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Predicting whaler shark presence and interactions with humans in southern Queensland, Australia

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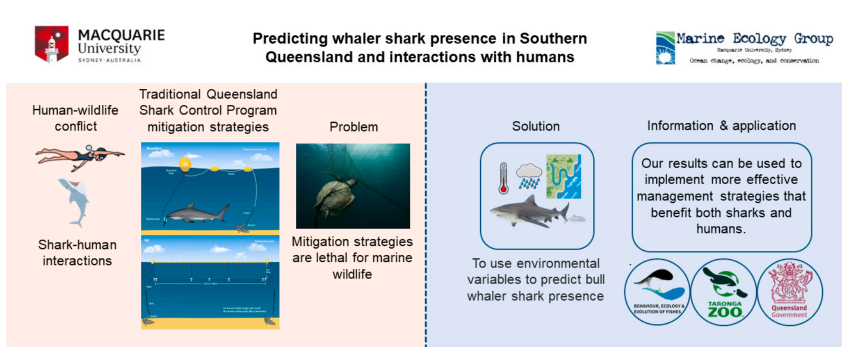
HIGHLIGHTS

- The number of shark-human interactions has been increasing over time.
- Long-term catch data analysed as a proxy for whaler shark distribution and abundance.
- Environmental variables predict bull whaler shark catches in Southeast Queensland.
- Results aid effective management strategies to reduce shark-human interactions.

GRAPHICAL ABSTRACT



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ABSTRACT

The Queensland Shark Control Program (QSCP) started in 1962 to reduce the number of shark-human incidents by deploying nets and drumlines across the most popular beaches. The program targets large shark species (white, tiger and bull sharks) that are potentially hazardous to bathers. However, this strategy is lethal for other sharks and marine wildlife, including threatened and endangered species. Thus, finding non-lethal strategies is a priority. To better manage shark-human interactions, establishing a better understanding of the factors that drive shark movement is key. Here we used sea surface temperature (SST), rainfall and distance to rivers as environmental variables to predict the presence of whaler sharks in southern Queensland based on 26 years of catch data from the QSCP. We found that SST is positively corelated to sharks caught by drumlines, while rainfall was associated with the number of sharks captured in shark nets. In addition, more sharks were captured by nets and drumlines further away from rivers, and nets captured roughly 10 times more sharks than drumlines over the period of study. In contrast to tiger sharks, the catch data indicate the number of whalers has not declined over the past 26 years. Our findings suggest that environmental variables can be used to predict the movement of large sharks and by incorporating this knowledge into management plans and public education programs, may ultimately reduce shark-human incidents.

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1. Introduction

Sharks play important roles in marine ecosystems (Tucker et al., 2022). They are responsible for the top-down control of prey species and may induce trophic cascades (Desbiens et al., 2021; M. Heupel et al., 2014; Pinnegar et al., 2000). However, sharks occasionally bite humans and consequently are part of a growing conflict between human and wildlife around the world (Niella et al., 2021). Worldwide, the number of shark bites has grown considerably over the last three decades (Curtis et al., 2012; West, 2011). Sharks are also among the most threatened taxa in the world (Dulvy et al., 2021) and this conflict complicates conservation efforts (Simpfendorfer et al., 2011).

Australia is among the nations with the highest per capita rates of shark-human incidents in the world (McPhee, 2014) and, according to the Australian Shark Incident Database (2022), most of these incidents are linked to only a few shark species: white sharks (*Carcharhinus carcharias*), tiger sharks (*Galeocerdo cuvier*), wobbegong sharks (*Orectolobus maculatus*), and bull sharks (*Carcharhinus leucas*). An observed increase in the number of incidents are mostly attributed to human population growth, urbanisation, human population dynamics (Baldridge, 1974), a rise in aquatic recreational activities (Baldridge, 1974; West, 2011) including surfing and SCUBA diving (West, 2011), climate induced changes, changes in shark and prey distribution (Chapman and McPhee, 2016), and a heightened societal awareness about such incidents due to an increase in the capacity for an almost instantaneous public reporting (Tucker et al., 2022). Nonetheless, these aspects alone are not enough to explain more than doubling of incidents per capita since the 1990s (Curtis et al., 2012).

Species of the family Carcharhinidae are commonly referred to as whalers (Last and Stevens, 2009). Within this family, *Carcharhinus* Blainville, 1816 is the most diverse genus, hosting 35 out of 57 species (Collareta et al., 2022; White et al., 2019). Among these 35 species, at least 21 can be found in Australia (Bray, 2023). Bull sharks (*Carcharhinus leucas* Valenciennes, 1839) occur globally in tropical to subtropical waters, from rivers and estuaries to the open ocean (Compagno, 1984; Last and Stevens, 2009), and are reasonably common along the east coast of Australia (Bray and Gomon, 2020). They are one of the few truly euryhaline elasmobranchs and readily migrate between freshwater and saltwater environments (Jensen, 1976; Montoya and Thorson, 1982). The life cycle of bull sharks is deeply connected to freshwater habitats (Werry et al., 2018). Females give birth in lower reaches of estuaries (Jensen, 1976), and both rivers and estuaries are important juvenile nursery areas (Werry, 2010). Juveniles can inhabit these areas for up to five years before moving out to the sea (Werry, 2010). At maturity, bull sharks reach about 220 cm in length and are most often found in the nearshore environment (Cliff and Dudley, 1991; Haig et al., 2018; M. Heupel and Simpfendorfer, 2008). Bull sharks are opportunistic foragers, and this fact combined with their habitat preferences (Niella et al., 2022) increases the likelihood of coming into conflict with humans.

Understanding how environmental variables influence bull shark movement is key to developing and implementing effective management of shark-human interactions (Smoothey et al., 2016). Factors that affect shark movement include environmental changes (Reid et al., 2011), habitat requirements (Barker and Williamson, 2010), predation risk (Skov et al., 2011), food availability (Espinoza et al., 2021), behaviour (Barker et al., 2011), and reproduction (Rustadbakken et al., 2004). It is also established that movements of bull sharks can be affected by different environmental variables such as estuarine habitat availability (Haig et al., 2018), rainfall (Werry et al., 2018), and water temperature (Lee et al., 2019; Smoothey et al., 2019). In Florida, Heupel et al. (2010) found that bull sharks present consistent patterns of long-term residence in the Caloosahatchee River within and across years. In Australia, various studies suggest that high rainfall increases primary production and prey abundance upon which bull sharks feed (Ryan et al., 2019; Werry et al., 2018). On the east coast of Southern Africa, bull sharks migrate south into temperate latitudes in summer before migrating north to warmer latitudes during winter and spring (Daly et al., 2014).

In Southeast Queensland, the Gold Coast is a prime example of an area situated on a naturally long coastline that is connected to various types of freshwater habitats such as river mouths, estuaries, and canals (Fig. 1). However, to facilitate population growth, developers have extended the natural waterfront land to create tidal canals for boating marinas in the new residential regions (Morton, 1992; Regional Population, 2023), which increases opportunity for recreational water activities. These canals extend the potential habitat area for bull sharks and thereby enhance opportunities for shark-human interactions.

The current strategy to reduce shark bites in Southeast Queensland is the Queensland Shark Control Program (QSCP) (Shark Control in Queensland, 2022). The program has deployed baited drumlines and large mesh nets along popular beaches to catch sharks larger than 1.5 m length, which are considered as potentially hazardous to humans (Paterson, 1990; Sumpton et al., 2011). In 2020 the QSCP began trials of drones and in 2021 trials of catch alert drumlines to review and adjust the program to match emerging science and community expectations (Shark Control in Queensland, 2022). These trials were accompanied with public environmental education in locations where new equipment were being tested (Shark Control in Queensland, 2022). However, the major focus of the program remains on lethal methods (baited drumlines and nets). Bull sharks, tiger sharks and white sharks are the target species by the QSCP (Sumpton et al., 2011) and all three species are listed for protection (The IUCN Red List of Threatened Species, 2023). White sharks are also listed as vulnerable under the Australian Environment Protection and Biodiversity Act 1999 (EPBC Act) (Species Profile and Threats Database, 2023). While the program is considered effective in decreasing the number of shark-human interactions (Sumpton et al., 2011; Werry, 2010), there is little knowledge on how the QSCP is affecting bull shark and other whaler shark populations in Queensland (Werry, 2010). Nor do we know how environmental variables drive the movement of bull sharks and other types of whalers in this area.

Here we make use of a long-term data set from the QSCP to monitor whaler shark population trends and shark movements in Southeast Queensland. Through the outcomes of this study, we hoped to contribute to a more effective management strategy that benefits sharks, people and the marine ecosystem more broadly. The aims of this study were to (a) explore whether environmental variables such as sea surface temperature (SST) and rainfall are connected with the number of bull sharks and other types of whalers caught by the QSCP, (b) determine if the number of bull sharks and other whalers captured by the QSCP has changed over the past 26 years, (c) determine if more bull sharks and other types of whalers are caught and/or incidents happen close to freshwater environments, and (d) assess if there is a difference in the number of sharks caught by the two gear types (drumlines versus nets).

2. Methods

2.1. Area of study and time period

This study was conducted using a compilation of data sets collected between January 1996 and May 2022 from four regions in Southern Queensland (24°S to 28°S latitude, and 152°E to 153°E longitude): Gold Coast (35 drumlines & 11 nets), Sunshine Coast (78 drumlines & 11 nets), Rainbow beach (12 drumlines & 3 nets) and Bundaberg (20 drumlines & 0 nets) (Fig. 2). These regions were chosen because the numbers and locations of deployed gear remained unchanged during the period of study. Stradbroke Island was excluded from this study because gear deployment in this region has varied over time.

2.2. Data collection

To achieve the aims of this study, it was necessary to acquire, manage

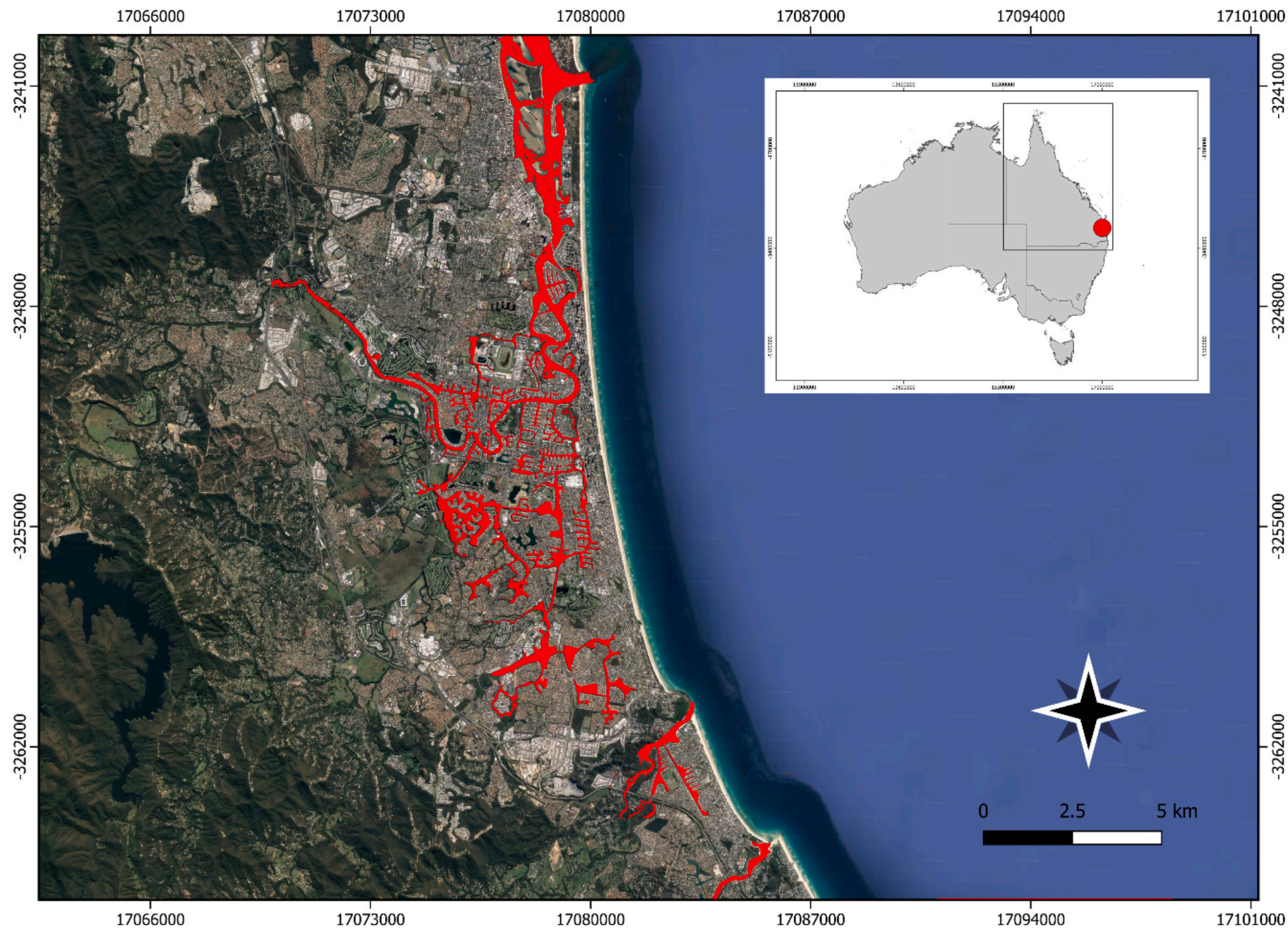

Fig. 1. Map of the Gold Coast, Queensland, Australia. The image shows part of the Gold Coast's coastline to exemplify that this area is surrounded by several canals, lakes, and river mouths. Freshwater areas are highlighted in red.

and build a compilation of data sets. All data were managed using R version 4.2.2 and Excel.

To access what was caught by the Queensland Shark Control Program (QSCP) over time and use this as a proxy to investigate spatial occurrence of whaler sharks in Southeast Queensland, we obtained the catch data from Queensland Department of Agriculture and Fisheries. Due to incomplete information and inaccuracies in this data set, data fields such as 'Area Name' and 'Beach Name' were used to locate gear deployment instead of the reported latitude and longitude in the data set.

The accuracy of shark identification has varied over the time in the QSCP. In 1992, a training program was implemented to train QSCP fishing contractors in identifying whaler sharks (Carcharhiniformes, Carcharhinidae). Data prior to that are largely unreliable for this group. However, as this study compares the results from the catch data with the Australian Shark Incident Database, and misidentification of bull sharks with other types of whalers is still common, we restricted the catch data to only show information related to the common names "Bull Whaler" and "Whaler" from January 1996 to May 2022. The information related to "Bull Whaler" refers to bull sharks. However, information related to "Whaler" does not detail species information. Here we assume all whalers captured were bull sharks. Other species of whaler commonly found in Southeast Queensland include bignose shark (*Carcharhinus altimus*), bronze whaler (*Carcharhinus brachyurus*) and dusky whaler (*Carcharhinus obscurus*) (Bray and Gomon, 2020). In total, 574 "Bull Whaler" and 39 "Whaler" sharks were caught in Southeast Queensland along the 26 years of study. All information related to both common names were merged, and they are referred as bull whalers.

The catch data is considered a 'presence-only' data set because it exclusively records information about animals when they were caught. To obtain information about when sharks were not captured, we acquired information about when gear were checked by contractors, but no bull whalers were captured (absence data). The presence-absence data were merged with the catch data then split based on gear type (drumlines and nets).

To determine if environmental conditions that lead to catches by the QSCP might be linked to shark-human incidents, we acquired the Australian Shark Incident Database (ASID) from the Taronga Conservation Society Australia. Due to the nature of a shark-human incident, identification of the shark responsible can be challenging and frequently the identification of the species responsible in the ASID is deduced or generic (Ryan et al., 2019; West, 2011). For this reason, the information related to the shark common names "Bull shark" and "Whaler shark" were both included and merged in this data set. Both provoked and unprovoked incidents were analysed.

To access the location of each gear deployed by the QSCP in Southeast Queensland (with the exception of Stradbroke Island), we acquired the gear location data set from the QSCP. The data included the regions (Gold Coast, Sunshine Coast, Rainbow beach and Bundaberg) and beaches where gear were placed, and the latitude and longitude of each gear when deployed. While drumlines are present in all four regions included in the present study, nets were deployed in only three regions: Gold

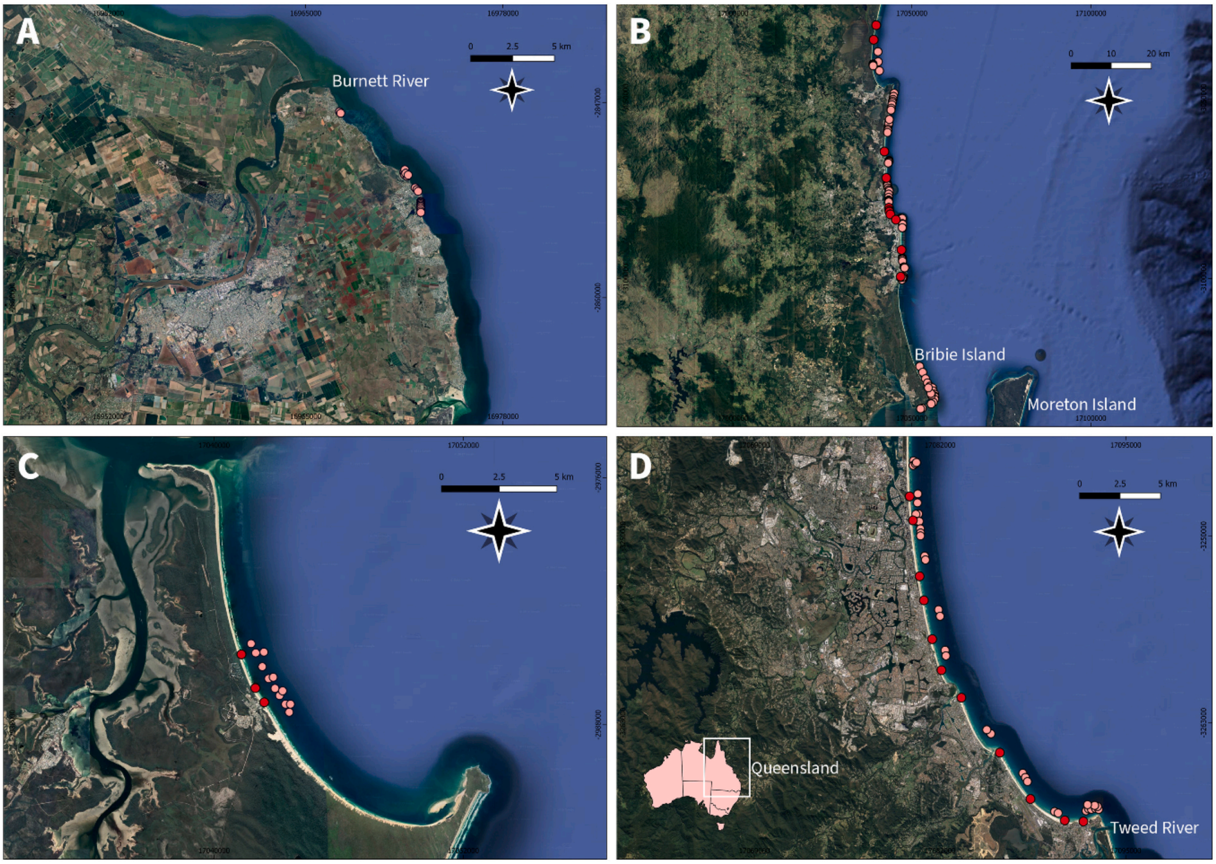

Fig. 2. Regions and gear types. The four regions assessed are: (A) Bundaberg, (B) Sunshine Coast, (C) Rainbow beach, and (D) Gold Coast. All sites are located in Southeast Queensland, Australia. Pink circles represent drumlines and red circles illustrate nets deployed.

Coast, Sunshine Coast and Rainbow beach.

Around 80 % of the location (latitude and longitude) of the incidents from the ASID and around 50 % of the coordinates acquired by the gear location data were not accurate, and both data sets needed cleaning. Some location mistakes were obvious and could be corrected easily, such as shark-human interactions and gear location giving coordinates on land. Other location data were less easily assessed for mistakes. To overcome these errors, the region and beach/river locations were used as a reference to allocate these coordinates in the most likely spots. Google maps and OSM Standard layer in QGIS Desktop 3.26.2 were used to adjust any suspect incident coordinates.

2.3. Environmental variables

Daily values of sea surface temperature (SST) with 0.02° spatial resolution were downloaded from the Australian Ocean Data Network (AODN) portal (aodn.org.au). The nearest quadrats of data available corresponding to each region were used to calculate average SST by month from January 1996 to December 2021.

Daily rainfall was obtained from the Bureau of Meteorology (BoM). Since most weather stations presented periods of missing information for rainfall, we used the closest weather stations that contained the most information available from 1996 to 2021. All rainfall information was recorded in mm. Average rainfall by month was calculated from January 1996 to December 2021.

2.4. Data analyses

To predict the presence of bull whalers in Southeast Queensland by testing the effects of environmental variables in the number of sharks caught by the QSCP, the catch data (counts of numbers of sharks captured per month for each region from 1996 to 2021) were fit into generalised linear models (GLMs). The dependent variable (catch data) was assumed to follow a negative binomial distribution with a log link. Negative binomial GLM analyses were conducted using the function glm.nb() in the MASS package (Venables and Ripley, 2002). Candidate predictor variables included the quantitative variables rainfall, SST and year, and the categorical variable region. An offset term, log(effort), where effort refers to the number of gear in each region, was included in all fitted models to account for the difference in the sampling effort among regions. Since the dependent variable is modelled using a log-link function, the inclusion of this offset term mathematically serves to re-express the dependent variable in units of catch per unit effort (CPUE). Predictors were selected among the candidates by first fitting multiple models using the function dredge() in the R package MuMIn (Bartón, 2023). Fitted models were then compared based on the Akaike information criterion (AIC). Gear type was included in the initial GLM analysis as a categorical variable, but the drumline and net data were fitted separately for subsequent analyses because catch data exhibited distinct functional relationships with predictors for the two gear types, consistent with previous findings (Werry et al., 2018). Model assumptions were evaluated using the R package DHARMa (Hartig, 2017) and showed no evidence of overdispersion. All analyses were conducted using R version 4.2.2.

Bull sharks are intimately associated with rivers and estuaries (Devloo-Delva et al., 2023; M. R. Heupel et al., 2010). For this reason, we predicted that more sharks would be captured by gear closer to rivers mouths. To test this hypothesis, we analysed the catch data at a finer spatial scale i.e. that of beach scale rather than region. The dependent variable in this analysis was the total number of bull whalers caught at each beach from January 1996 to May 2022. The independent variable was the distance of each gear to the closest freshwater source for every beach. As above, GLMs for the catch data were assumed to follow negative binomial distributions. Offset term, log(effort), was included to model the dependent variable in terms of CPUE for both gear types separately.

To determine if drumlines or nets were more effective at catching whalers, a summary of all bull whaler sharks caught by drumlines and nets for each region where both gear types were deployed was calculated by year from January 1996 to December 2021. A GLM with a negative binomial distribution was fit into the catch data to test if there was a significant difference in the total number of sharks caught by drumlines versus nets. Region and gear type were included as independent variables, and an offset term with the logarithm of the catch effort, log (effort), was included in the model to re-express the dependent variable as CPUE.

Since only a small number of incidents involving bull whaler sharks occurred in Southeast Queensland from 1996 to 2021, it was not possible to run a statistical analysis on the ASID data set. To investigate if there is an influence of SST, rainfall and distance to rivers on shark-human incidents, we conducted a descriptive analysis of the data.

3. Results

3.1. Generalised linear model (GLM) for drumlines

The best model for the drumline data was (Table S1):

$$\begin{aligned}\text{TotalSharksCaught} \sim{} & \text{MeanRainfall} + \text{Region} + \text{MeanSST} + \text{Year} \\ & + \text{MeanRainfall:Region} + \text{Year:Region} \\ & + \text{offset}(\textit{log}(\text{effort}))\end{aligned}$$

The catch per unit effort (CPUE) of sharks caught by drumlines varied significantly among regions ($\chi^2 = 12.94$, DF = 3, P = 0.004) and with SST ($\chi^2 = 18.50$, DF = 1, P < 0.001) (Fig. 3). The model suggested that for every 1 °C increase in temperature, there was 13 % increase in the chance of catching a bull whaler shark (95 % CI = 6 % to 19 %). We also found significant interactions between rainfall and region ($\chi^2 = 9.55$, DF = 3, $P = 0.02$) (Fig. S1), and year and region ($\chi^2 = 13.07$, DF = 3, P = 0.004) (Fig. S2), suggesting the manner in which shark abundance varied with rainfall differed between regions as did the catch over the study period.

3.2. Generalised linear model (GLM) for nets

The best model for the net data was (Table S1):

$$\begin{aligned}\text{TotalSharksCaught} \sim{} & \text{MeanRainfall} + \text{Region} + \text{Year} + \text{Year:Region} \\ & + \text{offset}(\textit{log}(\text{effort}))\end{aligned}$$

The CPUE of sharks caught by nets varied significantly with rainfall ($\chi^2 = 42.31$, DF = 1, $P < 0.0001$) and region ($\chi^2 = 7.08$, DF = 2, P = 0.02) (Fig. 4). The model suggested that for every 1 mm increase in rainfall there was 11 % higher chance of catching bull whalers (95 % CI = 7 % to 14 %). There was also a significant interaction between year and region ($\chi^2 = 7.19$, DF = 2, P = 0.02) (Fig. S3), suggesting the manner in which catch varied over time differed between regions.

3.3. Distance to rivers

Contrary to our expectations, more sharks were caught by drumlines further away from rivers or freshwater sources ($\chi^2 = 5.54$, DF = 1, $P = 0.01$) (Fig. 5A). Similarly, the number of sharks captured by nets showed a significant relationship with distance to a river or freshwater source ($\chi^2 = 8.55$, DF = 1, $P = 0.003$) (Fig. 5B).

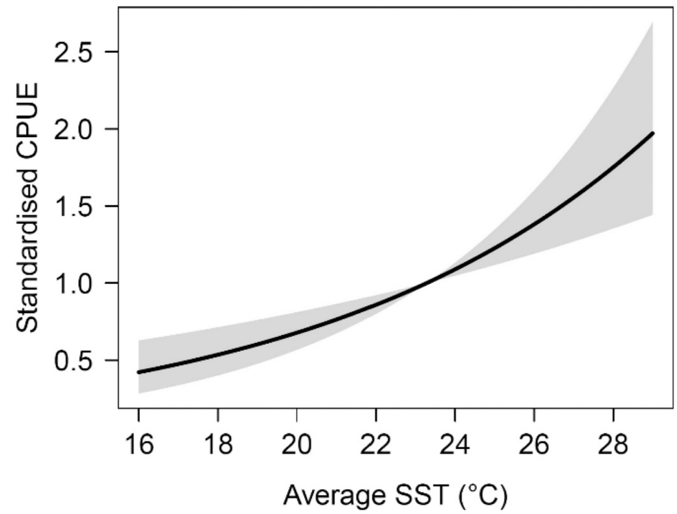

Fig. 3. The effects of sea surface temperature (SST) in the standardised catch per unit effort (CPUE) of sharks caught by drumlines. Standardised CPUE values were calculated as the predicted values of CPUE at a given value of SST divided by the predicted value of CPUE at the average value in the data set, 23.3 °C. The grey area corresponds to the 95 % confidence interval.

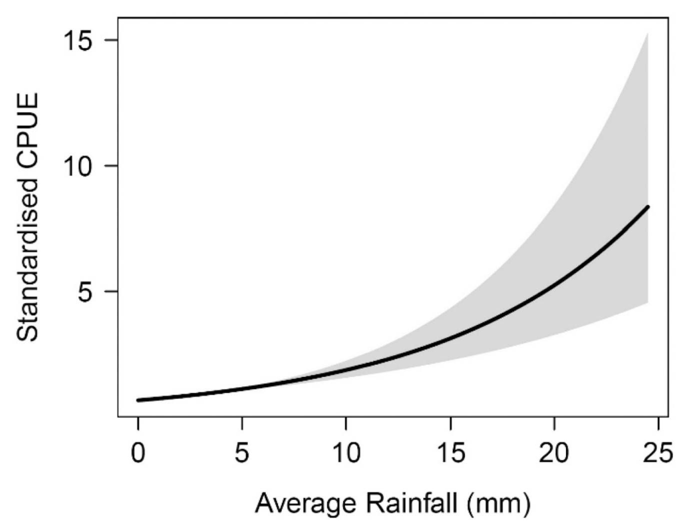

Fig. 4. The influence of rainfall in the standardised catch per unit effort (CPUE) for sharks caught by nets. Standardised CPUE values were calculated as the predicted values of CPUE at a given amount of rainfall divided by the predicted value of CPUE at the average value in the data set, 3.9 mm. The grey area corresponds to the 95 % confidence interval.

3.4. Gear type

Gear type and region had a significant effect in the catch per unit effort (CPUE) of sharks caught by year (gear type $\chi^2 = 267.43$, DF = 1, $P < 0.001$; region type $\chi^2 = 46.49$, DF = 2, P < 0.001). The model predicted that a net catches approximately 10 times more sharks than a drumline (95 % CI = 708 % to 1330 %). When expressing the raw shark counts used to fit this model as overall mean CPUE values, the average number of sharks caught per gear is clearly substantially higher for nets than drumlines (Fig. 6). There was no significant interaction between region and gear type ($\chi^2 = 4.60$, DF = 2, $P = 0.1$).

3.5. Incidents

There was a total of 15 shark-human incidents involving bull whalers

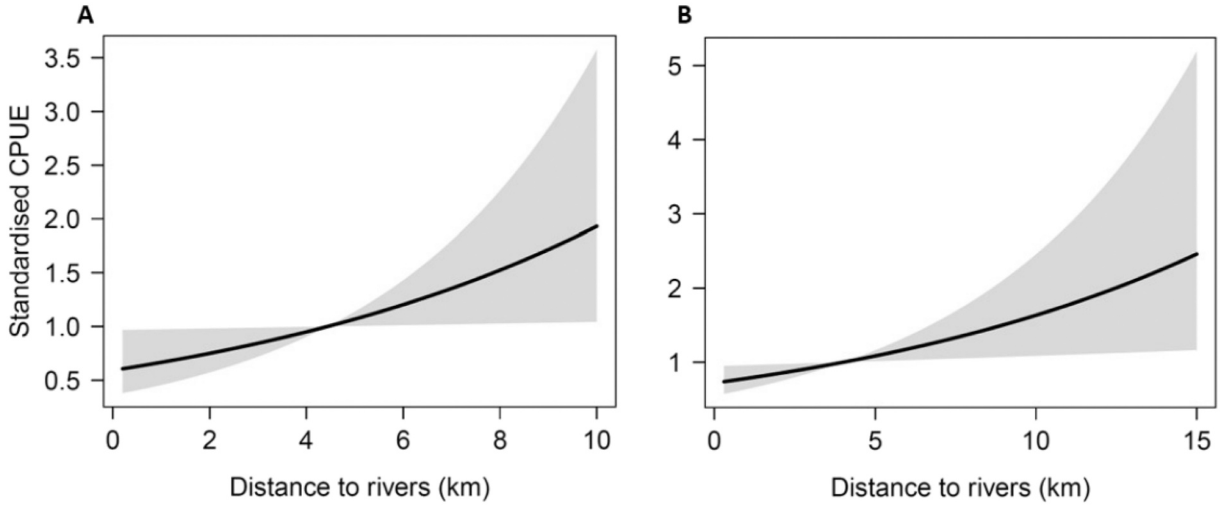

Fig. 5. Standardised catch per unit effort (CPUE) of bull whalers caught by (A) drumlines and (B) nets and the distance sharks were captured from the closest freshwater/estuarine habitat. Standardised CPUE values were calculated as the predicted values of CPUE at some arbitrary distance from the river divided by the predicted value of CPUE at the average distance in the data sets (4.5 km and 4.0 km for drumlines and nets, respectively). The grey area corresponds to the 95 % confidence interval. The broad confidence intervals at long distances reflect both substantial variation in CPUE among beaches as well as the relative paucity of beaches far from rivers.

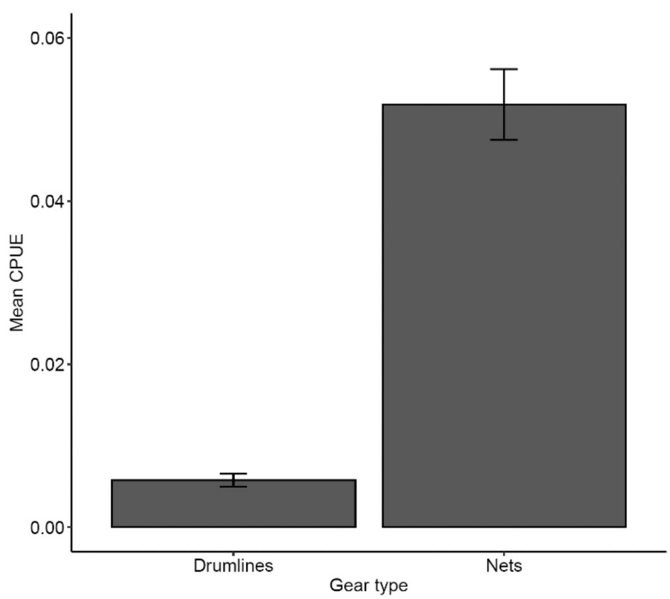

Fig. 6. Average catch per unit effort (CPUE) of sharks caught by drumlines versus nets in Southeast Queensland from 1996 to 2021. The graph illustrates that each net catches approximately 10 times more sharks than each drumline ($P < 0.001$). Error bars show standard error.

in Southeast Queensland from 1996 to 2021. Eleven out of 15 incidents happened when water temperature was between 26 and 28 °C (Table 1).

When looking at the effect of rainfall on shark-human interactions, 10 out of 15 incidents occurred on days when there was 0 mm rainfall (Table 1). Despite that, 14 out of 15 incidents occurred between 1 and 7 days after rainfall (Table 1).

Nine out of 15 incidents occurred in freshwater (Table 1). Even though the number of incidents was low, it suggests that the probability of shark-human interactions occurring in freshwater habitats may be higher than in other environments.

Table 1
Shark-human incidents are events where a shark bites a person (Australian Shark Incident Database, 2022). The details of all 15 incidents involving bull whaler sharks in Southeast Queensland from 1996 to 2021 can be found bellow, including incident date, incident location, sea surface temperature (SST), rainfall on the day of the incident, previous rainfall (for the 7 days before the incident, excluding the previous 24 h), and distance from the incident to the nearest freshwater source or estuarine environment.

Incident date	Incident location	SST (°C)	Rainfall (mm)	Previous rainfall (mm)	Distance to rivers (km)
22-Jan-96	Coomera river	26	0.00	3.40	0.0
20-Jan-97	Rainbow bay	25	0.80	1.80	2.8
28-Feb-97	Nerang river	27	7.60	64.60	0.0
16-Feb-02	Noosa	27	0.60	0.20	0.8
16-Dec-02	Miami lake canals	26	0.00	57.20	0.0
08-Feb-03	Burleigh lake canals	27	0.00	181.20	0.0
26-Feb-05	Brisbane river	27	0.00	0.00	0.0
12-Mar-07	Moore Park beach	29	0.00	0.80	9.7
15-Dec-07	Broadwater	27	0.00	19.00	0.0
06-Feb-12	Wurtulla beach	28	0.00	6.80	1.9
20-Mar-12	Nobbys beach	26	21.60	39.40	4.9
25-May-14	Chevron island	23	0.00	4.40	0.0
30-Jan-15	Nerang river	27	0.00	316.60	0.0
09-Jul-19	Bells creek	18	0.00	17.80	0.0
04-Jul-20	K'Gari	19	0.10	0.80	43.2

4. Discussion

The number of sharks captured by the QSCP from January 1996 to May 2022 was used to gain an understanding of environmental drivers of bull whaler shark movement of the coast of Southeast Queensland. We found that the number of sharks caught by drumlines increased with SST while rainfall had a variable impact between the four regions. The number of sharks captured by nets only increased with rainfall on the number of sharks caught. The number of sharks caught over the 26 years study period also varied between regions for both gear types. Contrary to expectations, more sharks were captured by drumlines and nets further away from rivers and nets captured roughly 10 times more sharks than drumlines over the period of study. Most shark-human incidents occurred in freshwater/estuarine environments when water temperature was between 26 and 28 °C and when rainfall had occurred in the week prior to the incident. Collectively, these data suggest that environmental variables are good predictors of both shark presence and shark-human incidents and should be incorporated into management actions.

Different studies have supported the hypothesis that short-term heavy rainfall (Werry et al., 2018) and high SST (Lee et al., 2019; Niella et al., 2020; Smoothey et al., 2019) are strongly associated with the presence of bull sharks. According to Werry et al. (2018), an increase in the CPUE of bull sharks in Queensland, Australia was observed in beach locations with higher SST. This result aligns with Smoothey et al. (2016), who also found that water temperature increases bull shark catches when SST is above 23.2 °C in Sydney Harbour. Similarly, Niella et al. (2020) found that bull shark presence increased in New South Wales when SST exceeds 22 °C. We found that SST had a positive effect on the CPUE of sharks caught by drumlines in Southeast Queensland. Therefore, the present research supports the theory that SST is an important predictor of bull shark presence. These results can impact the conservation of the species and contribute with shark-human interactions management as water activities have an exponential increase during warmer months (Lee et al., 2019).

Werry et al. (2018) found that bull shark catches in Queensland increased from 1 to 8 days after ≥100 mm rainfall. Niella et al. (2020) found similar effects in New South Wales. This study found a positive and significant effect of rainfall in the CPUE of sharks caught by nets, confirming that rainfall is also a good predictor of bull shark occurrence in Southeast Queensland. The most likely explanation for this pattern is prey availability. Due to rainfall, local in-water fronts can be formed by the interaction between murky freshwater/estuarine plumes with seawater, facilitating plankton blooms (Werry et al., 2018). These blooms provide sustenance for baitfish populations, consequently supporting prey availability for bull sharks (Meynecke et al., 2006; Werry et al., 2018). Rainfall also flushes prey such as mullet (*Mugil cephalus*) out of river systems, which can trigger the presence of bull sharks in river mouths (Niella et al., 2020; Werry et al., 2011, 2018).

A variety of studies have included different sites in their area of study to better understand bull shark movement and occurrence (Haig et al., 2018; Ryan et al., 2019; Smoothey et al., 2016; Werry et al., 2018). The current study included region in most of our models to better understand the differences in capture rates across all sites. Our results indicated that region had a significant effect in the number of bull whalers caught by drumlines, nets and when comparing both gear types. Additionally, significant interactions between rainfall and region, and year and region were detected for the drumlines catch data. A significant interaction between year and region was also found for the number of bull whalers caught by nets. It is apparent that there is considerable variation in catches in each region which are likely due to idiosyncratic differences in habitat and weather patterns over space and time. Further analysis of differences between all four regions in southeast Queensland might provide a deeper understanding of bull shark movement and behaviour in this area.

Given the dramatic decline in tiger shark numbers in Queensland from 1962 to 2017 (Roff et al., 2018), we predicted that a similar decline might also be present in bull whalers. In 2017, bull sharks were classified as 'Near Threatened' by IUCN (Haig et al., 2018). Presently, they are classified as 'Vulnerable' (The IUCN Red List of Threatened Species, 2023), which suggests that the population of bull sharks is decreasing globally. However, our long-term data set from Southeast Queensland indicated that bull whalers showed no sign of population decline in the years assessed. The fact we found significant interactions between year and region for both gear types suggested that temporal trends vary between regions, but there is no indication of general population decline.

The life cycle of bull sharks is deeply connected to freshwater/estuarine habitats (Heupel and Simpfendorfer, 2011; Werry et al., 2018). Gold Coast canals, the Nerang River and their associated creeks alongside with beaches supply a diversity of habitats often used by bull sharks (Werry et al., 2012). Interestingly, our data indicated that most bull whalers caught by drumlines and nets were further way from a river or freshwater environment. This may be related to an overlap between gear locations and bull shark habitat. The majority of the gear assessed by this study were deployed in marine coastal areas rather than river mouths, which is aligned with the fact adult bull sharks predominantly inhabit marine nearshore areas (Cliff and Dudley, 1991; Haig et al., 2018; M. Heupel and Simpfendorfer, 2008; Werry, 2010). A more detailed analysis of the data set that includes sex and size might be informative and should be a priority for future studies.

As both gear types present different methods for catching sharks, we expected to see a significant difference in the number of sharks caught by drumlines as opposed to nets. Our results demonstrated that nets are 10 times more effective at catching bull whaler sharks than drumlines. It is most likely that this result can be explained by the position in which nets and drumlines were located. All nets were placed in shallow waters close to shore while drumlines were located further away from beaches. Importantly, drumlines presented a bait to attract sharks. Prior studies have shown that even though bull sharks have preference for coastal habitats (Brunnschweiler et al., 2010; Espinoza et al., 2015; Heupel and Simpfendorfer, 2008; Snelson et al., 1984), they can still feed on prey found in deeper areas of the continental shelf (Hammerschlag et al., 2012; Matich et al., 2011). Studies have shown that drumlines are a much more selective shark-control measure than nets (Cliff and Dudley, 2011; Gribble et al., 1998; Paterson, 1990). Moreover, the amount of by-catch on drumlines is considerably lower than nets (Cliff and Dudley, 2011). For this reason, we recommend reducing the number or eliminating nets to reduce the by-catch of non-target species by shark control programs. The by-catch of non-target species is an emerging public concern and causes significant environmental impacts in marine ecosystems.

Lynch (2016) identified rainfall as a significant predictor of whaler shark incidents. The present study identified that 10 out of 15 incidents occurred on days when there was 0 mm rainfall. Nevertheless, 14 out of 15 incidents happened between 1 and 7 days after rainfall. These results indicate that a greater number of shark-human interactions occurred shortly after rainfall, suggesting that this factor may be a predictor of the presence of bull whalers in the water and/or a reflection of human behaviour as people are less likely to swim during rainfall events. Despite that, as rainfall is highest in Southeast Queensland during summer and autumn months (Ryan et al., 2019; South East Queensland: Climate and Water, 2023) and the number of incidents analysed by this research is small, we should treat this result with caution.

When we compared the number of sharks caught by the QSCP and the shark-human interactions involving bull whaler sharks from 1996 to 2021 in Southeast Queensland, we observed that (a) SST influenced the number of sharks caught by drumlines and the prevalence of shark-human incidents, and (b) rainfall had a strong effect on the number of bull whalers caught by nets and the incidents. Therefore, our results for catches seem to correspond with incidents, indicating that the conditions in which catches and incidents happen are similar. However, it is still important to analyse the context in which incidents and/or catches occur, and associate these with the ecology, life history and behaviour of the species involved (Ryan et al., 2019) to provide efficient management strategies that can benefit both people and sharks. Additionally, shark-human incidents are not just driven by shark movements, but also influenced by human behaviour. From the perspective of human behaviour (1) less bathers are likely to be swimming during rainfall events, (2) more people enter natural water bodies during weekends and school holidays (Baldridge, 1974), (3) there are more swimmers when water temperature is above 21 °C (Baldridge, 1988), and (4) recreational activities in freshwater environments has been encouraged by canal building and associated infrastructure. The outcomes of the present study provide opportunity for public education on the risks of shark bites in Southeast Queensland.

5. Conclusion

The link between environmental conditions and the presence of bull shark is quite complex. This and previous studies have shown that the presence of bull sharks is connected particular environmental conditions which clearly alter bull shark behaviour, movement, reproduction, and interactions with humans (Werry et al., 2018). Therefore, alterations to these conditions due to climate change must be considered when planning and implementing management and conservation strategies for bull sharks. It is quite apparent that the behaviour of sharks will shift in the future, causing significant implications for marine ecosystems and shark-human interactions.

The overlap between bull shark and human presence in Southeast Queensland pressures authorities to implement effective management strategies for shark-human interactions that protects people without harming sharks as these animals play important roles in marine ecosystems (Tucker et al., 2022). For this reason, we recommend the replacement of baited drumlines with SMART drumlines, and that authorities turn to the use of drones (Butcher et al., 2021) and/or aerial surveillance (Adams et al., 2020) to periodically detect large-shark species. Importantly, our data showed that nets are 10 times more effective at catching sharks than drumlines, but it present considerably higher numbers of by-catch (Cliff and Dudley, 2011). We also emphasise in the important role of public education about the real risk of shark-human interactions particularly regarding the environmental conditions that are associated with a higher probability of shark incidents (Ryan et al., 2019).

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CRediT authorship contribution statement

S.M. Lopes: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.E. Williamson:** Writing – review & editing, Supervision, Conceptualization. **Y. Lambreghts:** Writing – review & editing, Formal analysis, Data curation. **A.P. Allen:** Writing – review & editing, Formal analysis, Data curation. **C. Brown:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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