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# High survivorship of sandbar sharks (*Carcharhinus plumbeus*) following catch and release in a growing land-based fishery in Massachusetts

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**Abstract—**Directed land-based recreational catch-and-release fishing for sandbar sharks (*Carcharhinus plumbeus*) is growing in popularity in Massachusetts. Working with 21 volunteer fishermen of varying experience levels, we observed and documented the fishing gear, tackle, and techniques used to catch and release 67 sandbar sharks. The postrelease fate of each shark was monitored by using an acceleration data logger (ADL) tag embedded in a custom float package that was secured to the first dorsal fin with a galvanic timed release. All 67 packages were recovered after detachment following monitoring periods of 0.15–9.98 d. Examination of the depth, tailbeat period (TBP), pitch, and roll time series from 65 ADLs that recorded data revealed high survivorship for tagged sharks, with all of them alive at the time of tag detachment. Behavioral recovery was estimated to have occurred at an average of 6.36 h after release on the basis of trends in TBP for 54 sandbar sharks with at least 10 h of postrelease acceleration data. These results indicate that sandbar sharks are remarkably resilient to catch and release in the land-based shark fishery in Massachusetts.

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Recreational shark fishing is a popular activity with significant socioeconomic value to coastal communities along the East Coast of the United States and in the Gulf of Mexico region (Hutt and Silva, 2019; Guay et al., 2021). Traditionally, a large portion of the recreational shark fishing effort has occurred at sea aboard federally permitted charter boats and private fishing vessels. However, a recent rise in the popularity of shore- or land-based shark angling has resulted in increased effort within state waters (senior author, personal observ.; Guay et al., 2021). Because of how recreational catch and effort data are collected by the National Marine Fisheries Service Marine Recreational Intercept Program and Large Pelagics Survey, as well as the lack of a federal permit requirement for land-based shark fishing, data on the magnitude of catch or effort across this fishery are very limited (Weber et al., 2020; Guay et al., 2021). Nonetheless, it is well-documented that several shark species targeted or incidentally captured by land-based anglers are experiencing population declines and are prohibited from retention under state and federal laws (Kilfoil et al., 2017; Gibson et al., 2019). One such species is the overfished sandbar shark (*Carcharhinus plumbeus*) (SEDAR, 2017).

Directed land-based recreational fishing for sandbar sharks has occurred in Massachusetts for decades (Skomal, 2007). However, evidence indicates that land-based fishing effort for sandbar sharks and shark catch rates have increased dramatically in Massachusetts over the last decade (Skomal[1]). For example, conversations with recreational land-based anglers have revealed that catches of 5–10 sandbar sharks in a single trip are now common (senior author, personal observ.), and individual land-based anglers have conventionally tagged over 100 sandbar sharks in

[1] Skomal, G. 2023. Personal commun. Mass. Div. Mar. Fish., 836 S Rodney French Blvd., New Bedford, MA 02744.

a single season (Zewinski[2]). Under current Massachusetts state law, circle hooks must be used when targeting sharks with natural baits, and all sandbar sharks must be released (Regulation . . . 2023). However, anglers in Massachusetts are not required to possess an additional permit to engage in land-based shark angling nor undergo training on catch-and-release best practices prior to engaging in the fishery; in contrast, both a permit and training are required in Florida (Sharks . . . 2019).

In few studies have the effects of land-based capture and handling on shark mortality rates been examined. Weber et al. (2020) reported a postrelease mortality (PRM) rate of 17% for blacktip sharks (*C. limbatus*) caught in South Carolina, with mortality occurring because of physical trauma incurred during capture and foul hooking. Similarly, Kilfoil et al. (2017) reported low (6%) PRM of sand tigers (*Carcharias taurus*) caught in Delaware, with all mortality attributed to internal hooking. Most recently, Binstock et al. (2023) reported variable, species-specific PRM rates for bull (*Carcharhinus Leucas*) (7%), blacktip (50%), and tiger (*Galeocerdo cuvier*) (0%) sharks caught in Texas, with evidence that increasing water temperatures resulted in higher mortality rates for blacktip sharks. Mortality has also been suspected to have occurred in land-based fishing operations because of the removal of sharks from the water (i.e., air exposure) for extended periods during handling (Shiffman et al., 2017). However, to date, no direct relationship between time out of water and mortality has been reported. Because PRM rates for sharks are highly specific to species (e.g., Whitney et al., 2021) and geographic location (e.g., Mohan et al., 2020), there is a continued need to estimate these rates across all species, fisheries, fishing areas, and environmental conditions. Accordingly, the goals of this study were to assess the PRM rate of sandbar sharks caught in the land-based shark fishery in Massachusetts and to identify factors that adversely affect animal condition, postrelease behavior, and survival. We also briefly assessed the effect of animal behavior on tag retention.

## Materials and methods

Activities of this project were conducted under the New England Aquarium Animal Care and Use Committee protocol 2019-06.

### Study area and design

All project activities were conducted in cooperation with volunteer recreational land-based shark fishermen on Cape Cod and Nantucket in Massachusetts. Scientific researchers accompanied and observed fishermen during all trips, but anglers were free to choose the location of angling and received no input from scientific staff regarding the gear (e.g., rod and reel type or size), tackle (e.g., hook type or size), or techniques used to capture and handle sandbar sharks. Each participant's experience with land-based shark fishing was determined at the time of each trip on the basis of the following criteria:

Novice: less than 1 year of experience with land-based shark fishing or a total of <5 sharks captured and handled from land in their angling career;

Intermediate: more than 1 year of experience with land-based shark fishing or a total of 5–10 sharks captured and handled from land in their angling career; and

Expert: more than 2 years of experience with land-based shark fishing or a total of >10 sharks captured and handled from land in their angling career.

When a volunteer angler captured a sandbar shark, the following data were collected: rod and reel type (e.g., conventional versus spinning) and size (e.g., model or pound class); line type and strength; leader type, length, and strength; hook type (circle or J) and size; and bait type. Fight time (i.e., the time from when the shark was hooked to the time it was landed) was recorded to the nearest second. Handling location, or position of the shark during landing, unhooking, and tagging, was recorded as 1 of 3 locations: shark left in water (i.e., the majority of the body, including the head and gills, remained in the water), shark brought to the water line (i.e., only a portion of the animal remained in the water; this location includes instances when wave action briefly exposed the head and gills to air), or shark removed from water (i.e., the entire shark was out of the water for the entirety of the handling event). Air and water temperature at the time of capture were also noted.

Biological assessment and tagging activities were conducted where the shark was landed, and efforts were made to note the sex, measure the fork length (FL) to the nearest centimeter, and apply a tag package that included an acceleration data logger (ADL) (methods described in the next section) while fishermen were removing or attempting to remove the hook, so as not to artificially extend handling time. Hooking location was noted (jaw, inside mouth [esophagus or pharynx], gills, gut [hook not visible or accessible], or body [foul hooked]) along with the disposition of the hook (removed or retained). The presence, location, and severity of bleeding (none, light, moderate, or heavy), overt signs of physical trauma (e.g., abrasions and lacerations), and the extent to which fishermen physically restrained the shark (e.g., holding the body of the shark in place during unhooking) were also noted. Handling time (i.e., the time from landing to release, including time needed for tagging) was recorded to the nearest second, and total capture and handling duration was noted as the sum of fight and handling times. Following tagging, fishermen were responsible for releasing the shark and left to determine if revival was necessary. Revival time was noted to the nearest second, if applicable. Finally, each shark was assigned a release condition based in part on the ordinal scale reported in Weber et al. (2020) (Table 1).

[2] Zewinski, K. 2021. Personal commun. Popul. Ecosyst. Monit. Anal. Div., Northeast Fish. Sci Cent., Natl. Mar. Fish. Serv., NOAA, 28 Tarzwell Dr., Narragansett, RI 02882.

**Table 1**

Release condition categories assigned to sandbar sharks (*Carcharhinus plumbeus*) captured off Cape Cod and Nantucket in Massachusetts from June through September in 2019–2021. Conditions are based in part on those used by Weber et al. (2020).

| Category | Physical condition and release behavior |
|---|---|
| Excellent | No physical trauma other than hook wound, no bleeding, swam away rapidly |
| Good | No physical trauma other than hook wound, no bleeding, swam away slowly or appeared disoriented |
| Fair | Overt signs of physical trauma (abrasions and minor cuts), minor bleeding, swam away slowly or appeared disoriented |
| Poor | Overt signs of physical trauma (abrasions, minor cuts, and lacerations), moderate or severe bleeding, swam away slowly or appeared disoriented |

### Postrelease monitoring

To monitor the postrelease behavior and fate of sandbar sharks, custom tag packages that included an ADL and a float were created following the design outlined in Whitmore et al. (2016) and Whitney et al. (2021). Each package consisted of an ADL (Axy 4[3]; TechnoSmArt, Rome, Italy) that recorded triaxial acceleration at 25 Hz and depth and temperature every second, a SPOT-6 satellite transmitter (Wildlife Computers Inc., Redmond, WA), and a VHF transmitter (Advanced Telemetry Systems Inc., Isanti, MN). Each of these components was embedded in a custom tag float (107 × 68 × 50 mm in size and 151 g in weight in air). The package was designed to be <2% of the body weight of a tagged sandbar shark, meeting the recommended threshold intended to minimize the likelihood of tag-induced impairment to movement (Use of Fishes in Research Committee, 2014).

During tagging of each shark, 2 holes were drilled in the first dorsal fin, and a float package was secured on the left side of the fin (relative to the cranial–caudal axis) with cable ties, vinyl Peterson discs (Floy Tag & Mfg. Inc., Seattle, WA), and a galvanic timed release (GTR) (International Fishing Devices Inc., Northland, New Zealand). The GTRs dissolved in seawater and were sized in a manner to keep the ADL packages secured to sharks for a predetermined duration of approximately 1–4 d, and once that time was reached, the tags would release from the shark and float to the surface (Whitmore et al., 2016). The satellite transmitter would report its location through the Argos satellite network once it had reached the surface, and land- or sea-based excursions were made to recover the tag by using a multichannel VHF receiver (Advanced Telemetry Systems) following the methods described by Lear and Whitney (2016).

[3] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

### Data analysis

All analyses were performed by using the statistical software R (vers. 4.1.2; R Core Team, 2021), and statistical significance was accepted at $P<0.05$.

**Capture and handling characteristics** A series of qualitative and quantitative assessments were used to examine basic relationships between physical and biological aspects of the capture and handling events that may relate to release condition and PRM of sandbar sharks. Because of the opportunistic nature of sampling in this study, sample sizes were heavily unbalanced among many capture- and handling-related variables (e.g., line class, hooking location, and handling location) and autocorrelation structures violated model assumptions about sample independence (e.g., some anglers used only a single type or size of hook or line strength). Accordingly, box plots were created to qualitatively demonstrate general trends in the relationship between categorical variables related to capture and handling, with individual categories containing ≤5 observations.

Individual generalized linear models (GLMs) were constructed to quantitatively examine the effect of continuous and categorical variables with a sufficient number of observations on fight time and handling time. In fight time GLMs, data from a single anomalous capture event with an artificially inflated fight time were excluded from analysis (for a description of this event, see the "Results" section). Handling time GLMs were constructed with FL and *restraint* (binomial) as fixed effects. Data from 2 handling events were excluded from analysis because difficulties in the application of the ADL package artificially extended handling time beyond what was necessary for fishermen to prepare the shark for release. All GLMs were fit with data that had a Gaussian distribution in the R package lme4 (vers. 1.1-30; Bates et al., 2015). Model fit was assessed by visually examining residual plots.

**Postrelease fate and mortality and survival rates** After recovery of the ADL package, acceleration, depth, and temperature data were downloaded from the ADL, and the time of detachment of the package was noted as the time when the tag achieved an upright position and floated to the surface. To correct for variation in tag placement on the fin and attachment angle, acceleration data were rotated to be in the same orientation across all deployments. Rotation angles were determined by ensuring that the average acceleration of the $x$- and $y$-axis was close to 0; the $x$-axis correlated with the vertical velocity (i.e., ascending or descending in the water column), and the $y$-axis contained the largest dynamic acceleration. This approach ensured that the $x$-axis corresponded to the cranial–caudal axis of the animal (this axis pitches up and down as the animal ascends and descends), the *y*-axis corresponded to the lateral axis of the animal (which experiences dynamic acceleration during tailbeats), and the *z*-axis corresponded to the dorsal–ventral axis of the animal (Jorgensen et al., 2015).

Static acceleration (accel) was calculated by using a 3-s (75-point) running mean of the raw data, and dynamic acceleration was calculated as the remainder when subtracting the dynamic acceleration from the raw acceleration (Shepard et al., 2008). Body pitch and roll were calculated from the static acceleration, and the overall dynamic body acceleration (ODBA) (Wilson et al., 2006) was calculated from the dynamic acceleration:

$$Roll = \tan^{-1}(Y_{accel}, Z_{accel}); \quad (1)$$

$$Pitch = \tan^{-1}(-X_{accel}, Y_{accel}\sin Roll + Z_{accel}\cos Roll); \text{ and} \quad (2)$$

$$ODBA = \text{abs}(X_{accel}) + \text{abs}(Y_{accel}) + \text{abs}(Z_{accel}). \quad (3)$$

A continuous wavelet transformation of the *y*-axis acceleration data was used to calculate the power of periodicities over a period of 0.2–4.0 s by using the R package biwavelet, vers. 0.20.21 (Gouhier et al., 2021). The periodicity with the greatest power each second was ascribed as the individual's tailbeat period (TBP).

Postrelease fate was determined through visual examination of fine-scale vertical movement and acceleration profiles recorded by the ADL (Whitney et al., 2016, 2017, 2021). The sandbar shark is an obligate ram-ventilating species, and the fate of each shark at the time of tag detachment was assessed by using the following criteria:

Alive: consistent tailbeat patterns and changes in depth (i.e., vertical movements) and body position (i.e., pitch and roll) indicative of active swimming;

Dead: prolonged cessation of tailbeats in concert with a constant depth (indicative of rest on the seafloor); and

Predation: shift in the pitch and roll, an alteration of TBP and dive patterns, and potentially a lack of vertical thermal variation, which can indicate presence of the tag in a predator's stomach.

Total PRM was calculated as the proportion of all mortality events observed across monitored individuals. We calculated 95% confidence intervals (CIs) by using the Wilson method (Brown et al., 2001) in the R package binom, vers. 1.1-1 (Dorai-Raj, 2014).

**Postrelease recovery period** Behavioral recovery periods were evaluated for surviving sandbar sharks to address the sublethal effect of capture and handling on swimming or predator avoidance capabilities. Results from previous studies indicate that TBP is a suitable metric for assessing postrelease behavioral changes (e.g., Whitney et al., 2017, 2021; Grainger et al., 2022). Therefore, average TBP was calculated every 10 min from the time of release to 48 h after release for all sharks. With this approach, it has been found that behavioral recovery often occurs less than 10 h after release in multiple species (e.g., Whitney et al., 2017, 2021). Therefore, recovery time was not calculated for any sharks for which less than 10 h of postrelease acceleration data were available. Patterns in TBP were modeled by using nonlinear mixed effects models as an asymptotic relationship executed in the lme4 package (Bates et al., 2015):

$$TBP = A_{sym} + \left(R_0 - A_{sym}\right)\left(1 - e^{-e^{lrc}T}\right), \quad (4)$$

where $A_{sym}$ = the fully recovered TBP;
$R_0$ = the TBP immediately after release;
$lrc$ = the log rate constant that describes the rate at which recovery occurs; and
$T$ = the time after release.

To account for the repeated measures of TBP for each individual over 48 h, we included random effects so that all 3 model parameters ($A_{sym}$, $R_0$, and $lrc$) varied by individual. Recovery period was defined as the time after release when TBP reached 80% of the difference between $R_0$ and $A_{sym}$ (Whitney et al., 2016, 2017, 2021). By incorporating *individual* as a random effect, time to recovery could be calculated for each shark.

Fixed-effect GLMs were fit to time-to-recovery data to assess the influence of FL, fight time, handling time, and total time by using the lme4 package (Bates et al., 2015). Because of low and unequal samples sizes evident in some conditions nested in categorical variables (e.g., recovery time was only estimated for 2 sharks in poor condition and for 3 sharks that were left in the water), the following variables were excluded from models: hook disposition, handling location, and fish condition. Instead, box plots were created to qualitatively describe relationships between these variables and recovery period.

**Tag detachment** The results of the preliminary analysis of pitch, roll, and ODBA data revealed that numerous tagged sandbar sharks exhibited rolling behavior in which the body of the shark temporarily rolled >75° to the left (along the axis of forward motion, to the side with the ADL package) or to the right while the animal was actively swimming. In addition to these observations, multiple recovered float packages had scratches and abrasions, indicating that the rolling behavior might have resulted in contact of the tag with the seafloor. To investigate the extent to which rolling was linked to premature tag detachment, the depth, pitch, and roll of each individual were visually inspected for the 50 s surrounding the time of tag detachment. Tag detachment was identified as a positive pitch, indicating that the tag nose was pointed to the seafloor, while the depth was decreasing (i.e., the tag was floating to the surface). Rolling behavior was identified if individuals rolled to either the left or right side (>75°) while pitch values indicate that they were horizontal (<25° and >–25°) (Suppl. Figure). Additionally, this rolling behavior had to occur when the shark was presumed to be at the seafloor (i.e., within 1 m of the maximum depth the shark experienced in the 5 min before and after the roll) and <2 s prior to the estimated time of tag detachment. Each individual's tag detachment was categorized as associated with a left roll (<−75°) or a right roll (>75°) or was not associated with a roll.

To determine if rolls influenced tag retention, we analyzed the estimated error in tag retention across the 3 tag detachment categories. Release error was calculated as the duration the tag remained on the animal divided by the expected duration based on GTR size. Releases were classified as premature if the tag detached more than 25% (i.e., <−25%) earlier than expected. Release error was then compared across the 3 detachment categories to determine if rolling behavior immediately before a tag detachment influenced tag retention. Pairwise comparisons were performed by using Tukey's honestly significant difference (HSD) test. Data from tags that were retained on sharks for greater than 100% longer than the estimated GTR release time were excluded from analysis and were considered outliers.

## Results

A total of 67 sandbar sharks (47 females and 20 males), measuring 113–187 cm FL (mean: 140 cm FL [standard deviation (SD) 17]), were captured by 21 volunteer recreational fishermen (9 novice, 7 intermediate, and 5 expert anglers) and were tagged with ADL packages from June through September in 2019 (sample size [*n*]=14), 2020 (*n*=8), and 2021 (*n*=45) (Suppl. Table). Females and males ranged from 113 to 187 cm FL (mean: 144 cm FL [SD 18]) and from 113 to 152 cm FL (mean: 132 cm FL [SD 12]), respectively. Individual anglers were observed capturing 1–20 sharks (mean: 3 sharks [SD 4]), with expert anglers accounting for the largest number of sharks captured (*n*=39). Novice and intermediate anglers captured 17 and 11 sharks, respectively.

To capture sandbar sharks, fishermen used a range of bait and tackle, including 13–36 kg (30–80 lb) class conventional (*n*=1) and spinning (*n*=66) rod and reel setups spooled with 13–36 kg braided main fishing line and steel single-strand wire (*n*=33) or multistrand cable (*n*=34) leaders with lengths of 0.6–1.2 m (~2–4 ft) and rated at weight test of 36–181 kg (80–400 lb). Sharks were primarily captured with 8/0–18/0 circle hooks (*n*=58, 86.6% of capture events), but 9 sharks (13.4% of events) were captured on 8/0–10/0 J-hooks (Table 2). To capture sharks, volunteers used a variety of natural baits, including cut sections of Atlantic menhaden (*Brevoortia tyrannus*), bluefish (*Pomatomus saltatrix*), and little tunny (*Euthynnus alletteratus*) and whole live or dead American eels (*Anguilla rostrata*).

Sandbar sharks were primarily hooked in the jaw (*n*=59, 88.1%) but were also hooked inside the mouth (*n*=2), in the gills (*n*=4), and on the body (pectoral fin, *n*=2). All hooking locations were observed with both circle and J-hooks; however, a larger percentage of sharks caught on J-hooks were hooked inside the mouth, in the gills, or on the body (Fig. 1). Anglers removed hooks from 92.5% of captured sharks (*n*=62); the leader was cut and the hook retained in 5 sharks caught on circle hooks, 3 sharks hooked in the jaw and 2 sharks hooked in the gills. The majority of sharks had no bleeding or had minor bleeding localized around the hook wound. Two sharks hooked in the gills experienced heavy bleeding. In one of these animals, the J-hook was removed by using a dehooking device, and in the other, the leader was cut, leaving the circle hook embedded in the gills. Fight times ranged from 2.57 to 32.40 min (mean: 6.90 min [SD 4.75]), and 98.5% of fight times were less than 20 min. The longest fight time (32.40 min) was observed when a fisherman, fishing alone, hooked 2 sandbar sharks at the same time and did not begin retrieving the second animal until the first was released. Excluding this anomalous capture event, there was a significant positive relationship between shark FL and fight time (coefficient of multiple determination [$R^2$]=0.306, *P*<0.001) (Fig. 2A).

**Table 2**

Breakdown of data collected for the 67 sandbar sharks (*Carcharhinus plumbeus*) for which land-based capture and handling events were observed during June–September in 2019, 2020, and 2021 in Massachusetts.

| | Observations | |
|---|---|---|
| Variable | Number | Percentage |
| Sex | | |
| Females | 47 | 70.1 |
| Males | 20 | 29.9 |
| Hook type | | |
| Circle | 58 | 86.6 |
| J | 9 | 13.4 |
| Hooking location | | |
| Jaw | 59 | 88.1 |
| Mouth | 2 | 3.0 |
| Gills | 4 | 6.0 |
| Body | 2 | 3.0 |
| Hook disposition | | |
| Removed | 62 | 92.5 |
| Retained | 5 | 7.5 |
| Handling location | | |
| Brought out of water | 23 | 34.3 |
| Brought to water line | 39 | 58.2 |
| Left in water | 5 | 7.5 |
| Shark restrained | | |
| Yes | 47 | 70.1 |
| No | 20 | 29.9 |
| Fish condition at release | | |
| Excellent | 16 | 23.9 |
| Good | 44 | 65.7 |
| Fair | 5 | 7.5 |
| Poor | 2 | 3.0 |
| Bleeding | | |
| None | 62 | 92.5 |
| Light | 2 | 3.0 |
| Moderate | 1 | 1.5 |
| Heavy | 2 | 3.0 |

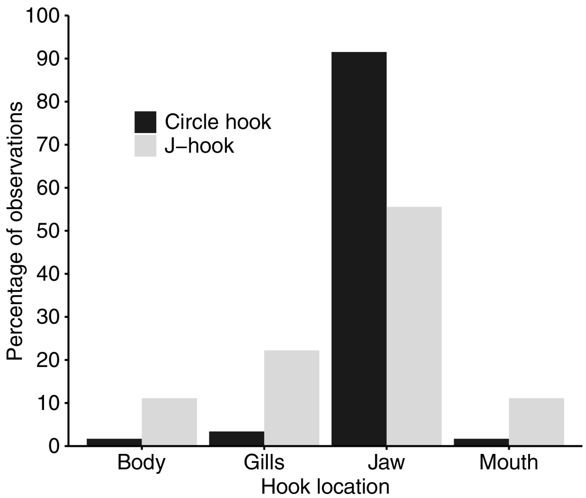


**Figure 1**

Relative percentage of hook locations observed by hook type for 67 sandbar sharks (*Carcharhinus plumbeus*) captured off Cape Cod and Nantucket in Massachusetts from June through September in 2019–2021. Fifty-eight sharks were caught on circle hooks, and 9 sharks were caught on J-hooks. Use of circle hooks yielded a higher percentage of capture events in which sharks were hooked in the jaw, and use of J-hooks had a higher probability of hooking sharks on the body, in the gills, or inside the mouth.

Once brought into the surf zone, sharks in the majority of cases were dragged to the water line ($n$=39, 58.2%) or completely out of the water ($n$=23, 34.3%) by fishermen holding them by the tail. Anglers left the shark in the water in 5 instances (7.5% of observed capture events). Forty-seven sharks (70.1%) were restrained during handling. Handling times ranged from 1.50 to 9.25 min (mean: 3.82 min [SD 1.27]), yielding total capture and handling event times of 5.25–34.33 min (mean: 10.72 min [SD 4.96]). There was a significant, positive relationship between FL and handling time ($R^2$=0.131, $P$<0.001) (Fig. 2B), but handling time was not significantly affected by the restraint of sharks ($P$=0.152). Qualitatively, sharks that were handled in the water or that were hooked in the gills generally experienced longer handling times (Fig. 3). At the time of release, all sharks were alive and assigned the following release conditions: excellent ($n$=16), good ($n$=44), fair ($n$=5), and poor ($n$=2). During handling, sharks experienced air temperatures ranging from 15.9°C to 28.9°C (mean: 23.4°C [SD 2.9]) and were captured in water temperatures ranging from 21.2°C to 27.7°C (mean: 24.1°C [SD 1.7]).

### Tag recovery and performance

All 67 ADL packages deployed on sandbar sharks detached and were recovered. Forty-one tags were recovered at sea, and 26 tags were recovered after washing ashore on Cape Cod or Nantucket. The ADLs remained attached to sandbar sharks for periods of 0.15–9.98 d (mean: 2.67 d [SD 2.08]) or 3.6–239.5 h (mean: 64.0 h [SD 49.9]). Two ADLs malfunctioned and did not record any data during the deployment period, and 3 ADLs stopped recording prior to detaching. Altogether, data sufficient for determining postrelease fate were available from 65 ADLs. A total of 27 tags (40.3%) released prematurely, earlier than their expected time based on the size of the GTR used.

### Postrelease survival and recovery

Results from the examination of the depth, TBP, pitch, and roll time series from the 65 ADLs reveal high survivorship for tagged sharks. All sharks were alive at the time of tag detachment, yielding a PRM rate of 0% (95% CI: 0.0–5.6%) or survival rate of 100% (95% CI: 94.4–100%).

Time to recovery was estimated for 54 of 56 sandbar sharks with at least 10 h of postrelease acceleration data. Recovery time was not estimated for 2 sharks whose TBP failed to reach their recovery value (i.e., 80% of the fully recovered TBP) and whose change in TBP was in the lowest 25th percentile during the time from release to 48 h after release. Of note, both of these sharks consistently had a TBP that was similar to the “recovered” values of the 54 sharks for which recovery time was estimated. Behavioral recovery in TBP for the 54 sharks was evident from 1.33 to 17.18 h after release (mean: 6.36 h [SD 3.52]) (Fig. 4). Results from the GLMs reveal no significant relationships between recovery time and fight time, handling time, total time, or FL ($P$>0.11). However, findings from qualitative analyses with box plots provide some evidence that sharks hooked in the gills and classified in fair or poor condition took longer to recover (Fig. 5).

### Tag detachment

Tag detachment in association with rolling behavior was examined for 60 individuals whose ADLs recorded data at the time of release. In 32 instances (53.3%), tags appeared to detach without any clear indication of rolling behavior. These tags detached close (mean: –9.2% [SD 36.1]) to the expected GTR duration, and only 25.0% ($n$=8) of these tags released prematurely (Fig. 6). Rolling was observed in 28 instances (46.7%) of tag detachment, including 11 instances (39.3%) when sharks rolled to the right (non-tag side) and 17 cases (60.7%) when sharks rolled to the left side (tag side). Only 4 tag detachments associated with rolls to the right (36.4%) occurred prematurely, a number that is not significantly different than the number of premature detachments not associated with rolling behavior ($n$=6) (Tukey’s HSD test: $P$=0.99). However, 88.2% ($n$=15) of tag detachments associated with rolls to the left side occurred prematurely, significantly earlier than detachments associated with rolls to the right (Tukey’s HSD test: $P$<0.001) and with detachments that were not associated with rolling behavior (Tukey’s HSD test: $P$<0.001). In total, 55.6% ($n$=15) of all premature releases ($n$=27) occurred when sharks rolled to their left side.

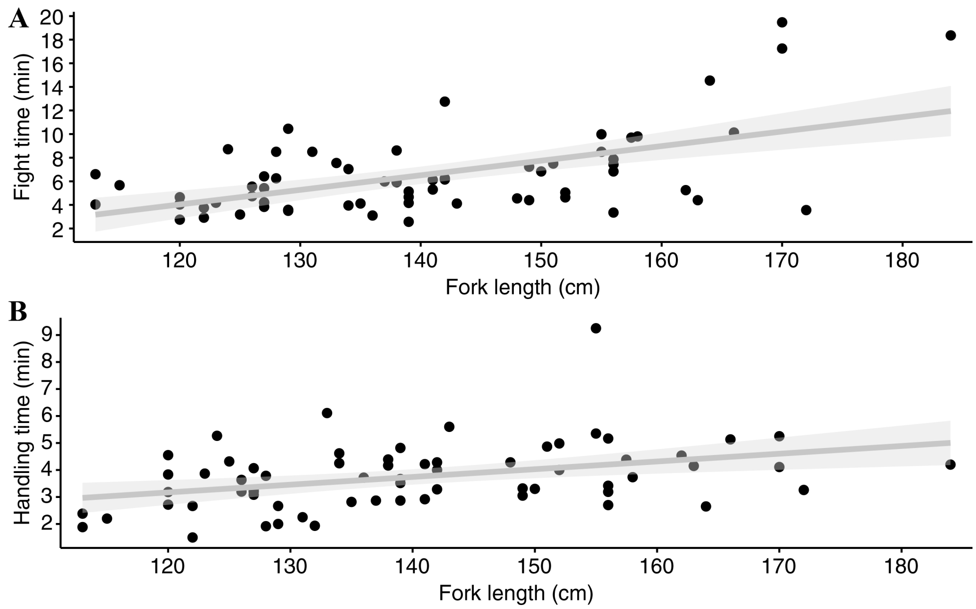


**Figure 2**

Relationship of (**A**) fight time (sample size [*n*]=66) and (**B**) handling time (*n*=65) with fork length (FL) for sandbar sharks (*Carcharhinus plumbeus*) captured in Massachusetts during 2019–2021. The gray line represents the linear relationship, and the gray shaded area indicates the standard error around the predicted relationship. In panel A, data for a single 32-min event of the capture of a 132-cm-FL female shark was excluded (and not plotted) because the volunteer angler hooked 2 sharks simultaneously and did not begin reeling this shark in until the first one was released. In panel B, data for 2 handling events were excluded because of difficulties in applying the acceleration data logger package that artificially extended handling time.

## Discussion

The lack of mortality (100% survival) observed in sandbar sharks following land-based catch-and-release activities adds to the growing body of evidence that this species is resilient and capable of surviving both the physical and physiological effects of capture and handling (e.g., Marshall et al., 2015; Whitney et al., 2021). Postrelease mortality of sharks caught on recreational hook-and-line fishing gear has been linked to physical trauma from internal hooking in the gut or gills (Kneebone et al., 2013; French et al., 2015; Kilfoil et al., 2017), foul hooking on the body (Sepulveda et al., 2015; Weber et al., 2020), extended fight times due to foul hooking (Heberer et al., 2010), and prolonged handling times (Mohan et al., 2020; Knotek et al., 2022). However, in our study, no mortality was identified in 2 sandbar sharks that were hooked in the gills and were bleeding severely at the time of release, with one foul-hooked individual having been fought for 32.40 min (i.e., nearly 5 times longer than the mean fight time observed across all sharks). In addition, no mortality was observed in 23 individuals that were completely removed from the water for 2.20–6.67 min during handling. These observations and the finding that the majority (90%) of sharks monitored in our study were released in excellent or good condition indicate that sandbar sharks are likely to survive land-based catch-and-release fishing in Massachusetts, as long as best practices are used consistently throughout the fishery.

Despite the resilience of this species, it should be understood that the true PRM rate of sandbar sharks caught and released by using land-based techniques in Massachusetts is most certainly greater than zero. Indeed, our research team necropsied 2 sandbar sharks that washed ashore 24–36 h after they were caught and released by land-based fishermen, as confirmed by the presence of an M-tag of the National Marine Fisheries Service Cooperative Shark Tagging Program in each carcass and information reported (by the capturing anglers) to this program (Zewinski[2]). Although the capture-and-handling event was not directly observed for either shark, anglers mentioned in their testimonials that 1 shark was hooked "deep" and was bleeding heavily during hook removal and that the other shark seemed physically exhausted and would not swim away despite being revived for several minutes. The specific cause of these mortalities cannot be determined, but their occurrence confirms that mortality can, and does, occur in the land-based shark fishery. For this reason, we recommend that a PRM rate of 5.6% (the upper limit of the 95% CI) be used when estimating mortality for stock assessment purposes.

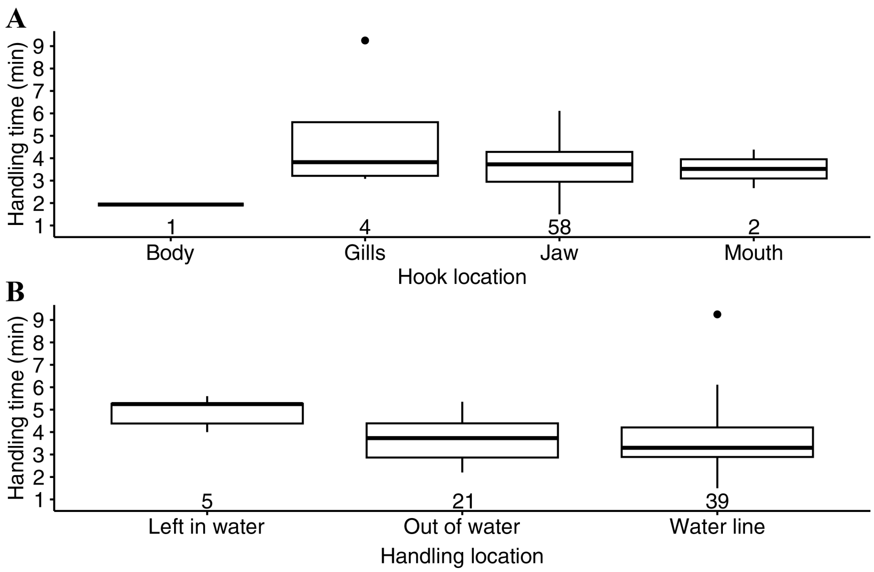


**Figure 3**

Box plots of the relationship of (**A**) hook location and (**B**) handling location with handling time for sandbar sharks (*Carcharhinus plumbeus*) captured in Massachusetts in 2019–2021. The numerals below the plots are the sample sizes for the types of hook and handling locations. The thick line within each box indicates the median, the upper and lower parts of each box represent the first and third quartiles (the 25th and 75th percentiles), the whiskers extending above and below each box correspond to 1.5 times the interquartile range, and the dots represent values outside this range.

Behavioral recovery from land-based catch and release occurred relatively rapidly in sandbar sharks (1.33–17.18 h), with 63% of individuals in our study recovering within 6.36 h after release (i.e., the mean recovery observed over all individuals). This mean recovery time is comparable to, but also faster than, what has been estimated for blacknose (*C. acronotus*) (11.7 h, Knotek et al., 2022), blacktip (10.5 h, Whitney et al., 2017; 29.6 h, Binstock et al., 2023), and bull (8.0 h, Binstock et al., 2023) sharks following catch and release in recreational fishing events and for sandbar sharks following capture in bottom longline fishing (11.7 h, Whitney et al., 2021). Although low and unequal sample sizes precluded statistical analysis in our study, sharks that incurred physical injury from being hooked in the gills or that were foul hooked and in poorer condition at release had longer recovery times than uninjured sharks (Fig. 5). A similar relationship has also been found for tiger sharks following bottom longline capture (Whitney et al., 2021). The ability of sandbar sharks to rapidly recover from land-based catch and release is likely a major factor contributing to the high survivorship observed in this fishery.

Postrelease monitoring periods achieved in our study were relatively short (mean: 2.5 d, 60 h) but were sufficient for monitoring the period during which the majority of PRM typically occurs in sharks (Ellis et al., 2017). For example, Whitney et al. (2021) documented that all ($n$=61) PRM events for several carcharhinid sharks, including sandbar sharks, occurred within 12 h, and Weber et al. (2020) reported that all PRM events for blacktip sharks caught in a land-based shark fishery occurred within 6 h of release, despite their monitoring of animals for weeks after release. These trends, combined with the direct observation of the mortalities of 2 sandbar sharks within 24–36 h of release (see the previous mention of necropsies in this "Discussion" section), provide strong evidence that the durations of ADL package deployments achieved in this study were sufficient for the detection of the majority of mortality events. This notion is also supported by reports from several other studies on recreationally caught sharks documenting that most or all PRM events occur within 24 h (e.g., Heberer et al., 2010; French et al., 2015; Whitney et al., 2017; Mohan et al., 2020). Nonetheless, it is possible that mortality occurred after monitoring ceased, particularly for the few sharks that were hooked in the gills or experienced physical trauma (e.g., Kneebone et al., 2013). Regardless, undocumented, delayed mortalities of sharks in poor condition were unlikely to have yielded total PRM rates exceeding the upper value of the 95% CI (i.e., 5.6%).

The experience level and attitudes of volunteer anglers may have contributed to the high survivorship of sandbar sharks monitored during this study. Efforts were made to observe anglers of all experience levels, but there was no

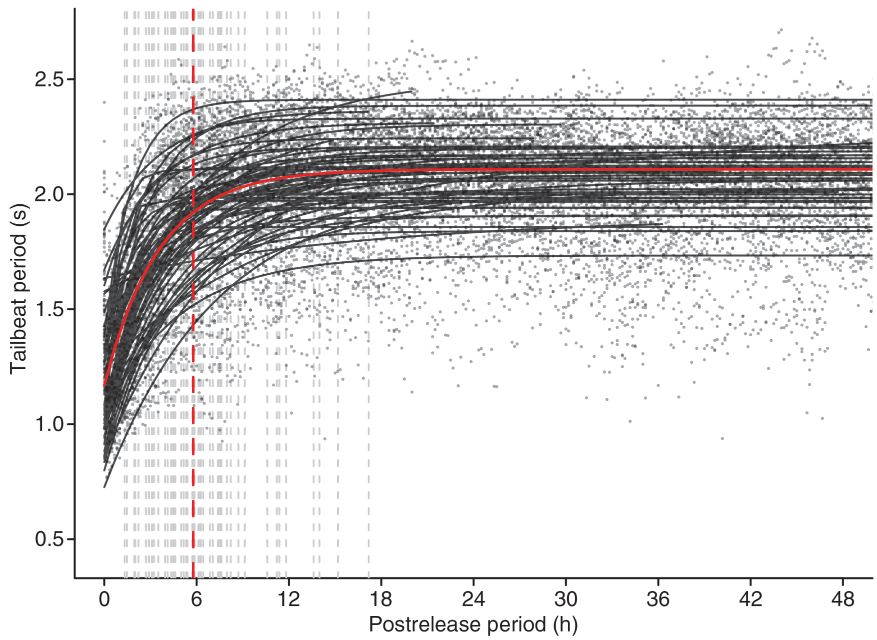


**Figure 4**

Estimated periods for postrelease behavioral recovery of 54 sandbar sharks (*Carcharhinus plumbeus*) for which at least 10 h of acceleration data were available. Sharks were captured in Massachusetts from June through September in 2019–2021. Recovery was modeled as a function of the tailbeat period (TBP) in seconds. The solid dark gray lines represent nonlinear mixed model estimates of TBP, and the vertical dashed gray lines indicate when behavioral recovery occurred (i.e., when TBP reached 80% of its asymptote). The solid red line depicts the nonlinear mixed model estimate for all sharks combined, and the vertical dashed red line represents the predicted recovery time over all sharks. The gray dots represent the average 10-min TBP calculated for each shark; darker shades of gray indicate overlapping values.

discernable effect of angler experience on fight time, handling time, or animal release condition. Furthermore, volunteer fishermen of all experience levels used similar techniques and fishing gear to capture and handle sandbar sharks, and many anglers expressed their intent to minimize fight and handling times however possible. Similar acknowledgement of the need to reduce negative effects of land-based recreational shark fishing has been observed in surveys of land-based shark fishermen in Florida (Guay et al., 2021) and Texas (Gibson Banks et al., 2023). Nevertheless, multiple anglers used J-hooks to capture sandbar sharks, a violation of current Massachusetts state law. Candid conversations with these anglers revealed that some of them were unaware of the regulation requiring circle hooks and that others assumed the hooks they purchased were circle hooks or never transitioned to circle hooks because of their familiarity with the use of J-hooks but not circle hooks. Given that J-hooks were more likely to hook sandbar sharks in places other than the jaw, improved outreach is needed to better inform land-based shark fishermen of fishing regulations and the benefits of using circle hooks to reduce physical injury.

Premature detachment of an ADL package was frequently encountered during this study (40.3% of packages were released more than 25% prematurely). The cause of premature release could not be determined in every instance; however, the correlation between shark rolling behavior and tag detachment provides evidence that some of the packages released because the sharks rubbed against the bottom. Identifying positional changes of animals from acceleration-only data during highly dynamic movements can be difficult (Noda et al., 2014), and it was particularly challenging to identify the exact instant when a tag detached from an animal (i.e., when acceleration data transitioned from indicating shark movements to indicating the release of a tag). Together, these factors introduced the potential for incorrect categorization of rolling behavior during tag release. However, the observation that premature releases were more common when sharks rolled to the left side supports our hypothesis of behaviorally driven detachment because rolling to the left would bring the tag package toward the seafloor. In the context of postrelease survival, the observance of rolling behavior in 19 of 27 instances (70.4%) of premature tag

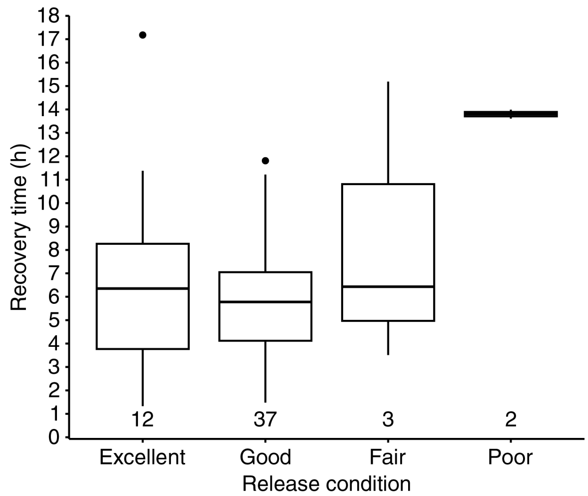


**Figure 5**

Box plots of the relationship between release condition and behavioral recovery period for sandbar sharks (*Carcharhinus plumbeus*) captured in Massachusetts during 2019–2021. The numerals below the plots are the sample sizes for the release conditions. The thick line within each box indicates the median, the upper and lower parts of each box represent the first and third quartiles (the 25th and 75th percentiles), the whiskers extending above and below each box correspond to 1.5 times the interquartile range, and the dots represent values outside this range.

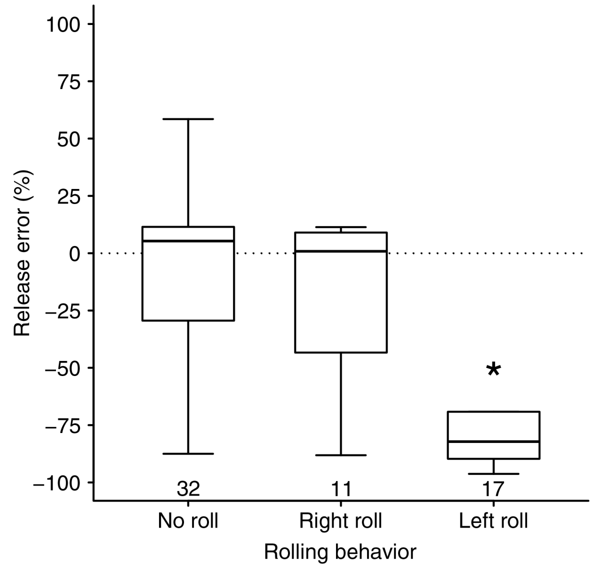


**Figure 6**

Box plots of the timing of the release of tag packages in relation to observations of rolling behavior at the time of tag release for sandbar sharks (*Carcharhinus plumbeus*) captured in Massachusetts during 2019–2021. Release error represents the deviation from the expected time of release (based on the size of the galvanic timed release used), with positive values indicating delayed release and negative values indicating premature release. The asterisk (*) denotes a significant difference in the occurrence of premature release following rolls to the left side (tag side). The numerals below the plots are the sample sizes for the rolling behaviors. The thick line within each box indicates the median, the upper and lower parts of each box represent the first and third quartiles (the 25th and 75th percentiles), and the whiskers extending above and below each box correspond to 1.5 times the interquartile range.

release is evidence of animal vigor and indicates that the individuals in these instances were likely to survive following premature detachment of the ADL package.

## Conclusions

The results of this study provide strong evidence that land-based catch-and-release fishing for sandbar sharks in Massachusetts is a sustainable practice when state regulations and best-practice guidelines are followed. Although total catch of sandbar sharks of the land-based shark fishery in Massachusetts, as well as across all U.S. states, is not well quantified, our estimated PRM rate of 5.6% indicates that incidental mortality in this fishery is very low and should minimally affect the ongoing recovery of the sandbar shark population in the Atlantic Ocean and Gulf of Mexico. Regardless, outreach efforts, particularly those targeting new entrants into the land-based fishery, should promote the awareness and use of best practices and compliance with existing state shark fishing regulations (e.g., requirements to use circle hooks and to leave animals in the water). Future research should be conducted to estimate PRM of sandbar sharks in land-based fisheries occurring in other states or regions where environmental conditions (e.g., warmer air and water temperatures) and handling practices may be different.

## Resumen

La captura y liberación de tiburones aleta de cartón (*Carcharhinus plumbeus*) en la pesca recreativa de orilla es cada vez más popular en Massachusetts. En colaboración con 21 pescadores voluntarios con distintos niveles de experiencia, observamos y documentamos los artes de pesca, los cebos y las técnicas empleadas para capturar y liberar 67 tiburones aleta de cartón. El destino de cada tiburón liberado se monitoreó utilizando una marca de registro de datos de aceleración (ADL) incrustada en un paquete flotador personalizado que se fijó a la primera aleta dorsal con una liberación galvánica temporal. Los 67 paquetes se recuperaron tras su desprendimiento después de periodos de seguimiento de 0.15-9.98 d. El examen de las series temporales de profundidad, periodo de latido de la cola (TBP), cabeceo y balanceo de 65 ADL que registraron datos reveló una elevada supervivencia de los tiburones marcados, todos ellos vivos al momento del desprendimiento de la marca. Se estimó que

la recuperación del comportamiento se había producido de 6.36 h en promedio, después de la liberación, con base en las tendencias del TBP de 54 tiburones aleta de cartón con al menos 10 h de datos de aceleración tras la liberación. Estos resultados indican que los tiburones aleta de cartón son notablemente resistentes a la captura y liberación en la pesquería de orilla de tiburones de Massachusetts.

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