Environ Biol Fish
https://doi.org/10.1007/s10641-023-01434-w

Seasonal occurrence and environmental drivers of pelagic shark species in Los Cabos, Mexico, assessed using citizen science

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Received: 18 November 2022 / Accepted: 21 May 2023

Abstract The Mexican Pacific is an area of high biodiversity due to its transitional location of both tropical and sub-tropical waters and many shark species inhabit the coastal areas of Los Cabos off the Baja California Peninsula, Mexico. Here, we used citizen science onboard a local shark tourism operator to determine the probability of pelagic shark presence relative to environmental factors using generalized additive models (GAMs) over a 3-year sampling period. Short-fin mako shark (*Isurus oxyrinchus)* presence had significant relationships with sea surface temperature (SST), wind speed, sampling site, and year. Smooth hammerhead shark (*Sphyrna zygaena*) presence was significantly influenced by wind speed, year, photoperiod, moon illumination, and SST. Silky shark (*Carcharhinus falciformis*) presence had significant relationships with SST, wind speed, site, and year. The use of a tourism operator allowed citizens to be involved in science and provided a platform to collect data. This monitoring program will be continued and provides a baseline dataset of pelagic shark species which can often be lacking from the local artisanal fisheries that target sharks in the area.

Keywords Generalized additive models · Elasmobranchs · Seasonality · Provisioning · Shark tourism

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10641-023-01434-w.

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Introduction

Environmental factors influence the horizontal and vertical movements of shark species, their distribution and abundance, as well as the type of habitat they use, which include, but are not limited to, sea surface temperature, salinity, bathymetry, geomagnetic anomalies, and primary and secondary productivity (Carrier et al. 2010). These variables influence the overall spatial ecology of marine species, most notably sea surface temperature with evidence of many species extending their home ranges to remain within temperature niches in response to warming oceans (Robinson et al. 2015). Environmental variables related to climate change need to be incorporated into models when examining population trends (Saltzman and White 2022).

Pelagic sharks include oceanic and semi-oceanic species, and they comprise a small group, representing 6% of cartilaginous fishes. Pelagic sharks are mainly represented by the orders Carcharhiniformes, Lamniformes, and Squaliformes (Camhi et al. 2009). These sharks are highly mobile, are not

Published online: 14 June 2023

associated with the sea bed, and inhabit the world's oceanic basins and over continental and insular slopes and rises (Compagno 2008). Studies on pelagic shark species including blue shark (Bigelow et al. 1999; Carvalho et al. 2011; Mitchell et al. 2014) and the short fin mako sharks (Adams et al. 2016; Nasby-Lucas et al. 2019) and silky sharks (Díaz-Delgado et al. 2021; Kindong et al. 2022) describe how environmental factors such as SST and productivity play essential roles in their spatial ranges and prey availability.

The Mexican Pacific extends from the north of the Baja California Peninsula to the Gulf of Tehuantepec and shark diversity is high in this area due to the mixing of both tropical and sub-tropical waters, due to the confluence of two current systems of California and North Equatorial, which have produced a wide variety of habitats for marine species (De La Cruz-Agüero 1994). Many pelagic species are found close to coastline of the Baja California Peninsula due to the deep bathymetry found close to shore. Pelagic shark species that are common include the short-fin mako shark *Isurus oxyrinchus* (Rafinesque 1810), the blue shark *Prionace glauca* (Linnaeus 1758), the smooth hammerhead shark *Sphyrna zygaena* (Linnaeus 1758), and the silky shark *Carcharhinus falciformis* (Müller and Henle 1841). None of these shark species are listed under the national conservation (DOF 2010) or fisheries (DOF 2006) legislation and are commonly caught in the Mexican artisanal fisheries that target sharks specifically for their meat, which is consumed locally (Sosa-Nishizaki et al. 2020).

Scientific assessments and fisheries-derived data available of large shark species living in the open ocean are frequently incomplete, poor, or lacking (Ferretti et al. 2008; Camhi et al. 2009; Bargensi et al. 2020). Most data on pelagic shark species are derived from fisheries as they utilize oceanic environments and are harder to study than coastal shark species. Pelagic species, however, visit coastal areas for feeding and reproduction, presenting an opportunity to collect information. In recent years, citizen science, as well as the use of tourist platforms, has proven to be a viable alternative for the study of abundance, movements, behavior, and habitat use of pelagic sharks (Meyer et al. 2009). Tourism has become the main activity for the sustainable use of several species of elasmobranchs around the world (Gallagher and Hammerschlag 2011) and offers a way of generating revenue from live sharks (Topelko and Dearden 2005; Johnson and Kock 2006; Laroche et al. 2007).

Los Cabos in Baja California Sur, Mexico, is a flourishing marine tourism destination, where marine biodiversity supports different tourism activities including diving, whale watching and, more recently, shark snorkelling tours. Shark tourism in Mexico already represents more than half the annual revenue of national shark fisheries (Cisneros-Montemayor et al. 2013) while most of the country's shark stocks are collapsed, overfished, or fully exploited (Arreguín-Sánchez and Arcos-Huitrón 2011). Because pelagic sharks are highly mobile and frequently found in very specific places in the marine environment (Hearn et al. 2010), shark tour operators use attraction methods (like chumming and baiting) in order to have higher possibilities for a recreational encounter. Although some negative effects have been related to shark provisioning operations, there is still an almost complete lack of information from multi-species shark diving sites (Meyer et al. 2009).

In the present study, we used the platform of a shark diving tourism company in Cabo San Lucas, Los Cabos (www.cabosharkdive.com), and citizen science to collection data to (i) investigate the environmental drivers that influence the presence of pelagic shark species, (ii) to determine their seasonal occurrence and abundance, and (iii) to establish a long-term monitoring program.

Materials and methods

Study area

The coastal areas of Los Cabos represent the union between the Gulf of California and the Pacific Ocean. Here, the continental platform is narrow and depths of over 500 m are found close to shore (Aguilar-Palomino et al. 1998). The area is influenced by 3 superficial currents: the California Current, the North Equatorial Current, and the North Equatorial Counter current. They each vary greatly throughout the year as a consequence of changes in speed and direction of the dominant winds. Sea surface temperature is as low as 18 °C during winter and late spring (December–May) and as high as 30 °C during the summer and fall (June–November) (Zúñiga-Flores 2004). Pelagic shark surveys were made in the vicinity of Cabo San Lucas Bay, and five main

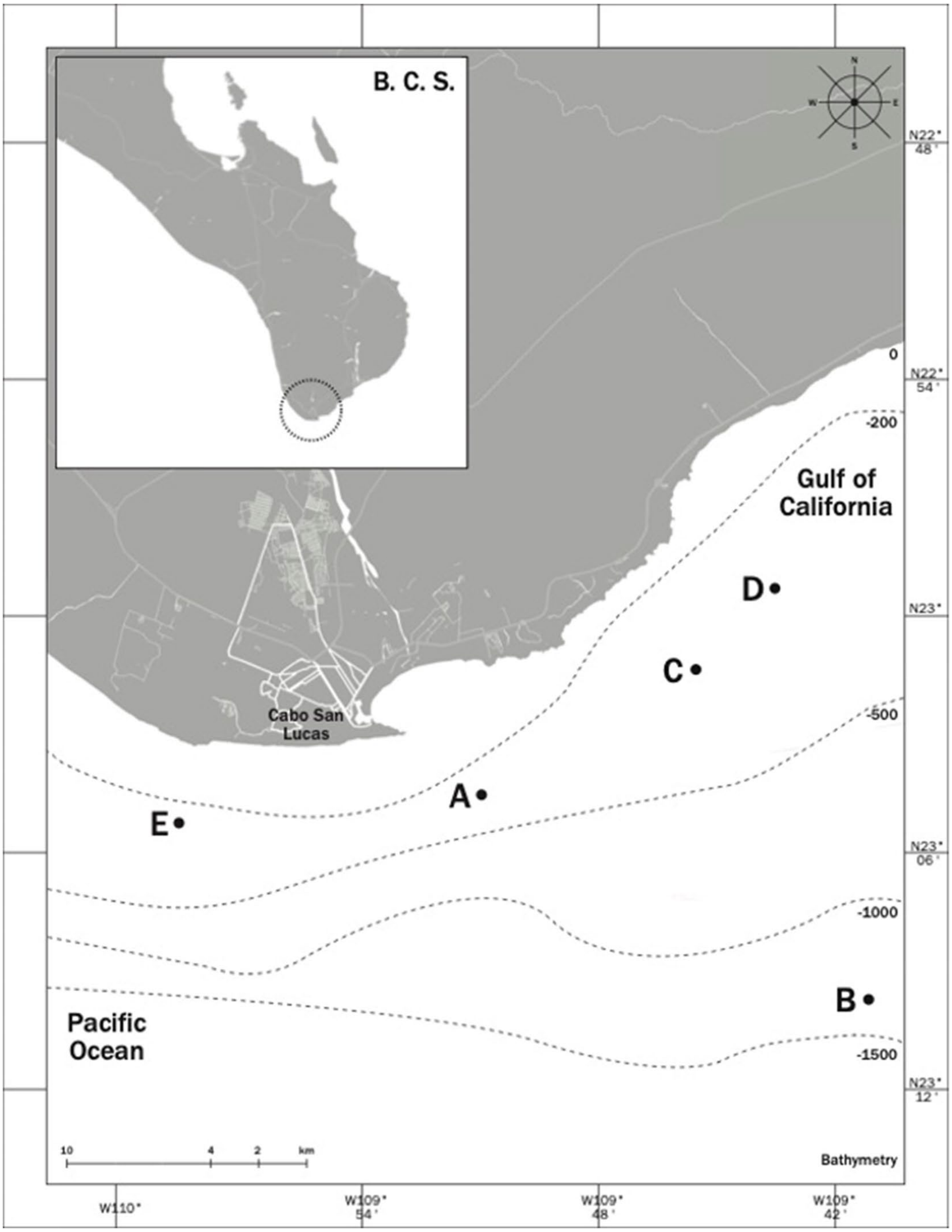


Fig. 1 Sampling site locations off Los Cabos, Baja California Sur (B.C.S), Mexico, where citizen science pelagic shark tours were conducted between January 2016 and December 2018

Table 1 Description of main sampling sites visited during pelagic shark surveys on boat shark tourism operator in Los Cabos, Baja California Sur (B.C.S), Mexico

Site	Site type	Depth	Location
A	Continental slope	450 m	Gulf of California/Pacific Ocean
B	Sea mount	180 m	Gulf of California
C	Continental slope	475 m	Gulf of California
D	Sea flat zone	700 m	Gulf of California
E	Continental slope	450 m	Pacific Ocean

sampling sites were visited ranging from 2 to 10 miles from the coastline and with depths between 180 and 700 m (Table 1, Fig. 1).

Fieldwork

Pelagic shark surveys were carried out between January 2016 and December 2018 on board a shark tourism boat (sports fishing boat 32 feet long). The site chosen on each sampling day depended on the wind and ocean conditions. When the boat arrived at a site, the engine of the boat remained off and provisioning methods were used to attract sharks for tourists to observe them whilst in the water. To attract sharks, a "chum" was first created by mixing seawater and dead fish which included skipjack tuna (*Katsuwonus pelamis*), yellowtail kingfish (*Seriola lalandi*), yellowfin tuna (*Thunnus albacares*), and mackerel (*Trachurus symmetricus*). This chum was continuously released into the ocean and the wind and current created a slick line with the aim of attracting pelagic sharks. A crate filled with dead fish and a fish head was also attached to the boat with a rope (Fig. 2). Tourists were given a briefing on safety and shark species identification. Once a shark appeared, the guides and tourists entered the water, and while snorkelling, the guides registered the number of sharks and the species. Average sampling time per survey was 3 h, which represents the time provisioning activities were carried out on each tour which occurred either in the morning between 0800 and 1200 h or between 1400 and 1700 h. Total abundance, shark species, and site location were recorded by a crew member along with environmental factors: wind direction, wind speed, and sea surface temperature (SST) in situ. Tourists helped fill in the data sheets before and after the activity. Moon illumination, photoperiod (day length), and chlorophyll concentration were also recorded on return to land.

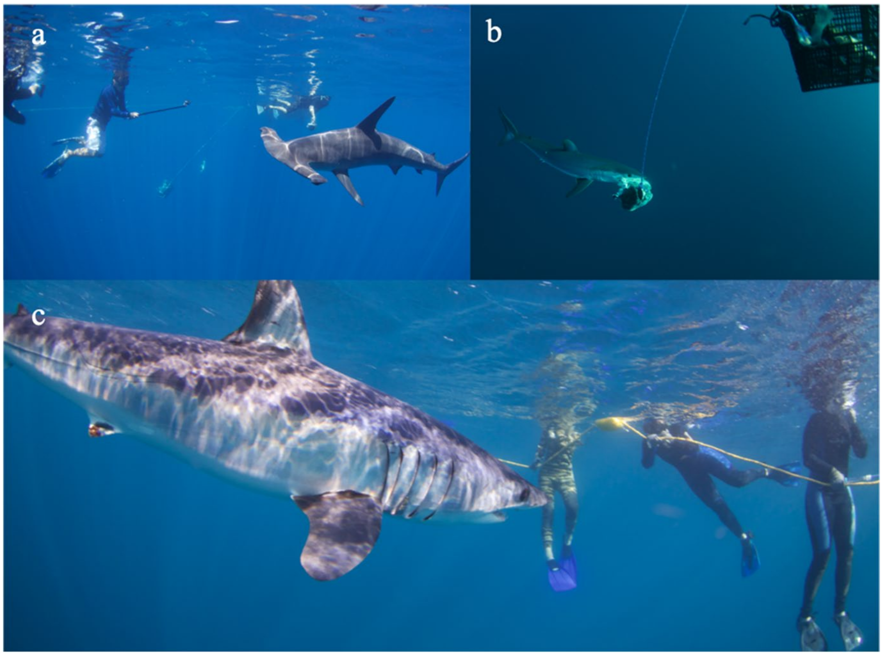


Fig. 2 Interactions between snorkelers and pelagic sharks during shark tours. **a** Snorkelers observing a smooth hammerhead shark. **b** Shortfin mako shark biting the bait and chum box. **c** Snorkelers staying on the safety line while interacting with a shortfin mako shark

Data analysis

All statistical analyses were completed using R (R Core Team 2020) version 4.0.2. Generalized additive models (GAMs) were used to determine the effects of the following predictor variables on pelagic shark presence: year, month, sampling site, SST, wind speed, wind direction, chlorophyll concentration, photoperiod, and moon illumination. Moon illumination represents the percentage of the moon's surface that is illuminated by the sun (0–100%) and was extracted from the "lunar" package in R (Lazaridis 2014; R Core Team 2020).

GAM models allow the evaluation of nonlinear relationships by using smoothing functions (Chambers and Hastie 1992). The degree of smoothing was restricted to avoid overfitting and so the number of basis functions was limited to 4. The response variable was the presence/absence of pelagic shark species and so binomial distributions with logit link functions were used. GAM models were built using the R package *mgcv* (Wood 2017) and displayed using the *visreg* package. Before models were built, the Pearson's coefficient of correlation was used to investigate correlation between the predictor variables. SST and month were positively correlated and so these variables were not included together in the models. A backwards-stepwise approach was used to determine the final model by first creating a full model and then removing each predictor variable and assessing the Akaike information criterion (AIC) score and deviance explained (%). Seasonality of each species was represented by the percentage of days sharks were observed in each month. This was calculated by dividing the number of days sharks were seen by the number of days sampled in each month, as tours were not run every day. Shark tours did not operate in September and so data was not collected.

Data were checked for errors and missing information, only data prior to 2019 were used for the analysis as at least one of the trained crew members was present on the boat during this time period to make sure all required information was collected. Missing information mainly included sex and length of sharks and so this was not included.

Results

A total of 518 pelagic shark surveys were completed over the 3-year sampling period. The sampling effort at each site was not even as we relied on the tourism operator which was also weather dependent (see Supplementary Information Appendix S1). Less morning surveys were conducted ($n=60$) than afternoon surveys ($n=458$) and so it was not possible to investigate time of day as a predictor of shark presence due to very uneven sampling effort. The overall number of surveys at each site is as follows: site A ($n=130$), site B ($n=52$), site C ($n=118$), site D ($n=114$), and site E ($n=104$).

I. oxyrinchus presence

The best-fitted GAM model for *I. oxyrinchus* included six predictor variables: the smoothing functions for wind speed, photoperiod, SST, illumination and the categorical variables site and year (Table 2) and can be expressed as follows:

$$logit(\mu_i) = \alpha + f_1(SST) + f_2(WindSpeed_i) + f_3(Photoperiod_i) + f_4(Illumination_i) + Year_i + Site_i$$

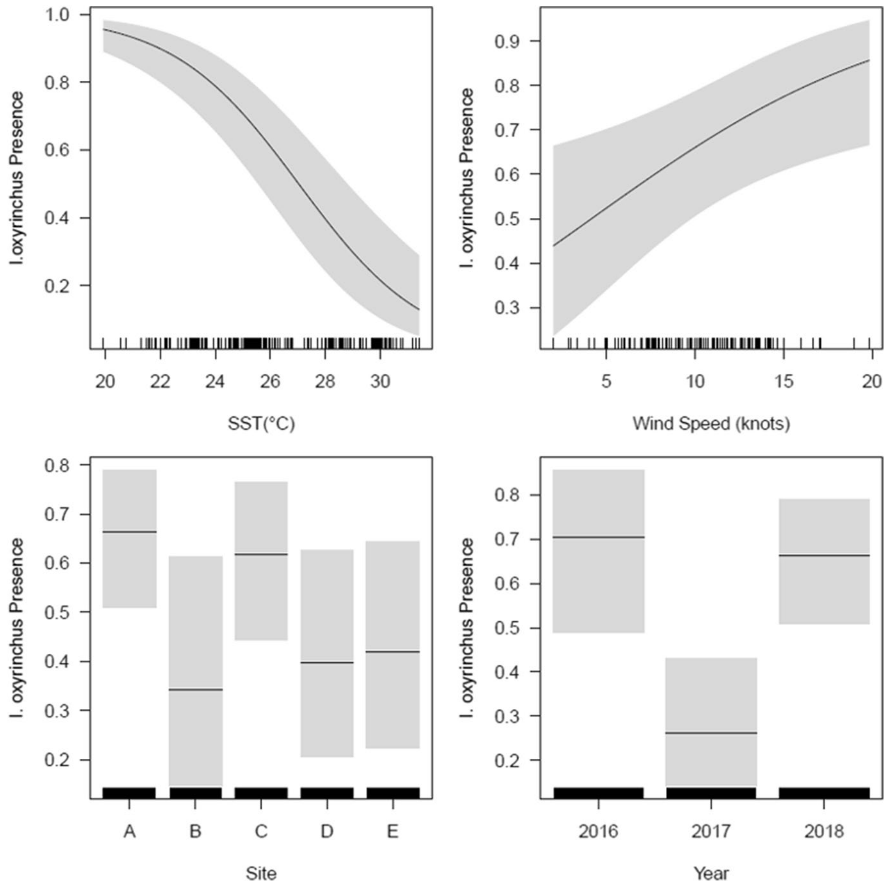
where μi is presence/absence of *I. oxyrinchus*, α is the intercept, and fx is the smoothing function (thin plate regression splines).

Four predictor variables were significant influencers of *I. oxyrinchus* presence, which included SST, wind speed, site and year (Table 2, Fig. 3). SST ranged between 20 and 31 °C across all years, and the

Table 2 Selection of generalized additive model (GAM) using Akaike information criterion (AIC) score and deviance explained to predict *I. oxyrhinchus* presence in Los Cabos considering the following variables: sea surface temperature (SST °C), chlorophyll, wind speed (knots), photoperiod (h), moon illumination, and wind speed. Model in bold represents final model selected (Significance ***$p<0.001$, **$p<0.01$, *$p<0.05$)

Model	AIC	Deviance explained (%)
SST, wind speed, year, site, photoperiod, illumination, chlorophyll	507.911	26.40
SST*, wind speed*, year*, site*, photoperiod, illumination**	**506.759**	**26.30**
SST, wind speed, year, site, photoperiod	509.830	24.90
SST, wind speed, year, site	509.740	25.00
SST, wind speed, year	513.151	23.90
SST, wind speed	525.060	19.80
SST	563.119	13.00

Fig. 3 Effect plots of the generalized additive model (GAM) used to evaluate relationships between shortfin mako shark (*I. oxyrinchus)* presence. Sea surface temperature (SST), wind speed, sample site, and year were significant predictors of presence. Shaded area represents two standard errors and rug plot (on the *x*-axis) shows observations of predictor variables



probability of *I. oxyrinchus* presence increased with decreasing SST. Wind speed ranged between 1 and 10 knots and had a positive relationship with *I. oxyrinchus* presence. The probability of sightings was significantly higher at sampling sites A and C. Year also was a significant predictor and 2016 and 2018 had a higher probability of *I. oxyrinchus* presence than 2017. Total abundance per survey ranged between 1 and 7 sharks, 1 was the most frequent abundance across all surveys (Supplementary Information Appendix S2). The distributions of explanatory variables with significant relationships with probability of shark presence can be found in Supplementary Information Appendix S3.

S. zygaena presence

The best-fitted GAM model for *S. zygaena* included six predictor variables: the smoothing functions for wind speed, photoperiod, SST, illumination, chlorophyll, and the categorical variable year (Table 3) and can be expressed as follows:

$$logit(\mu_i) = \alpha + f_1(SST) + f_2(WindSpeed_i) + f_3(Photoperiod_i)$$
$$+ f_4(Illumination_i) + f_5(Chlorophyll_i) + Year_i$$

where μi is presence/absence of *S. zygaena*, α is the intercept, and fx is the smoothing function (thin plate regression splines).

Five predictor variables were significant influencers of *S. zygaena* presence, which included wind speed, year, photoperiod, moon illumination and SST (Table 3, Fig. 4). Photoperiod ranged between 10.73 and 13.53 h and had a positive relationship with *S. zygaena* presence. Moon illumination had a positive relationship with *S. zygaena* presence. Wind speed ranged between 1 and 20 knots and had a positive relationship with *S. zygaena* presence. The year also was a significant predictor and 2017 had a higher probability of *S. zygaena* presence than 2016 and 2018. Total abundance per survey ranged

Table 3 Selection of generalized additive model (GAM) using Akaike information criterion (AIC) score and deviance explained to predict *S. zygaena* presence in Los Cabos considering the following variables: sea surface temperature (SST °C), chlorophyll, wind speed (knots), photoperiod (h), moon illumination, and wind speed. Model in bold represents final model selected (significance ***$p<0.001$, **$p<0.01$, *$p<0.05$)

Model	AIC	Deviance explained (%)
SST, wind speed, illumination, photoperiod, year, chlorophyll, site	461.894	30.10
SST, wind speed*, illumination***, photoperiod***, year***, chlorophyll**	**451.339**	**29.30**
SST, wind speed, illumination, photoperiod, year	454.550	27.90
SST, wind speed, illumination, photoperiod	469.756	24.80
SST, wind speed, illumination	546.199	11.40
SST, wind speed	558.718	8.97
SST	589.082	3.61

between 1 and 4 sharks, 1 was the most frequent abundance across all surveys (Supplementary Information Appendix S2).

C. falciformis presence

The best-fitted GAM model for *C. falciformis* included five predictor variables: the smoothing functions for wind speed, SST, chlorophyll, and the categorical variables site and year (Table 4) and can be expressed as follows:

$$logit(\mu_i) = \alpha + f_1(SST) + f_2(WindSpeed_i) + f_3(Chlorophyll_i) + Site_i + Year_i$$

where μi is presence/absence of *C. falciformis*, α is the intercept, and fx is the smoothing function (thin plate regression splines).

Four predictor variables were significant influencers of *C. falciformis* presence, which included SST, wind speed, site, and year (Table 4, Fig. 5). SST and wind speed had a positive relationship with silky shark presence. Silky shark presence was significantly higher at site B and site C. The year 2016 had a higher probability of silky shark presence than 2017 and 2018. Total abundance per survey ranged between 1 and 50 sharks, 1 was the most frequent abundance across all surveys.

Seasonality

Isurus oxyrinchus was observed in all months sampled but were more commonly observed between the months of January and May (Fig. 6). February had on average the greatest number of days with *I. oxyrinchus* sightings (65%). *Sphyrna zygaena* were observed between January and August but were most common between May and July (Fig. 6). June had on average the greatest number of days with *S. zygaena* sightings (65%). *Carcharhinus falciformis* were observed in every month of the year but were most common between May and November (Fig. 6). August had on average the greatest number of days with silky shark sightings (62%).

Discussion

The aims of the study were to investigate the environmental drivers that influence pelagic shark presence, to determine their seasonality and to establish a long-term monitoring program using a shark tourism operator. In the first 3 years of monitoring, we observed eight shark species, with *I. oxyrinchus*, *S. zygaena*, and *C. falciformis* being most abundant. Our results determined SST, wind speed, and year to be significant predictors of presence for all three species. Photoperiod and moon illumination were significant predictors for *S. zygaena* presence, and sampling site was a significant predictor for both *I. oxyrinchus* and *C. falciformis.*

Isurus oxyrhincus are known as a cold-water species and are in the family "Lamnidae" and have the ability to maintain core body temperature higher than that of surrounding water (Carey et al. 1981). In our study, they were most common in months where SST

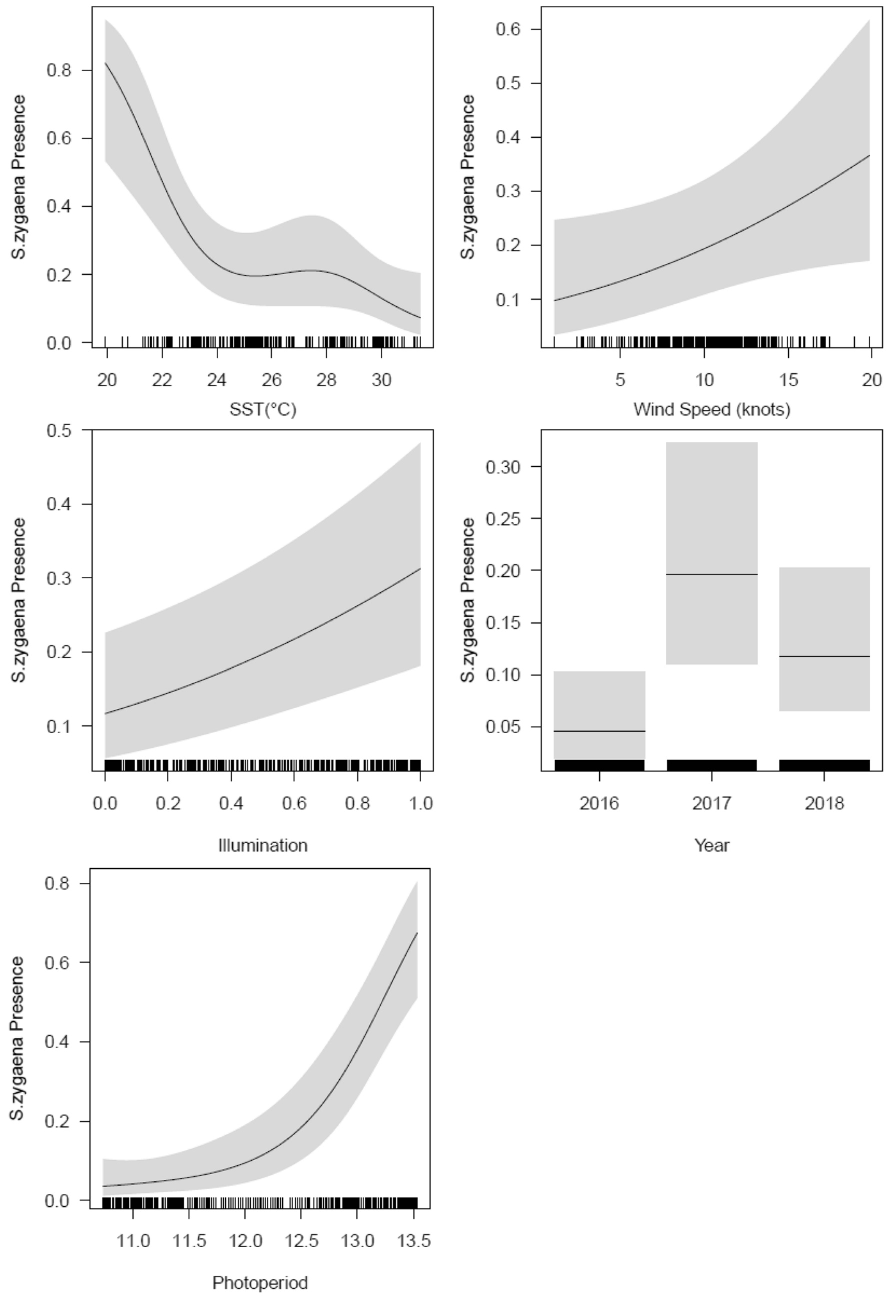


Fig. 4 Effect plots of the generalized additive model (GAM) used to evaluate relationships between smooth hammerhead shark (*S. zygaena*) presence. Sea surface temperature (SST), wind speed, year, photoperiod, and illumination were significant predictors of presence. Shaded area represents two standard errors and rug plot (on the x axis) shows observations of predictor variables

was lower than 25 °C. This species was also identified as one of the most abundant in the winter and spring landings in artisanal fisheries in the state of Baja California Sur, along with the blue shark (*Prionace glauca)* (Bizzarro et al. 2007). Globally, they are known to commonly inhabit waters between 17 and 22 °C (Compagno 2001; Carrier 2017), and in the Gulf of Mexico, they are usually found in water temperatures between 25 and 27 °C (Vaudo et al. 2016, 2017).

Data regarding *S. zygaena* is sparce in both Mexico and globally, despite of the fact that the species is common in the Gulf of California and Pacific Ocean (Ochoa-Díaz 2009). In the south of Portugal, sightings have been registered during the warm season (Couto et al. 2018), which has similar SSTs (~27 °C) to the transitional

Table 4 Selection of generalized additive model (GAM) using Akaike information criterion (AIC) score and deviance explained to predict *C. falciformis* presence in Los Cabos considering the following variables: sea surface temperature (SST °C), chlorophyll, wind speed (knots), photoperiod (h), moon illumination, and wind speed. Model in bold represents final model selected (significance ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$)

Model	AIC	Deviance explained (%)
SST, wind speed, site, year, chlorophyll, illumination, photoperiod	467.460	35.90
SST, wind speed, site, year, chlorophyll, illumination	465.935	35.80
SST***, wind speed*, site***, year*, chlorophyll	**464.062**	**35.80**
SST, wind speed, site, year	464.880	35.30
SST, wind speed, site	476.295	33.10
SST, wind speed	532.414	22.10
SST	530.402	21.80

season in Los Cabos when they were most commonly sighted on our pelagic shark surveys (May–July). Salomon Aguilar et al. (2009) suggested that the Gulf of California offers *S. zygaena* in the first years of life adequate temperature conditions (18 to 31 °C) between the months of May to September. *Sphyrna zygaena* could be resident in the area all year as this species is not known to be highly migratory (Diemer et al. 2011) and as recently described by Bensard et al. (2023) in the Mexican Pacific, smooth hammerheads utilize coastal resources for 2 years prior to offshore migration, showing long-term reliance to coastal habitats, which could be

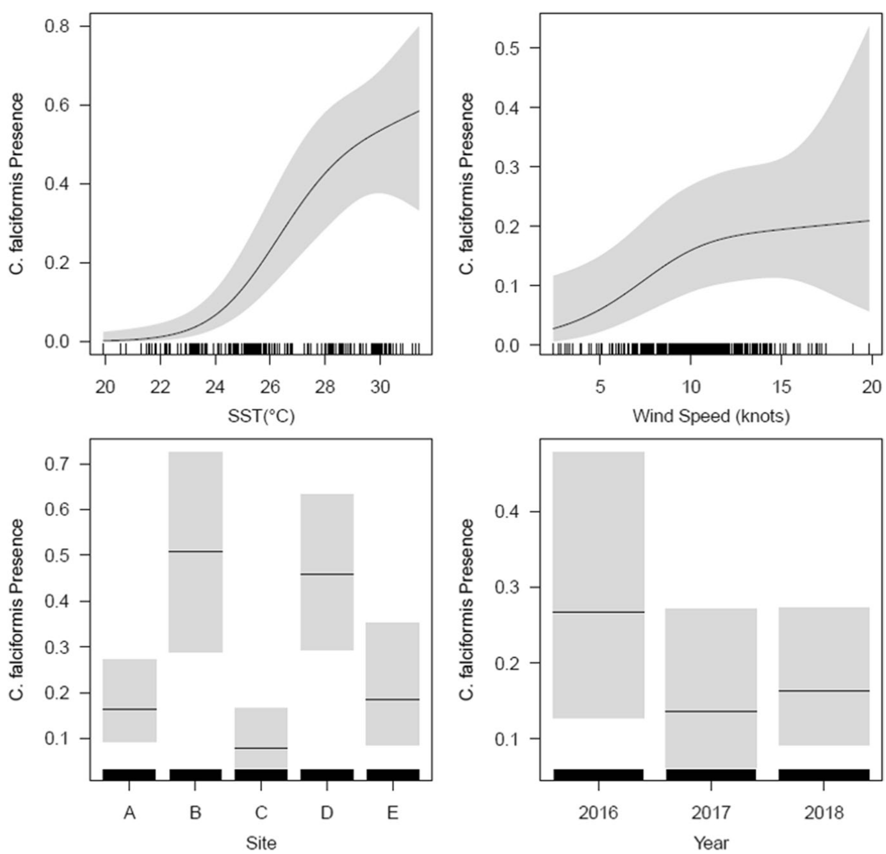


Fig. 5 Effect plots of the generalized additive model (GAM) used to evaluate relationships between silky shark (*C. falciformis*) presence. Sea surface temperature (SST), wind speed, sample site, and year were significant predictors of presence. Shaded area represents two standard errors and rug plot (on the *x* axis) shows observations of predictor variables

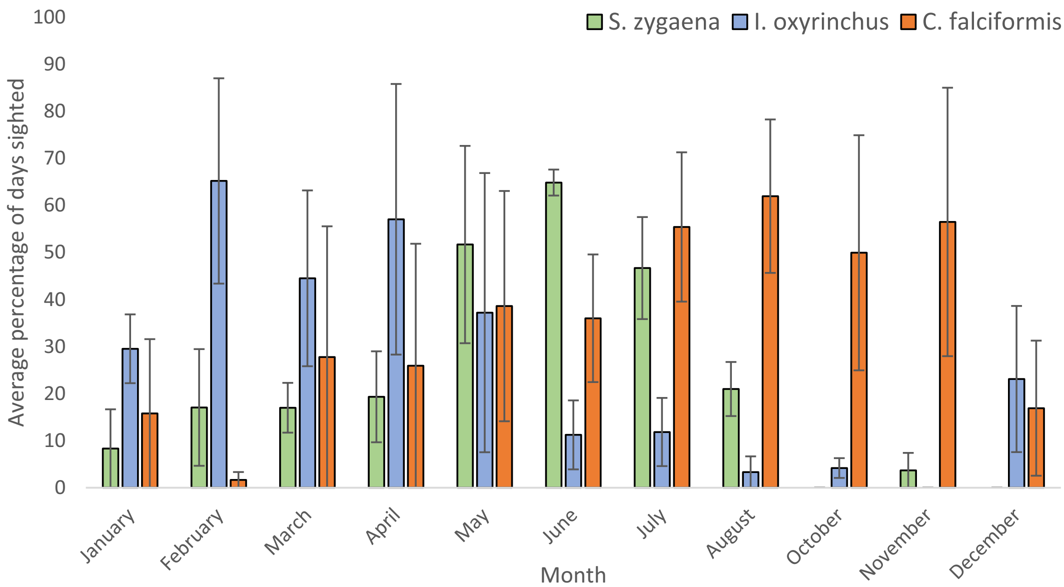


Fig. 6 Mean percentage of survey days with shark sightings per month in Los Cabos, Baja California Sur, Mexico. Error bars represent standard error of the variability across the three-year monitoring period between January 2016 and December 2018. The month of September was not sampled and is therefore not shown on graph

driven by the existence of secondary nurseries inhabited by older sharks. Tagging studies in an oceanic island in Portugal, described some juvenile smooth hammerheads remaining in the same area for up to 4 years (Afonso et al. 2022). *Sphyrna zygaena* can be considered a specialized predator (Castañeda-Suárez and Sandoval-Londoño 2004; Bolaño-Martínez 2009; Ochoa-Díaz 2009) while *I. oxyrinchus* and *C. falciformis* are more opportunistic feeders, explaining why *S. zygaena* could be resident and less migratory than the other two species. Studies in the Mexican and Ecuadorian Pacific concluded the jumbo squid *Dosidicus gigas* was one of the most consumed species by *S. zygaena* (Galván-Magaña et al. 2013) coinciding with Estupiñán-Montaño et al. (2019). In the Mexican Pacific, Ochoa-Díaz (2009) described adults sharks feeding mostly on *D. gigas* and juveniles consuming also the Pacific sardine (*Sardinops caeruleus*). The jumbo squid starts its migration into the Gulf of California in January reaching the most northerly position in April, when juveniles and subadults migrate along the coasts. During late August and September, the population moves south towards the mouth of the Gulf of California coinciding with a great increase of sardines in *D. gigas* diet (Ehrhardt 1983). This could mean available and reliable food resources for great part of the year for immature and mature *S. zygaena* in the Gulf of California. Additionally, *D. gigas* distribution in the area could be correlated with upwelling seasonality (Markaida et al. 2005). Upwelling areas are amongst the most productive in the world, and in the Gulf of California wind upwelling events are common in May, coinciding with our *S. zygaena* observations.

Sphyrna zygaena presence on our pelagic shark surveys using attraction methods could also be a result of an interspecific hierarchy with higher occurrences during months when *I. oxyrinchus* and *C. falciformis* occurrence is lowest. *Isurus oxyrinchus* are large (<4 m) dominant sharks and *C. falciformis* numbers on pelagic shark tours during June and July can reach over 50 individuals as they aggregate in large numbers near seamounts following breeding (Whitehead et al. 2022).

Carcharhinus falciformis are a warm water species and were most commonly present when temperatures were above 26 °C which also correlates with fisheries catches in the state of Baja California Sur (Bizzarro et al. 2007). SST seems to be a limiting factor for the species below 23 °C (Bonfil 2008). Our results show that *C. falciformis* were more commonly seen in August and November, coinciding with their way in and out of the Gulf of California for their summer breeding aggregations (Whitehead et al. 2022).

The sampling year had a significant relationship with presence of all three species. The location of the study area is greatly affected by El Niño–Southern Oscillation (ENSO). The La Niña phase occurs when trade winds across the Pacific Ocean strengthen, and warm water is displaced by cold nutrient-rich water from upwellings. In the El Niño phase, trade winds weaken and warm water remains close to the Pacific coastline of the Americas. *Isurus oxyrinchus* had a higher probability of being observed in the winters of 2016 and 2018, which were cooler La Niña years; this may be explained by its high metabolic rate (Sepulveda et al. 2007). In recent studies, shark species with high energetic requirements like scalloped hammerhead sharks (*S. lewini*) and tiger sharks (*G. cuvier*) also increased during La Niña conditions probably responding to shifting prey distribution (Osgood et al. 2021).

Carcharhinus falciformis had a higher probability in the summer months of 2016, this could be explained by one of the strongest ENSO events that occurred in 2015 and intensified during the winter between 2015 and 2016 (Klein 2015; Whitney 2015; Stramma et al. 2016). Moreover, the Northeast Pacific experienced anomalously warm conditions from 2013 to 2016 (Di Lorenzo and Mantua 2016; Peterson et al. 2017). "The Blob," a large patch of anomalously warm water was also located along the Pacific coast of the Baja California Peninsula until the end of 2015 (Cavole et al. 2016), which could explain *C. falciformis* presence, as this species is distributed throughout tropical pelagic waters and moves seasonally into warmer temperate waters (Last and Stevens 2009). Recent studies also found that elasmobranch species including blacktip sharks (*Carcharhinus limbatus*) and spotted eagle rays (*Aetobatus narinari*) (Osgood et al. 2021), whale sharks (Wilson et al. 2001; Sleeman et al. 2010), scalloped hammerhead sharks (White et al. 2015), and blue sharks (Adams et al. 2016) to be strongly influenced by El Niño events.

The probability of the occurrence of *Sphyrna zygaena* was highest in 2017, coinciding with a lower occurrence of *I. oxyrinchus* and *C. falciformis*. This could reflect avoidance of predation and competition from larger sharks (Bond et al. 2019), supporting that an interspecific hierarchy exists during the shark provision surveys, where smooth hammerheads only remain near the boat when there are no other sharks around the area. Particularly, small size smooth hammerheads sharks, as per field observation, are usually shy and precautious, not getting easily comfortable around attraction devices and snorkelers. Interspecific interaction and competition can be assumed when co-ocurring elasmobranchs (Heupel et al. 2019) occupy the same area, and high levels of competition may compel species to employ different behaviors to reduce niche overlap (White et al. 2004; Heithaus et al. 2013; O'Shea et al. 2013). Differences in the space use of some shark species may increase their survival by reducing competition and exposure to predators (Heupel et al. 2019). Thus, smooth hammerheads' highest observations in 2017 in our study area during shark provisioning surveys might be justified by the avoidance of interspecific competition and interactions with *I. oxyrinchus* and *C. falciformis*.

Wind speed affected all three species presence, with increasing wind speed increasing the probability of observing sharks. Sharks use their well-adapted sense of smell to detect chemical cues that allow them to detect prey from a distance (Bres 1993). Thus, higher wind speeds spread the "chum" further creating a larger slick lick used and therefore increasing the sampling area and the likeliness of a shark picking up the chemical cue. This was also seen in white sharks (*Carcharodon carcharias*) scavenging on whale carcasses in False Bay, South Africa, where at low wind conditions sharks were absent or low in abundance while at strong winds up to 28 sharks were present (Fallows et al. 2013).

Photoperiod only had a significant effect on the presence of *S. zygaena*; as days got longer, the probability of sightings increased. *S. zygaena* were often observed in the study area, even without attraction methods, very close to the surface, displaying knifing behavior (shark swims at the surface with dorsal fin fully out of the water) (Doyle et al. 2015). This species is known to prefer the upper 20 m of the water column especially in coastal areas (Pérez-Jiménez et al. 2005) and so this could be the reason photoperiod only had a significant effect on this species. Surface behavior can be due to thermal recovery after diving (Thums et al. 2013) and optimal foraging (Sims and Quayle 1998) with the main prey species of *S. zygaena* inhabiting the mesopelagic and demersal zone (Solís-Heredia 2022).

Moon illumination also had a significant effect on *S. zygaena* occurrence, the fuller the moon the higher the probability of observing them. Shark prey species may modify vertical distributions according to the lunar phase (Schabetsberger et al. 2013, 2015), suggesting that lunar phase (and illumination) influences the distribution of foraging sharks. In the marine environment, it is well known that moon phase can influence animal behavior in particular depth ranges, as seen in grey reef sharks (*Carcharhinus amblyrhynchos*) in Palau (Vianna et al. 2013). *Sphyrna zygaena* utilizes open oceanic waters as deep as 200 m but are known to feed from prey in the mesopelagic and demersal zone (Compagno 1984). The squid species *D. gigas* is one of their main food sources (Galván-Magaña et al. 2013; Solís-Heredia 2022), and it has been suggested that vertical migration of *D. gigas* is influenced by lunar phase (Gilly et al. 2006). In addition, several studies have described an increase of commercial loliginid squid catches during full moon (Young et al. 2006; Postuma and Gasalla 2010; Ulaş and Aydin 2011). Therefore, higher probability of observing *Sphyrna zygaena* during fuller moon might be explained by the positive relation between lunar phase and their prey species, resulting in sharks remaining near the surface for longer foraging periods.

Sampling site was a significant predictor of both *I. oxyrinchus* and *C. falciformis* presence. *Isurus oxyrinchus* sightings were more likely at sites A and C. Sites A and C are located near the southern wall of a submarine canyon in Cabo San Lucas Bay. The California current enters the Gulf of California winter in early spring, favouring the migration of *I. oxyrinchus* to this region (Mendizábal et al. 2000). The combination of this current and the bathymetric features favours upwelling events and prey availability and provides suitable habitat for pelagic sharks (Rogers et al. 2015). The probability of *C. falciformis* sightings was highest at sites B and D. *Carcharhinus falciformis* are highly migratory in the Eastern Tropical Pacific and migrate between the Revillagigedo Archipelago and the Gulf of California (Ketchum et al. 2020). They form summer aggregations at seamounts off San José del Cabo, one of which is situated close to site D which is also the closest site to shoreline. Site B is furthest from the coastline and is a shallow bank which could function as stepping-stone for this species along their migration route to the seamounts closer to the shore.

Sampling at sites was not even (Supplementary Information Appendix S1) as we relied on the tourism operator which meant that some sites were more frequently visited than others depending time of year, weather conditions and from previous successful locations of seeing sharks as the main priority was to provide paying guests with an encounter. For this reason, the results regarding probability at sites should be interpreted cautiously and this was the main limitation of the study. For example, site B and site E were never surveyed in April as this is a generally the month with most wind and these sites are harder to access, located the furthest away from the marina. Some sites were not visited throughout all of 2016 as they had not yet been discovered as promising sites for successful sightings.

Another limitation was that the boat often drifted from the original location, due to wind and current, with direction and intensity varying on each sample day and so the location of site samples is only representing the starting point of the chumming activity. The fact that attraction methods were used, may also bias distribution at more localized scale and may cause unusual interspecific interactions (e.g., cold-water shark species like shortfin mako sharks spotted at the same time and site than a semi-tropical species such as the silky sharks). Although shark provisioning arises some concerns regarding shark conditioning, several studies suggest attraction methods do not have long-time impacts on large-scale migrating and opportunistic foraging species (Hammerschlag et al. 2012; Becerril-García et al. 2020), characteristics attributable to the pelagic shark species of the present study. Stable isotopes analysis has been used to evaluate the effects of feeding bull sharks (*Carcharhinus leucas*) in Fiji and concluded that provisioning levels did not have long-time impacts on overall diet or behavior (Brunnschweiler et al. 2014).

The use of citizen science was integral for this study, as boat hire and gasoline are costly for researchers. The combination of tourism and science benefits both the tour company in which guests are informed about the study species and the researchers who use the platform to collect data, especially the long-term monitoring of species where there is little information available. Elasmobranchs are also quite large and conspicuous; therefore, it is feasible to train guides and tourists in basic data collection such as presence and relative abundance based on daily diving activities (Ward-Paige and Lotze 2011). Citizen science data on shark distribution and abundance has already been successfully applied in several locations (Bargensi et al. 2020) and proved to be a useful method to gather baseline information on shark and ray species in a data-poor region in the Mexican Caribbean (Blanco-Parra et al. 2022). Ward-Paige and Lotze (2011) concluded that, if used appropriately, citizen-collected data may be useful to describe elasmobranchs populations trends. In Palau, Vianna et al. (2014) validated shark abundance data collected by professional dive guides and their participation in shark populations monitoring programs.

The month of September was not sampled due to the cessation of the tour operator activity as cyclones and tropical storms hit Los Cabos coast during these months. Despite these limitations, we agree with Gallagher et al. (2015) that well managed shark tourism can prove to be a positive value for the conservation of several shark species. Several new tour operators have been established operating out of Cabo San Lucas in the last 3 years, thus extending this monitoring program to all operators should be established.

After 2018 to present date, there have been a high number of blue shark (*Prionace glauca*) sightings on pelagic shark tours during winter months (January–April) (unpublished data). The continuation of the pelagic monitoring program will give a better insight to the *P. glauca* population in the area.

The area of Los Cabos is a growing touristic destination where hotels and recreational activities happen and affect directly the marine ecosystem of the bay (e.g., several cruise ships are anchored and disembark in Cabo San Lucas marina). Some studies have reported declines in survival rates and changes in habitat structure for lemon sharks (*Negaprion brevirostris*) correlated with the development of large resorts in The Bahamas (Jennings et al. 2008). It is important to understand how species respond to changes in environmental effects due to the increase of human-related impacts on marine ecosystems (Schlaff et al. 2014). Moreover, in places like Cabo San Lucas, where large migratory sharks are popular, intensification of climate change and ENSO events may impact both shark tourism activities and citizen science by shifting shark distribution and migration patterns (Osgood et al. 2021). Thus, our long-term monitoring of these elusive vulnerable shark species will be continued in the area not only to assess environmental changes but also to evaluate the carrying capacity of pelagic shark tourism in Los Cabos.

Acknowledgements The authors thank shark tour guides and staff of Cabo Shark Dive for their contributions in the data collection. We also thank clients participating in shark tours for their support in logistics and data collection. We also acknowledge Fundación México Azul's founder Guillermo Mendoza and advisory board, and the organization's donors for their long-term support; without their monthly donations, this would have not been possible.

Author contribution Clara E. Calatayud Pavía conceived and designed the study, provided the survey protocol, trained the crew for data collection, collected data, provided funding and resources from Fundación México Azul, and prepared the manuscript. Francisco Mascareño Suárez helped with the survey protocol, collected data, standardized the database, and gave advice for the manuscript. Jacopo Brunetti and Miguel Eliceche provided resources from Cabo Shark Dive, provided shark attraction methodology, collected data, and gave support with local knowledge. Kathryn A. Ayres performed the GAM analysis, provided papers for the discussion, gave support and critical advice, and reviewed the manuscript.

Funding This work was supported by Fundación México Azul main donors: Mª Fernanda Carrera Compeán, Mark K. Gomley, Alfredo Suárez González, Dominik Joseph Bacher, Rodella Véjar Valenzuela, Productora Ganadera Coralia, and all our recurring donors.

Data availability The datasets generated during and analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Ethics approval This study did not require ethics approval.

Conflict of interest The authors declare no competing interests.

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