being a bycatch species, it forms a significant amount of international shark fin and meat industry on a global scale (Cordova-Zavaleta *et al.,* 2018), and thus, the overarching value of pelagic Blue sharks in the commerce of fins underscores its economic priority and the reason for high demand (Druon *et al.,* 2022).

Habitats of Blue sharks are usually associated with tropical, sub-tropical and temperate regions and usually found in depths ranging from the surface to 600 meters (Wu *et al.,* 2020). Their migratory nature allows them to undertake large-scale shifts of about thousands of kilometers with considerable variability of distances among some individuals (Penades-Suay *et al.,* 2022). In addition, these sharks are mainly predators with a diverse appetite of several species of cephalopod and teleost as well as periodically cetaceans, crustaceans and birds (Loor-Andrade *et al.,* 2017; Penades-Suay *et al.,* 2022). Nonetheless, evaluations of global spatial surveys have indicated that Blue sharks have a noticeably higher danger of exposure to fisheries exploitations because of their increased distributional overlap with preferred fishing grounds (Druon *et al.,* 2022). There is limited information on comprehensive patterns of catch distribution of Blue sharks that would provide potentially important spatio-temporal results to guide bycatch mitigation measures in industrial longline fishery in Kenya.

Silky shark *C. falciformis*

The Silky shark, *C. falciformis*, is an associate of the Carcharhinidae family among the requiem/gray sharks and one of the big-sized members with approximately 330 centimeters in total length in its genus (Bonfil, 2008). A highly cosmopolitan semi-pelagic shark generally inhabits inshore and offshore waters of the tropical oceans around the world. Silky sharks are also subject to fishing in largescale pelagic longline fisheries and bestow large quantities of both targeted and incidental bycatch (Francis *et al.,* 2023). Previous literature and recent surveys have indicated that Silky shark are ranked to a higher degree second valuable species after Blue shark to substantiate shark fin industry across the world (Filmalter *et al.,* 2021).

Nevertheless, intensified target and incidental harvesting of this shark species in both small-scale artisanal and pelagic industrial longline fisheries, has considerably reduced their stocks in Kenya and other WIO regions (Kiilu and Ndegwa, 2013). According to Murray *et al.,* (2023), the shrinking population of Silky sharks has surpassed a threshold to justify dozens of management measures like the listing of the species in Appendix 2 of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in 2016. This inclusion CITES (Cop17, Notification No. 2016/063), brought onboard compliance to stringent controls in the global commerce of any element of Silky shark (Filmalter *et al.,* 2021). Consequently, in 2017 the species was elevated to 'Vulnerable' status on the IUCN Red List of Threatened Species (Kiilu *et al.,* 2023; Murray *et al.,* 2023; Rigby *et al.,* 2017).

The growing concern of sustainable management of Silky sharks has achieved coupling efforts among several Regional Fisheries Management Organisations (RFMOs) but perceived not to suffice as the continuous decline of their stocks has not stopped (Murray *et al.,* 2023). Similar to Blue sharks, their intense migratory behavior that overlaps the occurrences of schools of tuna has made it susceptible to tuna fishery in both longline and purse seine fishing (Li *et al.,* 2023). There are no current assessments of the operationalization and success of robust spatial safeguards to the conservation of Silky sharks and studies may suffer constraints arising from the species increased movements, expansive habitats and stock composition (Murray *et al.,* 2023).

The current constraints experienced during surveys of elusive oceanic sharks have compelled scientists to rely upon fishery-dependent data that facilitates critical knowledge on geographic movement although, incomprehensive on size selection of gears, systematic spread of fishing effort and incomplete accounting of shark landings (Kiilu and Ndegwa, 2013; Murray *et al.,* 2023). Recent studies have acknowledged that the spatial arrangement of pelagic sharks is inherently associated with environmental factors that include temperature, ocean currents or salinity, which vary depending on seasons (Zhang *et al.,* 2024).

This study aims to evaluate the catch distribution and population structure of Blue shark and Silky shark correlated to identified environmental variables in order to provide information on a spatio-temporal scale that is valuable to possible bycatch mitigation controls by fisheries managers in Kenya. The focus of the study is on the industrial longline fishery in the Kenyan Exclusive Economic Zone (EEZ) and the outcome is structured in reference to sustainable utilization and protection of pelagic sharks with effective bycatch management measures. The consideration of environmental factors is justified on basis of potential areas for food and indicators of suitable feeding habitats that qualifies for size specific individuals. The constructed model comprises of predicted occurrence of these shark species for habitats using chlorophyll –a and seawater potential temperature as environmental contributors.

Materials and Methods

Area of Study

The study was undertaken using industrial longline catch data from the Kenyan EEZ for the years 2017–2023 in view of appraising the marine industrial catch data since enactment (2016) of the Fisheries Management and Development Act Cap 378. The coastline stretches about 600 kilometers and has an approximately 200 nautical miles of EEZ from the Kenyan baseline of the Indian Ocean within WIO region. The coastline borders Somalia in the North at Ishakani (-1° 30′ S) and (-5° 25′S) in Vanga for the southern border with Tanzania (Kenya Fisheries Service, 2024a). Kenyan EEZ has a rich spectacle of marine biodiversity that has attracted more than 80% of small-scale artisanal fishers and coastal semi-industrial vessels (Kenya Fisheries Service, 2024b). In addition, there is an evolution of an industrial fleet with seven (7) active industrial longliners as at the period of this study. Figure 1 below shows a map of the Kenyan EEZ generated by QGIS 3.34 Prizren.

Fisheries activities in the Kenyan coast are affected by northeasterly and southerly monsoon winds, which are both trade winds experienced seasonally every year. The northeast monsoon (NEM) season is experienced between the months of November and March, and usually associated with high temperatures, salinity and moderately a calm state of the sea (Okemwa *et al.*, 2023). Whereas, the southeastern monsoon (SEM) season runs across the months of April to October and often exhibit cool temperatures with lower salinity levels and unsmooth seas (Kiilu *et al.,* 2019; Kaunda-Arara *et al.,* 2009). In essence, marine fisheries in Kenya is influenced at both spatial and temporal extents and this is evident by the dynamic behaviour of small-scale artisanal fisheries exploring both nearshore and coastal waters with shift of gears for each season (Kiilu and Ndegwa, 2013).

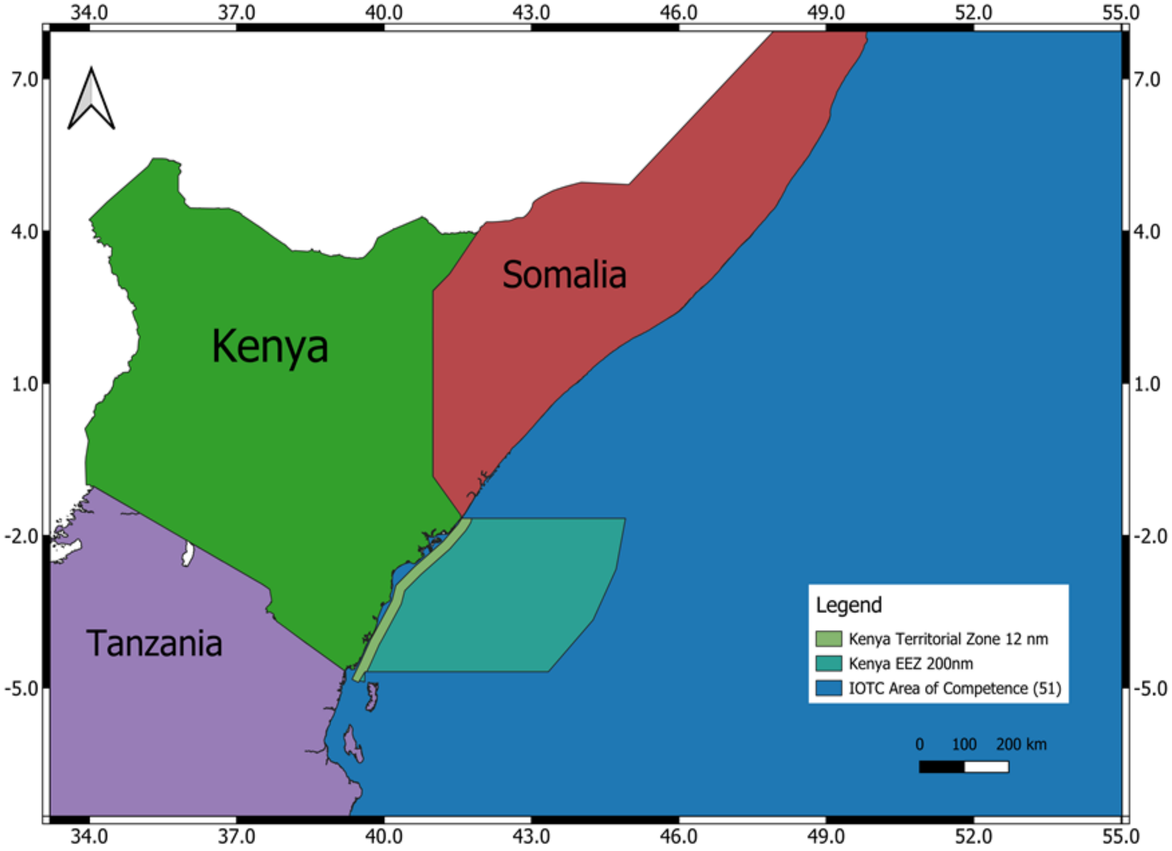

Figure 1. Map of the Kenyan Exclusive Economic Zone in the Western Indian Ocean. Developed using QGIS software 3.34 Prizren

Occurrence Data of *P. glauca* and *C. falciformis*

The data for both *P. glauca* and *C. falciformis* was sourced from the daily catch logbooks of Kenyan licensed industrial longline fishing vessels operating in the Kenyan EEZ and High seas from 2017 to 2024. In addition, fisheries scientific observer data onboard these industrial longline vessels from 2019 to 2024 was used for individual biological parameters of length sizes to complement occurrence data gathered for the study. Data cleaning was crucial, which comprised of elimination of inaccurate records of coordinates and length sizes for both daily catch logbook and observer data. Therefore, overall compiled data was 2449 records of catch data and 894 independent records of length sizes for both *P. glauca* and *C. falciformis*.

Spatial and Temporal Distribution Catch Data

The catch spatial and temporal distribution of both *P. glauca* and *C. falciformis* was evaluated using total catch data per year and respectively, total catches per NEM and SEM seasons. Frequency of distribution of individual fork lengths (FL) for was computed together with size classes of FL for individual species to understand the population structure of both species between small-sized and big-sized individuals. The Length bin-size for classes was calculated through the Sturges' formula: Bin Size = Range/*k* whereby, *k* = (log2 (n) + 1) and n is the number of observations (Scott, 2009). Catch distribution was evaluated using boxplots and both analysis of variance (ANOVA) with Tukey's post hoc test (Murray *et al.,* 2023) were used to make a comparison of disparities of *P. glauca* and *C. falciformis* catches.

Catch data of the two sharks under study was aggregated for NEM and SEM seasons. Seasonal data was analyzed to show temporal distribution of catches annually while spatial distribution of catches was evaluated using fishing coordinates. Moreover, density plot was employed to illustrate distribution of catches by visualizing both high and low concentration of *P. glauca* and *C. falciformis* at a spatial scale (Badger *et al.,* 2023). Furthermore, spatial and temporal distribution of cumulative fishing effort was computed using total number of hooks divided by total number of hours for the entire fishing period (2017-2024).

Data for Predictors

The data obtained for predictors of the model were original environmental variables, which were mass concentration of chlorophyll –a and seawater potential temperature. Additional variables like salinity, depth or dissolved oxygen concentration could not be obtained in totality for the occurrence data used for both *P. glauca* and *C. falciformis*, and thus, were eliminated as predictors. Therefore, environmental proxies identified originated from the Copernicus Marine Services products (Mercator Ocean International) with specifications as shown in table 1.

Table 1. Environmental variables specifications from Mercator Ocean International https://data.marine.copernicus.eu/products

Category	**Specification/Details**
NEMO Satellite	V3.6_STABLE
Sea Water Potential Temperature (°C)	
Data Set	Global Ocean Physics Analysis and Forecast
Data Assimilation	Sea ice concentration; Sea level; Sea Surface Temperature
Spatial Resolution	0.083°X0.083°
Temporal Resolution	Hours. Days. Months.
Elevation Depth levels	50
Format	NetCDF -3; NetCDF -4
Mass Concentration of Chlorophyll –a in Sea Water (primary production of biomass denoted as carbon per unit volume of seawater (NPPV) mg/m^{-3}day^{-1})	
Data Set	Global Ocean Biogeochemistry Analysis and Forecast
Data Assimilation	Satellite Chlorophyll -a
Spatial Resolution	0.25°X0.25°
Temporal Resolution	Daily. Monthly
Elevation Depth levels	50
Format	NetCDF -4

The variables in table 1 were selected under the context of Kenyan coastal seasonal exposures that influences the marine environment as discussed above and definitely, the direct association these variables have with presence, catch and size classes of *P. glauca* and *C. falciformis* (Kiilu *et al.,* 2023). Hence, the spatial extent of the Kenyan EZZ and high seas of the study area (Fig.1) covered a grid of 9° x 19° with latitude -0.1067° S to -9.5316° S and longitude 40.2208° E to 59.971° E. The temporal range was 2019 to 2024. The absence of 2017-2018 environmental dataset was considered through scaling down of occurrence data of both species and computing the model with 100 maximum iterations for convergence (Jamil *et al*., 2014). Both variables were visualized spatially to show the proportions of coverage in the area under the study.

Prediction and Model Evaluation

In addition, a Generalized Linear Model (GLM) (Jamil *et al.,* 2013) was used to compute a prediction model using the two environmental variables as predictors for occurrence of both *P. glauca* and *C. falciformis*. From findings of previous literature, aforementioned environmental proxy data is a significant factor to elaborate spatial distribution of these pelagic sharks in the study. Evaluation of model performance and diagnostics were performed using the Area Under the Receiver Operating Characteristics Curve (AUC-ROC) to assess sensitivity and specificity of probability of prediction (Carrington *et al*., 2022) and respectively, assess issues to ascertain assumptions of the GLM model output.

All aspects of data processing and analysis were conducted using R statistical program and packages used were gglpot2, dplyr, sp, e1071, ncdf4, raster, biomod2, dismo, randomForest, pROC and ggforce (R Core Team, 2024).

Results

Catch Composition and Population Structure of Species

Records totaling to 2449 (n = 2449) for catch data and 894 (n = 894) individuals for length FL data of *P. glauca* and *C. falciformis* were used for analysis of catch distribution and population structure from 2017 to 2024 and 2019 to 2024 respectively. It was evident (Fig. 2) that *P. glauca* had the highest catches between the two shark species with a total of ≈322.128 mT cumulatively with (87.6%) proportion. However, *C. falciformis* had catch estimates of ≈45.564 mT cumulatively with (12.39%) proportion of overall composition from 2017 and 2024. Similar results were observed for number of individual pieces harvested for *P. glauca* being way above *C. falciformis* with totals of 9585 (80.87%) and 2266 (19.12%) respectively.

In addition, analysis of catch composition by years revealed that in 2022 *P. glauca* was the most shark caught with ≈72.505 mT with a proportion of 22.5% followed by 2019 with ≈70 mT (21.7%) and 2021 with ≈14.2 mT (14.2%). Although, 2017 had the least catch composition of ≈2.262 mT with a 0.7% proportion, followed by 2020 with ≈23.08 mT (7.2%) of total catch composition of *P. glauca*. Respectively, in 2020 *C. falciformis* recorded the highest catches of ≈11.819 mT with 25.9% proportion, followed by 2021 with ≈9.242 mT (20.3%) and 2019 with ≈7.47 mT (16.3%). However, catches varied when compared to year 2024 that had the least catch composition with ≈3.06 mT (6.7%) and was followed by 2018 with ≈3.068 mT (6.7%) of the total catch composition of *C. falciformis*.

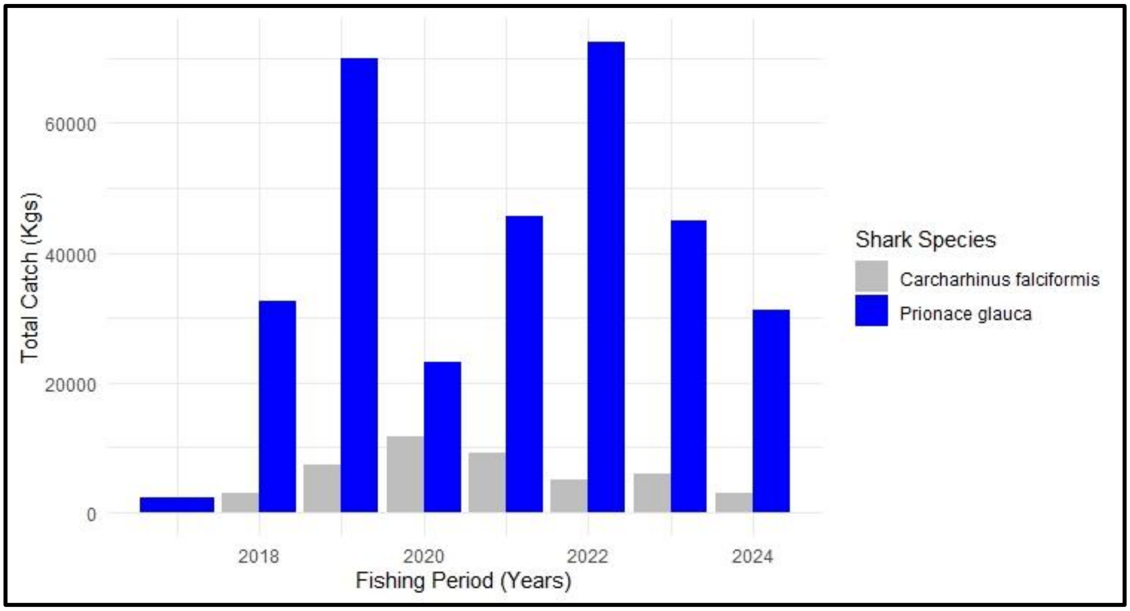

Figure 2. Catch composition (Kgs) of Blue shark *P. glauca* and Silky shark *C. falciformis* (2017-2024).

Analysis of total catches against cumulative fishing effort showed effort applied in fishing varied slightly across the fishing period (2017-2024) with 2019, 2022 and 2023 with the highest proportions of effort but lowest in 2017, 2018 and 2024 (Fig. 3 and 4). A comparison of cumulative fishing effort between *P. glauca* and *C. falciformis* showed that the level of effort applied in fishing of *P. glauca* was high hence the increased catch harvested but effort applied for *C. falciformis* was less and thus decreased catch harvested.

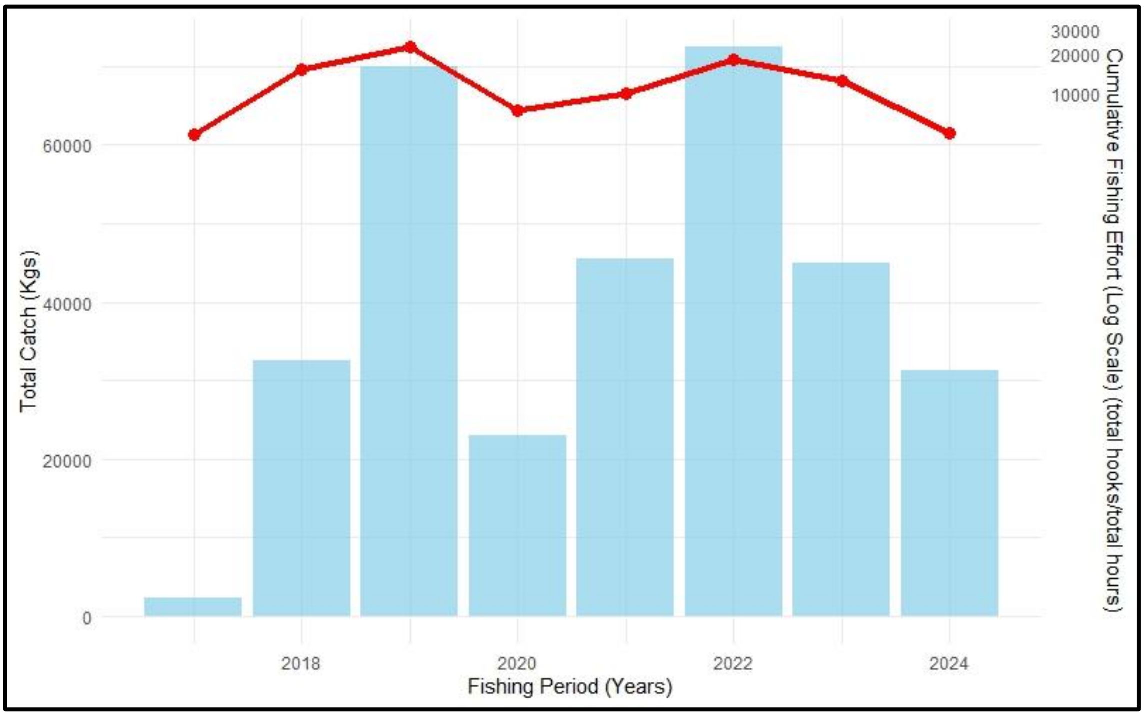

Figure 3. Catch composition (Kgs) against cumulative fishing effort for Blue shark *P. glauca* (2017-2024)

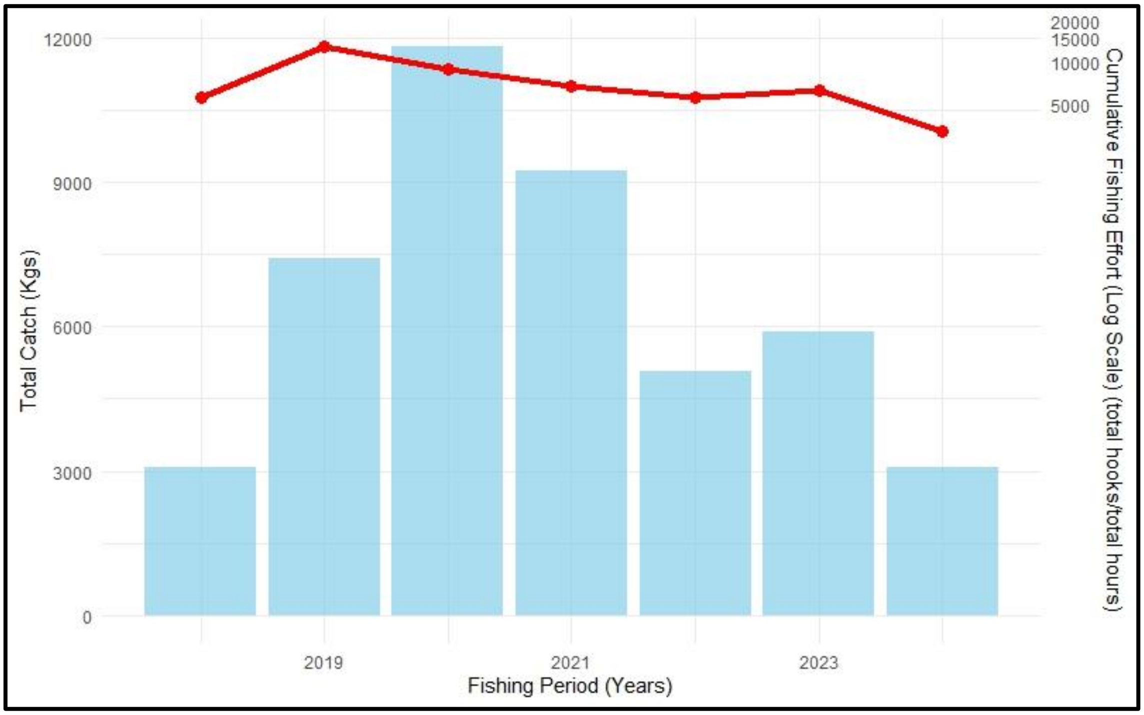

Figure 4. Catch composition (Kgs) against cumulative fishing effort for Silky shark *C. falciformis* (2017-2024)

Frequency distribution of lengths FL and size classes (Fig. 5) and a bin sizes of 21.36 (n = 802) for *P. glauca* and 22.25 (n = 91) for *C. falciformis* revealed unique population structures of both species. For instance, an asymmetrical distribution was observed for *P. glauca* that exhibited a negative skewness of 1.3 and a low kurtosis (Blanca *et al.,* 2013). However, *C. falciformis* had a bimodal distribution with -1.4 skewness and a high kurtosis. A high abundance of *P. glauca* was observed among individuals with lengths between 150 -280 cm FL and very individuals ranging between <100 – 150 cm FL as well as 280 - >300 cm FL. Nevertheless, *C. falciformis* had a majority individuals caught of sizes 50 – 200 cm FL and very few individuals were caught with more than 200 cm FL. In addition, the length frequency bimodal distribution of the species revealed potential abundance of several cohorts (Kiilu *et al.,* 2019) as shown by two peaks of >50 – 100 cm FL and >150 – 200 cm FL as shown in Fig. 6.

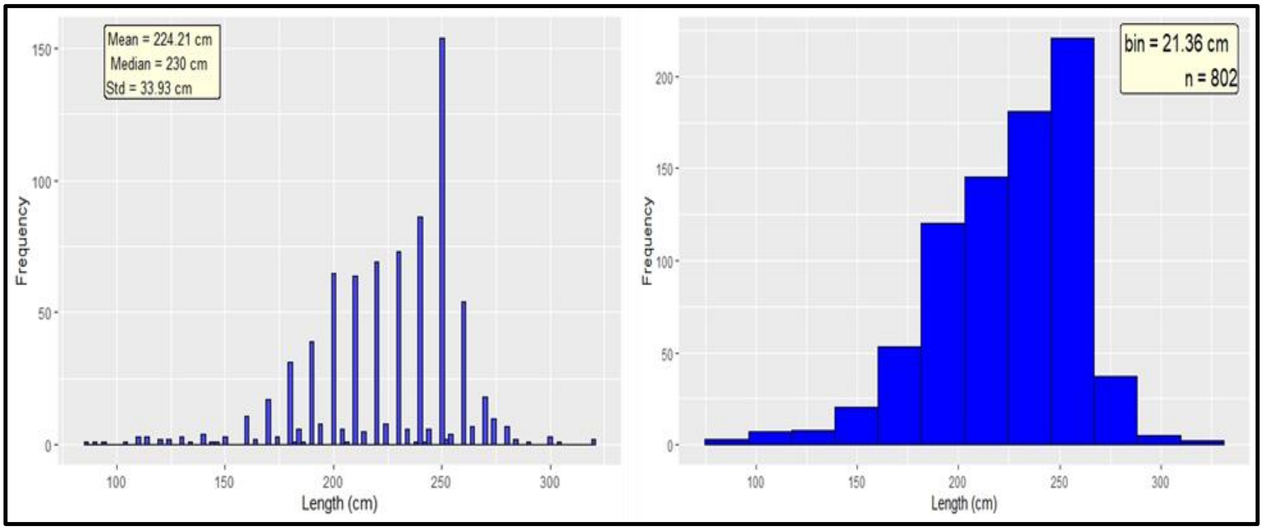

Figure 5. Length (FL) and size-class length (bin=21.36 cm) frequency distribution of Blue shark *P. glauca*

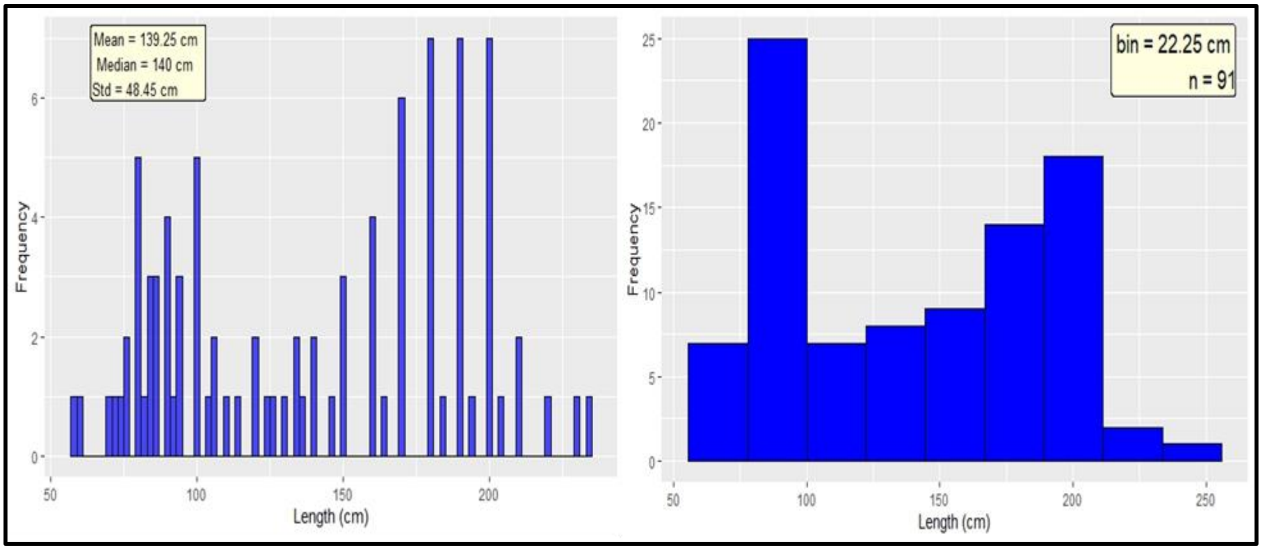

Figure 6. Length (FL) and size-class length (bin=22.25 cm) frequency distribution of Silky shark *C. falciformis*

Spatial and Temporal Distribution

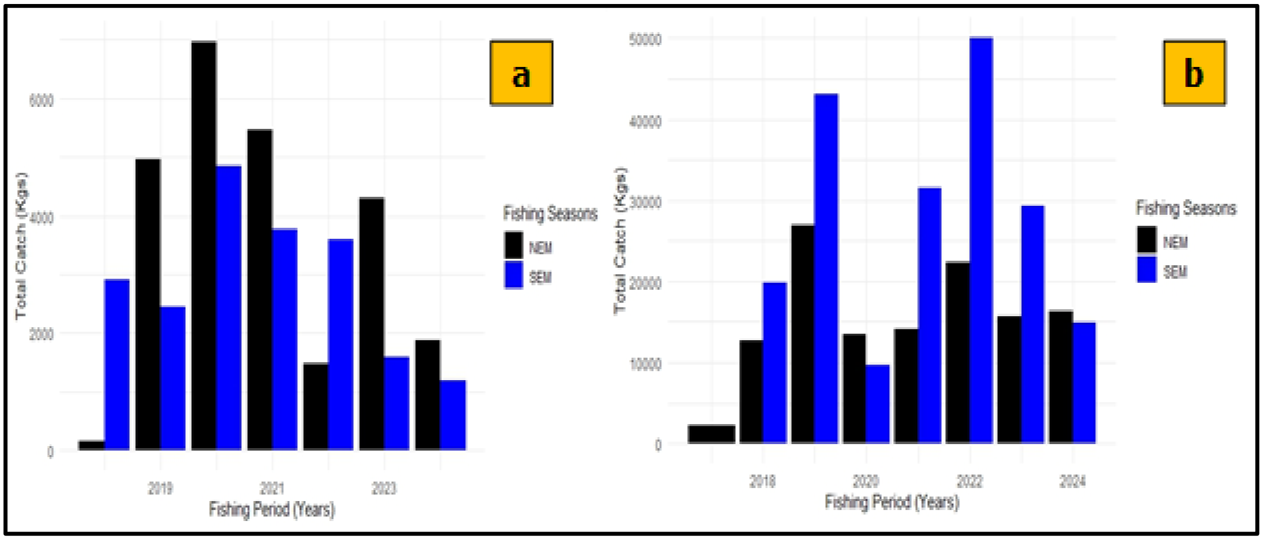

Figure 7. Seasonal distribution of catches in both NEM and SEM seasons for Silky shark *C. falciformis* (a) and Blue shark *P. glauca* (b) from 2017 to 2024.

Evaluation of seasonal catches (Fig. 7) showed that during SEM between 2017 and 2024, high catches were realized for both *P. glauca* and *C. falciformis* in 2019, 2021 and 2022. However, during NEM from 2017 to 2024, there was the lowest levels of catches for both oceanic shark species. On the contrary, computation of temporal distribution for cumulative fishing effort showed that highest proportion of cumulative effort invested in fishing was observed during NEM season whereas the lowest proportion of cumulative effort was observed during the SEM season. For instance, in figures 3 and 4, 2019 with both NEM and SEM seasons had the highest fishing effort with NEM taking the lead with more than ≈17,500 and ≈16,250 fishing effort respectively.

Spatial distribution of cumulative fishing effort (Fig. 8) also showed that high intensity of fishing was undertaken in the Kenyan EEZ and high seas with spatial extent of -4° S and -1° S, and 40° E and 50° E. In figure 8, the shows a high proportion of effort (pie chart) is applied in terms of number of hooks (blue colour) compared to proportion of fishing hours (red colour). Whereas the shading of grids from blue to lighter yellow within the Kenyan EEZ shows high intensity of cumulative fishing effort compared to the high seas with only blue shading of the grids.

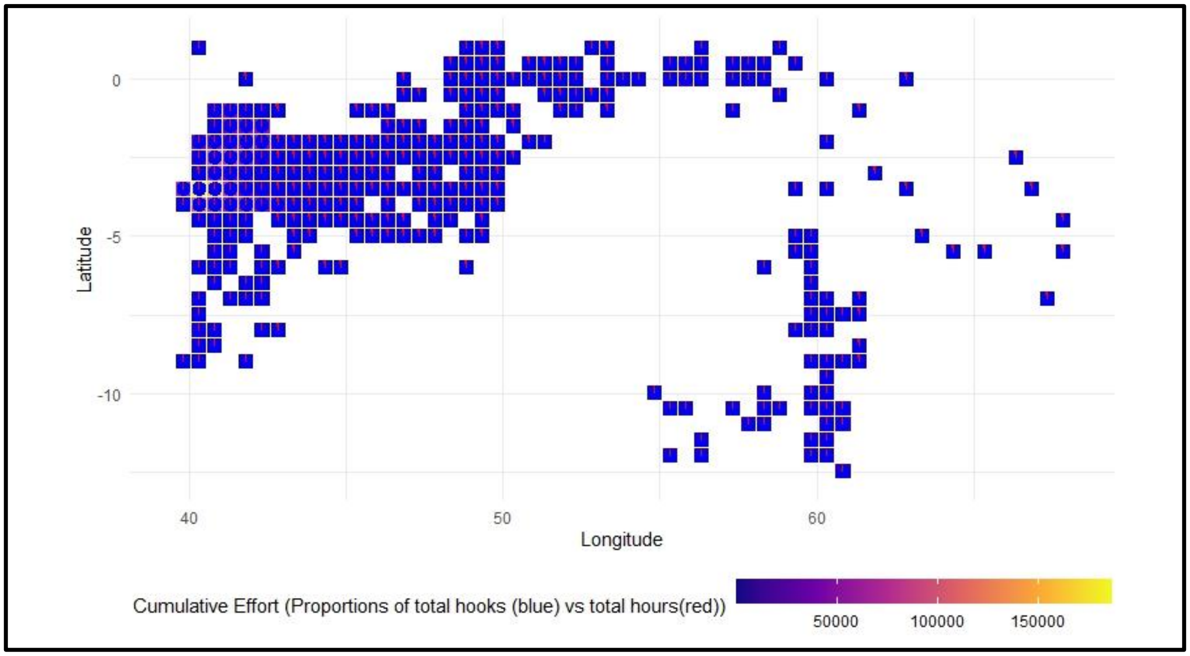

Figure 8. Spatial distribution of cumulative fishing effort for proportions of total hooks (blue) and total hours (red) from 2017 to 2024

Likewise, an evaluation of spatial distribution (Fig. 9) revealed that there was high distribution of catches of both shark species within the Kenyan EEZ, specifically between southern locations of (-5° S, 40° E) and (-5° S, 50° E), which shows increasingly high concentration of *P. glauca* catches. Then moving towards the northern waters of (-1° S, 40° E) and (1°N, 55° E) in the Kenyan EEZ and high seas, slightly beyond the Equator. Also, in the southern locations between (-10° S, 60° E), *P. glauca* showed pockets of high concentration. However, *C. falciformis* revealed a high concentration between (-5° S, 40° E) and (-1° S, 50° E) inside the Kenyan EEZ but in the high seas towards the Equator, the distribution was sparse with small pockets above the Equator between (1° N, 50° E) and (1° N, 65° E). Furthermore, density indices (Fig. 10) reinforced the results in figure 10 that *P. glauca* had high abundance distributed between latitudes of (-3° S) and (-4° S) with a spatial extent of longitudes between (40° E) and (43° E). Although, *C. falciformis* showed low abundance between those locations but with a high latitudinal coverage extending beyond (44° E).

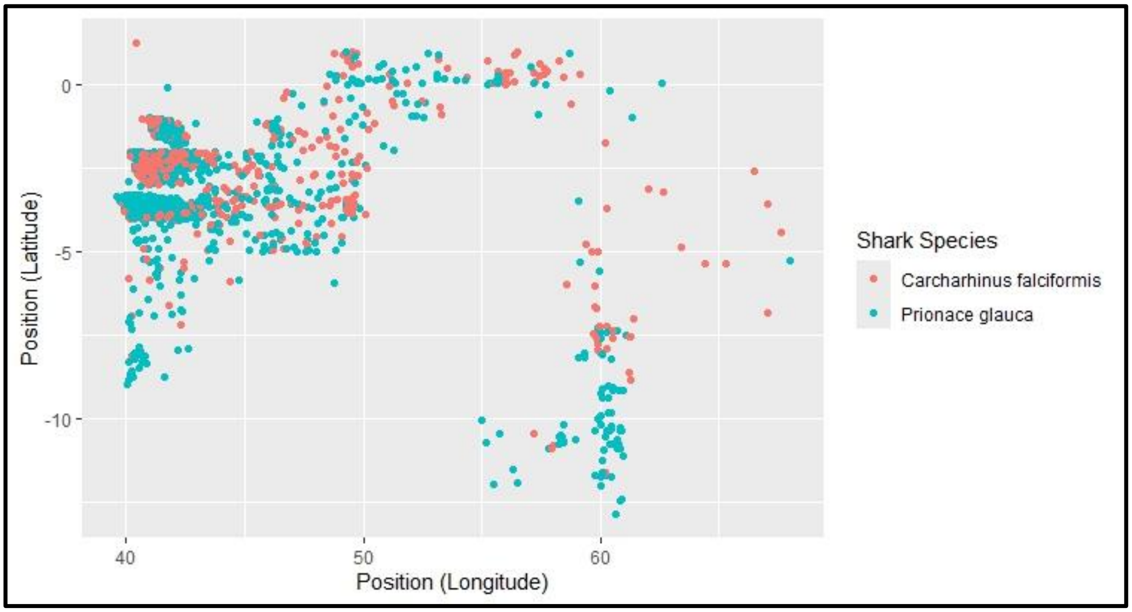

Figure 9. Spatial distribution of catches for Blue shark P. glauca and Silky shark *C. falciformis* within the Kenyan EEZ and High seas

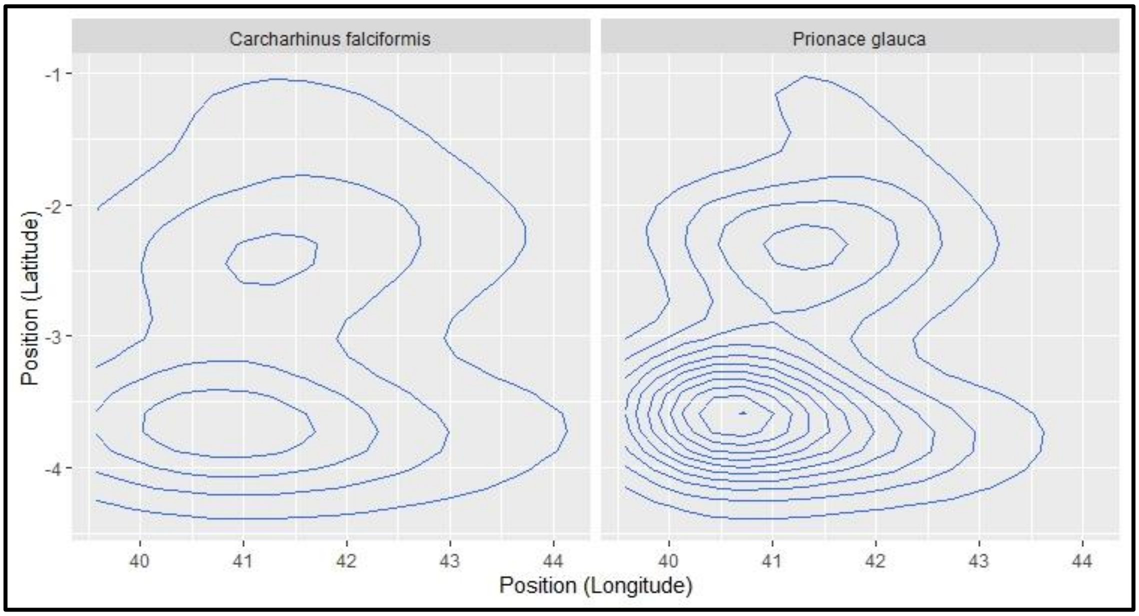

Figure 10. Spatial distribution showing concentration of catches for Blue shark *P. glauca* and Silky shark *C. falciformis* within the Kenyan EEZ and High seas

A comparison of abundance of both shark species (Fig.11) showed that *P. glauca* was widely distributed with average catch composition ranging between ≈30 mT and > ≈50 mT. However, *C. falciformis* had limited distribution of abundance with average catch compositions ranging between > ≈0.4 mT and < ≈10 mT.

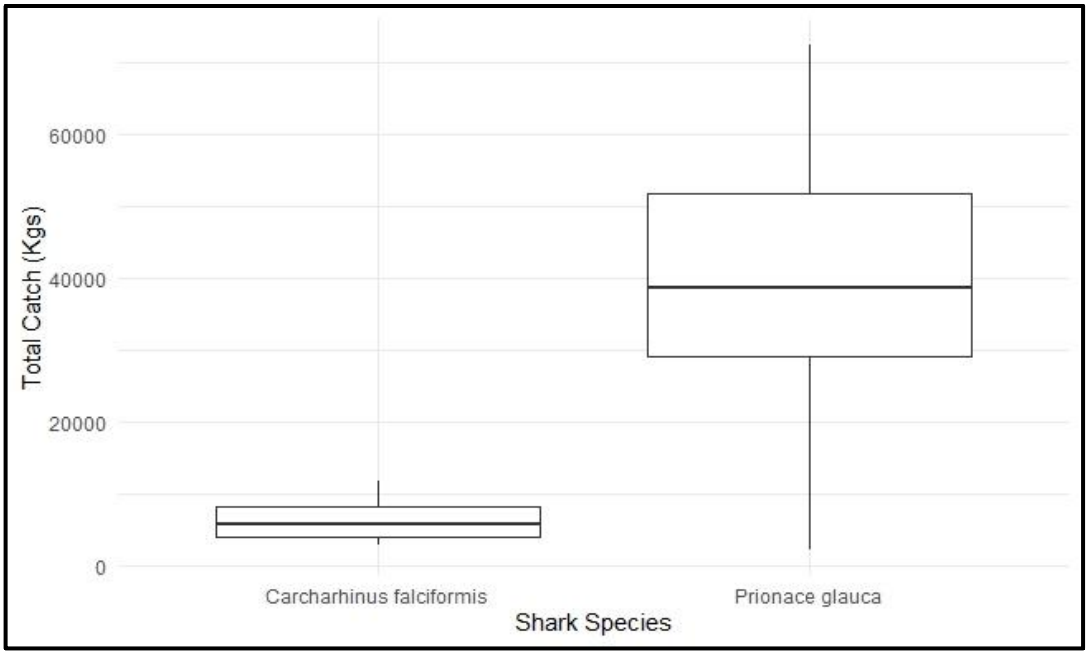

Figure 11. Comparison of Abundance distribution between Blue shark *P. glauca* and Silky shark *C. falciformis*

A linear regression model to compare distribution of abundance in catch and counts (Fig. 12) of *P. glauca* and *C. falciformis* showed that there was a strong relationship for *P. glauca* and a weak relationship of *C. falciformis* with R^2 of 77.7% for total counts and total catches.

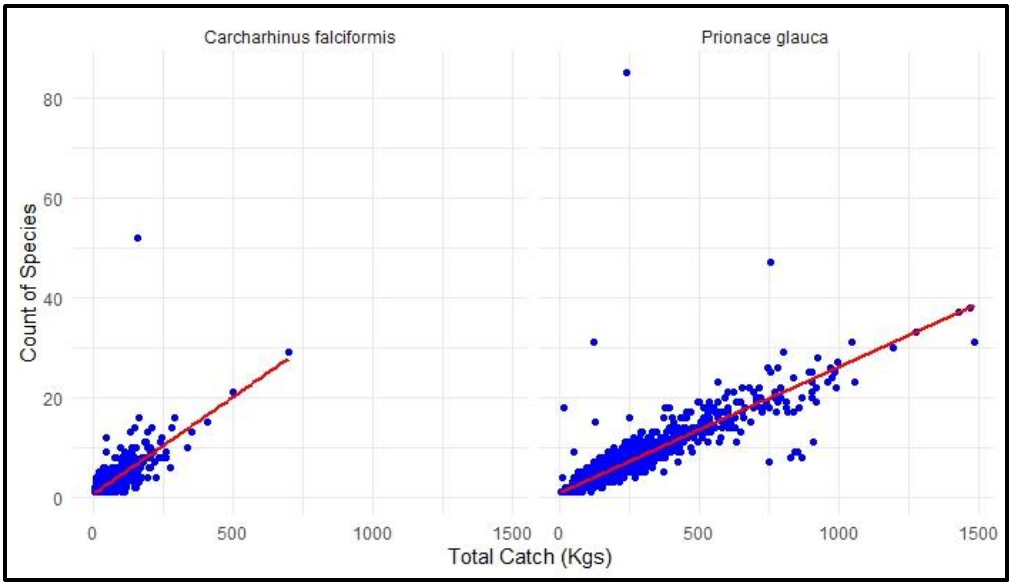

Figure 12. Linear regression to compare total counts and total catches of Blue shark *P. glauca* and Silky shark *C. falciformis*

Furthermore, results of ANOVA for mean variances comparison of abundance in total catches of *P. glauca* and *C. falciformis* (Fig. 13). Tukey's honest significant difference (HSD) (Nanda *et al.,* 2021) (Fig. 14) showed that there was indeed a high significant disparity of abundance between *P. glauca* and *C. falciformis*, which had a mean variance ranging about 33.757 mT of Tukey's comparison of means at a 95% family-wise confidence level.

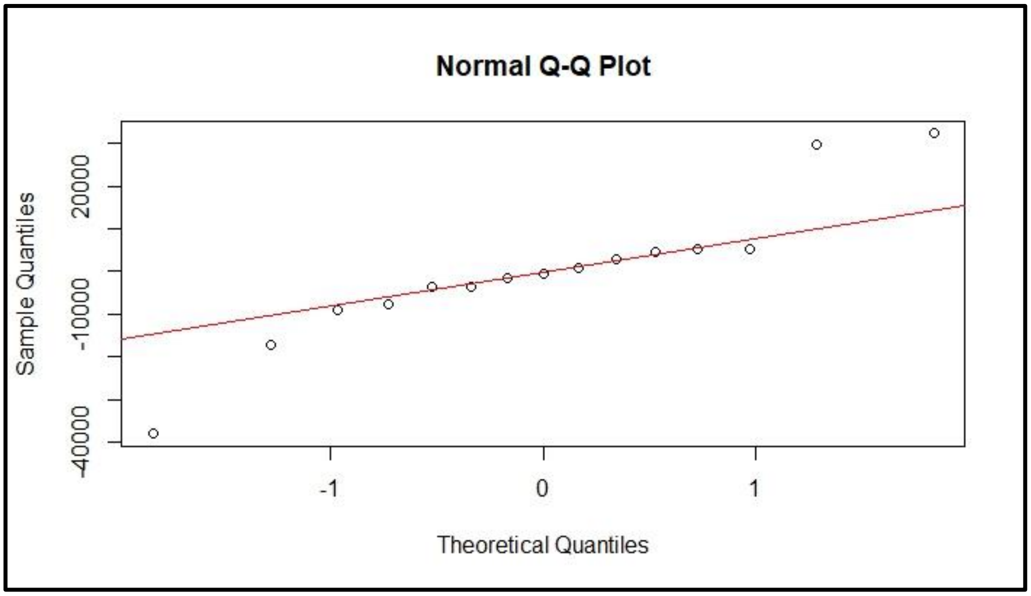

Figure 13. Normal Q-Q plot to compare mean variances of abundance in total catches of Blue shark *P. glauca* and Silky shark *C. falciformis*

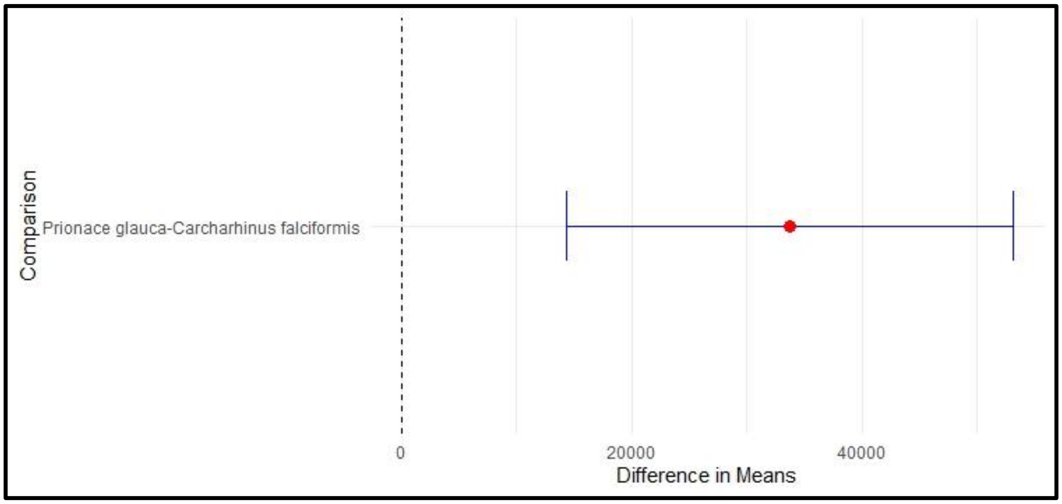

Figure 14. Tukey's HSD comparison of total catch abundance of Blue shark *P. glauca* and Silky shark *C. falciformis*

Environmental Predictors

Analyses of environmental variables at spatial scale (Fig. 15) showed that there was a high concentration of chlorophyll –a (mean NPPV mg/m^{3}day^{-1}) within the Kenyan EEZ and high seas, with concentrations ranging between >0.5 to <2.0 net primary productivity of biomass. Regions with close proximity to land masses were observed to have a high concentration of chlorophyll –a than deeper waters as shown in difference of darker to lighter shading. Concentration was distributed between positions of -7° S, 40° E and -7.5° S, 60° E. The concentration extends towards the northern equatorial regions of locations ranging from 0° N, 45° E to 0° N, 60° E.

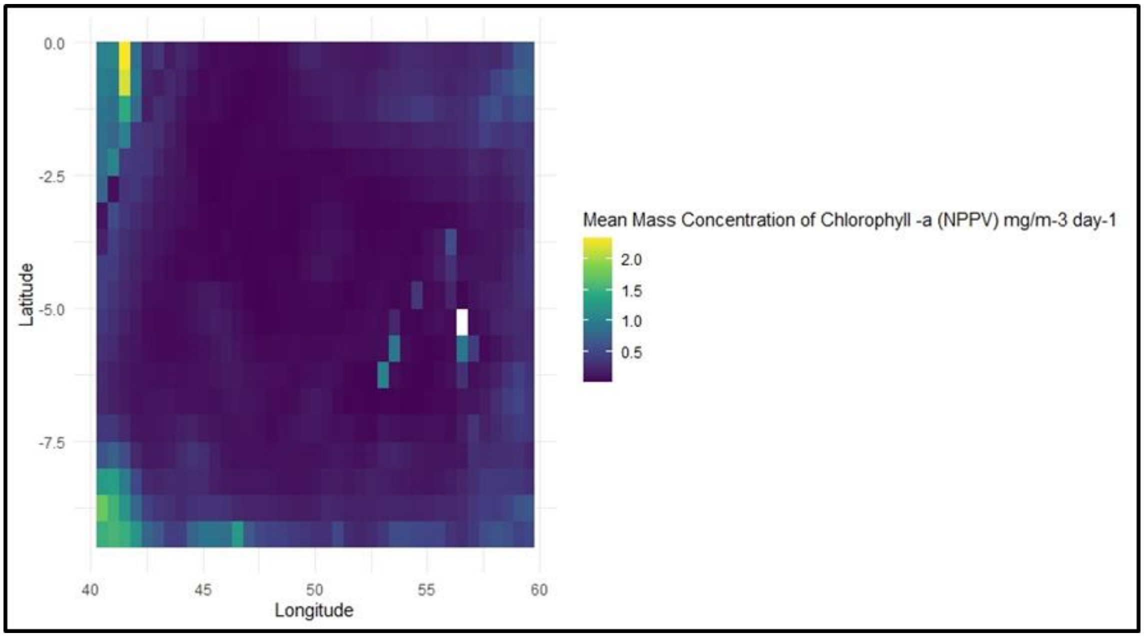

Figure 15. Spatial distribution of mean mass concentration of Chlorophyll -a (NPPV mg/m-3 day-1) within the Kenyan EEZ and High Seas. Data obtained from EU Copernicus Marine Services *https://data.marine.copernicus.eu/products*

Likewise, figure 16 with spatial extent of calculated mean seawater potential temperature (°C) revealed that Kenya's EEZ experienced relatively warm and cool seawater temperature ranging between 23°C and 27°C. Specifically, locations of -10° S, 40° E and -10° S, 50° E extending towards the northern equatorial region of about position -1° S, 40° E to 0° N, 50° E had a mix of warm and cool temperatures with only a difference of 1°C. However, towards the East along the Equator the temperatures were considerably high with > 28°C while further south below -10° S the temperatures were lower at < 23°C.

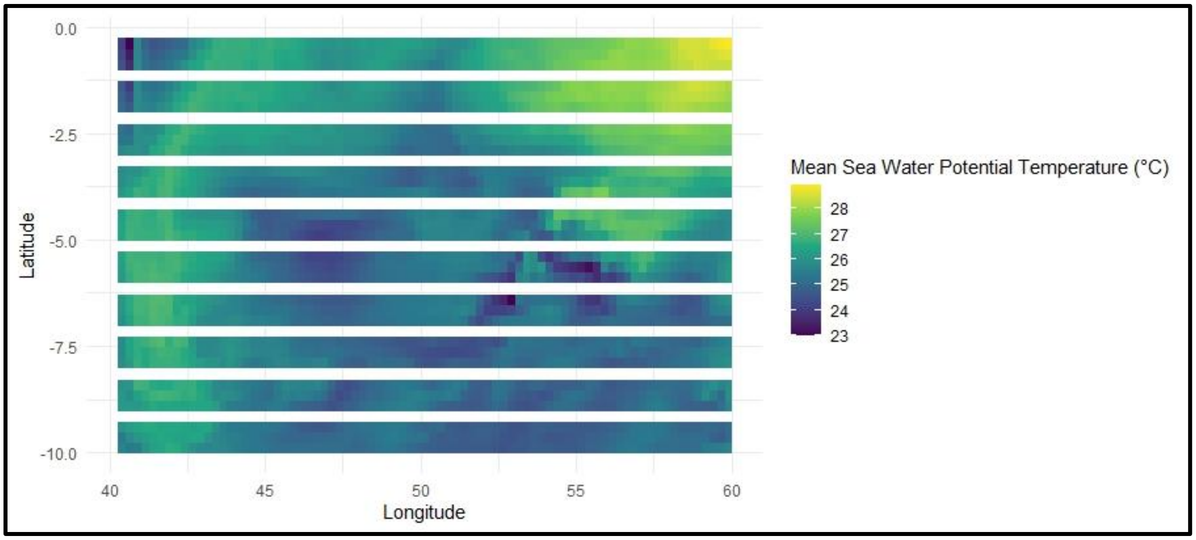

Figure 16. Spatial distribution of mean seawater potential temperature (TP) Celsius degree within the Kenyan EEZ and High Seas. Data obtained from EU Copernicus Marine Services https://data.marine.copernicus.eu/products

Model fitting and Evaluation

Generalized Linear Model (GLM) was used to predict distribution and abundance of both *P. glauca* and *C. falciformis* using proxies of mean seawater potential temperature (°C) and mean chlorophyll –a concentration (mean NPPV mg/m^{3}day^{-1}). For *P. glauca* (Fig. 18 and 19) and *C. falciformis* (Fig. 20 and 21) predicted presence or absence using catch data within the area under study. The results of model fitting for seawater potential temperature (°C) (Fig. 18 and 20) showed that the presences of both *P. glauca* and *C. falciformis* was influenced by temperatures ranging between 24°C and 27°C.

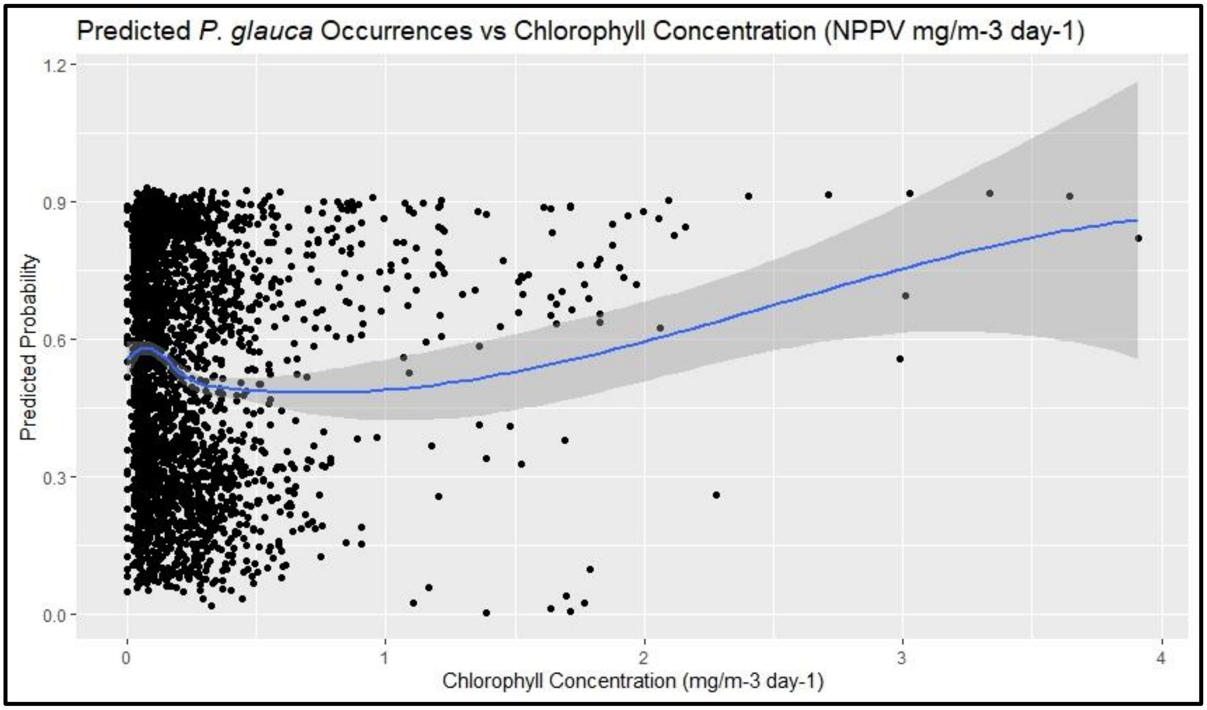

Figure 17. Predicted Presence of Blue shark *P. glauca* against mean Chlorophyll -a concentration (mg/m-3 day-1)

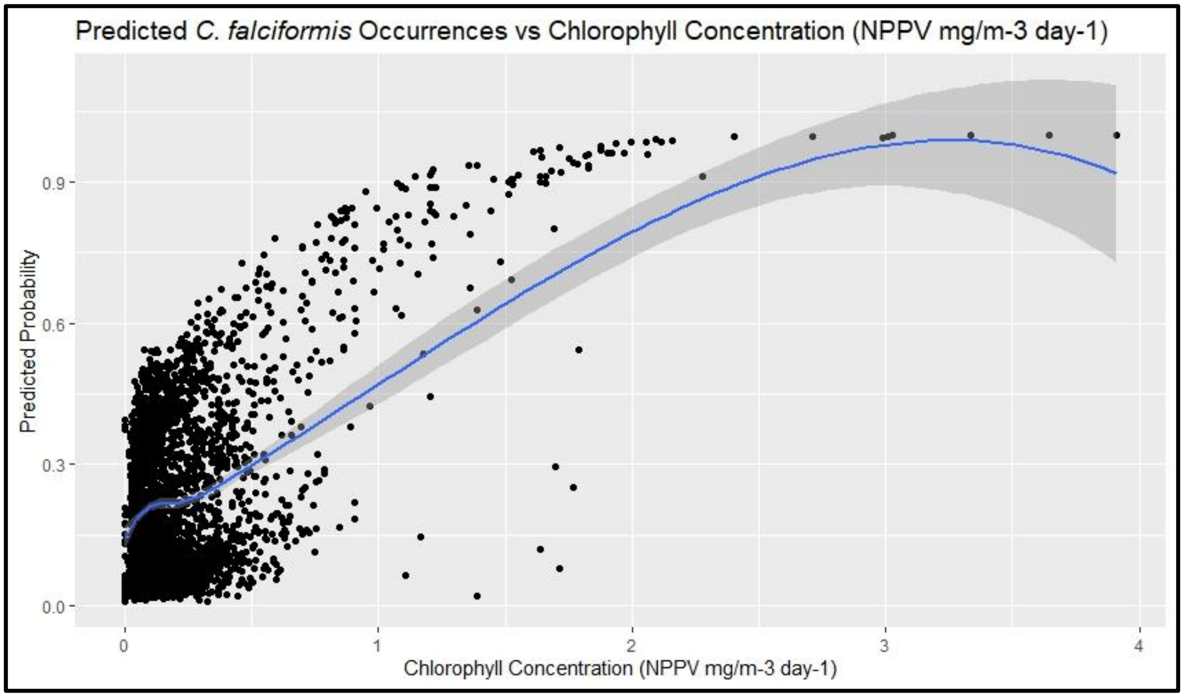

Figure 18. Predicted Presence of Silky shark *C. falciformis* against mean Chlorophyll -a concentration (mg/m-3 day-1)

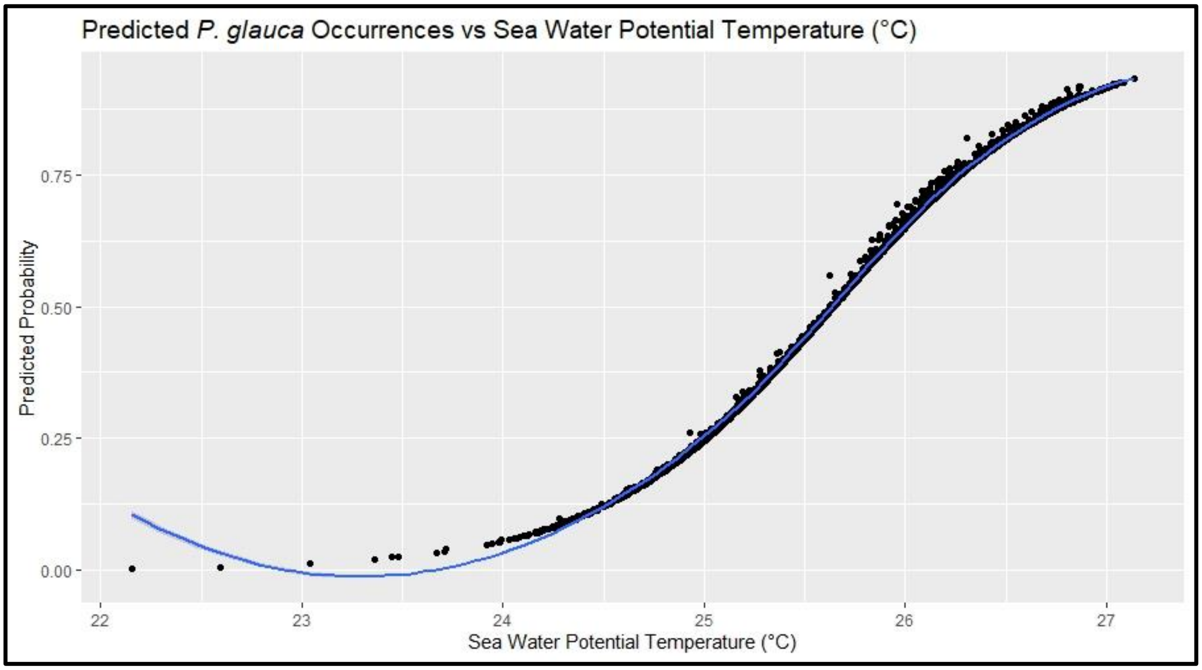

Figure 19. Predicted Presence of Blue shark *P. glauca* against mean Seawater potential temperature (°C).

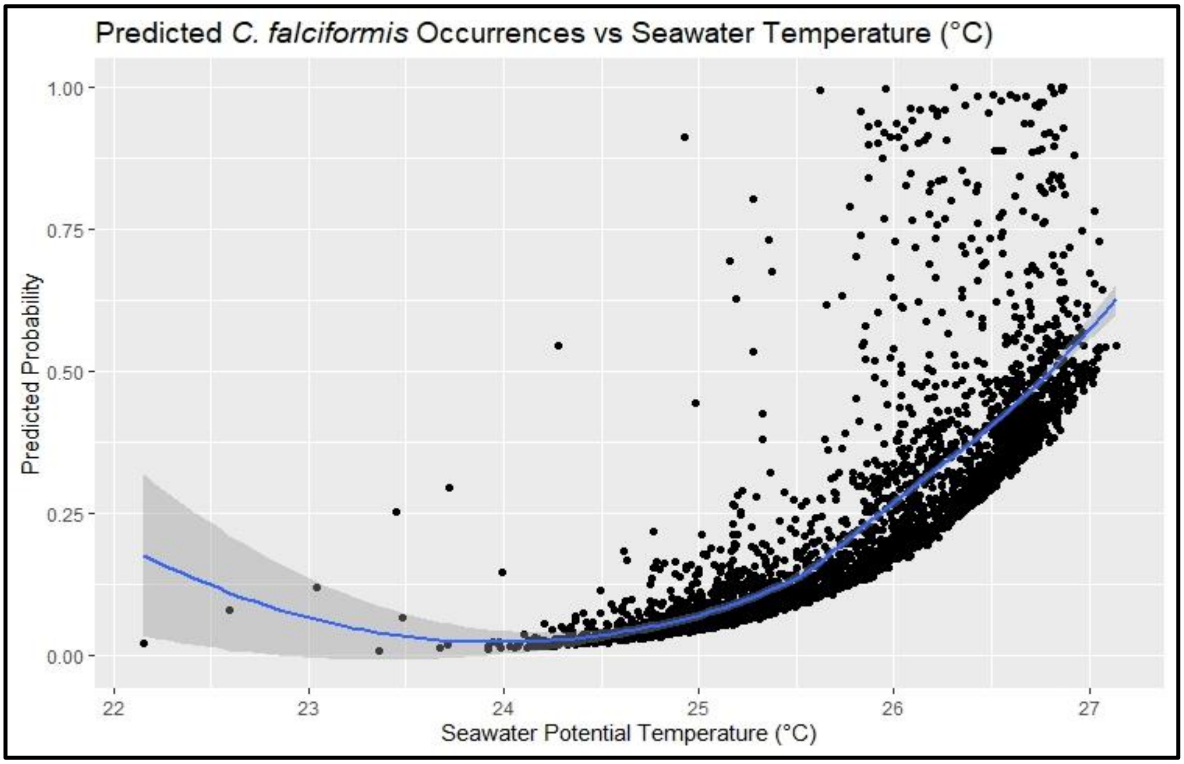

Figure 20. Predicted Presence of Silky shark *C. falciformis* against mean Seawater potential temperature (°C).

Their distribution differed whereby, prediction probability of occurrence within temperature range of 22°C to 27°C (Fig 19 and 20) was high for *P. glauca* in comparison to *C. falciformis*, which had a low prediction probability meaning that temperature inferring that seawater potential temperature did not have a major influence on distribution and abundance of Silky sharks. Although, high abundance was observed in warmer waters. Similarly, figures 17 and 18 above showed model fitting for mean mass concentration of chlorophyll –a prediction for presence of both *P. glauca* and *C. falciformis*. The findings showed that there was a high presence of both species in areas with high concentration of chlorophyll –a and few presence with low concentration. The predicted probability of presence of both species had a range of 0 – 1. Therefore, chlorophyll – a concentration was discovered as a major determinant of distribution and abundance for both species.

In evaluation of the model, Akaike Information Criterion (AIC) (Arnold, 2010) value was 2752 for *C. falciformis* and 3317 for *P. glauca* with both species having a number of fisher scoring iterations as 5 and 4 respectively. Thus, the model performance was stable for both species and fitted well with minimal iteration for convergence.

Discussion

The assessment of occurrences of both Blue shark *P. glauca* and Silky shark *C. falciformis* in both spatial-temporal abundance and distribution is a new study that was aimed to provide clarity whether or not these unique oceanic sharks stand a chance for better management and conservation strategies in Kenya as well as the WIO region. Currents trends globally concerning declining stocks of oceanic sharks remain as a wake-up call for comprehensive management of sharks caught as bycatch. The potential of environmental predictors observed in the analysis acknowledged the abundance and distribution of both shark species as shown in prediction model evaluation and diagnostics (Fig 21).

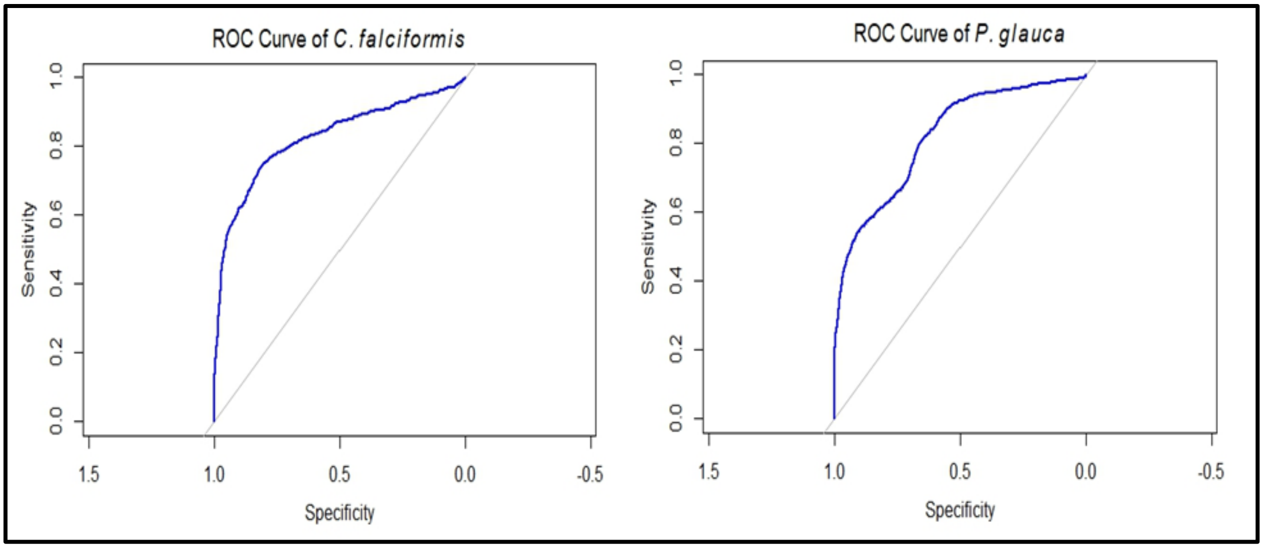

Figure 21. Model evaluation and diagnostic with AUC-ROC plots showing 0.8 sensitivity of the model to predict occurrence of both Silky shark *C. falciformis* and Blue shark *P. glauca* against mean Seawater potential temperature (°C) and mean mass concentration of chlorophyll –a (mean NPPV mg/m^{3}day^{-1}).

The results shows consistency with previous survey findings in the WIO region and across the globe, such that preference of habitats for oceanic sharks more often than not overlap with hotpot areas for industrial longline fisheries (Kiilu *et al*., 2019; Murray *et al*., 2023). The findings have shown that the high abundance and even distribution of Blue sharks *P. glauca* and Silky sharks *C. falciformis* in the Kenyan EEZ has put it at high risk of incidental harvesting all around the year with significant rise of catches experienced during the SEM season from June to August. Whereas during the NEM season (October and November) the impact of exploitation of these species is lowest particularly due to interchange of warm and cold seasons in the Kenyan EEZ (Okemwa *et al*, 2023). However, analyses of cumulative fishing effort showed that less abundance of catches during NEM resulted into high intensity of fishing effort applied compared to SEM, which puts both species of sharks susceptible to fishing especially within the Kenyan EEZ.

Spatially a high catch concentration of *P. glauca* was acknowledged in the cooler northern and southern waters of the WIO region but warmer regions towards inshore waters of Kenya the species was sparsely distributed leaving it at the mercy of large-scale industrial fisheries. However, *C. falciformis* revealed high tendency of migration due to its increasingly distant spatial extent in both cool and warm seasons although significantly susceptible to incidental catches by both small-scale artisanal fishers and large-scale industrial longline vessels. Chlorophyll –a concentration (mg/m-3 day-1) and seawater potential temperature (°C) underscored a substantial probability of prediction of abundance and distribution of both shark species and therefore, remains as potential indicators for habitat preferences for *P. glauca* and *C. falciformis* (Druon *et al.*, 2022; Filmalter *et al.*, 2021). High concentration of chlorophyll –a in regions towards the Equator with cooler temperatures imply that there is increased productivity of marine biodiversity because of the rich nutrients with those locations, usually associated with the upwelling phenomenon (Loor-Andrade *et al.,* 2017).

Distribution of abundance in terms of size classes informed that longline industrial fisheries often target larger individuals of *P. glauca* with fewer small-sized individuals caught by the same gear. However, *C. falciformis* is usually caught unselectively for both small and large sized individuals. In addition, it was revealed that there were two cohorts of *C. falciformis* caught, which would be vital to understand distribution of these size classes spatially (Kiilu *et al.,* 2019). Still, as seen by the large difference in means of catches for *C. falciformis* compared to *P. glauca*, reduced levels of abundance for *C. falciformis* is a conservation and management priority concern as it becomes vulnerable to exploitation with minimal assurance of reproduction (Rigby *et al.,* 2017).

Fisheries Management Implication

Whilst assessment of pelagic stocks pose huge constraints to fisheries scientists and managers, the need for tailored approaches to implementation of some conservation strategies is paramount. High patterns of abundance of Blue sharks and Silky sharks in the Kenyan EEZ highlights multi-faceted approach to mitigate over-exploitation of these sharks in a spatial-temporal understanding. In addition, this understand will enable to apply effective monitoring and enforcement efforts that will provide assurance for sustainable fisheries in both coastal and industrial fishing undertakings. Concerted efforts from catch documentation, reports of fisheries observers, electronic monitoring and stakeholder engagements as well as surveillance through a vessel monitoring system among other tools in the maritime domain awareness should be pulled together to reinforce management of these vulnerable species.

This study provides an understanding of the spatial temporal occurrences of Blue shark and Silky sharks, which managers can interrogate to adjust efforts that will align with the patterns of abundance and distribution of these two species. The challenges encountered during this study such as inadequate data for presence of species and environmental variables. In addition, lack of a centralized pool for both catch and effort fisheries data, limited stock information and surveys of various pelagic and demersal fisheries in Kenya among others can be taken as a topic for discussion among policy makers to set effective strategies to bridge gaps for fruitful management efforts. It is proposed that further studies in spatial-temporal assessments of oceanic sharks incidentally caught, as bycatch should be pursued with adequate data and environmental predictors to ascertain species occurrences in the Kenyan EEZ and High seas.

Acknowledgement

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