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Photo: Eva Ramey

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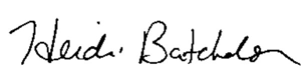

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Abstract:

Oceanic shark and ray populations have declined by 71% due to an 18-fold increase in fishing pressure over the past 50 years (Pacoureau et al., 2021). While a significant amount of work has been done to document oceanic shark declines worldwide, there is still a knowledge gap surrounding the conservation status of reef-associated sharks globally (MacNeil et al., 2020). As the world's coastlines and nearshore environments continue to experience increased pressure from human population growth, understanding the conservation status of sharks has become even more important. This study used presence/absence data to determine physical and anthropogenic factors that influenced shark distributions in the Florida Keys. An assessment of the habitat use patterns of local species can inform site-specific and species-specific protections (Rizzari et al., 2014). By increasing our knowledge of coastal shark distributions, abundances and habitat associations along the Florida Keys, the results of this study can help assess each species' risk from exposure to fishing, habitat degradation and climate change impacts. This study found that shark occurrences in the Florida Keys were highly influenced by the percentage of reef habitat along the reef tract. Region of the keys was also an important predictor of shark occurrences. Based on the findings of this study, several management recommendations specific to shark conservation are presented to increase habitat protection and minimize of fishing pressure on sharks.


Photo: Eva Ramey


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Introduction:

Shark populations around the world are in decline, primarily because of overexploitation and overfishing of sharks, as well as bycatch in fisheries (Booth et al., 2020; Dulvy et al., 2014). While a significant number of studies have documented shark declines, many of these studies used information on oceanic sharks and catch data from commercial fishing (Roff et al., 2016). Climate change and habitat loss due to coastal development also pose threats to shark populations that live further inshore in coastal waters and on coral reefs; hereafter called reef-associated and coastal sharks (Bruns & Henderson, 2020).

Continental shorelines are becoming increasingly populated by humans, and as coastal development grows, additional pressure is placed on coastal marine environments (Flower et al., 2020). Tropical coral reefs are especially impacted by coastal development and are in decline (Rizzari et al., 2014). The additional global pressure of climate change means that local management of coastal ecosystems is needed to address fishing pressure and habitat degradation in order to increase coral reef health (Hughes et al., 2010).

Reef-associated sharks vary in size and life history characteristics (Espinoza et al., 2014). These species also vary in their degree of mobility, site fidelity and degree of positive association with coral reef habitats (Espinoza et al., 2014; Roff et al., 2016). Most shark species demonstrate slow growth rates, long lifespans, delayed maturation, and low fecundity (Castro et al., 1999). These factors equate to a low reproductive potential for sharks, making them highly susceptible to long-term climate change and anthropogenic impacts (Wheeler et al., 2020).

Despite the important role that shark species play in reef communities, relatively few studies have addressed their distribution, abundance, and community structure in coastal habitats in the Florida Keys (Heithaus et al., 2007). Recent publications have suggested that some coastal sharks play an important role as apex predators in maintaining reef resilience (Roff et al., 2016). Other studies have suggested that reef sharks can play both major and minor roles in the trophic structuring of coral reefs (Rizzari et al., 2014). Variables relating to structural complexity of reefs have also been shown to influence the fish diversity on reefs (Gratwicke & Speight, 2005). Shark species that play the role of apex and meso-predators can promote the sustainability of food webs by engaging in opportunistic feeding and removing diseased and weak species from reef communities (Roff et al., 2016). Regardless of the type of role that different shark species play, the long-term consequences of the global depletion of sharks are uncertain and should be of great concern to coral reef managers (Rizzari et al., 2014; Roff et al., 2016).

The ability to quantitatively test the effect of habitat (e.g., coral reef cover and health) on shark abundance can be difficult. Different shark species exhibit different movement patterns within coral reef ecosystems and links between shark abundance and healthy reefs are still not well understood for some species (Roff et al., 2016). However, in some locations correlations between reduced shark abundance and degraded reefs have been reported (Espinoza et al., 2014; Rizzari et al., 2014; Sandin et al., 2008).

In 2015, the Global FinPrint project was launched by the Paul G. Allen Foundation to address the conservation status of reef-associated elasmobranch species and communities around the world.

The results of this worldwide assessment, in which 371 reefs were surveyed in 58 nations, revealed a critical picture of the state of shark conservation in many countries (MacNeil et al., 2020). Based on these results, it has been suggested that management regulations, including bans on gillnets/longlines, catch limits, large spatial fishing closures, and shark sanctuaries, be implemented to help reverse the decline in reef-associated shark populations (MacNeil et al., 2020).

The Florida Keys archipelago is a unique location, encompassed by the Florida Keys National Marine Sanctuary in the western Atlantic Ocean. This area was surveyed by the Global FinPrint project. The Florida Keys archipelago is made up of diverse habitats which are used by sharks at different life history stages (Heithaus et al., 2007). The archipelago is composed of over 1,700 islands that stretch from the southern tip of the Florida peninsula out to the Dry Tortugas National Park (Chiappone et al., 2005). In between many of these islands are deep and narrow channels that connect the shallow habitats on the Gulf of Mexico side of the keys with the Atlantic waters to the south (Heithaus et al., 2007). The Florida Keys National Marine Sanctuary employs a suite of marine management strategies within this vast archipelago. For example, the Florida Keys National Marine Sanctuary covers a total area of 9,900 km^2. The Dry Tortugas Research Natural Area within the sanctuary is a 158 km^2 no-fishing reserve (Hallac et al., 2013) (Appendix D). Additionally, a total of 18 Sanctuary Preservation Areas cover just under 5 nm^2 of the Sanctuary along the main island chain (National Marine Sanctuary Program, 2007), (Figure 1). Tourism in The Florida Keys continues to grow each year as it gains notoriety as a popular vacation destination. The impacts of the increasing human population growth in the Florida Keys can been seen across the island chain in the form of increased urban development. Fishing pressure and marine pollution has also increased (Chiappone et al., 2005).

Shark fishing in the Florida Keys is considered a "historical" fishery (McClenachan, 2009). A 2008 report used historical photos from trophy boards at Key West marinas to quantify fisheries declines over the past half-century (McClenachan, 2009). This report showed that between 1956 and 2007, the average length of sharks that were harvested by sport fishermen declined by more than 50% (McClenachan, 2009). Of the 16 individual sharks that were caught and photographed in that study, almost half of them were hammerhead sharks (*Sphyrna mokarran* and *S. lewini*) and white sharks (*Carcharodon carcharias*) and most of them were caught before the year of 1965 (McClenachan, 2009). In the early 20th century, gillnet fisherman who operated in the southern region of the Florida Keys archipelago reported landing roughly 100 sharks per day (Heithaus et al., 2007). Ongoing commercial shark fishing in Florida state waters is another factor cited for decreased shark populations, however, commercial shark landings in Florida have decreased in recent years due to federal quotas (Florida Fish and Wildlife Conservation Commission, n.d.-b), (Appendix C).

Sharks are currently a target of both charter boat sportfishing and shore-based recreational fishing in the Florida Keys, and sharks are shown to be economically important to the charter boat fishing industry (Shiffman & Hammerschlag, 2014). Because of their economic importance, it has been argued that under the right circumstances, the shark catch-and-release fishing industry in the Florida Keys may help further conservation initiatives as a form of ecotourism (Shiffman & Hammerschlag, 2014). In 2019, the Florida Fish and Wildlife Conservation Commission implemented a shore-based shark fishing permit system and banned the practice of chumming for sharks from shore (Appendix E). No such permitting scheme or bans have been put in place for offshore vessels.

Of the nine species accounted for in this study, five species are prohibited to catch in Florida State Waters and the rest are recreationally harvestable species with either a 54-inch fork length size catch limit or no minimum size limit (Table 1) (Florida Fish and Wildlife Conservation Commission, n.d.-b). For harvestable sharks, the daily bag limit is one shark per person per day and there is also an overlapping vessel limit of two sharks per vessel (Florida Fish and Wildlife Conservation Commission, n.d.-b). In addition to legal shark fishing in the Florida Keys, accidental bycatch of sharks by sport fisherman and commercial fishing is another concern (Bohnsack & Ault, 1996).

Table 1: Species harvestability regulations. Information obtained from the Florida Fish and Wildlife Conservation Commission on April 20th, 2021.

Shark Species	**Harvestability Regulations** (Based on Florida Fish and Wildlife Conservation Commission website.)
***C. acronotus* (blacknose shark)**	No minimum size limit
***S. tiburo* (bonnethead shark)**	No minimum size limit
***R. terraenovae* (Atlantic sharpnose shark)**	No minimum size limit
***G. cirratum* (nurse shark)**	54 inch (fork length) minimum size limit
***C. leucas* (bull shark)**	54 inch (fork length) minimum size limit
***R. porosus* (Caribbean sharpnose shark)**	Prohibited from harvest
***C. perezi* (Caribbean reef shark)**	Prohibited from harvest
***S. mokarran* (great hammerhead shark)**	Prohibited from harvest
***N. brevirostris* (lemon shark)**	Prohibited from harvest
***G. cuvier* (tiger shark)**	Prohibited from harvest
*Harvestable sharks have a bog limit of one shark per person per day and a maximum vessel limit of two sharks per vessel per day.	

Appropriate conservation and management regimes aimed at protecting sharks on a local scale can play an important role in supporting more widescale shark conservation efforts(Rizzari et al., 2014). To do this, a baseline understanding of the distribution and abundance of coastal sharks must be gained and their susceptibility to ecological and human impacts should be quantified. By assessing the habitat use patterns of local species, their ecological role can be clarified, and site-specific and species-specific protections can be implemented (Rizzari et al., 2014).

Empirical studies in some regions have shown that spatial marine management and zoning can play an important role in shark conservation (Bond et al., 2012). These studies have also shown that this in turn can support coral reef resiliency (Chapman et al., 2013). However, there is still much to be learned about the benefits and impacts of marine protected areas on individual shark species (Juhel et al., 2019). It has been suggested that when long-term data on changes in shark abundance are unavailable, comparisons between fishing zones and no-fishing zones can provide a glimpse into historical changes and the impacts of shark removal on reefs (Roff et al., 2016).

As a first step to address conservation and management of reef associated and coastal sharks, this study sought to assess the primary drivers that influence the distribution and relative abundance of reef-associated shark species in the Florida Keys National Marine Sanctuary. I hypothesized that shark distribution and would be influenced by both ecological factors and human impacts and that fishing pressure would have the greatest influence on shark distribution. By increasing our knowledge of coastal shark distributions, and habitat associations along the Florida Keys, the results of this study can help assess each species' risk from exposure to fishing, habitat degradation and climate change impacts. Information from this study can be used to improve the existing regulation to manage shark populations and simultaneously increase economic opportunities for catch-and-release sport fishing.

Methods:

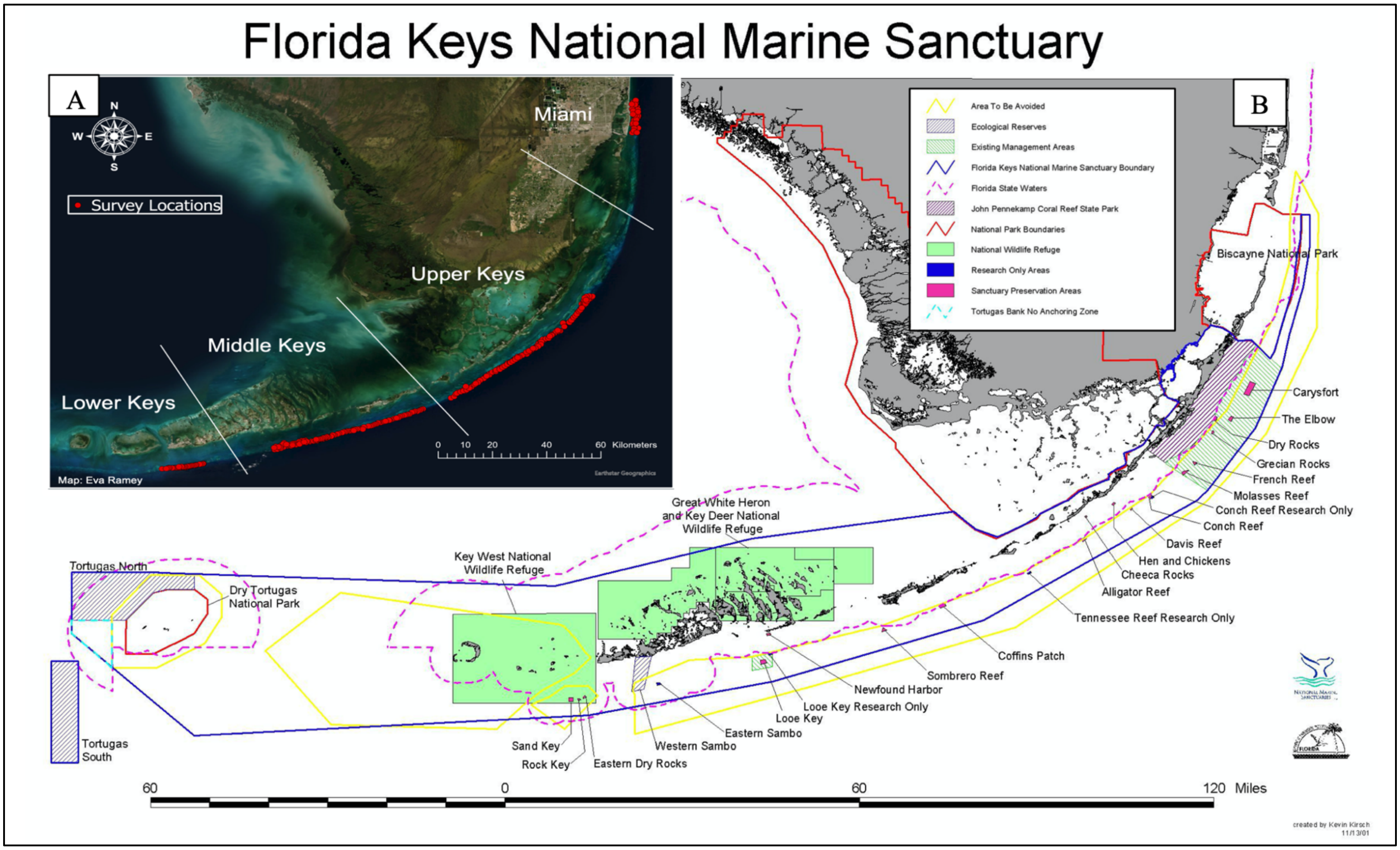
Surveys

Methods of data collection were consistent with those of Global FinPrint. The Florida Keys region was surveyed using baited remote underwater video sets (hereafter referred to as sets of BRUVS and described below) during the summer months in the years of 2016 and 2017 by over 60 individual observers. Reefs were chosen for sampling based on the presence (or closest alternative) of a continuous reef tract of approximately 10 km in length (MacNeil et al., 2020). Reef site selection for sampling also encompassed a mix of reefs that were open to fishing and restricted from fishing. Reefs sampled varied in distance from the urban center of Miami. While most of the sampling took place within the boundaries of the Florida Keys National Marine Sanctuary, surveys in the Miami region in 2019, which were not part of the Global FinPrint study, were also included in this study. The surveys in the Miami regions used the same survey protocols as the Global FinPrint study. The surveys within the Florida Keys National Marine Sanctuary were conducted during the months of May through August of 2016 and 2017. The surveys in the Miami region were conducted during April 2019.

Each set consisted of a GoPro Hero2, 3 or 4 video camera, that was mounted onto a frame with a 1.5 m long bait pole fixed within the field of view of the camera (MacNeil et al., 2020). Sets were deployed and retrieved using a rope and surface float. Bait used for surveys was consistent across all sets and consisted of 1 kg of frozen menhaden, from the family Clupeidae (MacNeil et al., 2020). Environmental data, including measurements of dissolved oxygen, salinity, wind speed, wind direction, tide state, cloud cover and surface water temperature were inconsistently taken at the before and after set deployments. Visibility was measured using a Secchi disc and recorded as Secchi depth in meters.

Within the dataset used for this analysis, nine reefs were identified by name, however, for the purposes of this study, four broader geographical regions were identified based on natural breaks in the sampling area. This meant that areas where sampling continued from one reef to another without interruption were grouped together. The four geographical regions used in the study were: 1. Miami (latitude of sets was greater than 25.75 °N); 2. Upper Keys (latitude of sets was between 24.72 and 25.75 °N); 3. Middle Keys (latitude of sets was between 24.53 and 24.72 °N); and 4. Lower Keys (latitude of sets was less than 24.72 °N). A total of 39 sets were deployed in the Lower Keys, 136 in the Middle Keys, 166 in the Upper Keys and 38 in Miami (Figure 1).

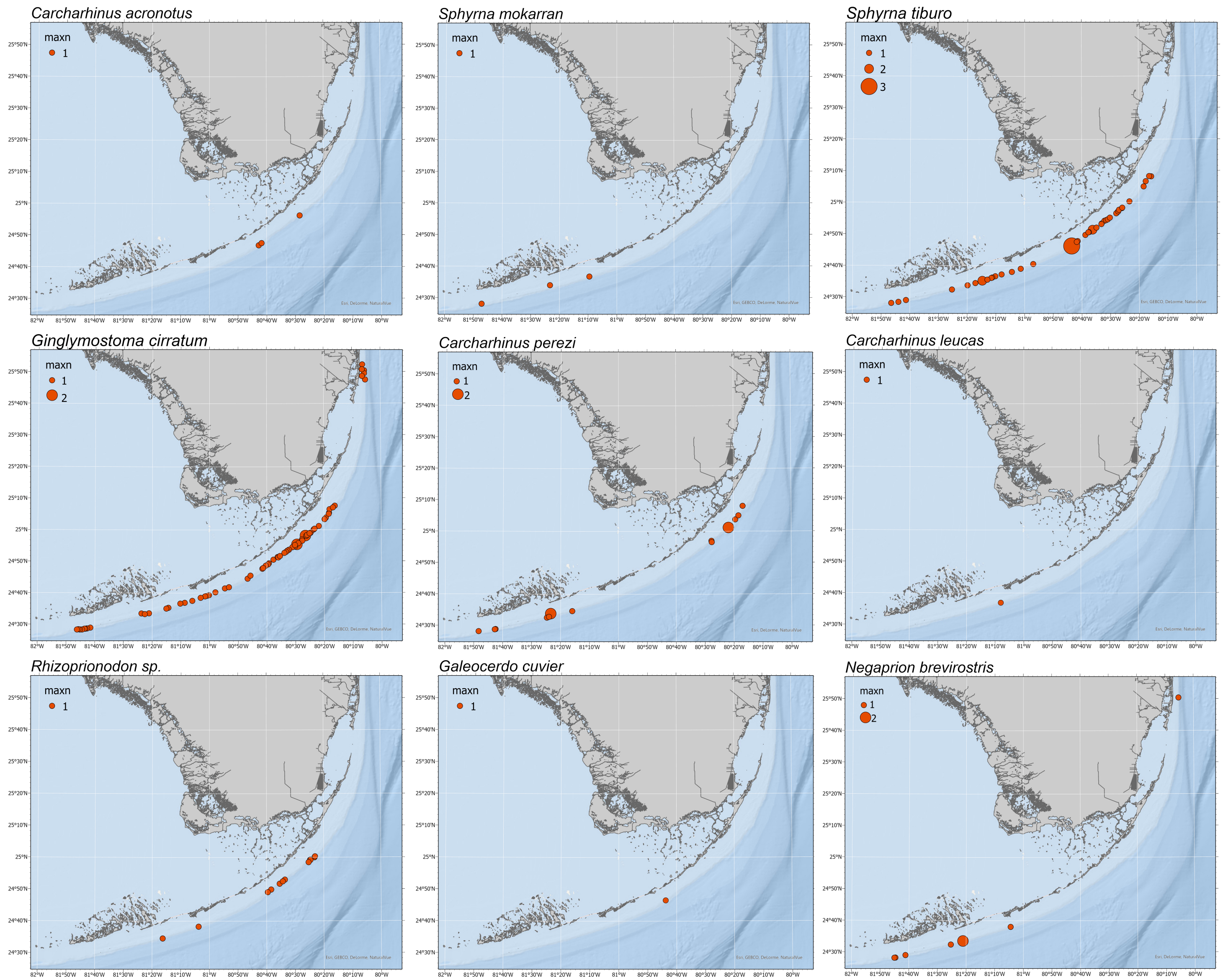
Figure 1: (A) Map of BRUV survey locations and regions used in this study. **(B)** Map of Florida Keys Marine Zones, retrieved from Florida Keys National Marine Sanctuary Management Plan on March 20th, 2021.



Within each reef sampling area, 50 sets (i.e., BRUVS) were deployed. Care was taken to avoid deploying sets directly on live corals, to avoid damaging the reef habitat. Each set was deployed at least 500 m away from the previous set. This spacing was chosen with the consideration of the size of the bait plumes and the average swimming speed of various shark species to reduce the likelihood of double counting of individual sharks (MacNeil et al., 2020). In total, over 800 sets were deployed within a depth of 4-30m.

All surveys were conducted during daylight hours and sets were retrieved after a minimum of 70 minutes of deployment (MacNeil et al., 2020). The length of video clips used for data collection was standardized to one-hour intervals from the time that the set had settled following deployment. The video from each set was reviewed twice by different trained and independent reviewers to ensure species identification was accurate (MacNeil et al., 2020). Both the FinPrint Annotator (v.1.1.44.0) and EventMeasure were used in analyzing the video from the sets (MacNeil et al., 2020). The average time in which species appeared in the video frame from the deployment time varied among species. If individual sharks could not be identified to species level, the lowest taxa to which the individuals could be identified was assigned.

Figure 2: Maps of individual shark species distribution and MaxN.



Of the approximately 800 sets that were deployed in the Florida Keys and Miami regions, 376 sets had video that was analyzed at the time of this analysis. This analysis was therefore undertaken using data from these 376 sets, 131 of which observed at least one shark. Of the sharks that were represented in the dataset, all were identified to the species level except for 17 individuals. One Requiem shark was unable to be identified to the genus level and was discarded from the dataset used for analysis. Of the other 16 individuals, 12 belonged to the genus *Rhizoprionodon* and 5 to the genus *Sphyrna*. While none of these 16 individuals were identified to the species level, the sharpnose sharks were grouped together and assigned the species code *Rhizoprionodon sp.* for the purposes of this analysis. The decision to group the sharpnose sharks by genus was made under the assumption that the sharpnose sharks belong to only two different species under the genus *Rhizoprionodon* and that they occupy similar ecological niches. Unidentified *Sphyrna* sharks were also grouped together with *S. mokarran* and called large-bodied hammerheads for the purposes of the analysis. However, it was recognized that these individuals could have belonged to one of several different species, which do not always share similar ecological niches.

The maximum number of individual sharks of a particular species that were identified within a single frame of a video was recorded to avoid double counting of individuals. This metric is hereafter referred to as MaxN (MacNeil et al., 2020). Given the efforts to avoid double counting, the numbers of sharks recorded in these surveys likely represents an underestimate of the true abundance of these species in the region.

<u>MaxN</u>

MaxN has been used in previous studies using BRUV data as an index of relative abundance (MacNeil et al., 2020; Willis et al., 2000). While MaxN has been identified as a standard metric of reporting relative abundance in the literature, it was not used in this analysis because only four of nine shark species represented in the dataset had a MaxN greater than one, and these occurrences were rare (seven occurrences in total for all species). The highest MaxN recorded was three. Instead, observed/not observed was assigned to each set for a given species. For example, if at least one individual was observed at a given set location, it was given a "1". If no individuals of that same species were seen at a given set location, it was given a "0". It is important to note that this observed/not observed data cannot be used to directly determine presence/absence of a given species since absence cannot be ruled out simply because a species was not observed. Therefore, these observed/not observed data serve as a metric for shark habitat use and can be used to help predict the distribution and relative abundance of individual species given certain predictor variables. Observed (1) vs. not observed (0) was used as a binomial response variable in the generalized linear regression models.

<u>Variable Selection</u>

To find variables that explained the observations of sharks, I used a combination of approaches. Candidate variables included those were shown to affect shark presence in the by previous literature as well as variables that had not been explored for shark distributions in the Florida Keys. This list consisted of variables on both the set-scale (water quality, weather conditions and depth) and region-scale (location, fishing pressure, proximity to protected areas and human population centers). Variable selection was ultimately limited by data availability on both scales as well as by timeframe for the analysis. A z-scale transformation was performed on the data for predictors, but model results were not significantly different, and the transformation did not account for the variance. All data reported are represented as the arithmetic mean ± standard error (SE).

Due to the inconsistency of the environmental data that was collected at the surface during set deployments, only a few environmental variables specific to each set were useful. Some environmental variables were unavailable for entire regions (e.g., the Miami region). From the list of available datasets, a limited number of potentially important predictor variables were prioritized based on their likely cause and effect mechanisms (Table 2). Effort was taken to eliminate confounding variables.

Table 2: Predictor variables used in generalized linear models.

Predictor	Type	Range	Mean ± SD	Complete Dataset
Depth (m)	Continuous	4.9 - 29.5	11.9 ± 3.6	Complete
Distance to Coastline (m)	Continuous	975.7 - 9653.5	7146.7 ± 1705.8	Complete
Distance to No Fishing Area (m)	Continuous	0 - 74578.8	8470.2 ± 1798.1	Complete
Distance to Mooring Buoy (m)	Continuous	27.2 - 14631.8	3078.8 ± 3524.1	Complete
Reef Percentage (%)	Continuous	0 - 100	24.6 ± 35.3	Complete
Water Temperature (°C)	Continuous	25.6 – 31.3	28.9 ± 1.2	43 missing values
Month	Continuous	4 - 8	5.9 ± 1	Complete
Water Visibility	Continuous	3 - 10	7.6 ± 1.7	91 missing values
Region	Categorical	NA	NA	Complete

Several variables used in the analysis were calculated using the software ArcGIS Pro 2.6. These variables included the distance from each set to the nearest coastline, mooring buoy, and Florida Keys National Marine Sanctuary Preservation Area. Additionally, the percentage of reef around each set was calculated. The percentage of reef for each set was computed within a 100 square meter radius circle that was centered at the set. The circle size minimized the overlap between circles and provided an ecologically relevant area for reef-associated sharks.

Table 3: List of resources used to create datasets for the following variables: Distance to no-fishing areas, distance to coastline, distance to mooring buoys, percentage of reef habitat surrounding survey sites.

Name of Resource	Data type	Retrieved from	Date Retrieved
Florida Keys Marine Protected Areas	Shapefile	Florida Keys National Marine Sanctuary Water Quality Protection Program website	February 2nd, 2021
Florida Keys Reef Tract Map	Shapefile	Florida Fish and Wildlife Conservation Commission website	February 2nd, 2021
Florida Coastline Map	Shapefile	Florida Fish and Wildlife Conservation Commission website	February 2nd, 2021
Florida Keys Mooring Buoys	PDF of GPS locations	Florida Keys National Marine Sanctuary website	April 17th, 2021
Miami Region Mooring Buoys	PDF of GPS locations	Miami-Dade County website	April 17th, 2021

Datasets used in this calculation were obtained from a variety of sources (Table 3). In ArcGIS Pro 2.6, the geoprocessing tool XY Table to Point was used to input the data for both the set locations and mooring buoy locations. The Clip tool was used to eliminate all habitat in the Florida Keys Reef Tract Map that was not classified as reef. The Dissolve tool was used to dissolve the Florida Keys Reef Tract Map by "ClassLevelTwo" based on the metadata for the shapefile. This allowed for the four different types of reefs, each of which was a separate polygon, to all be combined in the polygon titled Reef Habitat. A 100 m buffer around each set was created and the geoprocessing tool Summarize Within was then used to summarize the area of reef in square meters from the newly created Reef Habitat polygon within the 100 m buffer (Appendix A). The Calculate Field Tool was used to calculate the percentage of reef habitat within the 100 m buffer. The geoprocessing tool Near was used for the distance calculations and all distance measurements were recorded in meters. For the calculations of distance to nearest no-fishing-area, the following zones were considered no fishing areas used in the analysis: Sanctuary Preservation Areas, Research Only Areas and Ecological Reserves.

Data Analysis

Logistic regression models (hereafter referred to as GLMs or generalized linear models) were used to examine the drivers of presence/absence possibility (observed/not observed) of each shark species and all sharks at the set-level. The goal of these models is to describe the observation of shark species in terms of a linear combination of variables (i.e., predictors). Model selection for GLMs was based on minimization of Akaike's Information Criterion (AIC) (Table 5). A stepwise process of model selection (forwards and backwards) was used to select the most parsimonious model for each species (Table 5). Statistical significance was determined at the alpha level of 0.1. Presence of sharks in the dataset was rare, leading to the model being zero inflated. Therefore, $P < 0.1$was chosen due to low power in the models resulting from a small sample size of presence data. Sets with missing values were excluded from analysis.

The stepwise model selection process could not be completed for any species with the number of presence observations < 7. Some incomplete predictors removed enough missing values for presence observations that the GLMs could no longer be run for certain species. For the categorical predictor region, Lower Keys was selected alphabetically by the software R as the intercept, and all other regions were compared to the Lower Keys (Appendix F). To quantify the relationship between selected variables and observed shark MaxN, a loglinear model (Poisson GLM) was developed for each species as well as for all sharks. A dominance analysis was performed on the best fit GLMs to assess predictors' importance through the comparison of their contributions in the model (Azen & Traxel, 2009). All analyses were performed using the software R version 4.0.2 (R Core Team, 2020). The packages used included *MASS*, version 7.3-53.1 (Venables & Ripley, 2002), *dominanceanalysis*, version 2.0.0 (Navarrete & Soares, 2020) and *vegan,* version 2.5-7 (Oksanen et al., 2020).

Species richness was calculated as a measure of the number of different species observed in each region. The Shannon index and Simpson index (1-D) were used to evaluate the average diversity of species per region. The Simpson index indicates the measure of probability that two randomly selected individual sharks are identified as different species. The Simpson index is bounded between 0 (low diversity) and 1 (high diversity). The Shannon index (H) considers both the abundance of each species, and the evenness of species present within each region. The observations per unit effort (OPUE) in each region were calculated as the average number of sharks observed per 60-minute video (Figure 5).

Results:

One or more individual sharks were observed at 131 of the 376 sets analyzed for this study. A total of 157 individual sharks were observed. Approximately 45% of the sharks that were observed in this study were nurse sharks (n=70), followed by bonnethead sharks (33%, n= 44). All other species had less than 15 total observations (Table 4). More than one shark species was observed at seven sets. These included: one case of a nurse shark observed at the same set as a sharpnose shark (*Rhizoprionodon sp.*); two cases of nurse sharks observed at the same set as bonnethead sharks, and one case of a nurse shark observed at the same set as a lemon shark (*N. brevirostris*). Additionally, there was one occurrence of a blacknose shark (*C. acronotus)* and bonnethead shark at the same set and two cases where bonnethead sharks and lemon sharks were observed at the same set.

Due to the low number of shark observations in the dataset, predictors with no missing values were prioritized to maintain a sample size of 376 sets. The predictor variable "visibility" contained 91 missing values of the 376 sets. Most of the missing values for sets were in the Miami region and did not observe sharks. The GLMs were run excluding the missing values for the predictor visibility and excluding the variable entirely using the same dataset. In all cases, the models containing the variable with the missing values generated lower AIC scores after the stepwise process of model selection than those that excluded the variable entirely. For this reason, visibility was not used as a predictor variable in the final full GLMs generated in this study.

Table 4: Summary of shark sightings, abundance and MaxN.

Species	Common Name	No. Sightings	MaxN
Ginglymostoma cirratum	nurse shark	70	1-2
Sphyrna tiburo	bonnethead shark	44	1-3
Carcharhinus perezi	Caribbean reef shark	15	1-2
Rhizoprionodon sp.	unidentified species sharpnose sharks	12	1
Negaprion brevirostris	lemon shark	8	1-2
Sphyrna sp.	unidentified species large hammerhead sharks	4	1
Sphyrna mokarran	great hammerhead shark	3	1
Carcharhinus acronotus	blacknose shark	3	1
Galeocerdo cuvier	tiger shark	1	1
Carcharhinus leucas	bull shark	1	1

The average shark sighting occurred at 28 minutes into the 60-minute video recording. In all except one case, where sharks of different species were observed, individuals were seen more than 5 minutes apart from each other.

Reef Habitat:

Of the 131 sets where sharks were observed, 38% (n=51) had more than 25% reef habitat within a 100 m radius of the set location. However, at least one observation of each shark species occurred at a set that had less than 10% reef habitat within the 100 m radius buffer (Appendix A). Percentage of reef habitat was one of the best predictors of occurrences of sharks when all species were grouped together. Individually, nurse sharks and lemon sharks also had a significant positive correlation with percentage of reef habitat (Figure 4). Percentage of reef habitat was not a statistically significant predictor of the occurrences of sharpnose sharks*,* Caribbean reef sharks (*C. perezi*), nor bonnethead sharks (Table 5).

Region:

When all shark species were grouped together, region was a significant predictor of observation of sharks. More individuals were found in the Upper Keys region when compared to the Lower

Keys region and there was a statistically significant negative correlation with the Middle Keys (Table 5).

Only two species of sharks, nurse sharks and lemon sharks were observed in the Miami region (Figure 2). There was no statistically significant effect of region on bonnethead sharks and sharpnose sharks, however both species showed a positive correlation with Upper and Middle Keys regions compared to the Lower Keys and a negative correlation with the region of Miami compared to the Lower Keys (Table 5). There was no effect of region on the occurrence of lemon sharks or Caribbean reef sharks.

Month:

Month was a significant predictor of the occurrence of all sharks when species were grouped together, and sharks were more likely to be observed in the later summer months of surveying (Table 5). Lemon sharks also showed a positive correlation with survey month. There was no effect of month on the occurrence of nurse sharks, sharpnose sharks, Caribbean reef sharks, nor bonnethead sharks (Table 5).

Depth:

Depth was a significant predictor of occurrences of only lemon sharks, which were more likely to be seen at greater depths (Table 5). There was no effect of depth on any other shark species (Figure 4).

Water Temperature:

A statistically significant negative correlation with surface water temperature was found for lemon sharks (Table 5). Water temperature fluctuates based on many variables and water temperature in this study was taken only at the surface. It is possible that as the surveys moved later into the summer, the surface water temperature increased in the regions where lemon sharks were observed. The increasing surface water temperature may have driven the sharks to deeper waters.

Distance to no-fishing area:

Distance to no-fishing areas was a statistically significant driver of occurrences for only two species groups: sharpnose sharks and Caribbean reef sharks (Figure 4). Sharpnose sharks showed a positive correlation with distance to no-fishing areas, while Caribbean reef sharks showed a negative correlation (Table 5). There was no effect of distance to no-fishing area on any other shark species in this study.

Rare Occurrences:

Observations of tiger sharks, bull sharks, and blacknose sharks occurred rarely (between 1-3 observations) and there were not enough observations in the dataset to fit models for these species. These species were only observed in the Middle and Upper Keys regions (Figure 2). The one observation of a bull shark occurred at 15.7 m deep in the channel off the Seven Mile bridge in July 2017. The Seven Mile bridge channel is the widest channel found in the Florida Keys archipelago and allows for water transfer between the Gulf and Atlantic side of the Florida Keys (Figure 2). This region is also prone to high currents during tidal changes. The one observation of a tiger shark occurred in June 2016 off the coast of Long Key at 11.5 m deep. All three observations of blacknose sharks occurred in the Upper Keys region by sets that had no reef habitat within 100 m of the set (Figure 2).

Overall, percentage of reef habitat, region, and month were the most common predictors of the occurrence of shark species individually and when all sharks were grouped together. There was no effect of distance to coastline or distance to mooring buoy on the abundance of any species regardless of how they were grouped (Table 5). Variable significance was not identified in the Poisson GLM models for any species nor for all sharks. This may be due to the low number of occurrences where the MaxN for a species was greater than one. An example of an occurrence of a large-bodied hammerhead seen by the BRUV is shown in Figure 3.

The number of shark observations per unit effort OPUE was highest in the Upper Keys region, which was the largest of the four regions sampled (Figure 5). The Middle Keys region had the second lowest OPUE but showed the highest species richness and diversity index (Shannon and Simpson's) of the four regions (Figure 5). The Miami region ranked lowest for the four regions in all biodiversity related analyses including OPUE, species richness, and Shannon and Simpson's diversity index (Figure 5). The relative abundance of sharks was highest in the Upper Keys region.

Figure 3: Photo taken from baited remote video surveys conducted as part of the Global FinPrint's worldwide shark survey. Images obtained from: https://globalfinprint.org/findings/index.html

Table 5: Summary of GLMs after stepwise process to determine best fit model. Variables include both significant variables and other variables included in the best fit model.

	Variables *Significant variables are in **bold** and other not significant variables are in *italics*
All sharks	**Reef Percentage** + **Region** + **Month**
G. cirratum (nurse shark)	**Reef Percentage** + *Region*
N. brevirostris (lemon shark)	**Reef Percentage** + **Depth** + **Month** + **Water Temperature**
Rhizoprionodon sp. (sharpnose shark)	**Distance to No-Fishing Area** + *Region* + *Water Temperature*
C. perezi (Caribbean reef shark)	**Distance to No-Fishing Area**
S. tiburo (bonnethead shark)	*Region*

	All sharks	***G. cirratum*** (nurse sharks)	***N. brevirostris*** (lemon sharks)	***Rhizoprionodon sp.*** (sharpnose sharks)	***S. perezi*** (Caribbean reef shark)	***S. tiburo*** (bonnethead shark)
Reef Percentage	**Est.:** 0.011 **S.E:** 0.004	**Est.:** 0.010 **S.E:** 0.005	**Est:** 0.031 **S.E:** 0.012			
Water Temperature			**Est:** -1.551 **S.E:** 0.812	**CV:** 1.410e+00 **S.E:** 8.660e-01		
Distance to No-Fishing Area				**Est:** 2.841e-04 **S.E:** 1.373e-04	**Est:** -2.528e-04 **S.E:** 1.475e-04	
Distance to Mooring Buoy						
Distance to Coastline						
Month	**Est:** 0.558 **S.E:** 0.262		**Est:** 2.155 **S.E:** 0.936			
Depth			**CV:** 0.251 **S.E:** 0.123			
Lower Keys	*Intercept*	*Intercept*	*Intercept*	*Intercept*	*Intercept*	*Intercept*
Middle Keys	**Est:** -1.062 **S.E:** 0.512	**Est:** -0.282 **S.E:** 0.527		**Est:** 1.243e+01 **Est:** 2.741e+03		**Est:** 0.079 **S.E:** 0.678
Upper Keys	**Est:** 0.949 **S.E:** 0.487	**Est:** 0.887 **S.E:** 0.553		**Est:** 1.674e+01 **S.E:** 2.741e+03		**Est:** 0.785 **S.E:** 0.651
Miami	**Est:** -0.161 **S.E:** 0.749	**Est:** -0.242 **S.E:** 0.602		**Est:** -1.642e+01 **S.E:** 3.911e+03		**Est:** -16.08116 **S.E:** 1.0581e+03

*Significant variables are in dark gray and other not significant variables are in light gray. Estimated coefficients (Est.) and Standard Error (S.E) are shown for each predictor variable that was included in the bet fit models.

Figure 4: A dominance analysis was performed for models that included more than one predictor variable after the stepwise selection process. The McFadden index, R^2M is shown for each variable in the best for model. In order, general dominance and conditional dominance of predictors are shown for G. cirratum (**A**), Rhizoprionodon sp. (**B**), N. brevirostris (**C**), All sharks (**D**).

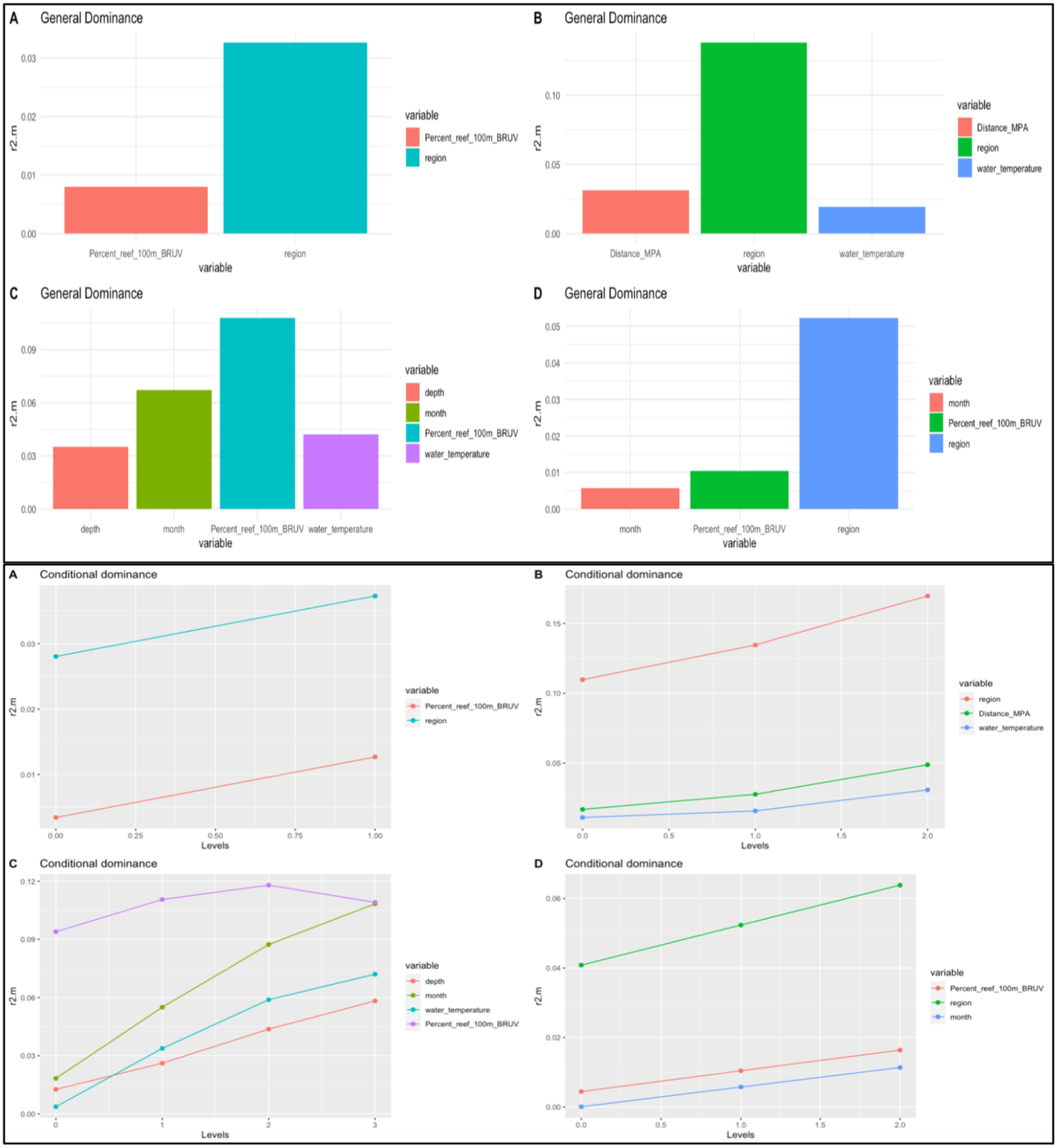
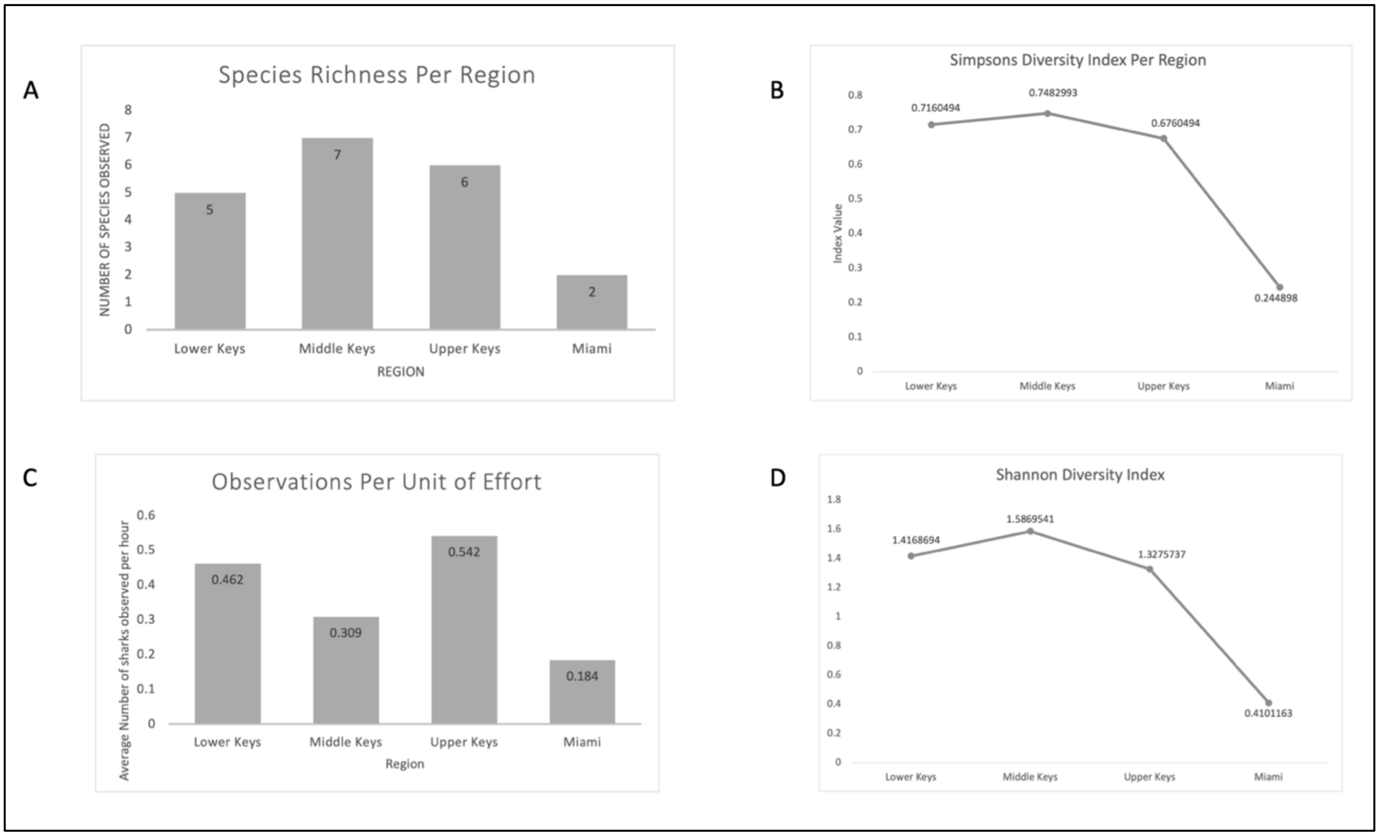


Figure 5: Species Richness by Region (**A**), Simpsons Diversity Index (**B**), Observations per unit effort (**C**), Shannon Diversity Index (**D**).



Discussion:

Drivers of Shark Distribution and Abundance:

This study provided the first wide range examination of the distributions of sharks along the entire length of the Florida Keys. It contributed valuable findings to help our understanding of species-specific occurrences in response to a range of environmental and anthropogenic drivers.

Most of the shark species observed in this study exhibited a wide range in distribution. These species are known to occupy diverse habitats and fill different ecological niches (Roff et al., 2016). Some of the species exhibit strong site fidelity while others are highly mobile (Bond et al., 2012). This study showed that shark occurrences were influenced by the percentage of reef habitat along the Florida Keys reef tract. Region was also an important predictor of shark distribution. It is possible that the same pattern of correlation within regions that was seen for nurse sharks was the same as that for all sharks when species were grouped together because nurse sharks dominated the dataset.

While the amount of reef habitat is a primary indicator of shark presence it must be recognized that each shark species has its own unique life history characteristics. Therefore, it cannot be assumed that all sharks will respond to the same ecological and habitat factors, such as hard coral cover. It was for this reason that a GLM model for each species was developed to examine the impact of the ecological and anthropogenic drivers on the selected species individually.

Previous research has shown that site fidelity of certain shark species is influenced by many factors, including depth, water temperature, and reef habitat (Bond et al., 2012; Espinoza et al., 2014; Rizzari et al., 2014; Vianna et al., 2013). This study showed that reef habitat was the most common significant indicator of shark occurrence. Some studies have similarly documented the importance of reef habitat and marine protected areas for shark populations (Chapman et al., 2013).

Seasonality:

Month was a statistically significant predictor of all sharks when species were combined and individually for lemon sharks. Several shark species appeared in the same months, however the findings for the predictor of month may be biased by the process of surveying different regions in different months. Different species may be present during different seasons and more information on the movement patterns of some of these migratory species is needed. Some of the large-bodied species, including tiger sharks and great hammerhead sharks, are known to migrate along coral reef ecosystems and in pelagic and coastal waters. These species can have large home ranges of up to 100 km^2 (Roff et al., 2016). Great hammerhead sharks exhibit a seasonal southward migration towards the Florida Keys from the Northern Gulf of Mexico in the winter months (Heithaus et al., 2007). Future year-round sampling could possibly shed more light on movement patterns and seasonality of these migratory species.

Anthropogenic Impacts:

Region was identified as an important predictor of shark occurrence. This finding should be interpreted with some caution given that survey effort was not conducted evenly throughout the regions. Significantly fewer sharks were seen in the Miami region and only two species were identified. This indicates that there is possibly a larger pattern of habitat degradation and anthropogenic impacts in waters close to Miami, a result that was not fully examined within the scope of this study. Distance to coastline and distance to no-fishing zones were two predictors that showed a strong negative correlation with one another. This may be due to the absence of no-fishing areas close to Miami and the closer proximity to shore of the reefs surveyed in the Miami region. The general lack of significance of distance to coastline in the models may be due to the uniform distribution of sampling sites along the reef shelf in the Lower, Middle and Upper Keys regions.

This study both directly and indirectly examined several drivers related to anthropogenic disturbance including the occurrence of sharks and their proximity to no-fishing areas. The region of Miami that was surveyed lies outside of the boundaries of the Florida Keys National Marine Sanctuary and is therefore not protected by the Florida Keys National Marine Sanctuary marine zoning scheme (Appendix D). Several studies have shown that large marine protected areas can have significant positive effects on shark conservation (Bond et al., 2012; Chapman et al., 2013). One of the most surprising findings of this study was the lack of effect that the no-fishing areas had on shark occurrences. However, most of the no-fishing areas within the Florida

Keys National Marine Sanctuary are small and many are strategically situated around areas with live coral (Appendix D). Given that percentage of reef habitat is positively correlated with shark occurrence, an argument can be made for protecting more coral reef habitat in the Florida Keys. While the protection of reef habitat may be beneficial, the conservation potential of other management measures must not be overlooked, nor should the value of the other coastal habitats that are used by some sharks (Bruns & Henderson, 2020; Espinoza et al., 2014). Interestingly, this study showed that Caribbean reef sharks, which are known to show strong site fidelity (Garla et al., 2006) and are often resident on specific reefs in the Florida Keys, were less likely to be seen close to no-fishing areas. While the no-fishing areas may provide preferable reef habitat for Caribbean reef sharks, the negative correlation with proximity to no-fishing areas may be due to the impacts of increased human presence in those areas. Previous research has shown that remoteness and location protection in the Florida Keys leads to higher catch rates of larger sharks (Heithaus et al., 2007).

The lack of effect of the predictor "distance to mooring buoy" on any shark species may be because the mooring buoys are relatively evenly distributed through the region. The mooring buoys in the Florida Keys and Miami regions are spread out along the reef bank, with much larger numbers of mooring buoys found surrounding artificial reefs and protected areas that serve as popular diving and snorkeling sites.

Historical Shark Declines:

Overall, the results of this study suggest that the Florida Keys shark population is dominated primarily by nurse sharks, whose unique suction-feeding abilities allow for foraging flexibility (Heithaus et al., 2007). The occurrence of large-bodied and migratory species, such as tiger sharks, great hammerhead sharks and bull sharks were surprisingly low in this study, possibly due to historic fishing pressure on these species.

It is possible that several of the large-bodied species that were rarely observed in this study have been greatly reduced in the Florida Keys (Heithaus, 2004). The reasons for the possible decline of abundance of these species of sharks in the Florida Keys remains relatively unknown but studies like this and others can shed light on the current baseline for shark populations and inform conservation and management decisions (Heithaus et al., 2007). Without reliable historical data, it is impossible to accurately quantify the shifts that may have occurred in shark abundance and community composition in the Florida Keys, however it has been suggested that nurse sharks may have been less vulnerable to the high levels of shark exploitation resulting from the historical commercial gillnet fishery (Heithaus et al., 2007).

It is possible that some of the variation in habitat use recorded in this study may be influenced by predator avoidance and shark community composition. Bonnethead sharks are small bodied and often show strong site fidelity in shallow and more coastal waters (Heupel et al., 2006). The numerous observations of bonnethead sharks found on the reef tract further from shore may mean that larger shark species (great hammerhead sharks and bull sharks), which are known to eat small sharks (Heithaus et al., 2007), have been reduced. Therefore, bonnethead sharks have expanded their habitat range because they are no longer as susceptible to predation from larger sharks.

Study Limitations and Areas for Further Analysis:

Several shark species known to live in the Florida Keys region were not observed during this study and several coastal habitats where sharks are known to occur (such as Backcountry, Hawk Channel and passes between keys) were not included in the BRUV surveys that produced the data used in this study (Heithaus et al., 2007). Additionally, BRUV surveys were limited to relatively shallow depths (<30m) and therefor shark diversity in deeper shelf habitats and pelagic environments was not accounted for.

In comparison, past studies that used longlines and drumlines to sample in a greater variety of habitats observed a higher diversity of species even within a much smaller area of the Florida Keys (Heithaus et al., 2007). All sampling methods have limitations, however, to obtain the most accurate estimates of shark species composition and relative abundance, the use of multiple sampling techniques and types of bait should be used simultaneously (Espinoza et al., 2014; Heithaus et al., 2007). It is well known that the bait plumes from BRUVS attract some shark species more readily than others depending on the type of bait used (Wraith et al., 2013). Additionally, the presence of bait at BRUVS has been shown to influence the behavior of different shark species at BRUVS (Sherman et al., 2020): some sharks may exhibit aggressive behavior at BRUVS while others may show avoidance (Robbins et al., 2006).

A comparison between the species richness found in this study and that reported by Heithaus et al. (2007), shows that while the use of BRUVS is effective in recording many of the species found in the Florida Keys, it may underestimate the occurrences of certain species. The method used for recording species numbers at each survey location, MaxN, may also provide an underestimate in some cases due to the inability to distinguish between different individual sharks and the same shark visiting the BRUV multiple times (See methods section for explanation of how MaxN is calculated).

Survey data used in this study was originally collected as part of the Global FinPrint worldwide assessment of coastal shark populations using standardized methods for selecting survey locations (MacNeil et al., 2020). While this type of standardization is necessary for comparing regions at a global scale, the data loses resolution on a local scale. In the case of the Florida Keys, 140 km of reef tract was surveyed but the BRUV surveys did not encompass all potential shark habitat. Therefore, important data on potential drivers of species distribution and abundance were inevitably missed. The results presented here suggest that the limitations of this method should be considered when interpreting the results of the global scale surveys conducted by Global FinPrint, especially when downscaled to regional (i.e., Florida Keys) or local scales (i.e., subregion or reef system).

The Florida Keys region is considered to have a relatively high abundance of sharks compared to other regions and countries, even though not all shark habitat types were surveyed, nor attractive baits for each shark species were used (MacNeil et al., 2020). If the Global FinPrint data from the Florida Keys region produced an underestimate of shark diversity and abundance, then it can be assumed that many smaller regions (with less continuous reef tract and therefore less sampling) may have an even larger negative bias of shark diversity and abundance. Consequently, this type of negative bias has the potential to make the Florida Keys appear more diverse and productive regarding shark diversity and abundance compared to other countries with lower abundances using the same survey methods.

Improving Future BRUV Sampling:

A limitation of using GoPro cameras and other small, single-lensed cameras for BRUV surveys is the limited field of view. This can also lead to an underestimate of sharks in the area because absence from the video does not necessarily mean that the sharks are absent from the site. A potential alternative to this survey method would be to use 360° cameras. While the use of 360° cameras for BRUV surveys would greatly increase the amount of time and effort needed for data analysis, the benefits of this method include increased potential of shark detection and identification, which translates into more data on rare species, as well as less understood and less frequently observed interactions of different shark species visiting the survey sites.

One of the limitations of addressing the distribution patterns and relative abundance of sharks in this study was the lack of consistent and reliable data relating to water quality and other environmental factors. Despite additional logistical challenges in the field, the collection of water quality data (i.e., water temperature, dissolved oxygen, turbidity, current direction, and flow) in situ, at the depth of the set, would greatly enhance the analysis of species-specific habitat associations. The quality of baited remote video is also impacted by conditions related to water quality (i.e. turbidity at the BRUV) and can impact detection and result in undercounting of sharks that are present (Espinoza et al., 2014).

Water clarity (visibility) was not used as a predictor in the final GLMs because it was an incomplete dataset. However, exploratory modeling using GLM showed that visibility was only potentially significant for nurse sharks. This significance may be due to factors not considered directly in the model such as tidal current strength or the proximity to channels and cuts in the reef. This could also be an artifact of using baited remote video as a survey method. Nurse sharks tend to be relatively darker in color than other sharks and if they were swimming close to the bottom, they may be harder to detect in the video.

Although all sets were deployed during daylight hours as part of the standardized method of this study, it is known that some species of sharks are more active at twilight and at night (Vianna et al., 2013). If survey hours were expanded to include hours of darkness, species diversity and estimates of abundance might increase. Additionally, the comparison of day and night surveys could provide possible changes in shark community composition with respect to the time of day.

Future Data Analysis:

Nearly half of the videos from the approximately 800 sets that were deployed during this study have yet to be fully analyzed. The additional data provided by these sets may fill in some of the gaps in sampling mentioned in this study, as well as provide insight into the distribution of some of the rarely observed shark species. Across the industry, artificial intelligence (AI) and machine learning methods are used to increase the efficiency of baited remote video analysis (Salman et al., 2016). This technology would expedite future BRUV studies focused not only on elasmobranchs and other large-bodied predators, but also on teleost fish species, and potentially provide useful information related to predator/prey relationships on reefs. The use of AI has great potential to increase the usefulness of BRUVs in addressing important questions about shark biology, and subsequent development of effective shark conservation policies. If AI is also coupled with 360-degree cameras and automated collection and downloading of environmental data on each BRUV, one could obtain a higher degree of resolution of critical factors that drive shark diversity and abundance, and in a near real time fashion.

The selection of variables relating to anthropogenic impacts used in this analysis was limited by availability of data. Some potentially important predictor variables that have proven difficult to quantify may need more examination in the future. These include site-specific fishing pressure, boat density in certain regions (as it relates to shark fishing pressure and incidental bycatch), and shore-based population density and increasing development (as these affect water quality and reef health).

<u>Evaluating the Need for Further Shark Conservation Measures:</u>

The results of the worldwide Global FinPrint assessment in 2020 revealed a critical picture of shark conservation in many countries (MacNeil et al., 2020). It included a quantitative assessment of the shark conservation potential in different regions based on projected change from implementing different conservation measures (MacNeil et al., 2020).

It was suggested that management regulations, including bans on gillnets/longlines, catch limits, large spatial shark fishing closures and shark sanctuaries, may have a positive impact on reef-associated shark populations (MacNeil et al., 2020). While the impacts of these measures may be less significant in regions where shark populations are already on the brink of extinction, regions where shark populations are generally classified as abundant have a high potential for recovery from human impacts (MacNeil et al., 2020). One of the regions where Global FinPrint considered shark populations to be abundant is the Florida Keys Archipelago.

Despite the shifts that may have occurred in shark abundance and community composition in the Florida Keys, the establishment of a current baseline assessment of distribution and abundance provided by this study is still important. It can be used to inform current policy decisions regarding future marine spatial planning and shark conservation in the Florida Keys National Marine Sanctuary. Given the diversity in morphologies of coastal shark species in the Florida Keys and variety of ecological niches that they fill, a mixed approach to conservation and management is needed. A single conservation approach does not address the needs of all species. The region surveyed in this study is within the boundaries of both the Florida Keys National Marine Sanctuary and Florida State Waters. This means that several avenues can and should be taken to address shark conservation under either or both state and sanctuary regulations. The following management recommendations should be considered given the findings of this study:

Increase Zoning and Protection of Reef Habitat

Both private and charter fishing boats in the Florida Keys can be found fishing close to the boundaries of some of the closed no-fishing zones or Sanctuary Preservation Areas. This practice (commonly referred to as "fishing the line") can allow for fishermen to benefit from spillover of fish from inside the closed area (Chen et al., 2020). In some cases, the creation of buffer zones surrounding smaller no-fishing areas has been shown to be a useful tool to support conservation efforts inside of marine protected areas (Claudet et al., 2008). These buffer zones often allow a limited amount of extractive activity and can improve the efficacy of the no-fishing area (Claudet et al., 2008). Given the small size of most of the no-fishing zones in the Florida Keys National Marine Sanctuary, the creation of buffer zones would provide additional protection to important reef habitat for sharks.

In the Florida Keys, many artificial reefs have been created by shipwrecks (Pendleton, 2004). Many of these wrecks were created purposefully to encourage recreation in the form of diving and snorkeling. Artificial reefs can provide important habitat to fish species (Pendleton, 2004). Due to the increasing pressure on coral reefs from recreational activities, it is possible that the creation of more artificial reefs may take some of the pressure off native reef habitats that coastal sharks utilize for feeding. To support the process of increasing marine zoning, a previous study of stakeholder perceptions of marine reserves in the Florida Keys National Marine Sanctuary suggested numerous ways in which marine resource managers can improve their public outreach and information dissemination strategies (Suman et al., 1999). One recommendation to increase local buy-in is to better integrating fishers into the planning process (Suman et al., 1999). Fishers hold important resource information that is necessary for the effective marine zoning, and it is important to acknowledge and incorporate this information in the planning process. Other stakeholder groups, including dive operators and conservation groups, currently demonstrate a much higher level of participation in the marine protected area designation process (Suman et al., 1999).

The coastal waters adjacent to the city of Miami are not currently protected by no-fishing zones. Given the low abundance and biodiversity of sharks in the region, it may be beneficial to implement a marine zoning scheme in the Miami area to minimize fishing impacts on sharks in the area and protect important habitat.

The significance of the recommendation for increased zoning to shark conservation would be to protect shark habitat and prey species and increase the area in which sharks can safely reside without being impacted by fishing pressure. Such a zoning measure could potentially provide increased resiliency for coral reefs against degradation caused by anthropogenic disturbance.

Require Vessel Permits and Catch Reporting

The Florida Fish and Wildlife Conservation Commission claims that the permit system for shore-based shark fishing allows important data to be collected on numbers of people participating in shore-based shark fishing (Appendix E). While this information can be valuable in monitoring shark fishing impacts close to shore, many more anglers engage in shark fishing on offshore reefs in the Florida Keys.

The next step in shark conservation is for managers and policy makers to obtain consistent data on the harvest and fishing impacts on all shark species. A permit system resembling the shore-based shark fishing permit system should be implemented for recreational shark fishing vessels. Accurately recorded locations and numbers of people engaging in the offshore recreational shark fishery would provide valuable information that could be used to improve shark conservation and management.

The development of cell phone applications that log location and allow for shark catch photos to be uploaded and identified could greatly expedite the record keeping for the recreational catch and release shark fishery. Data that is recorded for fishing locations would need to be kept confidential and not displayed in any public form. Studies from the Florida Keys have shown that data on recreational fishing distribution is hard to obtain because anglers are hesitant to release proprietary fishing information. If anglers trust that data will be kept confidential, it may be easier to obtain fisheries data that can contribute to conservation efforts (Black et al., 2015). Monitoring and recordkeeping of shark catch data would allow for better tracking of long-term changes in shark populations. This recommendation, to require vessel permits and catch reporting, would likely have a significant impact on shark conservation.

Ban Offshore Chumming for Sharks

Chumming the waters with bait attracts sharks to an area (Hammerschlag et al., 2012). While some bait may attract certain species more than others, the possibility of catching a threatened or endangered shark species increases when chumming. Some recreational fishermen in the Florida Keys have reported chumming the water for large fish. Even though the fishermen were not targeting sharks, sharks are often attracted to this chum and interfere with the fishing efforts. Just as chumming for sharks while engaging in shore-based fishing was banned in 2019, this practice should also be banned on fishing vessels and other private boats in Florida State Waters in the Florida Keys. Better protection of offshore sharks is imperative for their long-term conservation.

Ultimately, conservation efforts that aim to protect and recover coastal shark species in the Florida Keys should one day allow us to regain the historical populations that once existed. To this end, time should not be wasted in implementing the management strategies suggested above. All management strategies that are implemented must also be adaptable, as shark species distribution, abundance, and community composition are not stagnant and continue to change with increasing anthropogenic impacts and climate change drivers.

This study found that shark occurrences in the Florida Keys were highly influenced by the percentage of reef habitat along the reef tract. Region was also an important predictor of shark occurrences, with the Miami region showing the lowest species richness and abundance, and the Middle Keys region having the highest. Shark surveys showed predominantly nurse sharks (*G. cirratum*) and bonnethead sharks (*S. tiburo*), two species associated with reefs and coastal habitats. Widespread historic fishing pressure on large-bodied and migratory species may account for the relatively low number of occurrences of great hammerhead sharks (*S. mokarran*), bull sharks (*C. leucas*) and tiger sharks (*G. cuvier*). From these findings several management recommendations specific to shark conservation are presented including the need for increased habitat protection, and the minimization of fishing pressure on sharks.

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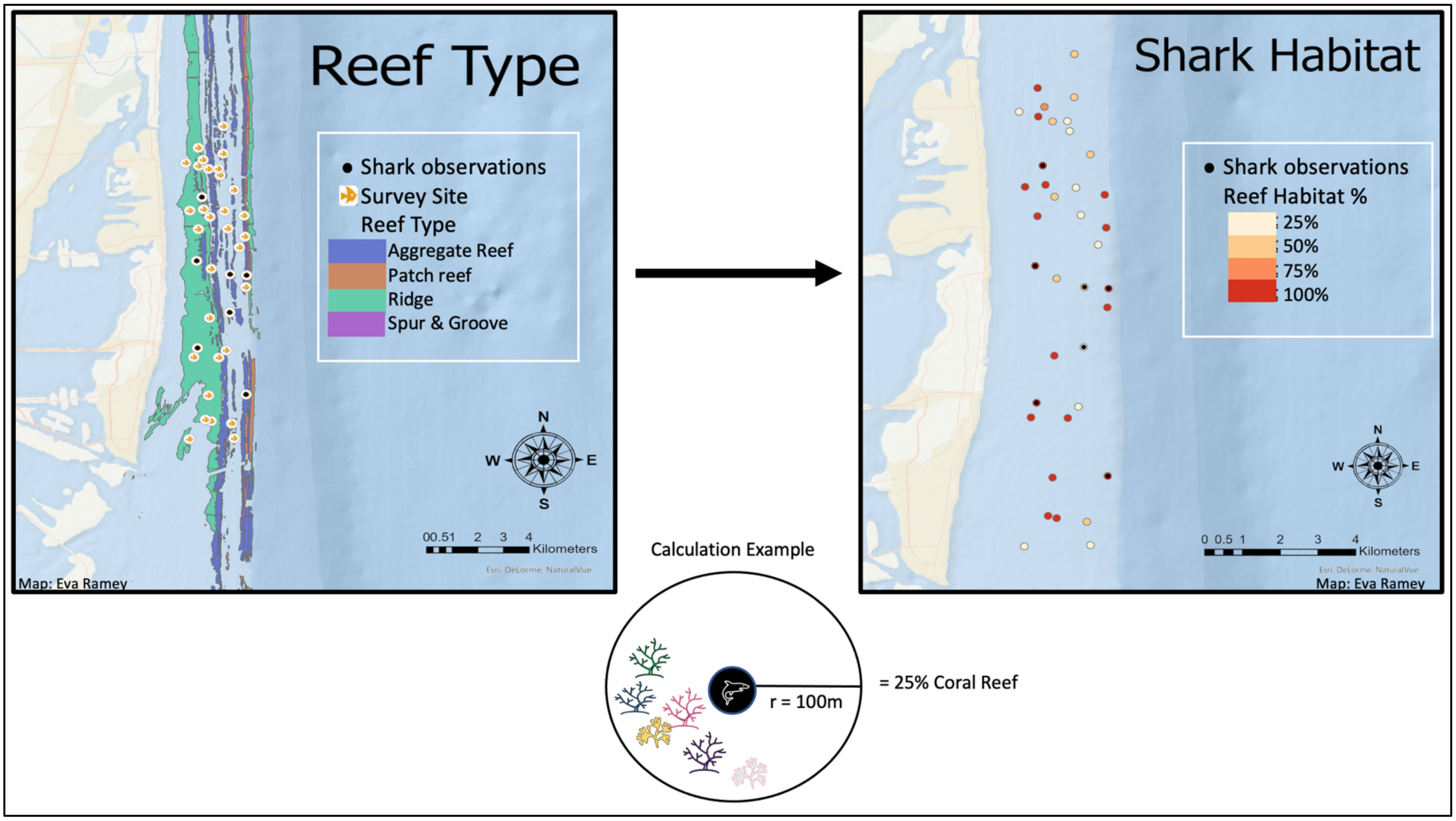
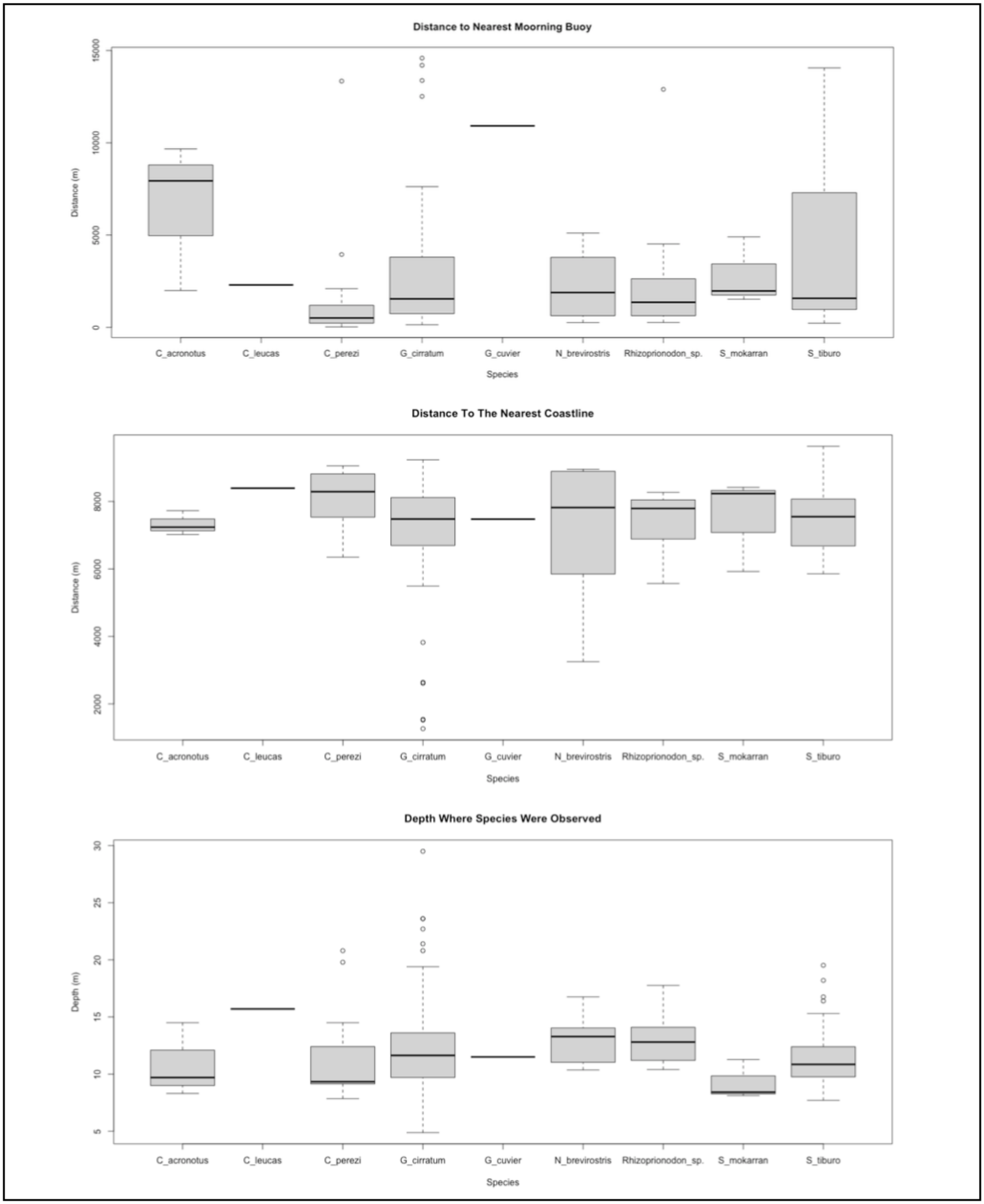
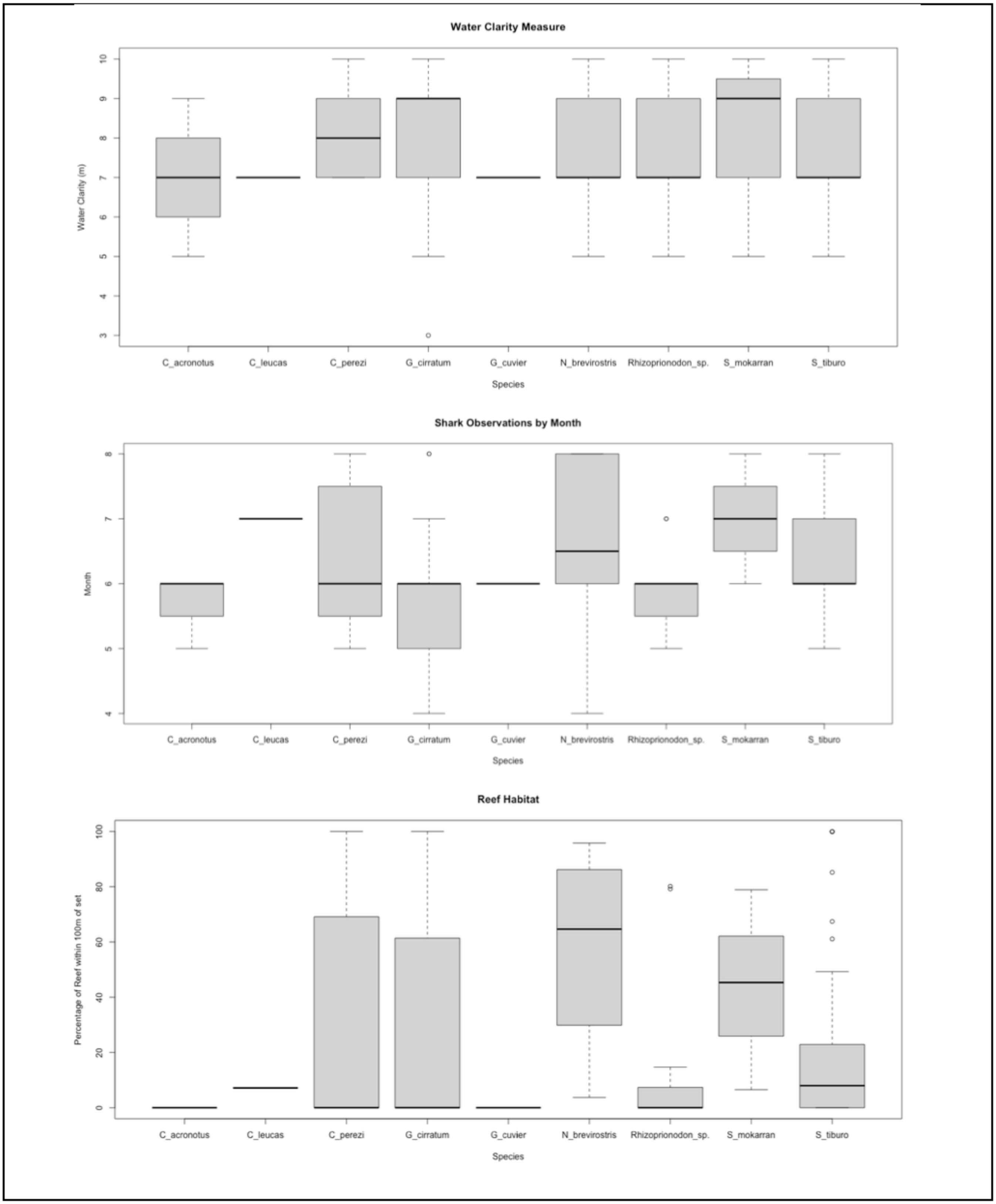
Appendix A: An example of how reef habitat was calculated per survey site. Map of reef type shows the Florida Keys reef tract being broken down by class and excluding all non-reef habitat. Map of shark habitat shows color coded dots based on the calculated percentage of reef habitat within the 100 square meter radius around each survey point.

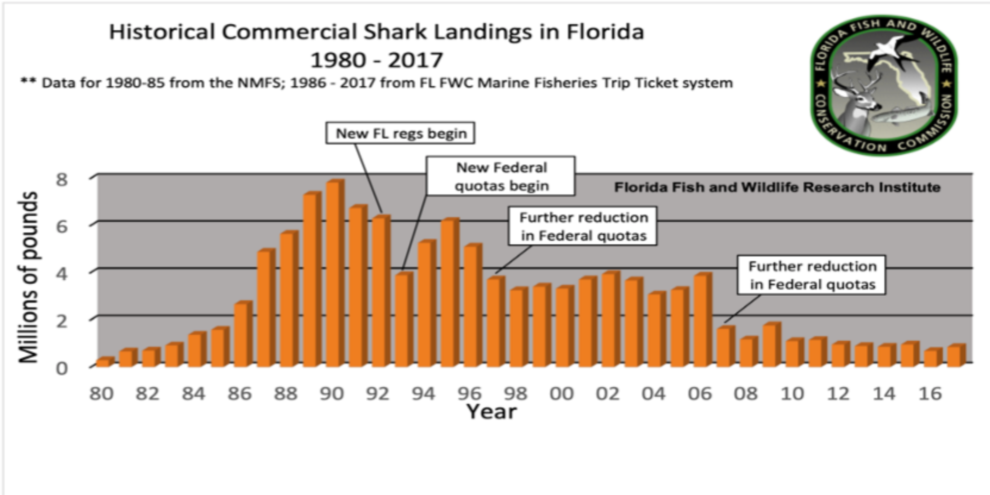


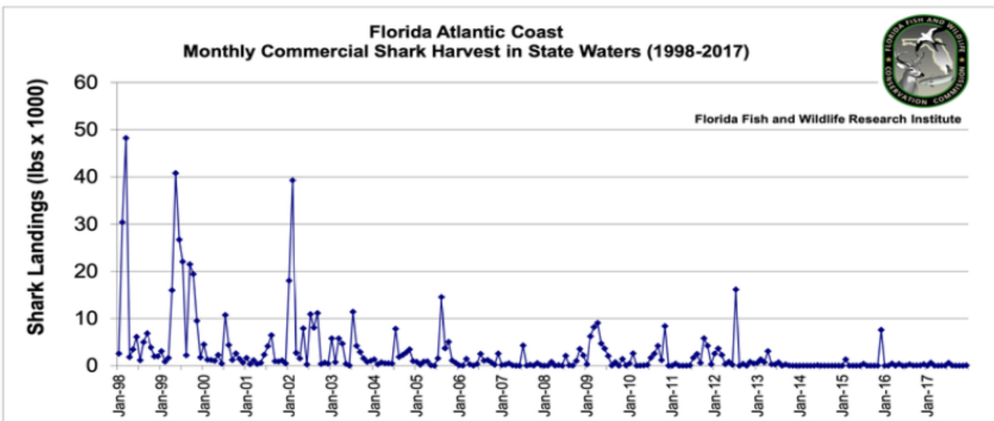
Appendix B: Box and whisker plots of variables used in GLM analysis by species. Bars represent the median for each species, boxes represent the lower and upper quantiles and whiskers show the highest and lowest observed values.

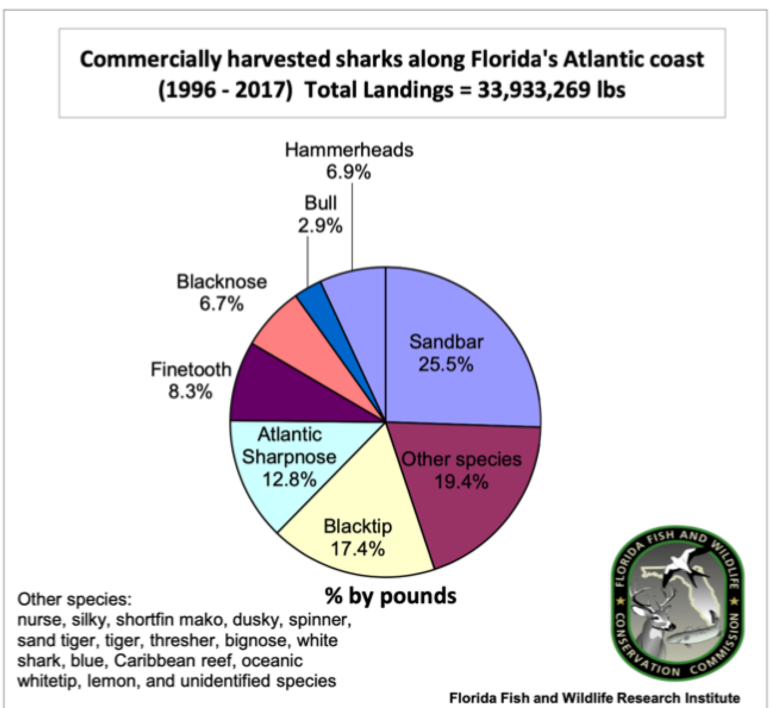



Water Clarity Measure
Water Clarity (m)
Species
C_acronotus
C_leucas
C_perezi
G_cirratum
G_cuvier
N_brevirostris
Rhizoprionodon_sp.
S_mokarran
S_tiburo
Shark Observations by Month
Month
Reef Habitat
Percentage of Reef within 100m of set

Appendix C: Data on historic shark landings in the Southern Florida retrieved from the Florida Fish and wildlife Conservation Commission website.







Appendix D: Current Marine Zoning Scheme, The Florida Keys National Marine Sanctuary.

Overview:
The goal of the Florida Keys National Marine Sanctuary (FKNMS) is to protect the marine resources of the Florida Keys (National Marine Sanctuary Program, 2007). The FKNMS is administered by NOAA and is jointly managed under a co-trustee agreement with the State of Florida (National Marine Sanctuary Program, 2007). In 2001, the sanctuary's boundary was amended to include the Tortugas Ecological Reserve (National Marine Sanctuary Program, 2007).

Marine Zoning:
Before the FKNMS was established, two smaller sanctuaries (Key Largo and Looe Key) protected reef habitat within the archipelago (National Marine Sanctuary Program, 2007). The current FKNMS boundaries encompass both smaller sanctuaries as well as four wildlife refuges (managed by the U.S. Fish and Wildlife Service), six state parks and three state aquatic preserves (National Marine Sanctuary Program, 2007). Adjacent to the FKNMS are three national parks, including Everglades National Park, Biscayne National Park and Dry Tortugas National Park (National Marine Sanctuary Program, 2007). There are five types of zones in the FKNMS:

Sanctuary Preservation Areas (SPAs)
There are 18 small SPAs that combined total about 6.5 square nautical miles of the FKNMS (National Marine Sanctuary Program, 2007). These areas protect shallow areas of reef by limiting consumptive activity including fishing. Non-consumptive activities such as diving, and snorkeling are allowed within the SPAs (National Marine Sanctuary Program, 2007).

Ecological Reserves
Two Ecological Reserves (Western Sambo Ecological Reserve and Tortugas Ecological Reserve) make up about 160 square nautical miles of the FKNMS (National Marine Sanctuary Program, 2007). Ecological Reserves seek to protect diverse habitats including spawning grounds and nursery areas for fish (National Marine Sanctuary Program, 2007). Consumptive activities are banned in Ecological Reserves and non-consumptive activities are only allowed if they are compatible with resource protection (National Marine Sanctuary Program, 2007).

Special-use (Research-only) Areas
Research areas are set aside solely for the research and education (National Marine Sanctuary Program, 2007).

Wildlife Management Areas
A total of 27 Wildlife Management Areas can be found within in the FKNMS. Wildlife Management Areas seek to protect threatened and endangered wildlife and their habitats, while also allowing for public use (National Marine Sanctuary Program, 2007). These zones include bird and sea turtle nesting areas and have their own internal zoning plans with no-access buffers, no-motor zones, no-wake zones, and closed zones (National Marine Sanctuary Program, 2007).

Existing Management Areas
Existing Management Areas are protected areas that were established prior to the 1996 Sanctuary management plan (National Marine Sanctuary Program, 2007). Existing Management Areas are

managed in partnership with prior existing authorities in these areas including the Florida Department of Environmental Protection, and the U.S. Fish and Wildlife Service (National Marine Sanctuary Program, 2007).

References:

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Appendix E: Current Shark Fishing Regulations, Florida Fish and Wildlife Conservation Commission

Commercial Shark Fishing:
Commercial shark fishing in Florida State Waters has been a contributing factor to the decline in shark populations and commercial shark landings in Florida have decreased in recent years due to more stringent federal quotas (Appendix C)(Florida Fish and Wildlife Conservation Commission, n.d.-b).

Shore-Based Shark Fishing:
In 2019, the Florida Fish and Wildlife Conservation Commission approved changes to current shore-based recreational shark fishing regulations to increase the safety to both sharks and humans (Turner, 2019). Any shark fishing that is shore based now requires that anglers take an annual "shark-smart" fishing education course and get a shore-based shark fishing permit (Florida Fish and Wildlife Conservation Commission, n.d.-a). Shore-based shark fishing permits are required for anglers over the age of 16 (Florida Fish and Wildlife Conservation Commission, n.d.-a). Anglers over the age of 65, who are exempt from holding many other fishing permits, are required to obtain a permit to engage in shore-based shark fishing (Florida Fish and Wildlife Conservation Commission, n.d.-a).

Florida Fish and Wildlife Conservation Commission's Shore-Based Shark Fishing course teaches basic hark identification and points out common mistakes that are made in shark identification between banned and harvestable species. Basic shark identification includes fin placement, tail shape and interdorsal ridge placement. If a banned shark species is caught, the shark must be kept in the water with its gills submerged and released immediately (Florida Fish and Wildlife Conservation Commission, n.d.-a). If the species cannot be identified, it must also be released. If the shark dies in the struggle when it is caught, anglers must call the Fish Kill Hotline (800-636-0511) . If a sawfish or a giant manta ray are accidentally caught, anglers must report the catch the Florida Fish and Wildlife at 844-472-9347 for sawfish , and to NOAA fisheries at 727-824-5312 for mantas (Florida Fish and Wildlife Conservation Commission, n.d.-a).

Required fishing gear includes non-offset and non-stainless steel circle hooks, along with heavy tackle (minimum 80-pound test)(Florida Fish and Wildlife Conservation Commission, n.d.-a). The longer it takes for a shark to be released, the less likely it is to survive. Therefore, the Shore-Based Shark Fishing Course teaches recreational fishermen the following best practices: minimize fight time, do not target sharks if conditions are rough, never bring a shark over 5 feet long onto a vessel unless it is to be harvested (Florida Fish and Wildlife Conservation Commission, n.d.-a). To protect both people and sharks, chumming for sharks from shore is prohibited.

Charter Boat Shark Fishing:
While regulations have been put in place to require permits and education for shore-based shark fishing, shark fishing from recreational charter boats remains an economically viable industry in the Florida Keys (Figueira & Coleman, 2010). The Florida Keys Fun Fishing website quotes that, “Sharks are capable of putting any angler to task as these fish are big, mean, powerful, unpredictable and most of all EXCITING!” Other recreational shark fishing charter companies include similar language on their websites, citing the challenge and excitement of catching large fish and sharks. Several of these websites also specify that they engage in catch and release fishing of sharks. Of 22 recreational shark fishing charter boat captains who were surveyed in Florida in 2014, 17 of them responded that a healthy population of sharks was very important to them (Shiffman & Hammerschlag, 2014). In some regions, the economic value of sharks has been shown to be greater alive than dead (Vianna et al., 2012).

In 2014, scientists from the University of Miami argued that if the right measures were taken, charter boat catch-and-release fishing of sharks in the Florida Keys could contribute to their conservation (Shiffman & Hammerschlag, 2014). However, it was not clearly specified in their report what the proper measures to be taken are. Regulations that ensure shark safety are needed monitor the fishery to ensure compliance and track impact, then the charter boat catch-and-release fishing of sharks in the Florida Keys may be able to contribute to conservation initiatives through education, awareness, and monetary support.

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Appendix F: Best Fit GLM Model Summaries

```
Call:
glm(formula = presence ~ Percent_reef_100m_BRUV + region + month,
    family = binomial(logit), data = sharks)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.4504  -0.9633  -0.6573   1.1645   2.1447

Coefficients:
                        Estimate Std. Error z value Pr(>|z|)
(Intercept)            -4.263477   1.645641  -2.591  0.00958 **
Percent_reef_100m_BRUV  0.010948   0.004178   2.620  0.00879 **
regionMiami            -0.160769   0.748844  -0.215  0.83001
regionMiddle_Keys      -1.061753   0.512340  -2.072  0.03823 *
regionUpper_Keys        0.948797   0.486850   1.949  0.05131 .
month                   0.557518   0.261940   2.128  0.03330 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 427.96  on 332  degrees of freedom
Residual deviance: 398.66  on 327  degrees of freedom
AIC: 410.66

Number of Fisher Scoring iterations: 4

Call:
glm(formula = presence ~ Percent_reef_100m_BRUV + region, family = binomial(logit),
    data = cirratum)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.0172  -0.7314  -0.5183  -0.4267   2.2098

Coefficients:
                        Estimate Std. Error z value Pr(>|z|)
(Intercept)            -2.068673   0.545264  -3.794 0.000148 ***
Percent_reef_100m_BRUV  0.009896   0.004940   2.003 0.045152 *
regionMiami            -0.242104   0.601685  -0.402 0.687407
regionMiddle_Keys      -0.281851   0.527248  -0.535 0.592947
regionUpper_Keys        0.886562   0.552838   1.604 0.108790
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 314.13  on 332  degrees of freedom
Residual deviance: 301.33  on 328  degrees of freedom
AIC: 311.33

Number of Fisher Scoring iterations: 4


Call:
glm(formula = presence ~ depth + Percent_reef_100m_BRUV + month +
    water_temperature, family = binomial(logit), data = brevirostris)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-1.12070  -0.18339  -0.09890  -0.03975   2.74712

Coefficients:
                       Estimate Std. Error z value Pr(>|z|)
(Intercept)            22.57263   17.99605   1.254   0.2097
depth                   0.25131    0.12322   2.039   0.0414 *
Percent_reef_100m_BRUV  0.03144    0.01249   2.518   0.0118 *
month                   2.15463    0.93610   2.302   0.0214 *
```

```
water_temperature      -1.55113    0.81165  -1.911   0.0560 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 67.923  on 332  degrees of freedom
Residual deviance: 50.781  on 328  degrees of freedom
AIC: 60.781

Number of Fisher Scoring iterations: 8

Call:
glm(formula = presence ~ region + Distance_MPA + water_temperature,
    family = binomial(logit), data = sharpnose)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-0.77819  -0.27084  -0.14199  -0.00008   2.84895

Coefficients:
                    Estimate Std. Error z value Pr(>|z|)
(Intercept)       -6.084e+01  2.741e+03  -0.022   0.9823
regionMiami       -1.642e+01  3.911e+03  -0.004   0.9967
regionMiddle_Keys  1.243e+01  2.741e+03   0.005   0.9964
regionUpper_Keys   1.674e+01  2.741e+03   0.006   0.9951
Distance_MPA       2.841e-04  1.373e-04   2.069   0.0385 *
water_temperature  1.410e+00  8.660e-01   1.628   0.1035
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 89.808  on 332  degrees of freedom
Residual deviance: 72.893  on 327  degrees of freedom
AIC: 84.893

Number of Fisher Scoring iterations: 19


Call:
glm(formula = presence ~ Distance_MPA, family = binomial(logit),
    data = perezi)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.4070  -0.3504  -0.2701  -0.1706   3.3005

Coefficients:
               Estimate Std. Error z value Pr(>|z|)
(Intercept)  -2.4494996  0.3950264  -6.201 5.62e-10 ***
Distance_MPA -0.0002528  0.0001475  -1.713   0.0867 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 109.81  on 332  degrees of freedom
Residual deviance: 102.37  on 331  degrees of freedom
AIC: 106.37

Number of Fisher Scoring iterations: 9


Call:
glm(formula = presence ~ region, family = binomial(logit), data = tiburo)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.5793  -0.5793  -0.4155  -0.4001   2.2649
```

```
Coefficients:
                    Estimate Std. Error z value Pr(>|z|)    
(Intercept)         -2.48491    0.60093  -4.135 3.55e-05 ***
regionMiami        -16.08116 1058.11187  -0.015    0.988    
regionMiddle_Keys    0.07878    0.67839   0.116    0.908    
regionUpper_Keys     0.78495    0.65066   1.206    0.228    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 215.18  on 332  degrees of freedom
Residual deviance: 202.93  on 329  degrees of freedom
AIC: 210.93

Number of Fisher Scoring iterations: 17
```