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EDITED BY
K. David Hyrenbach,
Hawaii Pacific University, United States

REVIEWED BY
Jorge Manuel Morales-Saldaña,
McGill University, Canada
Steven Lombardo,
South Florida Water Management District, United States

*CORRESPONDENCE
Brett B. Sweezey
brett.sweezey@noaa.gov

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Spatiotemporal patterns and habitat use of silky and sandbar sharks at Flower Garden Banks National Marine Sanctuary

Brett B. Sweezey[1]*, Jay R. Rooker[1], Michael A. Dance[2], Eric R. Hoffmayer[3], William B. Driggers III[3], J. Marcus Drymon[4,5], Marissa F. Nuttall[1,6], Brondum M. Krebs[2], Creed C. Branham[2], Landes L. Randall[1], Susan K. Lowerre-Barbieri[7], Shane Cantrell[8], Brett J. Falterman[9] and R. J. David Wells[1]

[1]Department of Marine Biology, Texas A&M University, Galveston, TX, United States, [2]Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA, United States, [3]National Oceanic and Atmospheric Adminstration (NOAA) Southeast Fisheries Science Center, Pascagoula, MS, United States, [4]Coast Research and Extension Center, Mississippi State University, Biloxi, MS, United States, [5]Mississippi-Alabama Sea Grant Consortium, University of Southern Mississippi, Ocean Springs, MS, United States, [6]National Oceanic and Atmospheric Administration (NOAA), Office of National Marine Sanctuaries, Flower Garden Banks National Marine Sanctuary, Galveston, TX, United States, [7]Fisheries and Aquatic Sciences, University of Florida, Gainesville, FL, United States, [8]Galveston Sea Ventures, Galveston, TX, United States, [9]Fisheries Research Support LLC, Mandeville, LA, United States

Introduction: Understanding the spatiotemporal movements of organisms within marine protected areas are essential for evaluating the efficacy of management practices designed to protect and conserve species. However, establishing management regulations to encompass species with large spatial extents can impose significant challenges when baseline data are limited. Flower Garden Banks National Marine Sanctuary (FGBNMS) in the northwestern Gulf of Mexico is a unique MPA for evaluating these concerns, as its remote offshore location provides natural benthic habitat for tropical fishes and foraging opportunities for many highly migratory species such as tunas, billfishes, and sharks. The silky shark (*Carcharhinus falciformis*) and sandbar shark (*Carcharhinus plumbeus*) are two elasmobranchs that frequent the sanctuary and surrounding habitats, yet their spatiotemporal movement patterns within this region remain poorly understood.

Methods: Movement patterns of 23 silky and 22 sandbar sharks were investigated using acoustic telemetry from August 2022 to October 2025. Acoustic receivers were deployed along the continental shelf at 17 banks within the sanctuary, four non-sanctuary banks, and 14 artificial reefs.

Results: Silky sharks displayed variable connectivity, preferring natural banks in winter and spring and year-round presence at artificial reefs in summer. Conversely, sandbar sharks showed consistent, year-round presence across both natural banks and artificial habitats, with 46% of detected individuals observed beyond the FGBNMS acoustic network compared to only 9% of detected silky sharks.

Discussion: These findings expand our understanding of species habitat linkages and demonstrate that sanctuary banks, non-sanctuary banks, and artificial reefs collectively constitute interconnected habitat use that is integral for two highly migratory shark species in the Gulf of Mexico.

KEYWORDS
***Carcharhinus falciformis*, *Carcharhinus plumbeus*, connectivity, FGBNMS, Gulf of Mexico, movement, MPA, shark**

1 Introduction

Marine ecosystems are under constant threat from anthropogenic stressors, including climate change (Doney et al., 2012), ocean acidification (Fabry et al., 2008), pollution (Shahidul Islam and Tanaka, 2004), and overfishing (Coll et al., 2008). Over time, repetitive exposure to these stressors can cause deleterious effects leading to the degradation of marine ecosystems, loss of biodiversity, and decline in productivity (Dayton et al., 1998). To mitigate the impact of such stressors on the marine environment, area-based protections have been used as a tool to preserve unique seascapes critical for marine organisms (Aburto-Oropeza et al., 2011; Watson et al., 2014). Marine protected areas (MPAs) can be used to conserve crucial habitat for endangered species, restore exploited fisheries populations, provide social and economic benefits for communities, and provide adaptive management strategies to mitigate the negative impacts of climate change for future generations (Ban et al., 2019; Watson et al., 2014). Following the Convention on Biological Diversity Aichi Target 11 goal to conserve 10% of the global oceans by 2020, there was a rapid increase in the development of MPAs, expanding protected area coverage from 0.67% in 2000 to 8.2% in 2023 (CBD, 2010; UNEP-WCMC and IUCN, 2023). Currently, MPAs cover approximately 36.3 million km^2, and the continued expansion of MPAs is necessary to meet future goals of protecting 30% of the ocean by 2030 and mitigating further anthropogenic impacts on marine ecosystems (UN-DESA, 2025; UNEP-WCMC and IUCN, 2025).

Flower Garden Banks National Marine Sanctuary (FGBNMS) was established in 1992 as an MPA on the continental shelf of the northern Gulf of Mexico. The sanctuary provides substrate for many foundational invertebrate species (e.g., corals, sponges, gorgonians) and critical habitat for tropical invertebrate and reef fish populations (Clark et al., 2014). These shelf-edge banks encompass a variety of coral reef ecosystems, ranging from shallow carbonate cap reefs (17–50 m) to deeper mesophotic coral communities and coralline algae banks (50–150 m). Various fish communities within the sanctuary (e.g., snappers, groupers, and jacks) are prey for large pelagic predators (e.g., tunas, billfishes, and sharks) and are important target species for commercial and recreational fisheries. Previous research has documented seasonal aggregations at these banks associated with spawning events and nursery habitat for elasmobranchs (Stewart et al., 2018), underscoring their role as ecologically significant offshore habitats (Grüss et al., 2018; Rooker et al., 2019). In response to growing evidence supporting the high ecological activity associated with offshore banks (Rooker et al., 2019; Wetmore et al., 2020), FGBNMS was expanded in 2021 to include 14 additional banks along the Texas and Louisiana continental shelf edge. However, despite the ecological importance of this offshore ecosystem, information on how pelagic species use the expanded sanctuary remains limited.

Understanding the spatial and temporal movement patterns of marine predators is fundamental to effective conservation and management, as species-specific habitat use and seasonal residency patterns directly determine the degree of protection afforded by area-based management tools and the spatial and temporal boundaries within which regulatory measures must operate to be effective (Franks et al., 2021; Heithaus et al., 2008; Wootton, 1993). Elasmobranchs play an important role in shaping ecosystems via top-down control through direct predation and indirect non-consumptive risk effects (Wirsing et al., 2007). In marine environments with high biodiversity, such as coral reef systems, separate or overlapping ecological niches have been observed among elasmobranch species at similar trophic levels (Papastamatiou et al., 2006). However, movement patterns and habitat use can be strongly driven in younger sharks by the need to optimize predator avoidance strategies or foraging opportunities (Yates et al., 2012). Additionally, shifts in physicochemical properties, such as dissolved oxygen and water temperature, can affect habitat suitability, forcing species to alter their movement patterns to remain within preferred environmental ranges (Howey et al., 2017; Speed et al., 2012). Fluctuations in spatiotemporal behaviors can be used to predict ecological ranges and to inform predictions of future movement patterns of individual species (Block et al., 2011).

The silky shark (*Carcharhinus falciformis*) and sandbar shark (*Carcharhinus plumbeus*) are two species that frequent FGBNMS and are classified globally as Vulnerable (VU) and Endangered (EN), respectively (Rigby et al., 2021a, 2021b). The individuals of each species observed at FGBNMS represent distinct life stages. Juvenile silky sharks (~1 m) are the primary life stage documented at the sanctuary, whereas adult sandbar sharks (>1.5 m) are the dominant size class observed among these offshore banks (Childs, 2001). Adult silky sharks are commonly found in offshore open-water habitats (Compagno, 1984), but juveniles tend to be associated with benthopelagic habitats, such as deep reefs near continental shelf edges that may serve as nursery grounds, before transiting to open-ocean environments to avoid the threat of predation from larger shark species (Branstetter, 1987; Talwar et al., 2023; Yokota and Lessa, 2006). In contrast, adult sandbar sharks occupy coastal and benthic environments along the continental shelf (Compagno, 1984). Given their distinct foraging strategies, both species likely exert significant top-down pressure in this offshore ecosystem, collectively regulating prey assemblages across diverse ecological niches (Galindo-Rosado et al., 2023; McElroy et al., 2006). While ecological overlap may be limited, previous research has documented adult sandbar sharks foraging on other elasmobranchs, which may influence the habitats and spatial extent of silky sharks throughout the sanctuary (McElroy et al., 2006). Predator-prey interactions are energetically costly; thus, silky sharks may prioritize risk-aversion behaviors to minimize spatial overlap with larger predators (Heithaus et al., 2008). Given the distinct life stages between species, the movement patterns and habitat associations of juvenile silky sharks and adult sandbar sharks at FGBNMS may reflect different ecological demands. Currently, there is limited information on how ontogeny, movement ecology, and habitat use drive spatial use within the sanctuary, and characterizing these behaviors will help estimate the degree of protection afforded to these highly migratory species during these specific life stages (Childs, 2001).

Acoustic telemetry is a widely used method for collecting spatiotemporal data on tagged species to estimate their distributions across small and large geographic scales (Casselberry et al., 2025; Lubitz et al., 2023; Nyce et al., 2025). Passive acoustic telemetry

entails tagging a target species with a transmitter and deploying receivers capable of detecting signals from the transmitters; however, tracking these movements is limited by the number and geographic distribution of receivers placed throughout a study site. Previous research has used acoustic tagging methods to elucidate large-scale movement patterns (Cagua et al., 2015) and evaluate the efficacy of MPAs for highly mobile species (Espinoza et al., 2015). Here, we used acoustic telemetry to characterize the movement patterns and habitat use of the silky and sandbar sharks in and around FGBNMS. The primary objectives of this study are: (1) Determine the large-scale space use of silky and sandbar sharks detected beyond the FGBNMS acoustic network; (2) Determine the spatial and temporal movement patterns of silky and sandbar sharks within the FGBNMS acoustic network; (3) Estimate the species-level residency of silky and sandbar sharks across three distinct habitats: sanctuary banks, non-sanctuary banks, and artificial reefs; (4) Estimate the daily co-occurrence between silky and sandbar sharks at habitats among the FGBNMS acoustic network.

2 Methods

2.1 Study site and acoustic array

This study monitored movements in the northwestern Gulf of Mexico located between 28° 22' N and 27° 22' N and 94° 32' W and 89° 56' W, which included FGBNMS. The study site (hereafter referred to as the FGBNMS network) encompassed 17 natural banks within the sanctuary and four non-sanctuary banks (Claypile, Ewing, Jakula, Sackett), 10 oil and gas platforms (HIA-547C, HIA-379B, HIA-386A, HIA-389A, VR-408A, VR-397A, SMI-160, SMI-205A, WD-143, ST-308), two fishing aggregation devices (FADs; FAD 1, FAD 2), and two wrecks (Wreck 1, Wreck 2 – located in lease block HIA-424 and WD-105, respectively) adjacent to the sanctuary (Figure 1). All non-bank structures will hereafter be referred to as artificial reefs. Shark movement patterns were monitored using a network of 57 acoustic receivers (VR2TX and VR2AR; 69 kHz; InnovaSea, Halifax, Nova Scotia, Canada) deployed at the previously mentioned locations within the study area to capture movement patterns both within and beyond the sanctuary. Acoustic release cannisters (ARC; RS Aqua Ltd, Portsmouth, UK) were used at the 14 sanctuary banks associated with the expansion. The specific locations chosen for each ARC receiver were estimated to be roughly the center of the sanctuary boundaries and an area that would minimize benthic disturbance while maximizing the horizontal field of view for the receiver.

2.2 Fish sampling and tagging

Silky and sandbar sharks were targeted throughout the year from August 2022 to July 2024 and collected using rod-and-reel in accordance with the fishing regulations of FGBNMS (Permit #: FGBNMS-2021-007; Figure 2). Silky sharks were brought on board, and an aerator with running seawater was placed in the mouth. Additionally, a damp towel was placed over the individual's eyes to minimize visual stimuli during this process. Sandbar sharks were kept in the water and secured along the side of the vessel with two tail ropes, one around the caudal peduncle and the second placed around the mid-section of the body posterior to the pectoral fins and anterior to the dorsal fin. Captured individuals were sexed and measured to the nearest centimeter for stretched total length (STL). An external roto tag (Q-flex® 1.5 Ear Tag, Premier 1, Washington, IA) was placed on the trailing edge of the primary dorsal fin for external identification and a V16 acoustic transmitter (60–120 sec delay; 1877-day battery life; InnovaSea, Halifax, Nova Scotia, Canada) was surgically implanted inside the coelomic cavity through a midline incision on the ventral surface 5–10 cm anterior of the cloaca. The individual was placed into tonic immobility during the surgery, and once the incision was closed with a single perpendicular median stitch using absorbable monofilament sutures, the shark was released. All individuals captured between both species were tagged opportunistically, except for certain individuals where muscle biopsies and whole blood samples were collected for a subsequent project. These individuals were not tagged to minimize stress during the capture-and-handling process. Additionally, a subset of four sandbar sharks captured within 30 nm of the sanctuary boundaries, to reduce uncertainty about which individuals would be detected in the receiver array, was tagged using standardized longline gear with a one-hour soak time during the 2023 NOAA Southeast Fisheries Science Center bottom longline (Permit #: HMS-SRP-23-31), following the methodology described by Driggers et al. (2008).

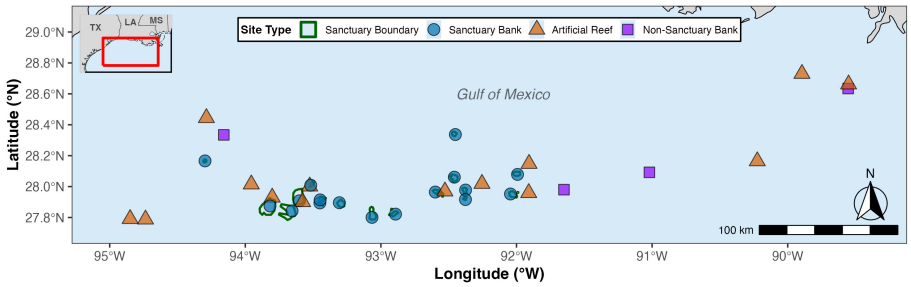

FIGURE 1
Map receiver locations across the northwestern Gulf of Mexico (blue circles = sanctuary banks, orange triangles = artificial reefs, purple squares = non-sanctuary banks). The red rectangle in the inset map shows the study area for this project relative to the greater Gulf of Mexico.

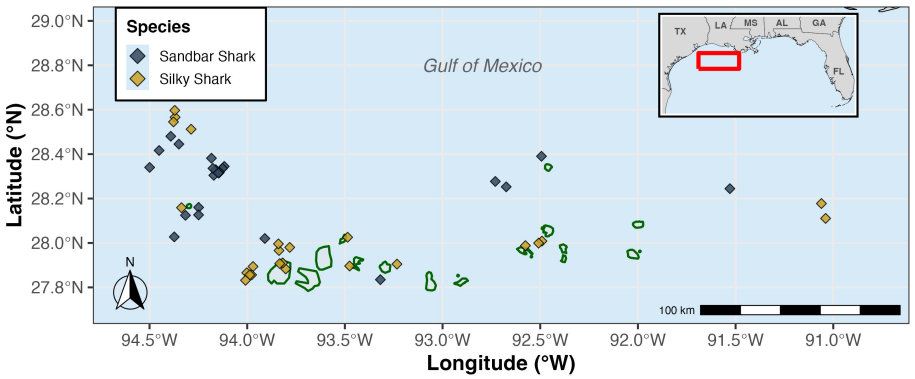

FIGURE 2
Capture and tag locations for 34 silky (*Carcharhinus falciformis*) and 29 sandbar (*Carcharhinus plumbeus*) sharks between August 2022 and October 2025. The boundaries of Flower Garden Banks National Marine Sanctuary are depicted by green outlined polygons. The red rectangle in the inset map shows the study area for this project relative to the greater Gulf of Mexico.

2.3 Data collection and processing

Data were downloaded from acoustic receivers annually (at a minimum) during summer (2023–2025) using VUE and Fathom software (Innovasea, Halifax, Canada). Detections from tagged individuals identified by acoustic receivers beyond the study area were provided by collaborative telemetry networks (Integrative Tracking of Aquatic Animals in the Gulf of Mexico; iTAG and the Ocean Tracking Network). Prior to data analysis, false detections were filtered using a conservative approach in the R package *glatos* (version 0.8.0), which removed any detections that were not subsequently detected on the same receiver within 3600 seconds, or within 10 times the nominal transmitter delay of 120 seconds (Pincock, 2012).

2.4 Network analysis

Seasonal movement networks for silky and sandbar sharks were aggregated into 35 discrete nodes, with each node representing a distinct topographic or structural feature within the FGBNMS network. These nodes represent individual receiver stations or closely grouped clusters, providing a standardized spatial framework for comparing movement between species. Seasonal movement networks were constructed by pooling detections across all study years within each season, rather than generating separate networks for each season-year combination. Seasons were designated into meteorological quarters: winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). This approach was adopted because the number of observed transitions within individual season-year combinations was insufficient to yield robust network metrics, particularly for sandbar sharks, where movements between nodes were observed less often than for silky sharks. The purpose of pooling seasons across years therefore would be to maximize the number of transitions between nodes while retaining the seasonal structure necessary to evaluate temporal variation in habitat use. Receivers with detections from tagged individuals beyond the network study area were excluded from network analyses. Network edges were weighted by the number of observed transitions between receiver nodes, such that individuals with greater site fidelity and repeated movements contributed proportionally more to network structure than recently tagged individuals with fewer detections, thereby partially decoupling network metrics from interannual variation in cohort size. Receiver nodes were classified into two habitat types: natural banks (including all sanctuary and non-sanctuary banks) and artificial reefs. Networks were created using the *igraph* (Csárdi et al., 2025), *tidygraph* (Pedersen, 2025), and *spatsoc* (Robitaille et al., 2019) packages in R (version 4.3.3; R Core Team, 2024).

To quantify how receiver locations function within the observed movements and to identify sites with the greatest connectivity, we calculated two complementary network metrics at the receiver node level within seasonal networks: (1) degree centrality and (2) eigenvector centrality (King et al., 2024; Lédée et al., 2015). Degree centrality represents the count of unique connections to a given node and functions as a metric of use frequency, identifying key movement hubs within the network. In contrast, eigenvector centrality is a continuous metric normalized between 0 and 1 that identifies preferred habitats by quantifying the degree to which a node is connected to other highly connected nodes within the network. Receiver nodes with no detections were assigned degree centrality = 0, and eigenvector centrality was calculated only for nodes with degree centrality > 0. Two fine-scale tracking receiver arrays were deployed for a subsequent study at Stetson and East Flower Garden Bank and configured so that multiple receivers detected a single tag signal; however, this arrangement could potentially artificially inflate degree centrality at those sites. To avoid this, these receivers were combined into a "single node" to provide a more accurate measure of degree centrality at each location. Repeated detections at a single node without subsequent movement to a different node did not generate additional edges, preventing raw detection frequency from inflating node-level network metrics.

A two-step modeling approach adapted from King et al. (2024) was used to examine network centrality patterns. First, a combined-species generalized linear mixed model (GLMM) examined whether degree centrality differed between species across seasons and habitat types, using a negative binomial error distribution and log-link

function to accommodate overdispersion, with species, season, and habitat types as categorical fixed effects and receiver node as a random effect. Second, species-specific models examined the independent effects of season and habitat type on degree and eigenvector centrality within each species, using GLMMs with a negative binomial error distribution for degree centrality and beta regression models with a logit link for eigenvector centrality, testing season, habitat type, and their interaction. In both modeling steps, the unit of analysis was the receiver node, where degree and eigenvector centrality values represent pooled movement data from all individuals detected at each node within each seasonal network rather than individual shark-level measurements. Nested models were compared via hierarchical likelihood ratio (LR) tests, which produce chi-squared test statistics by comparing the log-likelihood of nested models. Significant interactions were explored using estimated marginal means (EMM) and *post hoc* pairwise comparisons with Tukey adjustments. All analyses were conducted in R using the *glmmTMB* (Brooks et al., 2017) and *emmeans* (Lenth and Piaskowski, 2025) packages.

2.5 Species residence indices

Monthly residence indices (RI) were calculated to quantify the temporal extent of individual shark presence within the study region following methods adapted from Hutchinson et al. (2023). To ensure consistency with network centrality analyses, we calculated RIs using the same 35-node receiver network used for degree and eigenvector centrality. Monthly RI was calculated by dividing the number of days an individual was detected at any receiver in a given month by the total number of days in that month. Residence indices values ranged from 0 (no detections during the month) to 1 (detected every day of the month). Monthly RI values were then aggregated by season to assess seasonal variation in residency. The RI distributions between species were compared across seasons using summary statistics, and patterns were visualized with boxplots aggregated across years, with annual means plotted to identify interannual variation.

To test for temporal differences in residence indices, a repeated-measures analysis of variance (RM-ANOVA) was applied, with individual sharks as a random effect to account for repeated measurements across months and years. The effects of season, year, and month were fixed as categorical predictors of monthly RI. Prior to analysis, RI values were arcsine-square-root transformed to address significant departures from normality confirmed by Shapiro-Wilk tests, as RI values are between 0 and 1. While residuals remained statistically non-normal following transformation, linear mixed models (LMMs) are generally robust to mild violations of normality with sufficient sample sizes. The LMM implementing RM-ANOVAs were fitted using the *lme4* R package (Bates et al., 2015), which accommodates unbalanced data through restricted maximum likelihood estimation, with significance assessed via Satterthwaite approximations for degrees of freedom in the *lmerTest* R package (Kuznetsova et al., 2017). For significant effects, planned pairwise contrasts were conducted with Tukey's HSD adjustment for multiple comparisons using EMMs. The resulting EMMs were back-transformed to the original RI scale for ease of interpretation. Separate RM-ANOVAs were conducted for each species to characterize species-specific temporal patterns.

To quantify fine-scale temporal overlap at sites where both species occurred, a Simple Ratio Index (SRI) was calculated for each receiver node within the 35-node network using daily co-occurrence as the temporal unit, where two individuals were considered to co-occur at a site if both were detected on the same calendar day. The SRI ranged from 0 (no temporal overlap) to 1 (complete temporal overlap). Sites with SRI < 0.05 were classified as negligible temporal co-presence, following conventions for temporal association indices in marine predator studies (Mourier et al., 2012). The spatial scale of co-occurrence was defined by the detection radius of the acoustic receivers, using a conservative estimate of 300 m based on previously published detection range estimates for receiver configurations in offshore environments (Huveneers et al., 2016). Depth was not incorporated as a metric for spatial partitioning in this analysis as the assumed detected range exceeded the maximum site depth within the FGBNMS network (approximately 250 m), suggesting that receivers were capable of detecting tagged individuals throughout the entire water column, precluding the ability to distinguish vertical spatial positioning between species.

3 Results

3.1 Acoustic tracking

A total of 24 out of 34 (70.5%) acoustically tagged silky sharks, and 24 out of 29 (82.8%) acoustically tagged sandbar sharks were detected between August 2022 and October 2025 (Supplementary Figure 1). All tagged silky sharks were juveniles and included both females and males (12 F, 11 M; mean STL ± SD = 116.3 ± 19.4 cm, range: 90.0–164.6 cm), while all tagged sandbar sharks were adult females (mean STL ± SD: 202.3 ± 14.9 cm, range 165.9–227.7 cm) with the exception of one male; however, this individual was never detected within the array and was excluded from this study (Supplementary Table 1). Some larger juvenile silky sharks were captured during this study; however, even the oldest estimated individual (SL-05, ~3.3 years at tagging) would have been approximately five years of age by the end of the study period – still below the estimated minimum age of maturity for female silky sharks (~7 years). Therefore, this analysis did not compare movement and habitat use between juvenile and adult silky shark size classes. Silky shark detections totaled 231,396 (mean ± SD: 10,061 ± 13,593, range: 3 – 43,076) over 1,155 days using 25 of 35 receiver nodes (74%). Sandbar shark detections totaled 69,139 (mean ± SD: 3,143 ± 5,888, range: 2 – 23,502) over 1,069 days using 24 of 35 receiver nodes (71%). Despite a similar number of tagged individuals per species, silky sharks were detected 3.3 times as often as sandbar sharks (200.3 vs 64.7 detections per day). Individual tracking durations averaged 204 ± 252 days for silky sharks and 342 ± 231 days for sandbar sharks. Both species were detected at 15 overlapping sites, representing 44% of the acoustic receiver network.

3.2 Network metrics

The spatiotemporal habitat uses within the FGBNMS network varied between silky (Supplementary Figure 2) and sandbar (Supplementary Figure 3) sharks. In the nested likelihood ratio tests for combined species, the effect of species differed significantly in overall degree centrality (χ^2 = 18.0, df = 1, p < 0.001, LR = 8.12 × 10^3) and in the species-seasonal interaction, indicating that seasonal movement patterns differed between species (Table 1). Season alone did not significantly affect degree centrality when controlling for species (p = 0.140), confirming that seasonal effects were driven by species-level differences rather than a shared response to environmental conditions. Habitat type (natural banks vs. artificial structures) did not affect degree centrality, indicating that neither species preferentially used natural banks over artificial reefs at the network level. The distinct species main effect in this model justified separate species-specific analyses to characterize differences in movement behaviors.

Silky sharks exhibited pronounced seasonal shifts in habitat connectivity. Degree centrality varied significantly across seasons (χ^2 = 14.75, df = 3, p = 0.002), with a significant season-habitat interaction (χ^2 = 9.80, df = 3, p = 0.020) indicating the relative importance of natural banks versus artificial reefs shifted seasonally (Supplementary Table 2). Degree centrality at natural banks was highest during spring and winter (EMM: 3.29 and 3.06, respectively) and dropped in the summer (EMM: 0.39), representing an 8.5-fold decline from spring (Table 2). Artificial reefs showed comparatively stable connectivity across all seasons (EMMs: 0.80–2.23), suggesting they serve as a consistent habitat regardless of season. Silky shark eigenvector centrality also varied significantly across seasons (χ^2 = 9.14, df = 3, p = 0.028), independent of habitat type, whether as a main effect or an interaction. Eigenvector centrality peaked in fall (EMM: 0.168) and was lowest in summer (EMM: 0.033), indicating silky sharks not only used fewer sites in the summer but the elevated fall eigenvector centrality is consistent with the higher degree centrality observed at artificial reefs during the fall (EMM = 2.23). This suggests increased connectivity through artificial reef habitats during this period. In contrast to silky sharks, sandbar sharks showed no seasonal shifts in the relative importance of natural banks versus artificial reefs, indicating temporal consistency in network connectivity. Sandbar shark degree centrality showed no significant seasonal variation, habitat effect, or season-habitat interaction (all p > 0.19; Supplementary Table 2). Similarly, eigenvector centrality showed no significant seasonal or habitat effects (all p > 0.92; Supplementary Table 2), indicating that sandbar sharks maintained temporally consistent network connectivity across seasons, with no evidence of habitat preference among seasons as was observed in silky sharks. The seasonal-habitat interaction had reduced degrees of freedom (df = 2), reflecting sparse spring data in which only four nodes recorded non-zero eigenvector centrality values, including a single artificial structure node; results from this interaction term should be interpreted with caution.

3.3 Residency indices

Monthly RIs were similar between species; silky sharks exhibited a mean monthly RI of 0.304 ± 0.279 (median = 0.186, range: 0.032–1.000; Figure 3), while sandbar sharks exhibited a mean monthly RI of 0.273 ± 0.280 (median = 0.167, range: 0.032 – 1.000; Figure 4). Repeated-measures ANOVAs revealed species-specific temporal structure in residence indices (Supplementary Table 3).

Silky sharks showed no significant seasonal variation in RI. Using back-transformed EMMs for seasonal RI, pairwise comparisons revealed no significant seasonal differences (all Tukey HSD p > 0.29), indicating that silky sharks maintained temporally similar residency throughout the year, with individual variation exceeding seasonal effects. In contrast, sandbar sharks exhibited significant seasonal variation in monthly RI ($F_{3,115}$ = 3.90, p = 0.011; Supplementary Table 3). *Post-hoc* pairwise comparisons revealed that spring RI was significantly higher than summer (Tukey HSD, t-ratio = 3.09, df = 111, p = 0.013), while no other seasonal comparisons were significant (all p > 0.09). Year effects were non-significant, indicating consistent seasonal patterns across 2022–2025. Additionally, month-level analysis revealed significant fine-scale temporal structure ($F_{11,111}$ = 2.02, p = 0.033), suggesting elevated site use in spring followed by a decline in summer.

3.4 Habitat use

Among the 35 receiver nodes, both species were detected at 15 sites (43% of the acoustic network); however, the SRI revealed near-complete temporal separation at these shared sites (mean ± SD: 0.002 ± 0.006, median: 0.000, range: 0.000–0.025). All 15 co-occurrence sites had SRI < 0.05, indicating negligible temporal overlap. Only two sites showed any days with both species present: Stetson Bank (9 co-occurrence days out of 321 total detection days; SRI = 0.025) and HIA-379B (2 co-occurrence days out of 357 total detection days; SRI = 0.006). The remaining 13 sites had no days with simultaneous detections of both species despite overlapping use across the study period. The SRI did not differ between natural banks (mean = 0.002, n = 11 sites) and artificial structures (mean = 0.001, n = 4 sites), indicating that temporal separation occurred consistently across habitat types.

Movement network analysis revealed species-specific patterns in how sharks connect habitats within the FGBNMS network. Silky sharks exhibited 2.4 times as many movements (Figure 5) as sandbar sharks (Figure 6; 153 vs. 65 movements) with greater network complexity (63 vs. 40 unique pathways) and higher rates of bidirectional movements (70% vs. 35% of pathways used in both directions), indicating more intensive and repeated use of certain corridors. The most connected node for silky sharks was EFGB, which facilitated 59 movements in total and served as a primary node linking both natural banks and artificial structures. The predominant movement pattern involved transitions between sanctuary banks (33.3% of movements) and bidirectional movements between sanctuary banks and artificial reefs (54.9% combined), indicating frequent habitat switching. The top movement corridor was between two adjacent nodes, HIA-389A and EFGB (21 movements), with silky sharks regularly transiting between an oil and gas platform and a sanctuary bank. In contrast, sandbar sharks displayed a more diffuse movement network with lower site fidelity, reflected in lower network density (7.2% vs. 12.5% of possible connections) and fewer repeated pathways. The most connected

TABLE 1 Nested likelihood ratio tests for combined-species analysis of degree centrality.

Parameter	df	χ^2	*p*-value	LR
Species	1	18.00	< 0.001	8.12×10^3
Season	3	5.47	0.140	15.4
Habitat Type	1	0.77	0.380	1.47
Species x Season	3	16.23	0.001	1.51×10^8
Species x Habitat	1	0.03	0.869	2.70×10^4
Season x Habitat	3	4.51	0.212	224.4

Models tested effects of species, season, habitat type, and their interactions using negative binomial generalized linear mixed models with receiver node as a random effect. LR, likelihood ratio relative to null model.

sites for sandbar sharks were Claypile Bank and Stetson Bank (20 movements each), with the strongest corridor between them (16 bidirectional movements). Notably, sandbar sharks made substantially greater use of non-sanctuary banks (24.6% of movements) compared to silky sharks (0%), whereas silky sharks were frequently detected near artificial reefs, suggesting broader-scale habitat selection that extends beyond the sanctuary's natural banks (Figure 7). While sanctuary bank-to-sanctuary bank movements comprised the largest single category (27.7%), sandbar sharks exhibited more diverse movement patterns across all habitat-type combinations, consistent with their use of the FGBNMS network on a larger regional scale rather than being concentrated within the sanctuaries' boundaries.

3.5 Large-scale space use

Beyond the FGBNMS network, 13 individuals (two silky sharks, 11 sandbar sharks) were detected at 34 external receiver stations, demonstrating broader connectivity across the northwest Atlantic Ocean. External receiver detections accounted for approximately 0.47% of total detections (1,406 of 302,168), but there were species-specific differences in movement patterns and geographic ranges. Silky sharks exhibited limited regional movement, with only two individuals (9% of detected sharks) observed outside the FGBNMS network. Both silky sharks were detected off the coast of Corpus Christi, TX, located approximately 280–340 km southwest of FGBNMS. In contrast, sandbar sharks exhibited extensive long-distance movement across multiple regions of the Gulf of Mexico and the northwest Atlantic Ocean. Regional movements from 11 individuals (46% of the detected population) were detected across nine distinct coastal regions spanning the western Gulf of Mexico to southern New England. Detections outside the FGBNMS network included seven individuals in Florida Keys National Marine Sanctuary, four off South Carolina, three in the Chesapeake Bay, North Carolina, and the West Florida Shelf, one along the Georgia coast, and one as far north as Massachusetts.

Return migrations to the FGBNMS network were documented for two sandbar sharks, both observed in the Florida Keys National Marine Sanctuary. One individual (SB-11) completed a 522-day round-trip from Ewing Bank (November 24, 2023) through Florida Keys National Marine Sanctuary (May 13 – July 10, 2024) and returned to Wreck 2 on April 29, 2025. The second individual (SB-32) departed Sackett Bank (March 5, 2025) and reached the Florida Keys National Marine Sanctuary 28 days later (April 2, 2025), then returned to Stetson Bank on August 14, 2024, after 162 days. The longest documented regional movement pattern was exhibited by SB-07, which traversed sites near Corpus Christi, TX; the West Florida Shelf; the Florida Keys National Marine Sanctuary; the Carolinas; and off the coast of Massachusetts, spanning a cumulative minimum travel distance of approximately 6,548 km. The 11 tagged individuals detected outside the FGBNMS demonstrate regional-scale ecosystem connectivity, with multiple cumulative minimum distances exceeding 1,300 km (Supplementary Table 4). Mean cumulative distance across all externally detected sandbar sharks was 2,682 ± 2,187 km, reflecting substantial individual variation in movement extent. Mean travel time from FGBNMS to external sites was 85 ± 65 days (range: 14–213 days), indicating that departures from the network were followed by extended periods (weeks to months) before being detected elsewhere throughout the Northwest Atlantic Ocean.

TABLE 2 Estimated marginal means (EMMs) for significant effects from network centrality analyses.

Species	Network metric	Season	Habitat type	EMM	SE	95% CI
Silky Shark	Degree Centrality	Spring	Natural Bank	3.293	0.913	[1.913, 5.670]
		Summer	Natural Bank	0.386	0.196	[0.143, 1.043]
		Fall	Natural Bank	1.635	0.518	[0.878, 3.043]
		Winter	Natural Bank	3.055	0.855	[1.765, 5.287]
		Spring	Artificial Reef	0.988	0.391	[0.455, 2.146]
		Summer	Artificial Reef	0.801	0.344	[0.345, 1.858]
		Fall	Artificial Reef	2.234	0.733	[1.174, 4.250]
		Winter	Artificial Reef	1.748	0.604	[0.888, 3.441]
	Eigenvector Centrality	Spring	Combined	0.088	0.123	[0.159, 0.610]
		Summer	Combined	0.033	0.010	[0.006, 0.054]
		Fall	Combined	0.168	0.050	[0.036, 0.250]
		Winter	Combined	0.064	0.114	[0.112, 0.541]

EMMs are back-transformed to the response scale with standard errors (SE) and 95% confidence intervals (CI). For degree centrality, EMMs represent expected number of connections. For eigenvector centrality, EMMs represent eigenvector centrality scores (0–1 scale).

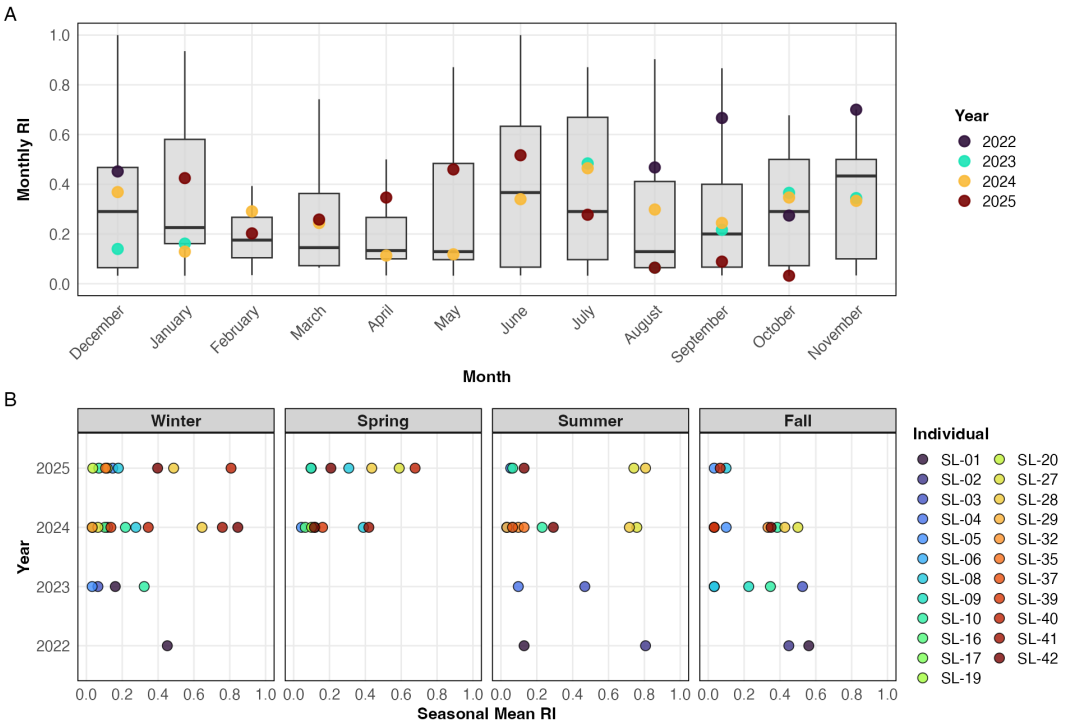

FIGURE 3
Residency indices (RI) for tagged silky sharks (*Carcharhinus falciformis*, n = 23) from August 2022 to September 2025 within the FGBNMS network. **(A)** Box-and-whisker plots representing the monthly RI for all individuals combined, displaying the minimum, lower 25th percentile, median, 75th percentile, and maximum values. **(B)** Seasonal mean RI for 23 detected silky sharks over the study period. Individuals detected in separate years and seasons are represented by the same color circle. Figure layout adopted from Hutchinson et al. (2023).

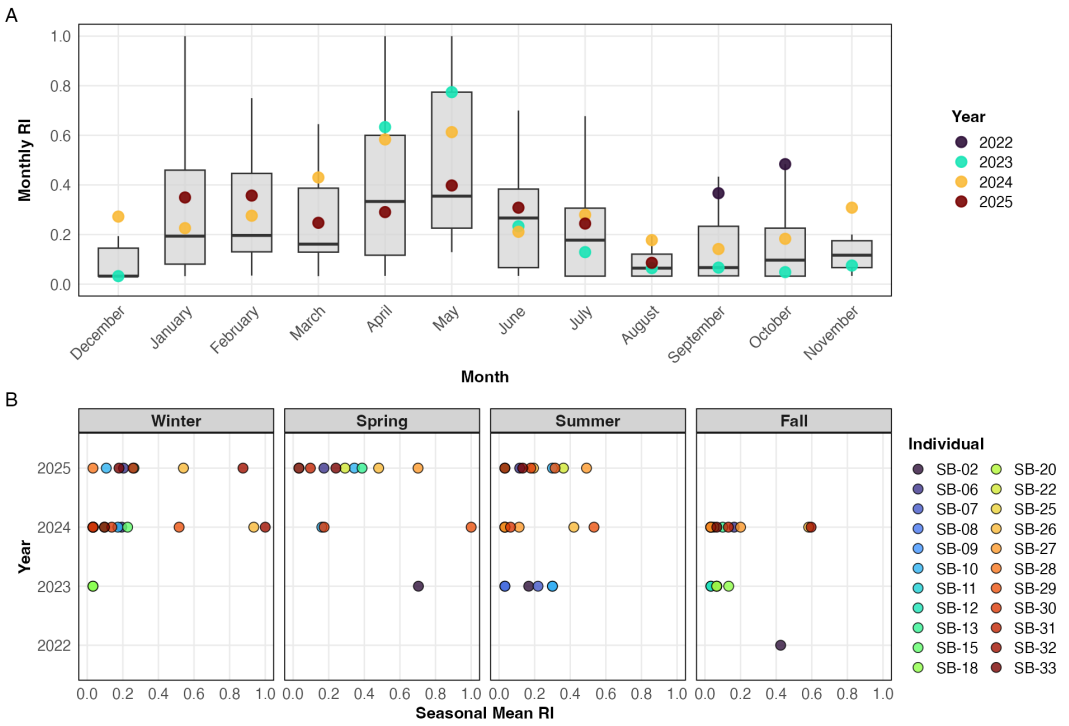

FIGURE 4
Residency indices (RI) for tagged sandbar sharks (*Carcharhinus plumbeus*, n = 23) from August 2022 to September 2025 within the FGBNMS network. **(A)** Box-and-whisker plots representing the monthly RI for all individuals combined, displaying the minimum, lower 25th percentile, median, 75th percentile, and maximum values. **(B)** Seasonal mean RI for 23 detected sandbar sharks over the study period. Individuals detected in separate years and seasons are represented by the same color circle. Figure layout adopted from Hutchinson et al. (2023).

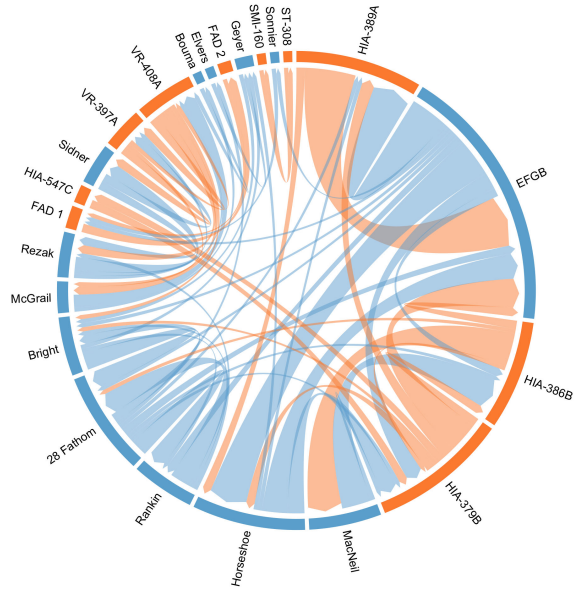

FIGURE 5
Chord diagram illustrating aggregated movement pathways of silky sharks (*Carcharhinus falciformis*) within the 35-receiver node FGBNMS acoustic network. Sectors on the circumference are proportional to the total number of movements associated with that site. The width of the chords is proportional to the number of movements observed for that specific pathway. Colors represent habitat types between sanctuary banks (blue) and artificial reefs (orange).

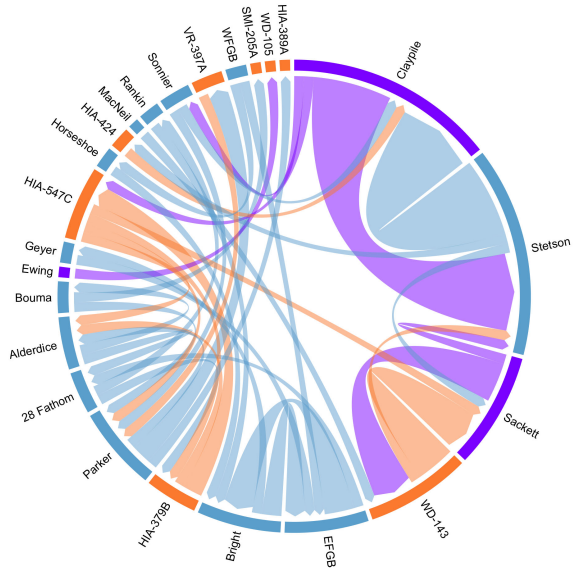

FIGURE 6
Chord diagram illustrating aggregated movement pathways of sandbar sharks (*Carcharhinus plumbeus*) within the 35-receiver node FGBNMS acoustic network. Sectors on the circumference are proportional to the total number of movements associated with that site. The width of the chords is proportional to the number of movements observed for that specific pathway. Colors represent habitat types among sanctuary banks (blue), non-sanctuary banks (purple), and artificial reefs (orange).

4 Discussion

This study provides a unique perspective on the fundamental differences between the spatiotemporal movement patterns and their habitat associations for two shark species at distinct ontogenetic stages within and around FGBNMS in the northwestern Gulf of Mexico. These observations reflect the functional diversity of FGBNMS as a habitat that simultaneously supports early life stages of silky sharks and the long-distance migratory behavior of adult female sandbar sharks, with important implications for the effective conservation and management of these species within marine protected areas.

4.1 Species-specific network connectivity and seasonal variation

The significant species-season interaction in degree centrality demonstrates that juvenile silky and adult sandbar sharks exhibit fundamentally different seasonal movement strategies within the FGBNMS network. These contrasting patterns likely reflect differences in their ontogeny, reproductive ecology, and trophic roles within Gulf of Mexico ecosystems. Silky sharks exhibited pronounced seasonal variation in both degree and eigenvector centrality, with natural banks serving as primary connectivity hubs during spring and winter, then declining in summer, whereas artificial reefs maintained comparatively stable connectivity throughout the year. This seasonal habitat switching suggests that silky sharks may respond to oceanographic conditions or prey availability (Heupel et al., 2019; Papastamatiou et al., 2006) that fluctuate temporally within the sanctuary region (Lovell et al., 2024). Similar seasonal shifts in space use driven by water temperature, dissolved oxygen concentrations, and prey distribution patterns have been observed in other shark species (Daly et al., 2014; Espinoza et al., 2015; Grubbs, 2010). The disproportionate importance of natural banks during spring, with connectivity more than three times higher than artificial structures, suggests that sanctuary banks near the shelf edge, with structurally complex mesophotic coral habitats, may provide increased foraging opportunities and likely provide diverse prey assemblages that concentrate silky shark activity during peak activity periods, consistent with observations of other shark species that exhibit seasonal aggregations at specific habitats (Ayres et al., 2021; Economakis and Lobel, 1998; Heupel et al., 2010). Artificial structures, including oil and gas platforms, maintained relatively stable importance throughout the year, likely serving as consistent foraging sites due to the persistent presence of reef-associated fish assemblages that attract pelagic predators (Dance et al., 2011; Rooker et al., 1997).

Silky sharks are primarily pelagic, highly mobile predators that often form aggregations around offshore structures and seamounts, exhibiting seasonal movements related to oceanographic conditions and prey availability (Bonfil, 2008; Branstetter, 1987; Talwar et al., 2023). The high site fidelity and seasonal habitat use patterns observed in this study suggest that FGBNMS may provide critical foraging habitat for juvenile silky sharks, potentially serving as a developmental habitat before individuals recruit to offshore oceanic habitats (Bonfil, 1997; Branstetter, 1987; Talwar et al., 2023), similar to habitat use observed for juvenile oceanic manta rays (*Mobula birostris*) observed in this region (Stewart et al., 2018). The coordinated seasonal variation in both network metrics – frequency of site use and importance of site connectivity – indicates that silky

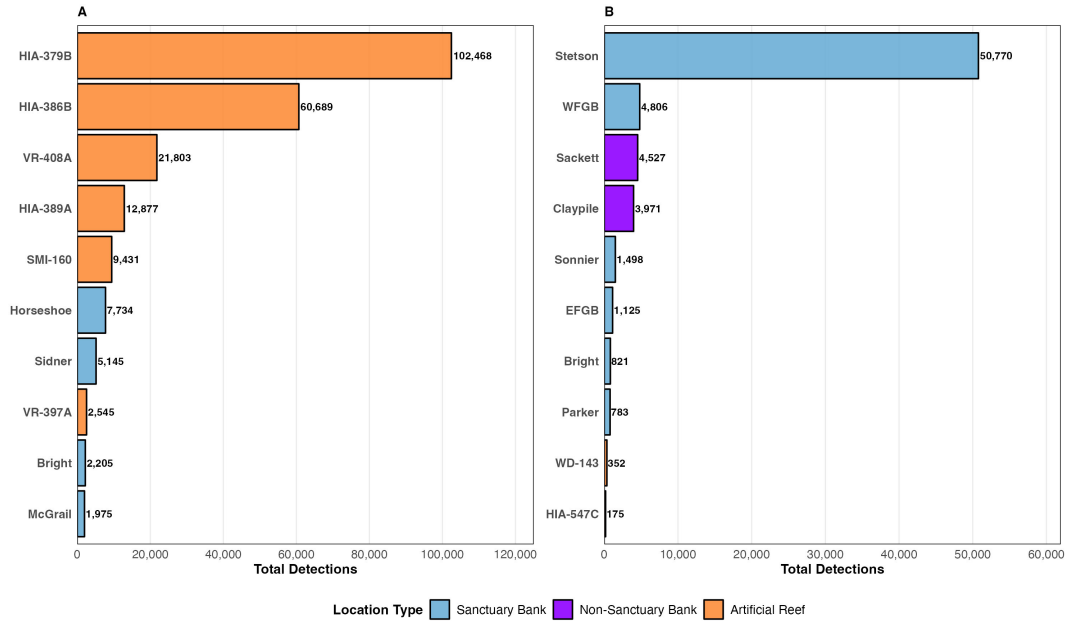

FIGURE 7
Top 10 receiver locations with the highest number of acoustic detections from **(A)** silky sharks (Carcharhinus falciformis, n = 23) and **(B)** sandbar sharks (*Carcharhinus plumbeus*, n = 22). Locations are colored by habitat type (sanctuary bank = blue, artificial reef = orange, non-sanctuary bank = purple).

sharks not only change which sites they use seasonally, but also alter their movement pathways and connectivity patterns, likely in response to seasonal shifts in prey availability or optimal environmental conditions (Díaz-Delgado et al., 2021; Lopetegui-Eguren et al., 2026).

In contrast, adult sandbar sharks exhibited consistent patterns in network connectivity across all seasons, with no significant seasonal variation in degree or eigenvector centrality. The temporal consistency in site connectivity may be attributed to the similar benthic characteristics of the mid-shelf coral community banks predominantly used by sandbar sharks (Claypile Bank, Stetson Bank, Sonnier Bank, and Sackett Bank), which are characterized by lower structural complexity and more variable environmental conditions than along banks on the shelf-edge (Nuttall et al., 2025; Sanchez et al., 2023). The use of these sites suggests sandbar sharks maintain stable habitat associations regardless of seasons, rather than changing habitats as observed in silky sharks. Sandbar sharks are coastal-demersal species with well-documented migratory patterns associated with reproduction, nursery habitat use, and seasonal temperature preferences (Crear et al., 2020; Grubbs et al., 2007; Rechisky and Wetherbee, 2003). Parturition occurs during late spring and early summer, with neonates appearing in coastal nursery areas along the U.S. Atlantic coast and the Gulf of Mexico (Baremore and Hale, 2012; Castro, 1993; Grubbs et al., 2007). Genetic evidence indicates that females show strong philopatry to nursery grounds, whereas males migrate, thereby facilitating gene flow throughout the Gulf of Mexico (Portnoy et al., 2010). The consistent network connectivity observed here may therefore reflect year-round use of FGBNMS as potential foraging habitats before migration to external parturition sites.

The contrasting patterns between species suggest fundamentally different strategies for using the FGBNMS network. Juvenile silky sharks appear to exhibit seasonal habitat shifts, alternating between periods of intensive use on natural banks during winter and spring before declining in summer. Alternatively, connectivity at artificial reefs was comparatively stable throughout the year. Due to the pelagic habitat preferences of silky sharks, the locations of artificial reefs, such as oil and gas platforms, may provide access to habitat as individuals move from the continental shelf edge towards open-ocean environments. Sandbar sharks, conversely, integrate FGBNMS into a larger-scale migration circuit, perhaps displaying long-term philopatry to this region while using natural banks and artificial reefs consistently within the FGBNMS network. These strategies likely reflect broader differences in movement ecology, with silky sharks exhibiting more localized seasonal movements within a core area along the shelf edge during their juvenile life stage, whereas adult sandbar sharks undertake extensive migrations that may be related to reproduction or foraging. The size-class differences between these species within the sanctuary may also influence their movement patterns, with smaller silky sharks potentially facing greater predation risk from larger elasmobranchs in the region (Childs, 2001) and therefore exhibiting more localized movements centered on structurally complex habitats that provide refugia (Ayres et al., 2021; Heithaus et al., 2009). Alternatively, sandbar sharks, with reduced predation pressure, may be able to undertake longer-distance movements and use a broader range of habitats with lower associated risks (Cortes, 1999; Grubbs, 2010).

4.2 Residency patterns and temporal dynamics

Despite similar mean monthly residence indices between species, species-specific temporal structure was evident. Silky sharks showed no significant seasonal variation in residence indices, indicating temporally consistent but individually variable site

association throughout the year. This pattern likely reflects the pelagic habitat use of this species, which associates opportunistically with reef structures rather than relying on them as core habitat. Additionally, the elevated number of acoustic detections near artificial reefs, specifically oil and gas platforms with large vertical structure, is consistent with observations of juvenile silky sharks associating with seamounts, which may serve as refugia, foraging aggregation points, or navigation landmarks during early ontogeny (Murray et al., 2023). Silky sharks would be expected to exhibit greater individual plasticity in habitat use than a more reef-associated species, such as a sandbar shark. Individual silky sharks may therefore adopt distinct movement strategies, ranging from resident to highly transient, depending on foraging opportunities or energetic state, a pattern consistent with behavioral specialization documented in other large-bodied pelagic sharks (Matich et al., 2011; Speed et al., 2011). In contrast, sandbar sharks exhibited seasonal variation in residence indices, with the highest residency occurring in spring, suggesting that sandbar sharks spend more time within the FGBNMS network during this time, but movement patterns among sites are not altered, as observed in other seasons. There is evidence of multiple small sandbar shark nursery areas along the U.S. East Coast and the Gulf of Mexico (Baremore and Hale, 2012; Carlson, 1999; Gibson-Banks et al., 2026; Grubbs et al., 2007). The relatively limited number of individuals that departed and did not return to FGBNMS may reflect the suggested triennial reproductive cycle of species (Piercy et al., 2016), in which females return to coastal pupping areas on a multi-year cycle and may use different foraging habitats between reproductive events rather than returning to the same sites annually.

4.3 Habitat use patterns and ecological niche partitioning

The high detection rate at 15 overlapping sites (43% of the acoustic network), combined with near-complete temporal separation, provides strong evidence for temporal niche partitioning between silky and sandbar sharks within the FGBNMS network. Although both species used the same spatial locations, they rarely co-occurred temporally, with only two sites showing any days with simultaneous detections. This temporal segregation likely reduces interspecific competition for resources and may also reflect predator avoidance behaviors, as adult sandbar sharks are known to prey on smaller elasmobranchs (Cliff et al., 1988; McElroy et al., 2006; Stillwell and Kohler, 1993). Temporal niche partitioning has been documented as a common mechanism enabling coexistence among elasmobranchs with overlapping habitat use (Marshall et al., 2008; Papastamatiou et al., 2006; White and Potter, 2004). Size-class differences between silky and sandbar sharks within the sanctuary may create a predation risk scenario in which smaller silky sharks actively avoid temporal overlap with larger sandbar sharks to minimize predation risk or competitive interactions (McCauley et al., 2012; Wirsing et al., 2007). Anti-predator behavior in sharks can be energetically costly, and complete temporal avoidance may represent a more efficient strategy than vigilance or evasive behaviors (Lima and Dill, 1990; Wirsing and Ripple, 2010).

The lack of differences in habitat preference between natural banks and artificial structures for both species suggests that artificial reefs function as ecologically equivalent nodes within the broader movement network. This finding aligns with previous research demonstrating that oil and gas platforms in the Gulf of Mexico support high fish densities and serve as important foraging habitats for pelagic predators (Ajemian et al., 2015; Dance and Rooker, 2019). The functional equivalence of natural and artificial structures within the movement network has important implications for conservation planning, as the future decommissioning of offshore platforms could potentially reduce available habitat and connectivity for this species within the region (Ajemian et al., 2015; Fowler et al., 2014). Juvenile silky sharks showed repetitive movements between natural banks and artificial reefs concentrated among the sanctuary banks, whereas sandbar sharks exhibited dispersed patterns across natural banks and artificial reefs on a larger geographic scale, corroborating findings of species-level differences in monthly residency. These movement patterns align with fundamental differences in foraging ecology, with silky sharks exhibiting central-place foraging similar to behavior observed near FADs (Hutchinson et al., 2019), whereas sandbar sharks display nomadic movements consistent with wide-ranging coastal migrations (Grubbs, 2010; Heupel et al., 2010). The higher connectivity in silky shark movements suggests well-established migratory corridors, likely driven by individuals exploiting foraging resources across multiple habitats. Conversely, the lower connectivity in sandbar sharks indicates more nomadic behavior, characterized by directional, one-way transitional movements through the region (Heupel et al., 2019; Speed et al., 2010).

4.4 Long-distance movements and regional connectivity

The stark contrast in long-distance movement patterns between species highlights fundamental differences in their spatial ecology and connectivity across the Gulf of Mexico. Only two juvenile silky sharks were observed at external sites outside the FGBNMS network, both detected off the coast of Corpus Christi, TX. These limited regional movements suggest that while juvenile silky sharks occupy shelf-edge habitats, detections outside of the FGBNMS network may be limited as these individuals shift to pelagic environments with no acoustic receiver coverage (Branstetter, 1987; Heupel et al., 2010; Speed et al., 2011). These movement patterns support previous observations of silky shark behavior in the western North Atlantic, where young individuals may exhibit a benthopelagic-shelf stage to exploit foraging opportunities with reduced predation risk at artificial reefs and shallow reef habitats (<30 m), then transition to a pelagic lifestyle in the open ocean before reaching maturity (>200 m; Bonfil, 1997; Branstetter, 1987; Talwar et al., 2023). The benefits of shifting toward pelagic environments may be linked to their early rapid growth rates (Branstetter, 1990) or driven by foraging behaviors associated with other offshore species such as tunas (Bonfil, 2008; Talwar et al., 2023). This is further supported by the absence of adult silky sharks observed throughout this study. In contrast, half of the detected sandbar sharks in this study were observed at external sites

spanning the Gulf of Mexico and the western North Atlantic Ocean, with multiple individuals exceeding 1,300 km straight-line distances. The return migrations documented by SB-11 and SB-32 provide compelling evidence for long-distance site fidelity and regional-scale ecosystem connectivity within the Gulf of Mexico. These movement patterns are consistent with previous tagging studies of sandbar sharks that have demonstrated extensive coastal migrations spanning hundreds to thousands of kilometers within the Gulf of Mexico and along the U.S. Atlantic coast (Altobelli and Szedlmayer, 2020; Kohler and Turner, 2020). The predominance of Florida Keys detections demonstrates large-scale ecosystem connectivity linking Florida Keys National Marine Sanctuary to FGBNMS. This pattern may reflect seasonal migrations related to reproduction or movements tracking oceanographic features and prey availability (Baremore and Hale, 2012; Hueter et al., 2004). The extended travel times between FGBNMS departures and external detections indicate that sandbar sharks may use intermediate habitats during these migrations or move through areas without acoustic receiver coverage, highlighting the challenges of tracking highly mobile species across large spatial scales (Crossin et al., 2017; Hussey et al., 2015).

4.5 Conservation and management implications

The fundamental differences in spatial ecology between silky and sandbar sharks within FGBNMS have important implications for conservation planning and MPA design. However, these findings primarily reflect the movement ecology of juvenile silky and adult female sandbar sharks and may not fully represent the habitat use and connectivity patterns of other demographic groups within each species throughout this region. Silky sharks demonstrated relatively high site fidelity to the FGBNMS network, suggesting that the sanctuary provides meaningful habitat for individuals using this region. However, seasonal variation in habitat use and network connectivity suggests that habitat suitability may vary over time, with peak sanctuary use occurring in spring and winter. Additionally, silky sharks were frequently observed near oil and gas platforms, which predominantly fall outside of the sanctuary's boundaries. For sandbar sharks, non-sanctuary banks, including Claypile Bank and Sackett Bank, received substantial use yet currently afford no formal protections, and extensive long-distance movements to regions, including Florida Keys National Marine Sanctuary, indicate that FGBNMS provides only partial protection for this species. Individuals that spend time outside sanctuary boundaries (both at non-sanctuary banks and artificial reefs) may be exposed to bycatch and a heightened risk of discard mortality (Marshall et al., 2015; Morgan and Burgess, 2007), highlighting the need for coordinated management across the broader Gulf of Mexico to adequately protect these species during large-scale migrations (Graham et al., 2016; Hyde et al., 2022).

The functional equivalence of natural banks and artificial structures within the FGBNMS network suggests that both habitat types contribute to connectivity and space use for these species. As the oil and gas industry in the Gulf of Mexico continues to evolve, with platforms reaching the end of their operational lifespan, future decommissioning decisions will need to consider the potential ecological value of these structures as habitat and connectivity nodes for mobile predators (Ajemian et al., 2015; Fowler et al., 2014; Kolian et al., 2019; Macreadie et al., 2011). Rigs-to-reef programs, which convert decommissioned platforms into artificial reefs, may help maintain habitat availability and connectivity within the broader seascape, especially for juvenile silky sharks that likely use these habitats for foraging and refuge before transitioning into offshore environments (Branstetter, 1987; Dance and Rooker, 2019). Effective conservation strategies must account not only for the spatial extent of protection but also the temporal dynamics of species presence and the ecological interactions that structure community composition (Claudet et al., 2021; Garcia et al., 2008). For highly mobile species like sandbar sharks, regional-scale management approaches that coordinate protection across multiple jurisdictions and habitats may be necessary to ensure adequate conservation benefits throughout their annual movement cycles (Graham et al., 2016; Hyde et al., 2022; Mouton et al., 2025). The regional migrations documented for sandbar sharks in this study reveal frequent habitat use by multiple individuals and fine-scale navigational pathways along the Gulf of Mexico and U.S. East Coast, which were not previously documented with acoustic telemetry.

Understanding the cues and mechanisms underlying fidelity, whether driven by geomagnetic navigation, olfactory cues, or other sensory modalities, represents an important area for future research (Driggers et al., 2014; Hueter et al., 2004; Keller et al., 2021). Additionally, identifying the habitats and movement corridors used by silky and sandbar sharks after they leave FGBNMS will be critical to developing comprehensive management strategies that protect these species throughout their life cycle (Chapman et al., 2015; Conrath and Musick, 2010; Papastamatiou et al., 2010). Large-scale ecosystem connectivity, as evidenced by acoustic detections between FGBNMS and Florida Keys National Marine Sanctuary, underscores the importance of these reefs to mobile marine megafauna. While protecting entire movement corridors is unlikely to be practical, our findings provide modest evidence that these sanctuaries are important habitats along the migratory routes of sandbar sharks, and that protecting these sites is valuable for maintaining connectivity. As MPA networks continue to expand globally, incorporating species-specific movement data into future MPA design and evaluation will be essential for achieving effective conservation outcomes for highly mobile marine predators.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by the Institutional Animal Care and Use Committee (IACUC) reference number 160529 at Texas A&M University. Sharks tagged on the NOAA bottom

longline survey did not require approval in accordance with the National Marine Fisheries Service (NMFS). The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

BS: Formal analysis, Writing – original draft, Writing – review & editing, Data curation, Investigation, Methodology, Software, Visualization. JR: Conceptualization, Funding acquisition, Project administration, Writing – review & editing, Supervision. MD: Conceptualization, Funding acquisition, Writing – review & editing, Project administration, Supervision. EH: Writing – review & editing, Conceptualization, Funding acquisition, Investigation, Resources. WD: Writing – review & editing, Conceptualization, Funding acquisition, Investigation, Resources. JD: Writing – review & editing, Conceptualization, Funding acquisition. MN: Conceptualization, Writing – review & editing, Data curation, Investigation, Methodology, Project administration. BK: Writing – review & editing, Data curation, Investigation. CB: Writing – review & editing, Data curation, Investigation. LR: Data curation, Writing – review & editing, Investigation, Project administration. SL-B: Data curation, Writing – review & editing, Conceptualization, Funding acquisition. SC: Investigation, Resources, Writing – review & editing, Methodology. BF: Investigation, Resources, Writing – review & editing, Methodology. RW: Conceptualization, Funding acquisition, Writing – review & editing, Project administration, Supervision.

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Conflict of interest

Author SC was employed by the company Galveston Sea Ventures. Author BF was employed by the company Fisheries Research Support LLC.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author JD declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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