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White shark occurrence in Flower Garden Banks National Marine Sanctuary revealed from acoustic telemetry in an offshore MPA

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The outer continental shelf of the Gulf of Mexico (Gulf) is characterized by unique bathymetric features that provide critical habitat for marine fauna. Here, we demonstrate the utility of large-scale acoustic telemetry for monitoring an oceanic marine protected area (MPA) and document the first known occurrences of white sharks (*Carcharodon carcharias*) within Flower Garden Banks National Marine Sanctuary (FGBNMS). White sharks were tagged with acoustic transmitters in the western North Atlantic Ocean off the east coast of the United States and Canada. Nine white sharks were detected along the outer shelf ecosystem associated with FGBNMS over a three-year period (2022-2025), with some individuals traveling nearly 3,800 km from original tagging locations. Sharks were detected between January and August at seven natural banks (coral reefs) within FGBNMS, as well as surrounding natural and artificial reefs. Philopatric behavior was observed, with two individuals (1 male, 1 female) returning to the region in multiple years. This study adds to a growing body of evidence demonstrating the use of the Gulf by migratory white sharks, expanding our current understanding of their distribution in the western North Atlantic and highlighting the potential importance of FGBNMS and outer shelf banks to this species and other migratory taxa.

KEYWORDS

Carcharodon carcharias, conservation, coral reef, ecosystem connectivity, marine protected area (MPA), mesophotic reef, population recovery, Western North Atlantic Ocean

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Introduction

Marine ecosystems are increasingly threatened by both anthropogenic and environmental stressors that can lead to shifts in biodiversity and ecosystem function, highlighting the importance of developing conservation strategies to assess and manage ecosystems through time (Hughes et al., 2005; Butchart et al., 2010; Duarte et al., 2020). Marine protected areas (MPAs) are regions of the ocean where certain human activities (e.g., fishing, gear restrictions, anchoring, etc.) are restricted or prohibited as part of ecosystem-based management approaches to conserve essential habitats and vulnerable taxa (Halpern et al., 2010; Grorud-Colvert et al., 2021). MPAs have the potential to protect entire ecosystems, providing additional benefits to mobile marine species (O'Leary et al., 2018) and strengthening our ability to conserve biodiversity in a changing environment (Davies et al., 2017; Grorud-Colvert et al., 2021; Blanluet et al., 2024). Unfortunately, the effectiveness of MPAs is often compromised by the lack of critical information on habitat use, connectivity, and the benefits of MPAs on surrounding areas for marine taxa (Balbar and Metaxas, 2019; Conners et al., 2022).

The outer shelf of the northwestern Gulf of Mexico (also known as the Gulf of America; hereafter referred to as the Gulf) is characterized by a complex network of salt dome surface expressions (banks) that provide critical hard bottom habitat for a variety of marine organisms in a region with relatively limited hard substrate. The majority of these banks support foundational invertebrate communities characterized by a mixture of stony coral, sponge, gorgonians, and black corals, with the crests of the shallowest banks (<45m) supporting extensive hermatypic coral reefs (Johnston et al., 2016). Collectively, the banks are believed to serve a critical role in the persistence of many tropical invertebrate and reef fish populations in the Gulf, while the food-rich waters surrounding the banks are frequented by migratory pelagic predators (e.g., billfishes, sharks, tunas) and may serve as an important migratory corridor for a range of taxa (Stewart et al., 2018; Rooker et al., 2019; Ajemian et al., 2020). Flower Garden Banks National Marine Sanctuary (FGBNMS) is an MPA that was established and recently expanded to conserve the unique habitats and organisms of this outer shelf ecosystem (Office of National Marine Sanctuaries, 2024). Despite the considerable expansion of area within the sanctuary (17 banks spanning over 300 km of the shelf edge) and likely ecological importance of the banks to sustaining marine megafauna, our understanding of ecological connectivity and species' spatiotemporal utilization of habitats across these banks is extremely limited.

Here, we demonstrate the utility of a large acoustic telemetry array in FGBNMS in describing the first documented occurrence of white sharks (*Carcharodon carcharias*) in the sanctuary and surrounding outer shelf ecosystem. The white shark is a large, highly mobile, apex predator distributed primarily in temperate and subtropical waters of the world's oceans. The species utilizes both coastal and pelagic habitats, and in the western North Atlantic Ocean, white sharks are known to shift their habitat use between inshore and offshore regions and make large-scale migrations from waters off the northeastern United States (U.S.) and Canada to the southeastern U.S., including the Gulf (Curtis et al., 2014; Skomal et al., 2017; Franks et al., 2021). While white sharks in the western North Atlantic experienced significant population declines in the late 1900s leading to implementation of significant protective measures (Curtis et al., 2014; Pacoureau et al., 2023), recent data suggests the species is now recovering and reoccupying the northern and southern extent of their primary historical range (Winton et al., 2023; Guttridge et al., 2024; Allegue et al., 2025). Indeed, sightings of white sharks in the Gulf appear to be increasing (Drymon et al., 2025); however, records west of the Mississippi River are historically very rare, with no documented occurrences in FGBNMS despite consistent visual monitoring programs. The goal of this study was to describe the occurrence of white sharks in the sanctuary over a three-year monitoring period, to provide insight into their use of this unique ecosystem, and to highlight the value of offshore telemetry arrays in improving our understanding of ecosystem connectivity between MPAs and surrounding areas for highly migratory species.

Methods

The study region included the expansive system of banks along the outer shelf of the northwestern Gulf from Galveston, Texas, to the Mississippi River Delta in Louisiana (Rezak et al., 1990). Flower Garden Banks National Marine Sanctuary includes 17 banks: Stetson, West Flower Garden, East Flower Garden, Horseshoe, MacNeil, Rankin, 28-Fathom, Bright, Geyer, Elvers, McGrail, Bouma, Rezak, Sidner, Sonnier, Alderdice, and Parker (Figure 1). The majority of the sanctuary banks are located approximately 200 km offshore, with numerous additional named banks, artificial reefs, and oil and gas platforms located outside of the sanctuary along the reef tract. Many of the outer shelf artificial reefs support similar invertebrate and fish communities to the natural banks including dense bivalve, sponge, and hydroid communities as well as demersal and pelagic fish species (Sammarco et al., 2014; Schulze et al., 2020; Johnston et al., 2022).

A large-scale acoustic receiver array (VR2Tx and VR2AR, Innovasea) was established during July and August of 2022 to examine habitat use and ecosystem connectivity of fishes in FGBNMS and the surrounding outer shelf ecosystem. The array consisted of 32 receivers, with a single receiver at each of the 17 banks of FGBNMS, 4 surrounding banks (Claypile, Jakkula, Ewing, Sackett), and adjacent artificial reefs (n = 11) along the outer shelf (Figure 1). Additional receivers were located on the inner to mid shelf across the study area. Inside the sanctuary, receivers were moored to the seafloor using moorings installed by the sanctuary or ARC retrieval cannisters fitted with Dyneema line that allowed retrieval of anchors from each bank. Site depths ranged from 18 m to 125 m, with most between 50 and 70 m. The receiver array was downloaded annually in July in 2023, 2024 and 2025, providing 3 years of continuous monitoring. Data were shared through the Integrated Tracking of Aquatic Animals in the Gulf of Mexico (iTAG) telemetry network.

Tagging was conducted from 2014 through 2024 at multiple locations off eastern North America from South Carolina, USA to

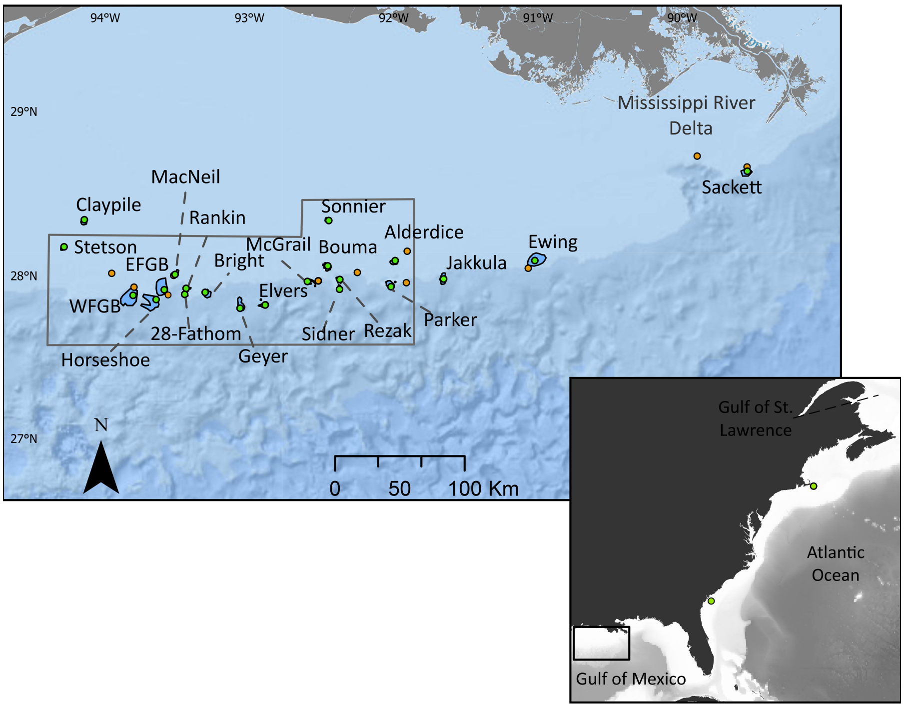

FIGURE 1
Maps showing study area and acoustic receiver array (n = 30 receivers) on the outer shelf of the northwestern Gulf. Receivers located at natural banks are denoted by green circles, while receivers located at artificial reefs are denoted by orange circles. Natural banks are labeled by name, and the extent of each bank is represented by blue polygons. Banks in the Flower Garden Banks National Marine Sanctuary (FGBNMS) are included within the bounding gray polygon, although actual sanctuary boundaries are restricted to the individual banks.

New Brunswick, Canada (Figure 1). White sharks (n = 311) were fitted with acoustic transmitters (V16-6H, V16-4H, V16AT-6H, V16P-6H, or V16TP-6H; 158 dB) programmed with a random transmission interval of 30–160 s and a maximum battery life of approximately 9 years. Each transmitter was tethered to a titanium dart and inserted externally into the dorsal musculature of free-swimming sharks using a tagging pole (Curtis et al., 2014; Winton et al., 2021). At the time of tagging, the total length (TL) of free-swimming sharks was visually estimated to the nearest 0.3 m via expert consensus using the research vessel's pulpit length for scale (Curtis et al., 2014). For captured sharks, TL was measured directly and the sex recorded. In most cases (*n* = 276), underwater video or photographs were also captured, allowing for sex determination and documentation of identifying characteristics (e.g. pigmentation patterns or scars; Winton et al. 2023).

Results

White sharks (n = 9) were detected at 14 reef sites along the outer shelf of the northwestern Gulf between 2022 and 2025 (Figure 2). All detections were recorded at banks and artificial reefs located between the 100 and 200 m isobath, with no detections of white sharks recorded on receivers maintained by the PIs over the inner and mid-shelf of this region during the study period. Five individuals were detected at seven different banks within FGBNMS: East Flower Garden, Horseshoe, Bright, Geyer, Rezak, Sidner, and Alderdice. Four individuals were detected at banks outside the sanctuary (Sackett, Ewing, Jakkula), while six of the sharks were detected at artificial reefs adjacent to the banks. Additional sharks not tagged in the current study were also detected at McGrail and Parker during this time period (Roach et al., 2026). Sharks detected in the study came from two tagging locations along the eastern U.S.: South Carolina (n = 2) and Massachusetts (n = 7) (Figure 1), and included six females and three males (Table 1). Time from tagging to detection in our array ranged from 8 months to 5 years. Three of the sharks were detected between 8–10 months after tagging and were thus likely a similar size at detection. However, the remaining six individuals were detected 2–5 years after tagging and were potentially larger at the time of detection.

Overall, 20 unique observations of white sharks were recorded between January and August along the outer shelf, with detections at various times during the 24-hour cycle (day and night) (Table 1). White sharks were detected in each year of the study: 2022 (n = 1), 2023 (n = 4), 2024 (n = 4), and 2025 (n =4). It should be noted that the array was not deployed until July of 2022, and a white shark was detected at Alderdice Bank within days of initial deployment. The majority of observations (55%) occurred during the spring (April – June), with 25% of observations occurring in the summer (July-August), and 20% during winter (January – February). Observations were brief, with five of the nine sharks detected on just one day. Of the four sharks that were detected on multiple days, WS-02 was detected across 50 (2023) and 45 days (2024), WS-04 was detected across 4 days, WS-05 was detected across 14 days, and WS-06 was detected across 7 days. However, no shark was present

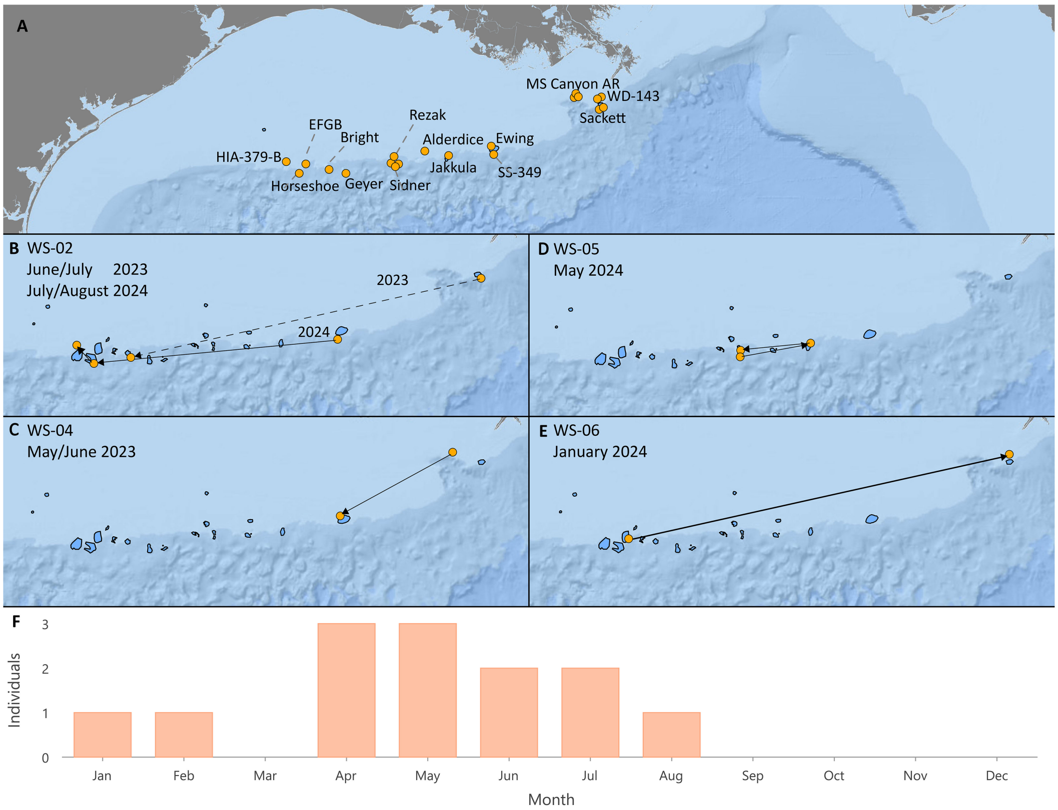

FIGURE 2
Locations of white shark detections (2022-2025) along the outer shelf of the northwestern Gulf **(A)**. Sites where sharks were detected are named in panel A and jitter was applied to show each occurrence and where more than one shark was detected. Movement pathways for individual white sharks that were detected at multiple locations in the array **(B–E)** are also shown. The extent of natural banks are represented by blue polygons. Seasonality of white shark presence within the study area is represented **(F)** as number of individuals detected by month.

at a single receiver (site) for longer than one day. By fall, white sharks detected in the array returned to waters of the western North Atlantic between the New York Bight and the Gulf of St. Lawrence (> 4,600 km; Skomal and Winton pers comm).

Considerable variability in individual movement and philopatry was observed among detected white sharks. In water (straight line) distance between tagging location and detection location in our array ranged from 2,100 km to over 3,750 km. Three individuals moved to the region within a year of tagging. WS-01 was tagged off Cape Cod in October of 2021 and was detected at Alderdice Bank (3,600 km) 280 days later in July of 2022. WS-03 was tagged off Cape Cod in early September of 2022 and was detected at Sidner Bank (3,631 km) 261 days later in May of 2023. WS-04 was also tagged off Cape Cod in September of 2022 and was detected 251 days later at an artificial reef along Mississippi Canyon (3,440 km) in May and subsequently Ewing Bank in early June of 2023.

Five individuals were detected at more than one location within a year and overall, white shark movement rates within the array ranged from 5.8 – 58.2 km per day for individuals detected at multiple sites. WS-04 was detected moving west (131 km) from an artificial reef near the edge of Mississippi Canyon to Ewing Bank from late May to June 2023 (Figure 2). WS-06 moved east (408 km) from East Flower Garden Bank to an artificial reef off the mouth of the Mississippi River (WD-143) across 7 days in January of 2024 (Figure 2). WS-07 was detected at two adjacent sites on the same day in February of 2025 (Table 1).

Two sharks, one male and one female, were detected in the array across multiple years, with both sharks returning during the same time of year. The female (WS-02) was detected in two successive years during summer, while the male (WS-05) was detected in three successive years during spring. WS-02 was observed moving west 377 km from Sackett Bank just west of the Mississippi River to Bright Bank over a period of 50 days from June through July 2023 (Figure 2). The shark then returned north to Cape Cod, Massachusetts during the fall of 2023 (Winton pers comm) before returning to the study area in 2024, where WS-02 was again detected moving west from an artificial reef adjacent to Ewing Bank (SS-349) to Horseshoe Bank and then a nearby artificial reef (HIA-379-B; 273 km total) over a period of 44 days from early July to mid-August (Figure 2). While WS-05 was detected in the array during spring in three different years, it was only detected at multiple locations in May of 2024, when it was detected moving east from Sidner to Jakkula Bank (71 km) and back west to Sidner in the span of 14 days (Figure 2). Still, this male made the same movement between the Gulf of St. Lawrence (fall, Winton pers comm) and FGBNMS (spring) for three successive years between 2022 and 2025, a roundtrip distance of at least 9,200 km per year.

TABLE 1 Observations (Obs) of white sharks detected on outer shelf natural and artificial reefs of the northwestern Gulf from 2022–2025.

Obs	Shark ID	Tag ID	Tag location	Tag date	Sex	TL (m)	Detect location	Detect date	#
1	WS-01	62517	Cape Cod, MA	10/1/2021	F	4.0	Alderdice*	7/8/2022	14
2	WS-02	5282	Cape Cod, MA	9/27/2019	F	3.1	Sackett	6/11/2023	4
3							Bright*	7/30/2023	11
4							SS-349	7/1/2024	9
5							Horseshoe*	8/13/2024	7
6							HIA-379-B	8/14/2024	2
7	WS-03	62504	Cape Cod, MA	9/1/2022	M	3.4	Sidner*	5/20/2023	7
8	WS-04	13614	Cape Cod, MA	9/21/2022	F	2.9	MS Canyon AR	5/30/2023	10
9							Ewing	6/2/2023	4
10	WS-05	3078	Hilton Head, SC	3/9/2021	M	3.4	Geyer*	5/9/2023	2
11							Sidner*	5/13/2024	1
12							Jakkula	5/16/2024	2
13							Sidner*	5/26/2024	3
14							Rezak*	4/9/2025	1
15	WS-06	62515	Cape Cod, MA	10/14/2021	F	2.4	East FGB*	1/24/2024	14
16							WD-143	1/30/2024	2
17	WS-07	13618	Cape Cod, MA	8/3/2022	F	3.4	WD-143	2/25/2025	1
18							Sackett	2/25/2025	3
19	WS-08	62495	Cape Cod, MA	8/25/2021	M	2.9	MS Canyon AR	4/11/2025	8
20	WS-09	3067	Hilton Head, SC	3/4/2021	F	3.5	MS Canyon AR	4/13/2025	8

For each observation, shark and tag ID, sex, estimated total length in meters, tag location and date (m/d/yyyy), detection location, detection date (m/d/yyyy), and number of detections (#) are given. Asterisk indicates within Flower Garden Banks National Marine Sanctuary. The names of several artificial reefs were abbreviated including: Mississippi Canyon Artificial Reef (MS Canyon AR), West Delta - 143 (WD-143), High Island - 379-B (HIA-379-B), and Ship Shoal-349 (SS-349).

Discussion

This study describes the first documented evidence of white sharks in the FGBNMS and provides insight into the use of the sanctuary and surrounding outer shelf ecosystem of the northwestern Gulf. Despite long term monitoring programs (> 35 years) for corals and fish communities conducted by FGBNMS scientists (Gittings et al., 1992; Office of National Marine Sanctuaries, 2024; Eisenbach et al., 2025), white sharks have been notably absent from both visual and ROV surveys. In three years of acoustic monitoring, nine sharks visited ten unique reef banks (including 7 of the 17 sanctuary banks) and four adjacent artificial sites (shipwrecks, oil and gas platforms) spanning 450 km of the outer shelf. It has long been hypothesized that outer shelf banks and platforms in the northwestern Gulf act as stepping stones (Hickerson et al., 2008; Sammarco et al., 2012; Schulze et al., 2020) for marine organisms and may serve a critical ecosystem function for migratory taxa moving through the open ocean. While the reef crests may be as shallow as 20–60 m, the waters surrounding the banks range from 100–200 m adjacent to the continental slope, which drops below 500 m to the south. White shark detections occurred within a relatively narrow latitudinal window along the outer shelf, and interestingly, individual sharks did not spend lengthy periods of time at any of the reef sites (typically less than 1 day). This suggests the natural banks and artificial reefs along the outer shelf may be used primarily as a migratory corridor for white sharks moving into the western Gulf. Similar rapid movements by migrating white sharks have been recorded in adjacent regions of the eastern Gulf and U.S. Atlantic during the southern migration phase (Lowerre-Barbieri et al., 2021; Guttridge et al., 2024). Moreover, while several studies have documented use of nearshore coastal waters during southern migrations (Curtis et al., 2018; Franks et al., 2021), similar use of outer shelf and slope habitat by migrating white sharks has been described in several regions of the world (Skomal et al., 2017; Bradford et al., 2020; Guttridge et al., 2024) and linked to potential foraging opportunities associated with depth.

White sharks were detected at outer shelf banks across multiple seasons from winter (January) through summer (August), with the majority of observations occurring during spring and summer. A spring peak in occurrence is in accord with the prevailing understanding that white sharks in the western North Atlantic migrate south to the U.S. South Atlantic and Gulf during winter and spring before moving back north in the summer (Curtis et al., 2014; Skomal et al., 2017; Curtis et al., 2018; Franks et al., 2021). While the primary drivers of these southern migrations are not completely clear, the timing aligns with cooling temperatures and changes in prey availability (Curtis et al., 2014). The spatial extent and timing of these movements mirrors the spawning migrations of bluefin tuna into the Gulf (Rooker et al., 2008; Rooker et al., 2019), although direct connections between the two migrations have not been established to date. Likewise, several reef and pelagic fishes are known to aggregate at outer shelf reefs of the northwestern Gulf during the winter and spring (Grüss et al., 2018; Wetmore et al., 2020; Sanchez et al., 2023), providing a potential prey base for white sharks.

The presence of white sharks in the Gulf during the summer months may represent a relatively new phenomenon as white sharks appear to be increasing in abundance across much of their range in the western North Atlantic (Skomal et al., 2012; Curtis et al., 2014), expanding in areas they were once quite rare. It appears this species has become increasingly common in the eastern Gulf off Florida during winter and spring (Lowerre-Barbieri et al., 2021), but observations west of the Mississippi River and during summer are historically uncommon. Historical records show that white sharks were rarely reported from the western Gulf from 1800-2010 (Casey and Pratt, 1985; Curtis et al., 2014). Moreover, until recently, movement into this region of the Gulf was not demonstrated by any of the satellite-linked white shark tagging studies (Skomal et al., 2017; Franks et al., 2021; Roach et al., 2026). The fact that white sharks were detected during summer at offshore banks in the northwestern Gulf could reflect a potentially expanding white shark population in the western North Atlantic Ocean. Reasons for range edge expansion could be due to a myriad of factors ranging from population growth due to successful conservation strategies, recovery of important prey species, and/or shifts in ocean temperatures (Pacoureau et al., 2023; Allegue et al., 2025). However, since white sharks appear to be increasing in abundance at both high and low latitudes simultaneously, the latter may be less likely.

Collectively, these findings add to a growing body of evidence demonstrating the increasing role of the Gulf as seasonal habitat for migratory white sharks in the western North Atlantic (Lowerre-Barbieri et al., 2021; Drymon et al., 2025; Roach et al., 2026). However, it is unclear to what degree sharks exhibit philopatric behavior to specific regions of the Gulf. Here, we documented philopatric behavior in two of the nine sharks, with one male shark detected in each of the three years of monitoring (April and May, 2023-2025) and one female shark detected in 2023 and 2024 (June to August). Philopatric behavior has been sporadically observed for overwintering white sharks but is well documented at summer sites off the northeastern U.S. (Winton et al., 2023), Canada (Franks et al., 2021; Bowlby et al., 2022), and other regions of the world (Bonfil et al., 2005; Jorgensen et al., 2010). While philopatry may be linked to regions with consistent foraging opportunities (Franks et al., 2021), it is interesting to note that both sharks that returned to the region in multiple years were likely sub-adults and it is possible that immature sharks may be more likely to return to the western Gulf year after year than mature sharks that may migrate to different regions for mating/gestation (Domeier and Nasby-Lucas, 2013; Skomal et al., 2017). Still, additional long-term monitoring is needed to better understand philopatric behavior.

Electronic telemetry has rapidly improved our understanding of animal movement in marine ecosystems and there are now more acoustic transmitters at large in the world's oceans than any time in history (Matley et al., 2022). Findings from this study highlight the benefits of large-scale acoustic telemetry arrays to better understand the ecological value of MPAs for marine taxa, even when tagging does not occur directly in the region of interest. While telemetry infrastructure is often deployed nearshore in estuaries and along the inner continental shelf (Welch et al., 2025), our study also demonstrates the value and potential of large-scale offshore receiver arrays in remote, but productive, open ocean environments. Offshore ecosystems are logistically challenging and expensive to monitor (Game et al., 2009; Blanluet et al., 2024); however, acoustic telemetry allows for year-round passive monitoring that can provide unique insights about species that are perceived to be uncommon and/or expanding in range. While it seems likely that the western North Atlantic white shark population is in recovery and becoming more common in the Gulf, it is important to note that the first observations of white sharks in FGBNMS were the direct result of investment in ecosystem connectivity research and long-term acoustic monitoring. These findings expand our current understanding of white shark distribution and habitat use in the Gulf and western Atlantic Ocean and highlight the importance of MPAs like FGBNMS in conserving migratory pathways and critical habitats for large migratory sharks.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical approval was not required for the study involving animals in accordance with the local legislation and institutional requirements. All tagging operations were conducted under the authority of the Massachusetts Division of Marine Fisheries.

Author contributions

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

editing, Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Supervision.

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Conflict of interest

Author BF was employed by 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.

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References

Ajemian, M. J., Drymon, J. M., Hammerschlag, N., Wells, R. J. D., Street, G., Falterman, B., et al. (2020). Movement patterns and habitat use of tiger sharks (*Galeocerdo cuvier*) across ontogeny in the Gulf of Mexico. *PloS One* 15, e0234868. doi: 10.1371/journal.pone.0234868

Allegue, H., Bordeleau, X., Winton, M. V., Skomal, G. B., Joyce, W., Barajas, V. L., et al. (2025). Systematic assessment of the increasing presence of white sharks in Atlantic Canadian waters. *Mar. Ecol. Prog. Ser.* 761, 145–161. doi: 10.3354/meps14855

Balbar, A. C., and Metaxas, A. (2019). The current application of ecological connectivity in the design of marine protected areas. *Global Ecol. Conserv.* 17, e00569. doi: 10.1016/j.gecco.2019.e00569

Blanluet, A., Game, E. T., Dunn, D. C., Everett, J. D., Lombard, A. T., and Richardson, A. J. (2024). Evaluating ecological benefits of oceanic protected areas. *Trends Ecol. Evol.* 39, 175–187. doi: 10.1016/j.tree.2023.09.003

Bonfil, R., Meyer, M., Scholl, M. C., Johnson, R., O'Brien, S., Oosthuizen, H., et al. (2005). Transoceanic migration, spatial dynamics, and population linkages of white sharks. *Science* 310, 100–103. doi: 10.1126/science.1114898

Bowlby, H. D., Joyce, W. N., Winton, M. V., Coates, P. J., and Skomal, G. B. (2022). Conservation implications of white shark (Carcharodon carcharias) behaviour at the northern extent of their range in the Northwest Atlantic. *Can. J. Fish. Aquat.Sci.* 79, 1843–1859. doi: 10.1139/cjfas-2021-0313

Bradford, R., Patterson, T. A., Rogers, P. J., McAuley, R., Mountford, S., Huveneers, C., et al. (2020). Evidence of diverse movement strategies and habitat use by white sharks, Carcharodon carcharias, off southern Australia. *Mar. Biol.* 167, 96. doi: 10.1007/s00227-020-03712-y

Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., et al. (2010). Global biodiversity: Indicators of recent declines. *Science* 328, 1164–1168. doi: 10.1126/science.1187512

Casey, J. G., and Pratt, H. L. Jr. (1985). Distribution of the white shark, Carcharodon carcharias, in the western North Atlantic. *Memoirs South. California Acad. Sci.* 9, 2–14.

Conners, M. G., Sisson, N. B., Agamboue, P. D., Atkinson, P. W., Baylis, A. M. M., Benson, S. R., et al. (2022). Mismatches in scale between highly mobile marine megafauna and marine protected areas. *Front. Mar. Sci.* 9, 897104.10.3389. doi: 10.3389/fmars.2022.897104

Curtis, T. H., McCandless, C. T., Carlson, J. K., Skomal, G. B., Kohler, N. E., Natanson, L. J., et al. (2014). Seasonal distribution and historic trends in abundance of white sharks, *Carcharodon carcharias*, in the western North Atlantic Ocean. *PloS One* 9, e99240. doi: 10.1371/journal.pone.0099240

Curtis, T. H., Metzger, G., Fischer, C., McBride, B., McCallister, M., Winn, L. J., et al. (2018). First insights into the movements of young-of-the-year white sharks (*Carcharodon carcharias*) in the western North Atlantic Ocean. *Sci. Rep.* 8, 10794. doi: 10.1038/s41598-018-29180-5

Davies, T. E., Maxwell, S. M., Kaschner, K., Garilao, C., and Ban, N. C. (2017). Large marine protected areas represent biodiversity now and under climate change. *Sci. Rep.* 7, 9569. doi: 10.1038/s41598-017-08758-5

Domeier, M. L., and Nasby-Lucas, N. (2013). Two-year migration of adult female white sharks (Carcharodon carcharias) reveals widely separated nursery areas and conservation concerns. *Anim. Biotelem.* 1, 2. doi: 10.1186/2050-3385-1-2

Drymon, J. M., Jargowsky, A. E., Hightower, C., and Powers, S. (2025). Fishery-independent camera surveys provide novel observations of white sharks (Carcharodon carcharias) off coastal Alabama. *Front. Mar. Sci.* 12, 1628084. doi: 10.3389/fmars.2025.1628084

Duarte, C. M., Agusti, S., Barbier, E., Britten, G. L., Castilla, J. C., Gattuso, J. P., et al. (2020). Rebuilding marine life. *Nature* 580, 39–51. doi: 10.52843/cassyni.dskw8j

Eisenbach, O. J., Johnston, M. A., O'Connell, K., Hannum, R., French, D. R., Nuttall, M. F., et al. (2025). *Long-term monitoring at East and West Flower Garden Banks: 2023 annual report*. National Marine Sanctuaries Conservation Series. (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Office of National Marine Sanctuaries). doi: 10.25923/23tc-6298

Franks, B. R., Tyminski, J. P., Hussey, N. E., Braun, C. D., Newton, A. L., Thorrold, S. R., et al. (2021). Spatio-temporal variability in White Shark (*Carcharodon carcharias)* movement ecology during residency and migration phases in the Western North Atlantic. *Front. Mar. Sci.* 8, 744202. doi: 10.3389/fmars.2021.744202

Game, E. T., Grantham, H. S., Hobday, A. J., Pressey, R. L., Lombard, A. T., Beckley, L. E., et al. (2009). Pelagic protected areas: the missing dimension in ocean conservation. *Trends Ecol. Evol.* 24, 360–369. doi: 10.1016/j.tree.2009.01.011

Gittings, S. R., Boland, G. S., Deslarzes, K. J. P., Hagman, D. K., and Holland, B. S. (1992). *Long-term monitoring at the East and West Flower Garden Banks*. (New Orleans: United States Department of the Interior).

Grorud-Colvert, K., Sullivan-Stack, J., Roberts, C., Constant, V., Costa, B. H. E., Pike, E. P., et al. (2021). The MPA Guide: A framework to achieve global goals for the ocean. *Science* 373, eabf0861. doi: 10.1126/science.abf0861

Grüss, A., Biggs, C., Heyman, W. D., and Erisman, B. (2018). Prioritizing monitoring and conservation efforts for fish spawning aggregations in the U.S. Gulf of Mexico. *Sci. Rep.* 8, 8473. doi: 10.1038/s41598-018-26898-0

Guttridge, T. L., Matich, P., Guttridge, A. E., Winton, M., Dedman, S., and Skomal, G. (2024). First evidence of white sharks, *Carcharodon carcharias*, in the tongue of the ocean, central Bahamas. *Front. Mar. Sci.* 11, 1451808. doi: 10.3389/fmars.2024.1451808

Halpern, B. S., Lester, S. E., and McLeod, K. L. (2010). Placing marine protected areas onto the ecosystem-based management seascape. *Proc. Natl. Acad. Sci.* 107, 18312–18317. doi: 10.1073/pnas.0908503107

Hickerson, E. L., Schmahl, G. P., Robbart, M., Precht, W. F., and Caldow, C. (2008). "The state of coral reef ecosystems of the Flower Garden Banks, Stetson Bank, and other banks in the northwestern Gulf of Mexico," in *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008*. Eds. J. E. Waddell and A. M. Clarke (Silver Spring, MD: NOAA Technical Memorandum NOS NCCOS 73), 189–217.

Hughes, T. P., Bellwood, D. R., Folke, C., Steneck, R. S., and Wilson, J. (2005). New paradigms for supporting the resilience of marine ecosystems. *Trends Ecol. Evol.* 20, 380–386. doi: 10.1016/j.tree.2005.03.022

Johnston, M. A., Embesi, J. A., Eckert, R. J., Nuttall, M. F., Hickerson, E. L., and Schmahl, G. P. (2016). Persistence of coral assemblages at East and West Flower Garden Banks, Gulf of Mexico. *Coral Reefs* 35, 821–826. doi: 10.1007/s00338-016-1452-x

Johnston, M. A., Nuttall, M. F., Hickerson, E. L., O'Connell, K., Blakeway, R. D., Embesi, J. A., et al. (2022). Characterizing the biological community before and after partial removal of an offshore gas platform in the northwestern Gulf of Mexico. *Environ. Manage.* 70, 1078–1092. doi: 10.1007/s00267-022-01714-8

Jorgensen, S. J., Reeb, C. A., Chapple, T. K., Anderson, S., Perle, C., Van Sommeran, S. R., et al. (2010). Philopatry and migration of Pacific white sharks. *Proc. R. Soc. B.* 277, 679–688. doi: 10.1098/rspb.2009.1155

Lowerre-Barbieri, S. K., Friess, C., Griffin, L. P., Morley, D., Skomal, G. B., Bickford, J. W., et al. (2021). Movescapes and eco-evolutionary movement strategies in marine fish: Assessing a connectivity hotspot. *Fish Fish.* 22, 1321–1344. doi: 10.1111/faf.12589

Matley, J. K., Klinard, N. V., Barbosa Martins, A. P., Aarestrup, K., Aspillaga, E., Cooke, S. J., et al. (2022). Global trends in aquatic animal tracking with acoustic telemetry. *Trends Ecol. Evol.* 37, 79–94. doi: 10.1016/j.tree.2021.09.001

O'Leary, B. C., Ban, N. C., Fernandez, M., Friedlander, A. M., García-Borboroglu, P., Golbuu, Y., et al. (2018). Addressing criticisms of large-scale marine protected areas. *BioScience* 68, 359–370. doi: 10.1093/biosci/biy021

Office of National Marine Sanctuaries (2024). *Flower Garden Banks National Marine Sanctuary Condition Report: 2009–2021* (Silver Spring, MD: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries).

Pacoureau, N., Carlson, J. K., Kindsvater, H. K., Rigby, C. L., Winker, H., Simpfendorfer, C. A., et al. (2023). Conservation successes and challenges for wide-ranging sharks and rays. *Proc. Natl. Acad. Sci.* 120, e2216891120. doi: 10.1073/pnas.2216891120

Rezak, R., Gittings, S. R., and Bright, T. J. (1990). Biotic assemblages and ecological controls on reefs and banks of the northwest Gulf of Mexico. *Am. Zool.* 30, 23–35. doi: 10.1093/icb/30.1.23

Roach, C. C., Tyminski, J. P., Hueter, R. E., Newton, A. L., Franks, B. R., Lowerre-Barbieri, S. K., et al. (2026). Use of the Gulf of Mexico as an overwintering area by western North Atlantic white sharks (*Carcharodon carcharias*). *Wildl. Res.* 53, WR25033. doi: 10.1071/wr25033

Rooker, J. R., Dance, M. A., Wells, R. J. D., Ajemian, M. J., Block, B. A., Castleton, M. R., et al. (2019). Population connectivity of pelagic megafauna in the Cuba-Mexico-United States triangle. *Sci. Rep.* 9, 1663. doi: 10.1038/s41598-018-38144-8

Rooker, J. R., Secor, D. H., De Metrio, G., Schloesser, R., Block, B. A., and Neilson, J. D. (2008). Natal homing and connectivity in Atlantic bluefin tuna populations. *Science* 322, 742–744. doi: 10.1126/science.1161473

Sammarco, P. W., Brazeau, D. A., and Sinclair, J. (2012). Genetic connectivity in scleractinian corals across the northern Gulf of Mexico: oil/gas platforms, and relationship to the Flower Garden Banks. *PloS One* 7, e30144. doi: 10.1371/journal.pone.0030144

Sammarco, P. W., Lirette, A., Tung, Y. F., Boland, G. S., Genazzio, M., and Sinclair, J. (2014). Coral communities on artificial reefs in the Gulf of Mexico: standing vs. toppled oil platforms. *ICES J. Mar. Sci.* 71, 417–426. doi: 10.1093/icesjms/fst140

Sanchez, P. J., Dance, M. A., Kraus, R. T., Hill, R. L., and Rooker, J. R. (2023). Fish community characterization of mid-shelf and shelf-edge mesophotic coral ecosystems in the expanded Flower Garden Banks National Marine Sanctuary. *Bull. Mar. Sci.* 9, 41–50. doi: 10.5343/bms.2022.0014

Schulze, A., Erdner, D. L., Grimes, C. J., Holstein, D. M., and Miglietta, M. P. (2020). Artificial reefs in the northern gulf of Mexico: community ecology amid the "Ocean sprawl. *Front. Mar. Sci.* 7, 447. doi: 10.3389/fmars.2020.00447

Skomal, G. B., Braun, C. D., Chisholm, J. H., and Thorrold, S. R. (2017). Movements of the white shark Carcharodon carcharias in the North Atlantic Ocean. *Mar. Ecol. Prog. Ser.* 580, 1–16. doi: 10.3354/meps12306

Skomal, G. B., Chisholm, J. H., and Correia, S. J. (2012). "Implications of increasing pinniped populations," in *Global Perspectives on the Biology and Life History of the White Shark*. Ed. M. L. Domeier (CRC Press, Boca Raton), 405–417.

Stewart, J. D., Nuttall, M., Hickerson, E. L., and Johnston, M. A. (2018). Important juvenile manta ray habitat at Flower Garden Banks National Marine Sanctuary in the northwestern Gulf of Mexico. *Mar. Biol.* 165, 111. doi: 10.1007/s00227-018-3364-5

Welch, R. J., Childs, A. R., Murray, T. S., Darnaude, A. M., and James, N. C. (2025). The role of acoustic telemetry in assessing fish connectivity within marine seascapes: a global review. *J. Fish Biol.* 106, 1285–1304. doi: 10.1111/jfb.16011

Wetmore, L. S., Dance, M. A., Hill, R. L., and Rooker, J. R. (2020). Community dynamics of fish assemblages on mid-shelf and outer-shelf coral reefs in the north-western Gulf of Mexico. *Front. Mar. Sci.* 7, 152. doi: 10.3389/fmars.2020.00152

Winton, M., Fay, G., and Skomal, G. B. (2023). An open spatial capture-recapture framework for estimating the abundance and seasonal dynamics of white sharks at aggregation sites. *Mar. Ecol. Prog. Ser.* 715, 1–25. doi: 10.3354/meps14371

Winton, M. V., Sulikowski, J., and Skomal, G. B. (2021). Fine-scale vertical habitat use of white sharks at an emerging aggregation site and implications for public safety. *Wildl. Res.* 48, 345–360. doi: 10.1071/wr20029