






FEATURE ARTICLE

Depredation rates and spatial overlap between Great Hammerheads and Tarpon in a recreational fishing hot spot

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Abstract

Objective: Shark depredation, the full or partial consumption of a hooked fish by a shark before it is landed, is an increasing source of human–wildlife conflict in recreational fisheries. Reports of shark depredation in the catch-and-release Tarpon (also known as Atlantic Tarpon) *Megalops atlanticus* fishery in the Florida Keys are increasing, specifically in Bahia Honda, a recreational fishing hot spot and a putative Tarpon prespawning aggregation site.

Methods: Using visual surveys of fishing in Bahia Honda, we quantified depredation rates and drivers of depredation. With acoustic telemetry, we simultaneously tracked 51 Tarpon and 14 Great Hammerheads (also known as Great Hammerhead Sharks) *Sphyrna mokarran*, the most common shark to depredate Tarpon, to quantify residency and spatial overlap in Bahia Honda.

Result: During the visual survey, 394 Tarpon were hooked. The combined observed shark depredation and immediate postrelease predation rate was 15.3% for Tarpon that were fought longer than 5 min. Survival analysis and decision trees showed that depredation risk was highest in the first 5–12 min of the fight and on the outgoing current. During the spawning season, Great Hammerheads shifted their space use in Bahia Honda to overlap with Tarpon core use areas. Great Hammerheads restricted their space use on the outgoing current when compared to the incoming current, which could drive increased shark–angler interactions.

Conclusion: Bahia Honda has clear ecological importance for both Tarpon and Great Hammerheads as a prespawning aggregation and feeding ground. The observed depredation mortality and postrelease predation mortality raise conservation concerns for the fishery. Efforts to educate anglers to improve best practices, including reducing fight times and ending a fight prematurely when sharks are present, will be essential to increase Tarpon survival and reduce shark–angler conflict.

KEYWORDS

acoustic telemetry, depredation, elasmobranch, Florida Keys, human–wildlife conflict

INTRODUCTION

Depredation, the full or partial consumption of a hooked fish before it is landed, is a socioecological problem raising conservation concerns in fisheries (Tixier et al. 2020b; Mitchell et al. 2022). Depredation is mainly committed by large-bodied species, including marine mammals (Read 2008; Werner et al. 2015), sharks (MacNeil et al. 2009; Mitchell et al. 2018a), and other fishes like groupers (Shideler et al. 2015). Depredation poses a three-pronged problem to fisheries by impacting the target species, predators, and fishers. If depredation occurs at a high frequency, it could represent a substantial source of mortality for target species. If unquantified, this can result in inaccurate stock assessments and influence population sustainability for target species (Peterson and Hanselman 2017; Sippel et al. 2017; Tixier et al. 2020a). As is common in terrestrial human–wildlife conflict (Mateo-Tomás et al. 2012; Ontiri et al. 2019; Viollaz et al. 2021), depredation can lead to retaliation against the predator (e.g., targeted physical harm or harvest) by fishers, which raises conservation concerns for *k*-selected species that are vulnerable to overharvest (Tixier et al. 2020b). Finally, depredation is both financially and emotionally taxing for fishers, resulting in the loss of valuable commercial catch (Gilman et al. 2008; Janc et al. 2021), expensive fishing gear (Tixier et al. 2020b), and return clients for charter fishing guides in addition to decreasing positive feelings toward recreational fishing (Casselberry et al. 2022). Ultimately, shark depredation is a source of deep-rooted, conflicting conservation needs among managers, conservationists, and anglers who are concerned for the sustainability of their target species (Casselberry et al. 2022; Hoel et al. 2022).

Although the majority of shark depredation research has focused on commercial fisheries (as reviewed by Gilman et al. 2007, Mitchell et al. 2018a, and Tixier et al. 2020b), shark depredation and associated angler conflicts do exist in recreational fisheries, particularly in the United States and Australia (Powell and Wells 2011; Weir and Nicolson 2014; Cook et al. 2015; Casselberry et al. 2022; Coulson et al. 2022). In the United States, anglers report that shark depredation is increasing, especially in Florida (Casselberry et al. 2022). Increased shark–angler interactions could be driven in part by both an increase in the popularity of recreational saltwater fishing (Shertzer et al. 2019; Midway et al. 2021) and regional shark conservation success, as closely regulated commercial and recreational fisheries have helped to stabilize declining

Impact statement

Shark depredation in recreational fisheries is an increasing source of human–wildlife conflict in the United States. This study quantified shark depredation in the Tarpon fishery and characterized the spatial ecology of Great Hammerheads and Tarpon in Bahia Honda in the Florida Keys.

shark populations (Curtis et al. 2014; Peterson et al. 2017; Carlson et al. 2019). Not only can high shark depredation rates potentially impact recreationally targeted fish populations (Kerns et al. 2012; Holder et al. 2020), but also sharks may alter their foraging behavior after successfully depredating. This can increase the potential for depredation to occur in the future (Mitchell et al. 2020), thus increasing the possibility that anglers will retaliate via targeted harvest of sharks (Casselberry et al. 2022). There is a clear need to quantify depredation rates in vulnerable fisheries and to work proactively with resource managers and anglers to develop solutions for reducing these negative interactions.

The recreational fishery for Tarpon (also known as Atlantic Tarpon) *Megalops atlanticus* is one of the most popular recreational fisheries in Florida (Tilmant 1989; Adams and Cooke 2015; Camp et al. 2018). In the spring, many adult Tarpon migrate to the Florida Keys from the Gulf of Mexico and southeastern U.S. Atlantic coasts (Griffin et al. 2018; Luo et al. 2020), forming large coastal prespawning aggregations. These migrations generally occur from April to June, when sea surface temperatures are between 26°C and 28°C (Griffin et al. 2022a), and the majority of females complete spawning by July (Crabtree et al. 1997). Prespawning aggregations are often the target of intense recreational fishing pressure since they occur close to shore, often in channels and passes (Sargeant 1991; Crabtree et al. 1992). The Tarpon sport fishery has served as an important source of income for Florida Keys residents since the 1920s (Schroeder 1924), and the flats fishery—consisting of Tarpon, Permit *Trachinotus falcatus*, and Bonefish *Albula vulpes*—contributes US\$272 million annually for the south Florida economy (Smith et al. 2023). In Florida, the fishery is almost exclusively catch and release. Since 1989, the Florida Fish and Wildlife Conservation Commission has sold limited tags to anglers who wish to harvest a state or world record Tarpon, and less than 44 tags have been sold each year since the early

2000s (Guindon 2011; B. Waters, Florida Fish and Wildlife Conservation Commission, personal communication).

Anecdotally, sharks have been a documented source of Tarpon fishing mortality in Florida throughout the past century (Springer 1938, 1940; see White and Brennen 2010 for a compilation of multiple historical accounts). Shark depredation was first recorded as early as 1911 in Boca Grande Pass and Captiva Pass on the west coast of Florida (Dimock 1911). Interactions with Great Hammerheads (also known as Great Hammerhaed Sharks) *Sphyrna mokarran* for anglers fishing in Bahia Honda Channel in the Florida Keys were reportedly common from the 1920s through 1940s (DeMaria 1996). Using active acoustic tracking, Guindon (2011) quantified postrelease mortality (i.e., both predation mortality and mortality from exhaustion) in the Tarpon fishery in Boca Grande Pass and Tampa Bay, Florida, and showed that overall postrelease mortality was 13%, with 64% of that mortality caused by shark predation. Guindon (2011) noted instances of depredation during the study but did not quantify depredation rates.

In the Florida Keys Tarpon fishery, depredation is reportedly increasing, with interactions occurring primarily with Great Hammerheads and Bull Sharks *Carcharhinus leucas* (A. J. Adams, personal observation). Griffin et al. (2022b) used broadscale acoustic telemetry to show that Great Hammerheads, Bull Sharks, and Tarpon demonstrated nonrandom overlap at specific sites throughout the Florida Keys, with sharks arriving at sites less than 1 h after an individual Tarpon was detected. These sites often coincided with known or putative Tarpon prespawning aggregation sites that are targeted by recreational anglers, including the Bahia Honda Channel (Griffin et al. 2022b). Tarpon anglers in Bahia Honda reported frequent interactions with Great Hammerheads, with charter fishing guides raising concerns about the future sustainability of their catch-and-release fishery (A. J. Danylchuk, personal observation).

In this study, we used a multifaceted approach to quantify shark depredation rates, identify factors that drive depredation, and examine spatial overlap between Great Hammerheads and Tarpon in Bahia Honda. To do this, we conducted standardized visual surveys of Tarpon fishing activities and used acoustic telemetry to monitor the movements of Great Hammerheads and Tarpon in Bahia Honda Channel, where fishing pressure is concentrated. This integrated approach aimed to provide a comprehensive understanding of Great Hammerhead and Tarpon spatial ecology as it relates to depredation in the Tarpon fishery in Bahia Honda. Moreover, such an assessment can lay the foundation for potential solutions aimed at mitigating mortality in the Tarpon fishery, as well as mitigating potential retaliation against sharks.

METHODS

Study area and recreational fishing practices

Bahia Honda Channel is located at the easternmost border of the lower Florida Keys, United States, between Bahia Honda Key to the east and West Summerland Key to the west (Figure 1). The channel lies within the boundaries of the Florida Keys National Marine Sanctuary (FKNMS) and is one of the deepest natural passes between keys (~7.6 m deep), connecting the Gulf of Mexico with the Atlantic Ocean (Hopkins 1986; Office of National Marine Sanctuaries 2009). It is a high-flow channel with a mean speed of 0.11 m/s (Smith 1994). The channel is traversed by two parallel bridges, each approximately 2 km long (Figure 1). To the north is the U.S. Route 1 Bridge, the construction of which was completed in 1982 and which is currently in use (Hopkins 1986); to the south are the remains of the Henry Flagler Overseas Railroad Bridge, which was built in 1912 (Willing 1957; Hopkins 1986). The old railroad bridge is not accessible to the public from land, except for a short span of bridge that is used as an observation deck for visitors to Bahia Honda State Park.

Bahia Honda is a well-known and popular fishing hot spot where Tarpon can be reliably captured throughout the spring spawning season, particularly by anglers that fish with spinning tackle (Sargeant 1991). Currently, fishing for Tarpon occurs almost exclusively from boats that anchor between the U.S. Route 1 Bridge pilings. Boat orientation to the bridge varies based on the direction of current flow, with boats anchoring north of the bridge on the outgoing current (ebb; current flowing from north to south) and south of the bridge on the incoming current (flood; current flowing from south to north). Anglers then drift their lines through the bridge pilings with the current. Once a Tarpon is hooked, the boat starts its engine, detaches from the anchor, and navigates through the bridge pilings, which allows the fight to occur away from the bridge as the boat drifts with the current.

Visual surveys of Tarpon angling and depredation

To quantify depredation rates in the Bahia Honda Tarpon fishery, visual surveys were conducted from the old railroad bridge that overlooks the U.S. Route 1 Bridge, where anglers target Tarpon during the prespawning aggregation. Visual survey days were selected based on a stratified random sampling design commonly used in creel surveys (Zischke et al. 2012), with a total of 5 days/week comprised of both weekend days and three weekdays from April 1

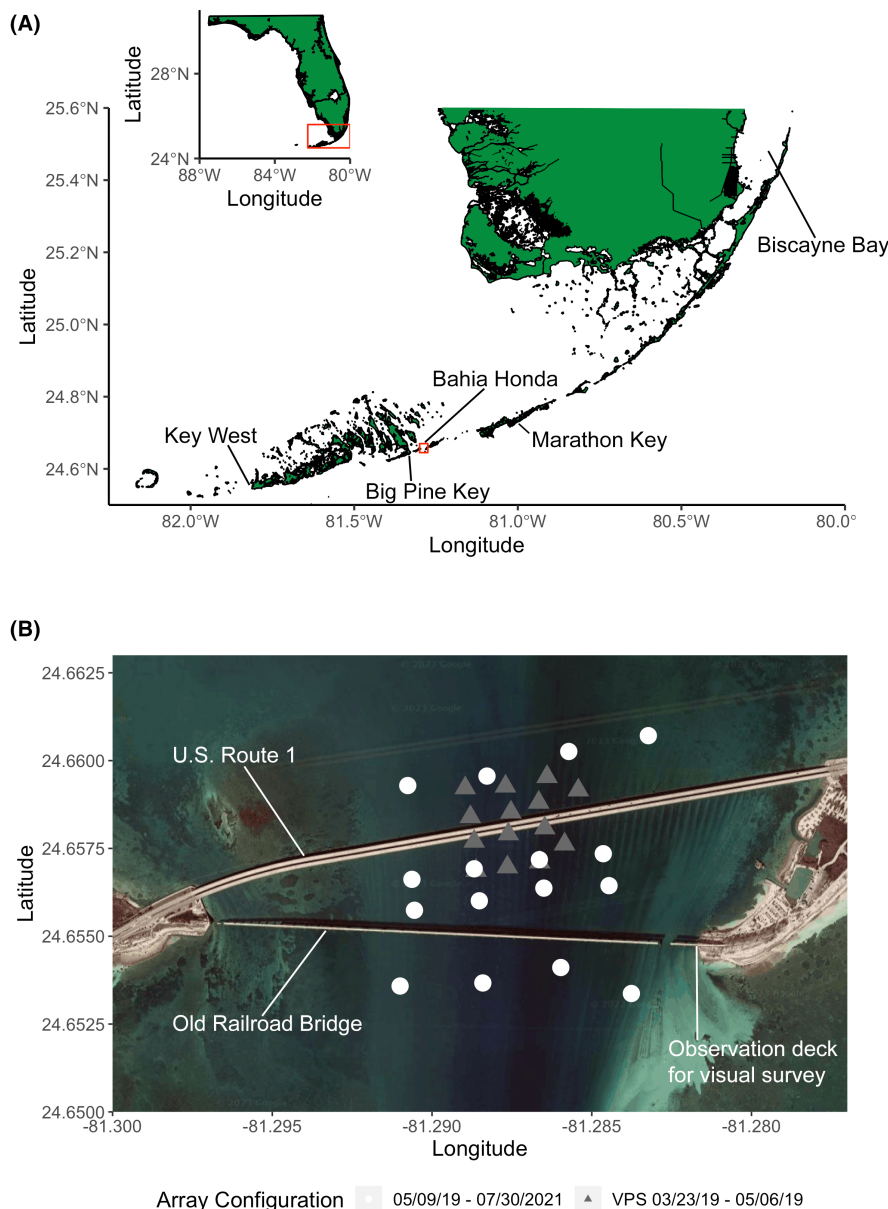


FIGURE 1 (A) Map of south Florida, with the location of the Bahia Honda Channel (red square) and an inset map of Florida; and (B) map of Bahia Honda Channel, with the original array configuration (gray triangles; virtual positioning system [VPS]) and the configuration that was maintained for the majority of the study (white circles).

to May 28, 2019, a period that coincided with the peak of the Tarpon recreational fishery in Bahia Honda. Surveys started at sunrise (between 0630 and 0700 hours) and ran until 1600 hours or started at 1000 hours and ran until sunset (between 1945 and 2015 hours). Observations were made using binoculars (magnification = 12×50 ; Crossfire model; Vortex Optics).

Fishing effort was continuously monitored throughout the day, with data recorded at 30-min intervals, including the time of day, number of boats fishing, tide, and current direction. When a boat left its anchor after hooking a Tarpon, the time was recorded. The angling event was monitored throughout its duration, and the

fight time, the number of other fish being fought on any boat in the channel, the number of times the Tarpon jumped, a description of the boat, and the fate of the fish were recorded. The fate of each fish was then categorized into one of seven designations detailed in Table 1, including landed, depredation, and postrelease predation. If a depredation event or postrelease predation occurred, the individual shark was identified, when possible, based on dorsal fin tags or—in the instance of one individual—a unique injury to the dorsal fin. The general location of the depredation in relation to the bridges was also noted. A depredation event was recorded if a shark was visually observed to make contact

TABLE 1 Observations of Tarpon fate in Bahia Honda Channel, Florida, during the standardized visual survey. Instances of depredation and postrelease predation were recorded if the observer saw the shark engage with the Tarpon. When possible, this was also confirmed with the angler.

| Designation | Description | Count | Percentage |
|-----------------------|--|-------|------------|
| Depredation | When a Tarpon was consumed by a shark before it was landed | 25 | 6.3 |
| Intentional break off | When an angler was observed intentionally increasing drag on the line to release the Tarpon, which mainly occurred during long fight times (>20 min) | 15 | 3.8 |
| Landed | When a Tarpon was brought successfully to the side of the boat, leadered, and released | 104 | 26.4 |
| Lost | Tarpon that either spit the hook while jumping or broke off the line at depth well away from the bridges but without a shark in sight | 65 | 16.5 |
| Lost in pilings | Tarpon that could not be successfully pulled out from the bridge and broke the line or that were able to swim back to the bridge pilings later in the fight | 119 | 30.2 |
| Postrelease predation | When a Tarpon was consumed at the surface by a shark after the Tarpon had been leadered and released | 4 | 1.0 |
| Unknown | Fate given to Tarpon that were primarily caught on the incoming current and whose fight ended while the boat was obscured from view by the US Route 1 Bridge | 62 | 15.7 |

with a hooked Tarpon, while postrelease predation was recorded if direct contact occurred at the surface after the Tarpon had been released. Fishing guides who regularly targeted Tarpon at Bahia Honda Channel and were interested in assisting with the study ($n=5$) also reported sightings of and interactions with tagged sharks weekly throughout the 2019 season, including on days when the visual survey was not conducted.

Great Hammerhead and Tarpon capture and tagging

Fishing for Great Hammerheads mainly occurred in close proximity to the Bahia Honda bridges. Great Hammerheads were caught by using both passive and active fishing methods that were designed to minimize bycatch and physiological stress while maximizing capture of the target species. The passive gear targeting Great Hammerheads was an anchored vertical longline with one to two gangions (~3 m of 454-kg-test monofilament attached to ~1 m of ~3-mm steel leader with a 680-kg-test barrel swivel and terminating at 18/0 or 20/0 circle hooks) baited with Crevalle Jack *Caranx hippos* or Great Barracuda *Sphyraena barracuda*. The gear was checked every 30 min, and gear recovery ensued as soon as a shark was observed on the gear. Similarly, Great Hammerheads were actively targeted by using a handline (~15 m of heavy line with ~3 m of 454-kg-test monofilament line to a ~1-m steel leader terminating at an 18/0 or 20/0 circle hook and a large poly ball at the other end). The baited handline was towed slowly behind the boat, mimicking the behavior of boats with hooked Tarpon. Once hooked, sharks were allowed to swim with the line and poly ball, closely followed by the boat, for approximately 10 min before being

brought to the side of the boat. This tired the shark to the point that it could be handled safely while keeping fight times short enough to minimize the physiological stress response (Gallagher et al. 2014; Gulak et al. 2015).

Great Hammerheads remained in the water and were secured to the side of the boat for tagging via looped ropes at the base of the cephalofoil and caudal fin. A coded acoustic transmitter (Model V16; 69 kHz; tag delay=90–180 s; Innovasea) tethered to a titanium dart (Large Ti Anchor; Wildlife Computers) was inserted at the base of the dorsal fin. All Great Hammerheads tagged in 2019 and 2020 were also outfitted with large, color-coded, and individually numbered cattle tags (Global Maxi Beef and Dairy Ear Numbered Tags; Allflex) near the apex of the dorsal fin (Stevens 2000) to allow for easy reidentification in visual surveys and by collaborating fishing guides. This would allow for a baseline understanding of the number of Great Hammerheads involved in shark–angler interactions in Bahia Honda through resighting of cattle-tagged individuals. Prior to application, cattle tags were treated with a biocide-free foul-release coating (Lightspeed; Prospeed USA Inc). A small hole was drilled with a 4.762-mm (0.1875-in) drill bit, and the tags were fastened through the fin using a tag applicator (Universal Total Applicator; Allflex). Prior to release, sex was determined and fork length (FL) and stretch total length (TL) measurements were obtained to the nearest 0.5 cm.

Beginning in May 2016, Tarpon were targeted on conventional spinning or fly-fishing gear and tagged internally with a coded acoustic transmitter (Model V16; 69 kHz; tag delay=60–120 s; Innovasea) throughout the Florida Keys, coastal Florida, Georgia, and South Carolina as part of a study examining broadscale migratory patterns (Griffin et al. 2018, 2022a). A detailed description of the tagging procedure was provided by Griffin et al. (2018).

Acoustic telemetry

Great Hammerheads and Tarpon were monitored simultaneously in a gridded passive acoustic telemetry array in Bahia Honda Channel consisting of 16 receivers (Model VR2W: $n=2$; Model VR2Tx: $n=14$, with internal sync tags [delay = 60–120 s]; Innovasea), with some overlapping receiver coverage (Figure 1). Receivers were deployed continuously from March 23, 2019, through July 30, 2021, and downloaded twice annually in March and August. To keep receivers upright throughout the deployment, they were moored approximately 1 m off the seafloor (average receiver depth \pm standard deviation [SD] = 4.6 ± 0.95 m), attached to a rebar pole, and nested in the top of a polyvinyl chloride (PVC) pipe. The receiver was supported by an eyebolt running through the PVC to keep the hydrophone exposed. The PVC and rebar were embedded in a 46- \times 46- \times 8-cm cement block weighing approximately 36 kg. Four rows of four receivers were used to cover the entire extent of the Bahia Honda Channel, with one row north of the U.S. Route 1 Bridge, two rows between the U.S. Route 1 Bridge and the old railroad bridge, and one row south of the old railroad bridge (Figure 1).

Data analysis

Visual survey

Summary statistics of visual survey data were generated to characterize the extent of Tarpon fishing pressure in Bahia Honda by using R version 4.1.2 (R Core Team 2021). Due to the nature of Tarpon fishing in Bahia Honda, fight times can often be brief (<120 s). Tarpon can easily spit the hook or break the line in the bridge pilings. Accordingly, depredation and postrelease predation rates were calculated for overall fishing effort and for fish that had a fight time greater than 5 min.

To estimate the seasonal number of Tarpon that were hooked and seasonal Tarpon mortality at Bahia Honda, an area-under-the-curve analysis was employed (English et al. 1992). To account for days when no observer was present for the visual survey due to the random sampling design, the total number of Tarpon that were observed as hooked daily from the visual survey was plotted and a seasonal estimate was generated by taking the integral of the curve using the DescTools package (Signorell et al. 2021). Overall seasonal mortality was then calculated by taking the percentage of observed mortality from the total calculated by the integral.

Decision trees were used to identify the factors that most influenced fishing outcomes (survival or mortality)

for Tarpon. Decision trees use recursive partitioning to generate parent and child nodes (leaves) by splitting the data (branch) on a predictor variable, composing an overall tree (Breiman et al. 1984; De'Ath and Fabricius 2000; Olden et al. 2008). For the decision tree analysis, instances of depredation and postrelease predation were combined and classified as mortality. Input variables selected for the initial trees to predict fish fate were as follows: current direction, the number of boats fishing when the Tarpon was hooked (boat count), the maximum number of boats observed that day (maximum boat count), fight time, the number of Tarpon jumps, the number of fish previously hooked that day, and the number of previous shark-related mortalities that day. Maximum boat count was found to be correlated with the boat count and the number of fish previously hooked that day (Pearson's product-moment correlation coefficient >0.65) and was dropped from further analyses. Data were randomly split into a training data set (75% of the data; $n=99$) for generating the initial tree and a test data set (25% of the data; $n=34$) for testing the tree's predictive power. Decision tree models were then trained using the C5.0 algorithm (Quinlan 1992) from the R package C50 (Kuhn and Quinlan 2021) and the classification and regression tree (CART) algorithm (Breiman et al. 1984) from the package rpart (Therneau and Atkinson 2019).

Tree performance was evaluated, and subsequent tuning was employed to improve predictive power on the test data set following the methods outlined by Lantz (2019) using the gmodels (Warnes et al. 2018) and caret (Kuhn 2021) packages to generate cross tables and confusion matrices. Since we valued identifying the factors that most influenced mortality, we sacrificed some overall model accuracy by penalizing incorrect classifications of mortality three times as much as incorrect classifications of survival when constructing a cost matrix (Lantz 2019). Additionally, due to the unbalanced nature of the data and our desire to accurately predict the underrepresented sample, we allowed the trees to split on nodes with a minimum number of four observations (Lantz 2019). After generating a completed tree, postprocess pruning was employed to help minimize overfitting (Lantz 2019).

Survival analysis (also called time-to-event analysis) was conducted to complement the decision tree (Benoît et al. 2012; Castro-Santos and Perry 2012; Harrell 2015; Capizzano et al. 2016; Lennox et al. 2017). Similar to the decision trees, depredation and postrelease predation occurrences were combined to represent mortalities. One of the features of survival analysis is the ability to account for right-censored data, in which the outcome is unknown beyond a certain point in time (Harrell 2015). Because of this, in addition to fish that were leadered and released, the following groups were included as censored

survivals in this analysis: fish that were intentionally broken off the line, fish that were lost away from the bridge, and fish that had an unknown fate. Cox proportional hazards regression was conducted to model survival using the same variables as the decision trees with the package *survival* (Therneau 2021). Kaplan–Meier survival curves (Kaplan and Meier 1958) were constructed for the data set overall and for variables that the Cox proportional hazards regression identified as significant using the package *survminer* (Kassambara et al. 2021).

Acoustic telemetry

Prior to data analysis, acoustic detection data were filtered for echoes, detections recorded in less than the programmed tag delay, and simultaneous detections to ensure that only valid animal movements were retained in the data set (Brownscombe et al. 2019). Additionally, because the study took place in a small area with the potential for tagging mortality, all Great Hammerheads and Tarpon were confirmed to be alive based on tag movements in a broader acoustic receiver array throughout the Florida Keys (see Griffin et al. 2022b for array details). Using the package *glatos* (Holbrook et al. 2021), the presence of individual Great Hammerheads and Tarpon in Bahia Honda was divided into events to calculate residence time. An event, or arrival, began when the fish was first detected in the Bahia Honda receiver array and ended once five consecutive detections had been missed (900 s for Great Hammerheads and 600 s for Tarpon). Given the extensive receiver coverage in the area and the high mobility of both Great Hammerheads and Tarpon, we felt that this was an adequate amount of time to be confident that the individuals had departed from the area. Events with more than one detection (lasting for more than 0 s) were used to generate average monthly and hourly residence time for both Great Hammerheads and Tarpon throughout the duration of the study. Acoustic telemetry data preparation and subsequent analyses were conducted in R version 4.1.2 (R Core Team 2021) using RStudio (RStudio Team 2021).

Generalized linear models with a binomial error distribution were created to identify drivers of Great Hammerhead presence in Bahia Honda. Weekly presence/absence data were generated based on the residency events for the 120 weeks in the study (April 10, 2019–July 18, 2021). The initial suite of predictor variables included cumulative weekly residence time (minutes) for Tarpon, cumulative daily number of Tarpon detected in the week (Tarpon count), mean weekly photoperiod, mean weekly sea surface temperature, lunar phase, and whether it was the spawning or nonspawning season for Tarpon. Daily

photoperiod was calculated using the package *maptools* (Bivand and Lewin-Koh 2021) based on the difference in time between sunrise and sunset. Mean photoperiod was then calculated for the week. Mean daily sea surface temperature was extracted from the National Oceanic and Atmospheric Administration (NOAA) Environmental Research Division Data Access Program (ERDDAP) server (<https://coastwatch.pfeg.noaa.gov/erddap/>; data set ID: jplMURSST41) using the *rerddap* (Chamberlain 2021) and *rerddapXtracto* (Mendelssohn 2021) packages for Bahia Honda (minimum latitude: 24.65337; maximum latitude: 24.66071; minimum longitude: −81.29100; maximum longitude: −81.28323). Mean weekly sea surface temperature was then calculated from the daily means. The lunar phase at the four-phase level was assigned to each day using the package *lunar* (Lazaridis 2014). A phase for the week was then assigned based on the phase that made up most days in that week. Spawning season for Tarpon was defined as April–July (Baldwin and Snodgrass 2008). Variables were checked for collinearity using the “pairs.panels” command in the package *psych* (Revelle 2021), with correlations greater than 0.65 discarded. Spearman correlation coefficients indicated that Tarpon residency time and Tarpon count were highly correlated (0.82), as were photoperiod and season (0.81). Tarpon count and season were retained in the candidate model set. Each remaining variable was considered in an individual model in addition to a global model consisting of the additive effects of all variables using the package *stats* (R Core Team 2021). The best performing model was then selected based on Akaike's information criterion corrected for small sample size (AIC_c) using the package *AICcmodavg* (Mazerolle 2020), and the package *performance* (Lüdtke et al. 2021) was used to assess model fit via both the Hosmer–Lemeshow test (Hosmer and Lemeshow 2000) and area-under-the-curve calculations.

The initial concept for the array was to design a fine-scale virtual positioning system covering a smaller area spanning the U.S. Route 1 Bridge, but significant environmental noise—likely from the combination of the strong current, boat traffic, and vehicle traffic transferred from the bridge pilings—made this goal infeasible. Therefore, the array was reconfigured on May 9, 2019 (Figure 1). To account for this, home range analyses were conducted only using data collected after the reconfiguration, while residency calculations included events from the original array deployment date (March 23, 2019). Range testing for the new configuration was conducted for sentinel receivers in each row of the array using the VR2Tx receivers' integrated sync tags (Brownscombe et al. 2020). This testing determined that 50% detection efficiency occurred between 117 and 133 m. To visualize space use of sharks and Tarpon under the Bahia Honda bridges, centers of

activity (COAs) were generated using the package VTrack (Campbell et al. 2012). Centers of activity were calculated at the hourly level to maximize the number of detections during each time window while maintaining high position accuracy (Simpfendorfer et al. 2002). Using adehabitatHR (Calenge 2006), COAs for both species were then used to generate kernel utilization distributions (KUDs) based on a constant smoothing parameter (h) of 150 m, with 50% and 95% utilization densities presented. Kernel utilization distributions were generated for each species overall and were also broken down to examine changes in space use based on season (spawning versus nonspawning, monthly), light level (dawn, day, dusk, or night), and current (incoming versus outgoing). Contours were visualized with the ggmap (Kahle and Wickham 2013), sf (Pebesma 2018), and rgeos (Bivand and Rundel 2021) packages.

Using the 50% KUDs, the degree to which Great Hammerhead and Tarpon space use overlapped in Bahia Honda based on season, light level, and current direction was calculated. The proportion of Great Hammerhead home range that overlapped with Tarpon home range was calculated for every month to compare differences between the spawning and nonspawning seasons, as well as each month–light level and month–current direction pair within the spawning season, using the “HR” method within the kerneloverlaphr command in adehabitatHR. Analyses of variance (light level) or t -tests (spawning season and current direction) were used to test for significant differences in percent overlap. Analyses of variance or t -tests, where appropriate, were used to test for significant differences in 50% KUD area for each level of season, light level, and current direction between the species and within each species.

RESULTS

Visual survey

Tarpon fishing observations occurred on 27 days and totaled 211 h. During this time, 394 Tarpon were hooked, with fight times ranging from 1 to 52 min (mean \pm SD = 9.0 ± 7.9 min). Between 2 and 42 fish were hooked each day, peaking from May 2 to May 5, 2019. This coincided with peak fishing effort, which ranged from 0 to 22 individual boats targeting Tarpon per day. Fishing pressure varied throughout the day but was generally most intense between 0900 and 1400 hours, when 8–9 boats fished each day, on average (Table S1).

Tarpon that were hooked in Bahia Honda were most commonly lost in the bridge pilings ($n = 119$) or landed ($n = 104$), whereas 25 instances of depredation and

four instances of postrelease predation were observed (Table 1). The mean fight time (\pm SD) to land a fish was 12.7 ± 7.7 min, while the mean fight times of events ending with depredation or postrelease predation were 9.5 ± 6.8 and 9.0 ± 4.2 min, respectively. On average, fish were lost or lost in the pilings between 4.3 ± 4.4 and 4.9 ± 5.0 min after hooking. Excluding fish that were lost or lost in the pilings in less than 5 min (lost in pilings: $n = 25$; lost: $n = 19$), the overall mortality rate in the Bahia Honda fishery was 11.6% ($n = 251$). A subset of fish ($n = 62$) was assigned a fate of “unknown.” This occurred exclusively for fish fought on the incoming current whose fight ended while the boat was obscured from view by the U.S. Route 1 Bridge. When fish of unknown fate were removed (leaving 189 observations), the overall mortality rate of Tarpon was 15.3%. Based on the 394 fish that were observed as hooked between April 2 and May 28, 2019, the area-under-the-curve method estimated that 792 Tarpon were hooked in Bahia Honda during daylight hours through April and May (absolute error < 0.02). Given the overall observed mortality rate of 7.4% (29 mortalities among the 394 fish hooked), regardless of fight time, an estimated 58 Tarpon are lost each year to shark depredation or to immediate, surface-bound postrelease predation. Although tagged sharks were regularly detected via acoustic telemetry in Bahia Honda shortly after tagging, observed occurrences of depredation and postrelease predation in Bahia Honda were rarely caused by tagged Great Hammerheads ($n = 4$ individual sharks; detailed in Figure S1).

The CART and C5.0 algorithms both identified fight time, boat count, current direction, the number of Tarpon jumps, and the number of fish already hooked as factors influencing Tarpon survival. Although the CART algorithm had higher overall prediction accuracy (0.74) than the C5.0 algorithm (0.68), it had poor predictive power for correctly classifying mortality on the test data set (0/5 mortalities were correctly classified). In contrast, C5.0 performed much better at classifying mortality, as it correctly identified 80% (4/5) of mortalities from the test data. The C5.0 algorithm first split the data at a 12-min fight time, followed by current direction (incoming versus outgoing) and 30 fish that were already hooked (Figure 2). The number of observations in each terminal node ranged from 2 to 32. Most mortalities were predicted on an outgoing current at fight times less than 12 min. Attribute usage was highest for fight time (99.0%), boat count (82.8%), the number of fish already hooked (65.7%), and current direction (63.6%).

Like the C5.0 decision tree, the survival analysis showed that mortality was highest early in the fight and was influenced by current direction. Cox proportional

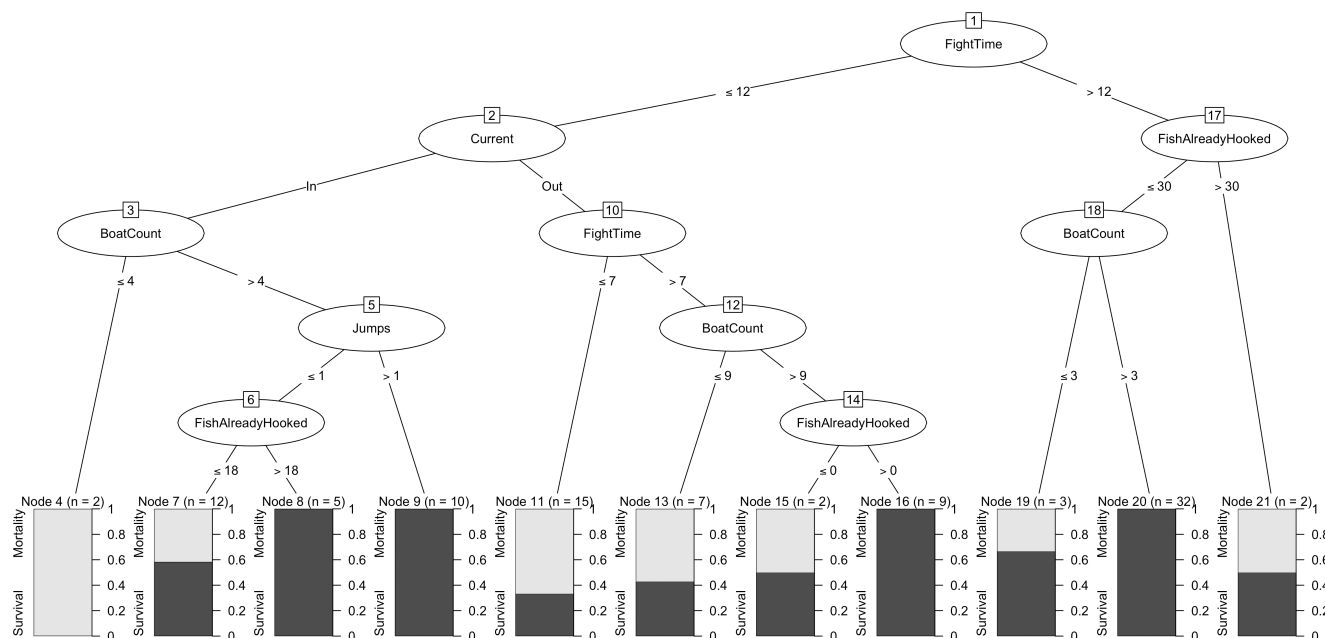


FIGURE 2 Decision tree generated by the C5.0 algorithm on the training data, showing the importance of fight time, current direction, boat count, the number of Tarpon jumps, and the number of fish previously hooked when determining survival or mortality of Tarpon in the Bahia Honda Tarpon fishery based on visual observations made between April 1 and May 28, 2019.

hazards regression identified current direction as the only significant variable in the model ($p=0.003$). Fish that were caught on the outgoing current had a lower survival probability than those caught on the incoming current (Figure 3). Overall, 43% of the decline in survival probability was encompassed in the first 12 min of the fight (Figure 3).

Acoustic telemetry

After data filtration, the array registered 5656 detections from 14 individual Great Hammerheads and 31,592 detections from 51 individual Tarpon (Figure 4). A total of 18 Great Hammerheads were tagged in proximity to Bahia Honda Channel, and 200 Tarpon were tagged throughout the southeastern United States. Tagged Great Hammerheads had a mean FL (\pm SD) of 273.6 ± 36.6 cm (range = 207.0–331.5 cm), with a female : male sex ratio of 13:3. Two Great Hammerheads were not detected at Bahia Honda after tagging, but they survived tagging based on detection history outside of the Bahia Honda array. All Great Hammerheads were mature at the time of capture based on clasper calcification for males and estimated size at maturity for females in the Gulf of Mexico and northwestern Atlantic (224 cm TL [176.0 cm FL]; Piercy et al. 2010). Nineteen Tarpon that were detected in Bahia Honda were tagged in Bahia Honda, and 14 were tagged elsewhere in the Florida Keys. The remaining 18 were tagged outside of the Florida Keys along the Gulf of

Mexico and Atlantic coasts, as far north as Georgetown, South Carolina. Mean FL (\pm SD) of tagged Tarpon was 139.5 ± 25.0 cm (range = 68.6–175.3 cm). Both tagged Great Hammerheads and Tarpon showed repeated seasonal use of Bahia Honda from March through June throughout the study (Figure 4). Mean Great Hammerhead monthly residency event duration increased steadily from January to June and was longer during the day than at night (Figure 5). Tarpon residency event duration was longest from December through May, with no discernible pattern related to time of day (Figure 5).

Binomial generalized linear models of weekly Great Hammerhead presence in Bahia Honda found that the cumulative daily number of Tarpon detected per week was the most important driver of presence. The model containing Tarpon count alone carried 71% of the AIC_c weight (Table S2) and was selected as the best performing model ($n=120$; AIC_c = 113.41; residual deviance = 109.41 on 118 degrees of freedom). Great Hammerhead presence was highest when 20 or more Tarpon were detected through the week ($p=0.008$; Figure 6). Model accuracy was 72.2% based on the area under the curve, and the model was deemed to have good fit by the Hosmer–Lemeshow test ($p=0.79$).

The filtered detections generated 1961 COAs for Great Hammerheads and 10,192 COAs for Tarpon. For both Tarpon and Great Hammerheads, the 99% KUD encompassed the entirety of the Bahia Honda array (Figures S2 and S3), but the area encompassed by monthly 50% KUDs was significantly larger for Great Hammerheads

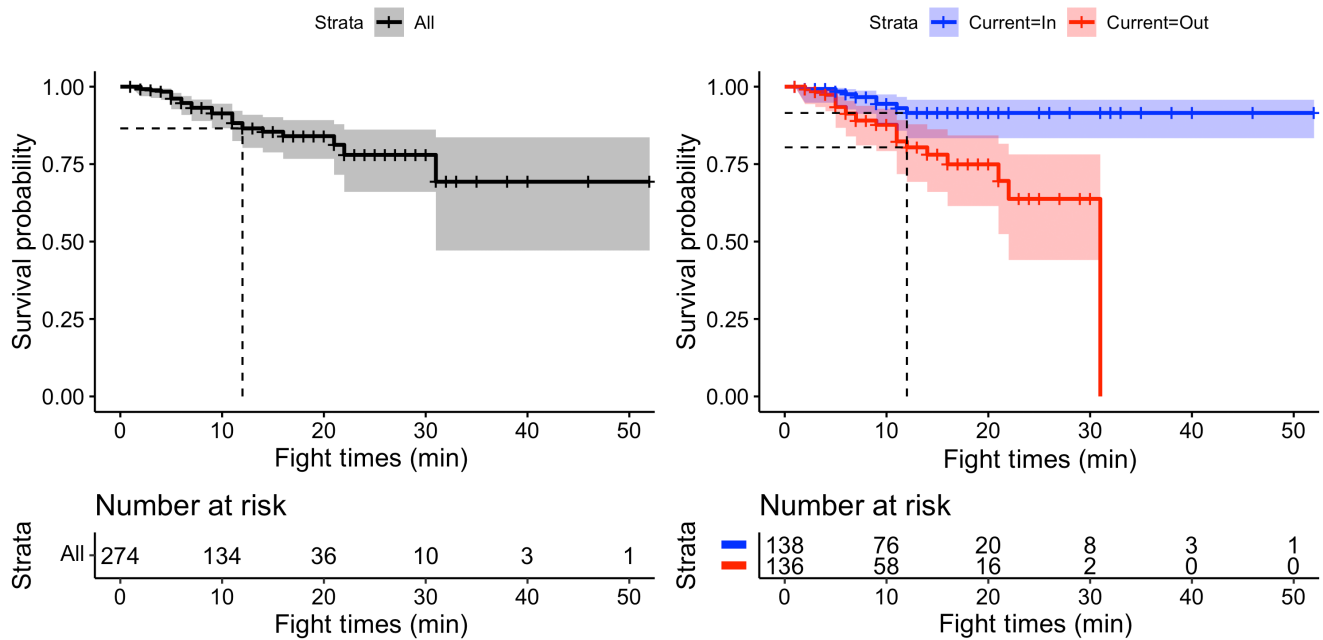


FIGURE 3 Kaplan–Meier survival curves showing declines in overall survival probability (left panel) as well as differences in survival probability for Tarpon caught on the incoming current versus the outgoing current (right panel). Survival probability is outlined by shaded log–log confidence intervals. The dashed lines indicate survival probabilities at a 12-min fight time.

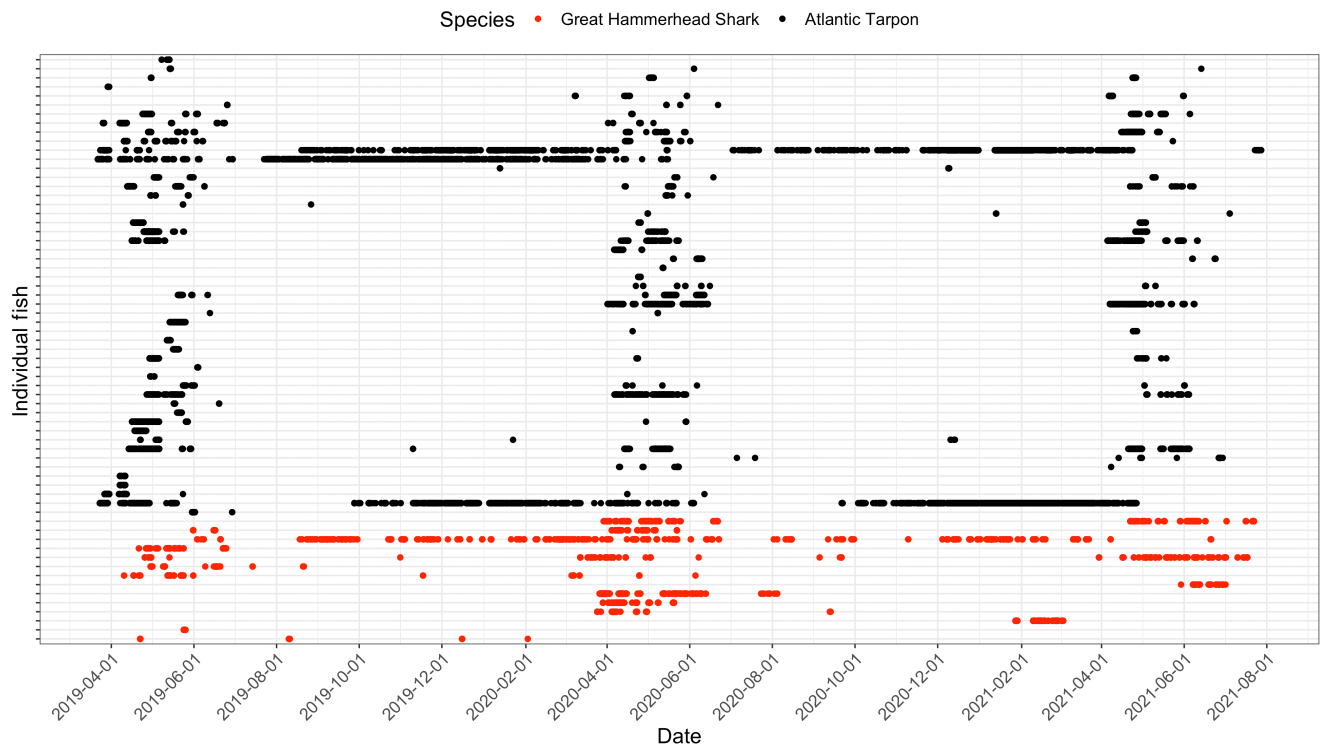


FIGURE 4 Acoustic detections of Tarpon (black) and Great Hammerheads (red) in Bahia Honda Channel, Florida, throughout the study period.

than for Tarpon ($p < 0.001$; Table 2). During the Tarpon spawning season, Great Hammerhead space use appeared to be concentrated around the U.S. Route 1

Bridge and the center of the array, corresponding to areas of high Tarpon fishing pressure (Figure 7). Tarpon movements were largely concentrated around the U.S.

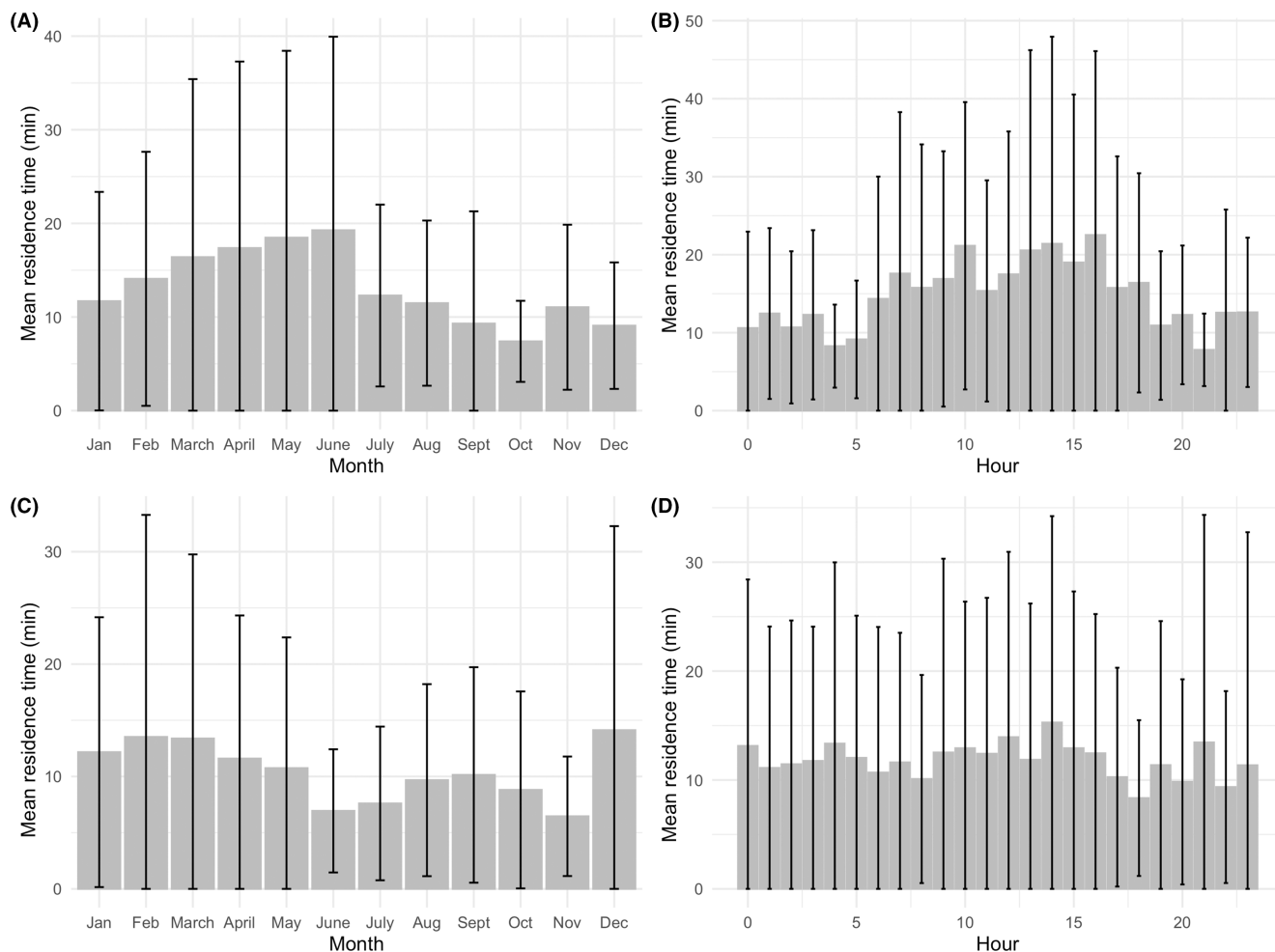


FIGURE 5 Mean (\pm SD) monthly and hourly residency event durations for (A), (B) Great Hammerheads and (C), (D) Tarpon through the duration of the study.

Route 1 Bridge in the northwestern and central portions of the array (Figure 7). Tarpon had significantly larger 50% KUDs during the spawning season relative to the nonspawning season ($p=0.02$). The size of Great Hammerhead 50% KUDs did not change between the Tarpon spawning season and the nonspawning season ($p=0.10$); however, the percent overlap between Great Hammerhead and Tarpon 50% KUDs was significantly higher during the spawning season ($p=0.005$).

During an outgoing current, Great Hammerheads largely concentrated their space use in the center of the array, whereas they ventured into more northern portions of the array during the incoming current (Figure 8). Tarpon space use consistently remained in the center of the array on both currents, with a shift toward the eastern side of the channel during the incoming current (Figure 8). During the Tarpon spawning season, the degree to which the Great Hammerhead and Tarpon 50% KUDs overlapped did not change significantly between the outgoing and incoming currents ($p=0.79$). Great Hammerheads used a significantly larger area during

the incoming current than during the outgoing current ($p<0.001$), but there was no significant difference in space use for Tarpon based on current flow direction ($p=0.64$). The positioning of Great Hammerhead 50% KUDs was similar regardless of time of day, with the exception of dusk, when detections were less common in the northern part of the array (Figure S4). Tarpon movements were predominantly under the U.S. Route 1 Bridge and the center of the array but were slightly more diffuse at night and dawn compared to day and dusk (Figure S5). There were no significant differences in the size of 50% KUDs for each species or the percent overlap of 50% KUDs based on light level during the spawning season ($p>0.05$).

DISCUSSION

This is the first study to examine the fine-scale movements of Great Hammerheads in relation to a prey species and depredation. We found that Great Hammerheads

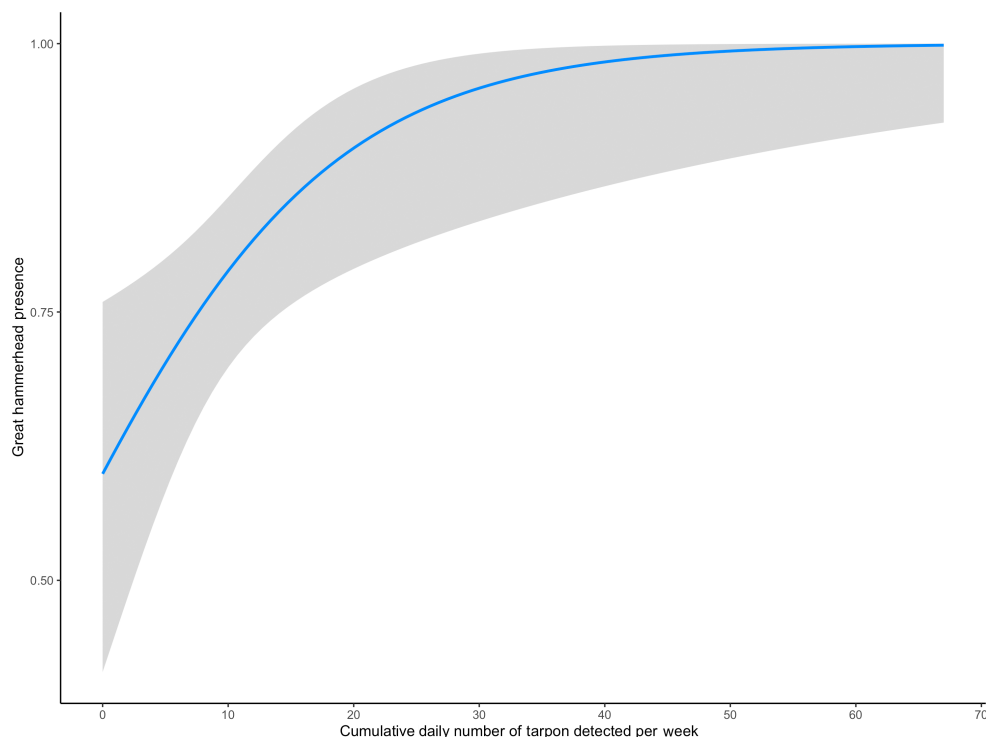


FIGURE 6 Predictive plot of the binomial generalized linear model for variation in Great Hammerhead presence in Bahia Honda Channel, Florida, with the cumulative daily number of Tarpon detected per week. The mean (blue line) is bounded by the 95% confidence interval (gray shading).

TABLE 2 Mean area (km^2 ; $\pm\text{SD}$) encompassed by monthly 50% kernel utilization distributions for Great Hammerheads and Tarpon in Bahia Honda Channel, Florida.

| Category | Great Hammerhead | Tarpon |
|--------------------|------------------|------------------|
| Overall | 0.36 ± 0.060 | 0.25 ± 0.055 |
| Spawning season | 0.33 ± 0.017 | 0.23 ± 0.059 |
| Nonspawning season | 0.38 ± 0.070 | 0.30 ± 0.035 |
| Incoming current | 0.34 ± 0.028 | 0.29 ± 0.079 |
| Outgoing current | 0.24 ± 0.012 | 0.31 ± 0.031 |
| Dawn | 0.31 ± 0.069 | 0.31 ± 0.099 |
| Day | 0.33 ± 0.011 | 0.27 ± 0.053 |
| Dusk | 0.28 ± 0.073 | 0.29 ± 0.059 |
| Night | 0.33 ± 0.051 | 0.33 ± 0.066 |

likely aggregate in Bahia Honda to prey on Tarpon, which drives interactions in the recreational fishery. Although both species are present year-round, Great Hammerhead presence and space use are tightly linked to high densities of Tarpon in the prespawning aggregation during the spring. The concurrent increase in recreational fishing during the spawning season results in significant levels of depredation driven by both environmental factors and angler behaviors.

Depredation in Bahia Honda

Our study shows that the Tarpon in the purported prespawning aggregation in Bahia Honda are under concerted fishing pressure, resulting in depredation events. Depredation or postrelease mortality generally occurred faster than the average fight time to land a Tarpon (9.0 or 9.5 min versus 12.7 min), emphasizing the need to reduce fight times to reduce mortality. We presented three different levels of predator-induced mortality in the fishery to account for the nature of Tarpon fishing in Bahia Honda, where fish often spit the hook or break off the line in the bridge pilings in less than 5 min. The decision to remove short fight times was supported by the survival analysis, which showed that mortality was unlikely in the first 5 min of the fight. A 15% mortality rate for Tarpon with a substantial fight time was observed in April and May 2019 during the visual survey, and depredation was the primary source of observed mortality.

Great Hammerheads may be frequenting Bahia Honda as a foraging ground regardless of fishing activity, thus allowing for opportunistic depredation events, which are more energy efficient than preying upon free-swimming fish (Stephens and Krebs 1986). This was supported by the decision tree and survival analyses, which identified high mortality at short fight times. Close examination of the survival analyses shows that the probability of survival on

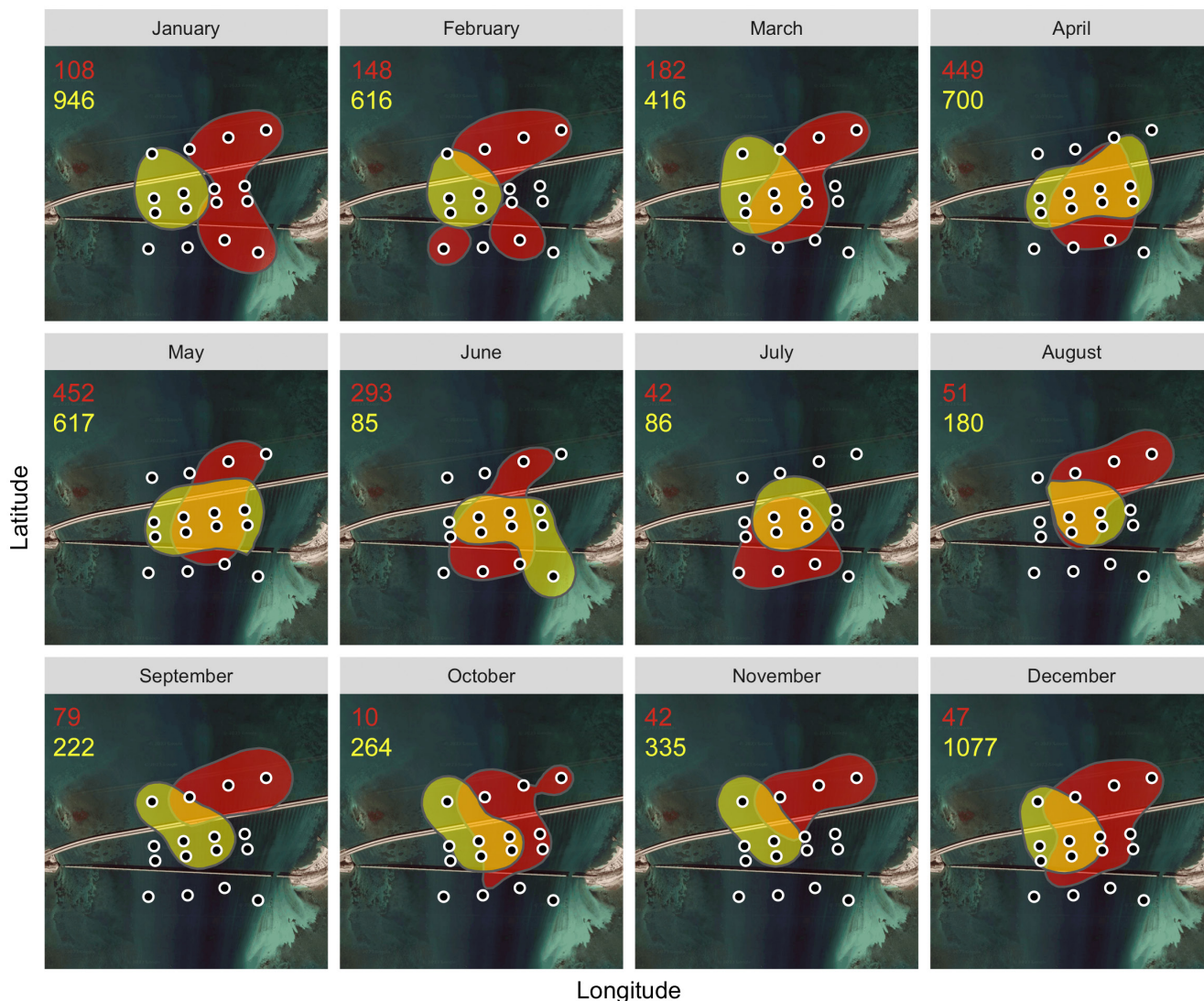


FIGURE 7 Monthly Great Hammerhead (red) and Tarpon (yellow) 50% kernel utilization distributions (KUDs) in Bahia Honda Channel, Florida, across the duration of the study period. Points represent acoustic receiver locations. The counts of centers of activity used to generate the KUDs for each month are included on each panel for Great Hammerheads in red and Tarpon in yellow.

the outgoing current begins to drop precipitously after a 5-min fight time, which may be indicative of the amount of time it takes a shark in the area to find the hooked Tarpon. The auditory and mechanosensory cues that alert Great Hammerheads to a struggling fish may be greatest early in the fight (Brownscombe et al. 2014), when Tarpon are most energetic and jump frequently. Since depredation occurs relatively early in the fight, sharks are likely already present in the area when the fish is hooked, as opposed to being drawn in from a distance.

The shift in Great Hammerhead space use on the outgoing current may explain why depredation and postrelease predation mortality are higher when the flow direction is outgoing. The area used by Great Hammerheads on the outgoing current is smaller and corresponds to where the majority of the fight occurs.

This could facilitate more efficient feeding. Some anglers assert that the Tarpon bite in Bahia Honda is better on the outgoing current, but the visual survey found no significant differences in the number of fish hooked based on current direction (Pearson's chi-square test: $p > 0.05$). Caution should be used with interpreting the decision tree because of this method's tendency to overfit training data sets (Wang et al. 2010), but the agreement between the decision tree and the survival analysis regarding mortality early in the fight and current direction increases confidence in these results. Unlike current direction, light level did not alter Great Hammerhead space use. Great Hammerheads using Bahia Honda primarily during daylight hours may be driven by vision-based foraging due to their enhanced binocular visual field (McComb et al. 2009) or may be driven by the Tarpon

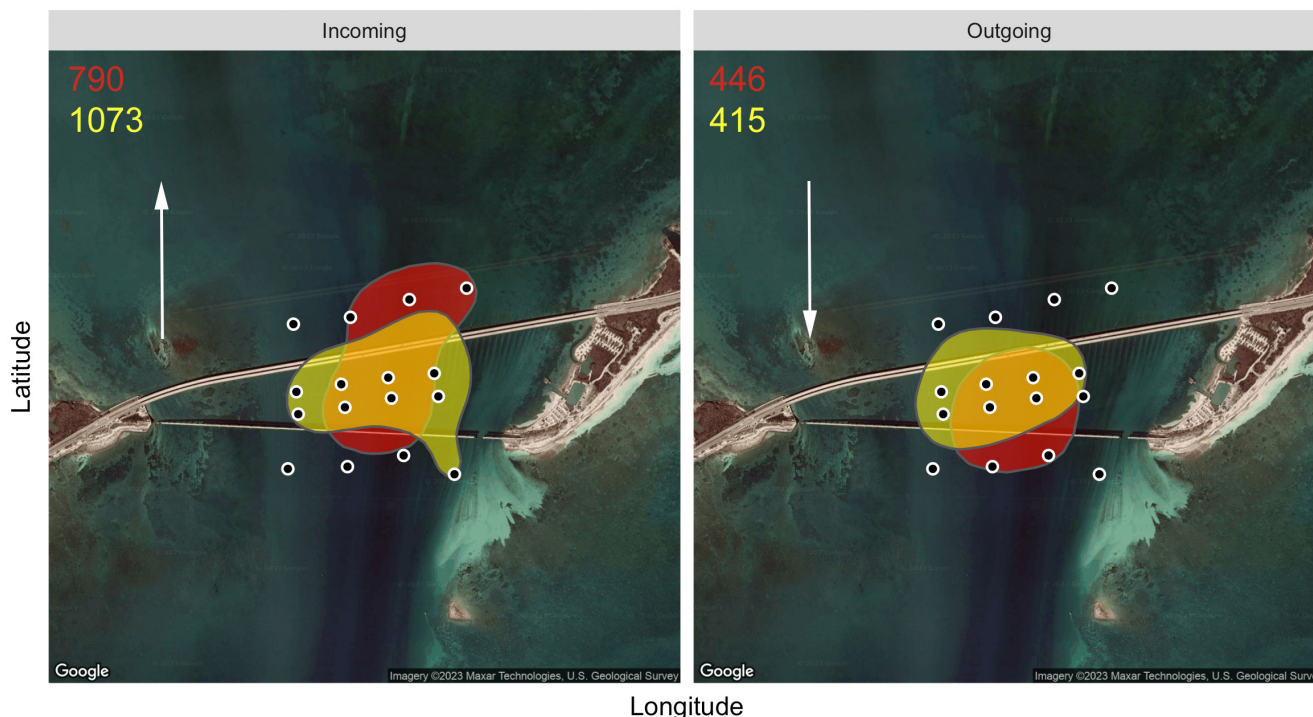


FIGURE 8 Great Hammerhead (red) and Tarpon (yellow) 50% kernel utilization distributions (KUDs) during the Tarpon spawning season based on current flow through Bahia Honda Channel, Florida. Points represent acoustic receiver locations. The counts of centers of activity used to generate the KUDs for each current direction are included on each panel for Great Hammerheads in red and Tarpon in yellow.

fishery itself, since the majority of fishing effort in Bahia Honda occurs during the day.

As with all acoustic telemetry studies, detection efficiency must be a prominent consideration when interpreting results (Brownscombe et al. 2019). It is possible that strong directional currents and heavy boat traffic in Bahia Honda Channel resulted in missed detections. The system was too noisy to support a fine-scale positioning system in close proximity to the U.S. Route 1 Bridge pilings. Reconfiguring the array increased spatial coverage in the channel and detection efficiency, as receivers were farther from the bridge. Generating COAs for each species based on 1-h time bins and defining new residency events after five consecutive missed detections could also help to account for missed detections to some extent.

The mortality rate observed for Tarpon in Bahia Honda is comparable to depredation rates found in recreational reef fisheries in Australia (Mitchell et al. 2018b, 2019), but our study observations were limited to mortalities at the surface. A survey of recreational and commercial fishers in Australia indicated that depredation can be more common at depth (Ryan et al. 2019). Subsurface depredation can be inferred based on changes in fish behavior during the fight, leading to much higher estimates of mortality when compared to surface observations (Holder et al. 2020). Additionally, postrelease predation

in the Tarpon fishery also occurs at depth minutes to hours after release, with sharks in the area capitalizing on the easy foraging opportunities offered by exhausted fish (Guindon 2011; Luo et al. 2020). Previous studies of postrelease predation with active tracking (Guindon 2011) were higher than our surface-bound observation estimate: 13% mortality compared to 1% mortality. Finally, Bull Sharks were never observed during the visual survey, but they are known to depredate Tarpon in Bahia Honda (K. Grubb, N. Wheeler, and B. Spano, fishing guides, personal communication) and to frequent the area in response to Tarpon presence (Griffin et al. 2022b). In south Florida, Bull Sharks have been implicated in altering long-distance movement behaviors of Tarpon, resulting in postrelease predation events (Hammerschlag et al. 2012). Thus, overall angling-related mortality for Tarpon that are fought longer than 5 min is very likely greater than 15% in Bahia Honda, emphasizing the importance of considering depredation and postrelease predation as conservation concerns.

The ecological role of Bahia Honda for Great Hammerheads

In tropical and subtropical coral reef environments, sharks rely on and seek out fish aggregations as a food source

(Mourier et al. 2016; Pickard et al. 2016; Griffin et al. 2022b). In addition to serving as a staging area for Tarpon spawning, Bahia Honda is clearly an important feeding ground for mature, primarily female Great Hammerheads. Great Hammerheads are globally assessed as “critically endangered” by the International Union for Conservation of Nature (IUCN) Red List (Rigby et al. 2019) and are undergoing stock assessment in the United States ([sedarweb.org/sedar-77](https://www.sedarweb.org/sedar-77)). They are capable of extensive annual migrations (Graham et al. 2016; Chin et al. 2017; Guttridge et al. 2017, 2022; Calich et al. 2018), but seasonal residency and philopatry have also been documented in Bimini, The Bahamas, during the winter months (Guttridge et al. 2017). The Great Hammerheads in this study exhibited similar levels of philopatry, with multiple individuals detected in Bahia Honda for two to three spawning seasons over the 3-year study period. This finding bolsters the hypothesis that food availability is a key driver of Great Hammerhead philopatry (Guttridge et al. 2017; Heim et al. 2021).

The extent to which Great Hammerheads rely on Tarpon as a food source year-round is currently unknown. It is clear that at a minimum, Tarpon serve as an important seasonal food pulse in the Florida Keys (Griffin et al. 2022b), with repeated annual use of Bahia Honda, especially by mature female sharks that may be in the late stages of gestation (Stevens and Lyle 1989; Ebert and Stehmann 2013; G. A. Casselberry, unpublished data). Information regarding Great Hammerhead diet composition is lacking (Gallagher and Klimley 2018), particularly in the northwestern Atlantic and Gulf of Mexico. Stomach content analyses conducted outside of the United States have been limited by sample size (de Bruyn et al. 2021; Chumchuen and Sukramongkol 2022) and show varying reliance on teleosts as prey (Stevens and Lyle 1989; Cliff 1995; Chumchuen and Sukramongkol 2022). Stable isotope analysis of mature Great Hammerheads (234–383 cm TL) in Australia indicated a heavy reliance on small sharks and rays as opposed to teleost fishes (Raoult et al. 2019), but reference samples for large-bodied teleosts were absent from the study. Since the Florida Keys has been identified as an important movement corridor for both Great Hammerheads and Tarpon (Lowerre-Barbieri et al. 2021), broadscale spatial ecology studies throughout the southeastern United States and stable isotope analyses would serve as nonlethal methods to provide further insights into the interconnected predator-prey dynamics of these two highly migratory species.

Implications of fishing-related predation for the Tarpon population

If depredation at the prespawning aggregation site drives Tarpon population declines, fishing quality throughout

the southeastern United States could be affected, given the extensive coastal migrations of Tarpon (Griffin et al. 2018; Luo et al. 2020). Tarpon lack a stock assessment (Adams and Cooke 2015), leaving the specifics of their population status in the United States largely uncertain. Habitat loss for juveniles and overharvest have led to global population declines (Adams et al. 2019; Wilson et al. 2019). This, in conjunction with their longevity (Crabtree et al. 1995; Andrews et al. 2001) and late maturation (Crabtree et al. 1995, 1997), makes the Tarpon population potentially vulnerable to declines from fishery-related mortality, in this case through depredation and postrelease predation.

Fishing mortality in spawning or prespawning aggregations has led to dramatic declines in numerous tropical and subtropical fish populations (see Sadovy de Mitcheson and Erisman 2012 for a review). The data presented herein, in conjunction with the findings reported by Griffin et al. (2022a), demonstrate the repeated return of mature Tarpon to the same prespawning aggregation site in the Florida Keys. Although depredation causes direct mortality to individuals, there could also be sublethal behavioral consequences that affect the aggregation and the broader Tarpon population. It is unknown whether Tarpon exhibit exclusive aggregation site fidelity within and across spawning seasons. Cues for aggregation formation in particular areas are also unknown. Our data show that subadults are present in Bahia Honda during the spawning season. If there is a degree of learning involved in the location of aggregation formation, the loss of many mature fish in conjunction with low recruitment could lead to aggregation collapse (Sadovy de Mitcheson and Erisman 2012).

Fishing guide responses to depredation and best practices recommendations

Many guides who frequently target Tarpon in Bahia Honda are concerned about the long-term consequences of depredation in their fishery, which manifests in varying ways. Guides have reported fishing the channel at shallower depths, which anecdotally catches smaller, presumably male fish. They would rather lose a mature male from the population than a large, highly fecund female (Grubb, personal communication). Twice, anglers were observed pulling the fish onto the gunwale of the boat while accelerating away in an attempt to evade an approaching shark, which always resulted in postrelease predation at the surface during the visual survey. During 36% of depredation events, boats accelerated toward the Tarpon and feeding shark in an attempt to create a “bubble cloud” of disturbed water around the Tarpon to help it escape. Although this action could temporarily separate the two fish, the Great Hammerhead always relocated the

Tarpon. Great Hammerheads can be hit by boat propellers during these types of interactions. Three sharks that were tagged during the study and a fourth shark that was observed during the visual survey had clear propeller injuries on their dorsal fins or the dorsal surface of their bodies. These injuries could be detrimental to individual Great Hammerhead health (Borucinska et al. 2020).

Although fishing guides have generally expressed that depredation is a threat to their fisheries and creates a negative customer experience (Casselberry et al. 2022), some guides in Bahia Honda have begun advertising the potential for shark depredation as a reason to book a charter with their company on their social media accounts and websites. If angler motivations for fishing in Bahia Honda shift from landing a Tarpon to interacting with a Great Hammerhead, this could lead to unnecessarily long fight times during which an angler plays the fish to extreme exhaustion, increasing the potential for depredation and postrelease mortality (Guindon 2011). Presumably, these guides are taking relatively inexperienced anglers fishing, since depredation tends to result in negative emotional responses for experienced anglers (Casselberry et al. 2022). Inexperienced anglers find depredation more thrilling because they are witnessing a predation event up close (Casselberry et al. 2022). Such anglers are likely unaware of Tarpon longevity, the “vulnerable” status of Tarpon on the IUCN Red List (Adams et al. 2019), and that Bahia Honda serves as a prespawning aggregation site. Without this knowledge, anglers are less likely to be invested in conservation issues for the fishery (Ryan et al. 2020; Griffin et al. 2023).

The first step toward reducing depredation and associated human–wildlife conflict in Bahia Honda should be through concerted efforts to communicate best practices directly to stakeholders and user groups (Cooke et al. 2013). Anglers fishing Bahia Honda should ensure that they are using sufficiently heavy tackle to land Tarpon in less than 9 min (since depredation occurred, on average, 9 min into the fight). Responsible guides should communicate to their clients the longevity of Tarpon, the biological significance of the spawning aggregation, and the need to reduce fight time to ensure Tarpon survival. Awareness of the outgoing current is essential, and fish should be released immediately if a shark is seen in the area. Exposing the Tarpon to air or creating a bubble cloud in an attempt to evade a shark in pursuit ultimately reduces the ability of a Tarpon to escape predators upon release by increasing the fish's physiological stress (Guindon 2011). Instead, guides and anglers should be aware of sudden behavioral changes during the fight—particularly an abrupt, dramatic increase in fight intensity (Holder et al. 2020), which could represent an attempt to avoid a predator. If this is observed, the line should be broken to release the

fish. This may allow the Tarpon to escape with more energy and may reduce mortality, but research into the effects of retained fishing gear is needed.

Advances in recreational fishing technology may also provide solutions to depredation. In Bahia Honda, anglers who fish with a side-scan sonar or similar commonly used fish finder technology (Cooke et al. 2021) can leverage this technology to monitor for incoming sharks and release fish or can change location to target fish outside of the channel accordingly. Testing potential emerging technological solutions, such as shark deterrent devices (Robbins et al. 2011; O'Connell et al. 2014; Hart and Collin 2015; Kempster et al. 2016; Huveneers et al. 2018; Thiele et al. 2020), could also be promising. These technologies have primarily been developed to reduce shark bycatch or shark bites and should be tested in specific fishery contexts before being marketed as a conservation solution. If behavioral changes and deterrent technologies prove ineffective, it may be reasonable to explore additional management solutions, including time–area closures or limiting the number of boats that can target fish in the channel.

Conclusions

Our research demonstrates that Bahia Honda is ecologically important for both Tarpon and Great Hammerheads as a prespawning aggregation area and as a feeding ground, respectively. Mitigating depredation in this area should be considered a pressing management need by the Florida Fish and Wildlife Conservation Commission and FKNMS to ensure successful reproduction for Tarpon in the aggregation and to reduce the potential for retaliation against sharks (Rigby et al. 2019; Casselberry et al. 2022). The stark dichotomy of angler and guide responses to depredation in Bahia Honda highlights the complexities of this fisheries management issue (Iwane et al. 2021; Coulson et al. 2022; Hoel et al. 2022). Depredation is emotionally charged (Casselberry et al. 2022), and the high tensions that exist between anglers and sharks are on full display in Bahia Honda. Depredation and associated socioecological conflicts (Mitchell et al. 2018a; Tixier et al. 2020b) are likely to increase as an unintended consequence of emerging shark conservation success (Carlson et al. 2019). Our work represents a first step toward characterizing predator–prey dynamics and addressing depredation in the Tarpon fishery at a fishing hot spot. Ultimately, angler education regarding best practices and stakeholder commitment to Tarpon conservation could be primary means to reducing this conflict, as has been demonstrated with other successful regional recreational fisheries regulations (Cowx et al. 2010; Cooke et al. 2012; Guckian et al. 2018).

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CONFLICT OF INTEREST STATEMENT

The authors state that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The acoustic telemetry data from this study are archived through the Ocean Tracking Network (<https://members.oceantrack.org/OTN/projects>). The Ocean Tracking Network dictates data be released after 2 years following the expiration of any given tag. Additional support and access can be provided by contacting the authors directly.

ETHICS STATEMENT

Great Hammerhead and Tarpon tagging procedures were conducted under UMass Amherst Institutional Animal Care and Use Committee Protocol 2019-0049 and 2016-0049, respectively. Visual surveys were conducted under Scientific Research Permit 03081915 from the Florida Department of Environmental Protection, Division of Recreation and Parks. Acoustic receiver deployments within the FKNMS were permitted under FKNMS-2018-032. Special Activity Licenses were issued by the Florida Fish and Wildlife Conservation Commission for Great Hammerhead tagging (SAL-19-2107-SRP, SAL-20-2107-SRP, SAL-21-2107-SRP) and Tarpon tagging (SAL-16-1205).

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SUPPORTING INFORMATION

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