Animal Biotelemetry

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Satellite telemetry reveals space use of diamondback terrapins

Margaret M. Lamont[1*], Melissa E. Price[1] and Daniel J. Catizone[1]

Abstract

Movement and space use information of exploited and imperiled coastal species is critical to management and conservation actions. While satellite telemetry has been successfully used to document movements of marine turtles, the large tag sizes available have limited use on smaller turtle species. We used small Argos-based satellite tags to document movement patterns of diamondback terrapins (*Malaclemys terrapin*), the only estuarine turtle species in North America. Movement data from ten terrapins in St. Joseph Bay, Florida were gathered between July 13, 2018 and July 22, 2021. We estimated seasonal space use using the daily locations generated from a Bayesian hierarchical state-space model to calculate minimum convex polygons (95% MCP) and kernel density estimates (50% and 95% KDE). Mean tracking duration was 125 days and mean home range size was 9.4 km^2 (95% MCP) and 8.1 km^2 (95% KDE). Seagrass habitat comprised 55.8% of all home ranges on average, whereas salt marsh comprised a mean of 3.0%. Mean elevation used by terrapins was – 0.13 m (95% MCP) and -0.35 m (95% KDE). Satellite telemetry provided broad-scale spatiotemporal movement and space use data; however, Argos error produced considerable noise relative to true terrapin movements given their size, speed, and behavior. Terrapin home ranges were greater than previously reported and three of the ten terrapins exhibited repeated long-distance, directed movements within the bay. Small patches of salt marsh habitat were centralized within home ranges, despite comprising only a small percentage for each terrapin. Moreover, the percentage of salt marsh present in each core use area was positively correlated with terrapin mass. Although considered an estuarine species, seagrass habitat comprised a large portion of terrapin home ranges; however, our data did not provide the detail necessary to understand how terrapins were using this habitat. As northward-expanding mangroves continue to infringe upon salt marsh habitat, there is potential for negative impacts to terrapin populations across the northern Gulf of Mexico. As salt marsh habitat continues to be infringed upon by northward-expanding mangroves impacts to terrapins across the northern Gulf of Mexico.

Keywords Terrapin, Gulf of Mexico, Home range, Telemetry, Turtle, Seagrass, Salt marsh

Background

Animal movement data can be used to infer behaviors and resource use of imperiled and exploited species, and as such are necessary for identifying effective conservation strategies. This is particularly critical for species that inhabit at-risk systems, such as seagrass meadows and wetlands [1, 2]. The locations of these habitats, linking terrestrial and neritic systems, make them vulnerable to threats from coastal development, sea-level rise, declining water quality, and propeller scarring [2, 3]. Though gathering space use data for imperiled species in these shallow-water systems can be challenging [4], it is essential as data gaps for estuarine and seagrass dependent species hamper population modeling, critical habitat

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assessments, and development of recovery plans for these species [4, 5].

The diamondback terrapin (*Malaclemys terrapin*) is a relatively small turtle that may play an important role in salt marsh habitats by foraging on the periwinkle snail (*Littoraria irrorate*; [6]), an herbivore that has potential to over-graze salt marsh vegetation [7]. Terrapins are distributed along the Atlantic and Gulf of Mexico coasts of the U.S.A. [6, 8]. Listed as vulnerable on the IUCN Red List [9], terrapin populations are declining throughout their range due to overexploitation in the pet trade, road mortality, and drowning in crab traps [10, 11]. Loss of habitat from sea-level rise and human development of coastal areas has also contributed to fragmented terrapin populations [8, 11, 12].

Movement data for marine turtles have primarily been gathered through satellite [13, 14] and acoustic telemetry [15, 16]. While these techniques are ideal for large turtles that use relatively deepwater (> 1 m) habitats and travel long distances, historically they have not been adequate for smaller turtle species, such as terrapins. Until recently, satellite tags were too large and heavy for small turtle species; even small juvenile sea turtles have been difficult to track for more than a few weeks using this technique [17, 18]. While acoustic tags are smaller than satellite tags, they are only detectable while underwater and as such, are less useful for species that remain primarily in intertidal or shallow water habitats and emerge frequently onshore [19]. Because of these limitations, home range and movement data for aquatic and terrestrial turtle species, including diamondback terrapins, have primarily been gathered by use of VHF radio telemetry and mark-recapture methods [12, 20–23]. Results of these studies suggested terrapins moved less than 10 km from their capture sites and used home ranges that were generally < 1 km^2.

Recent advances in satellite tag technology have resulted in tags small enough to use on large terrapins, generally females. Using satellite telemetry, [24] tracked two adult female diamondback terrapins in Northwest Florida for nearly 150 days each and documented one individual traveling almost 50 km from her original capture site. Home range sizes for these terrapins were also much larger than previously reported for the species. However, the small sample size in that study (n = 2) was insufficient for a broader scale (i.e., population-level) understanding of terrapin movements. We have expanded on this previous investigation to include nine additional terrapins equipped with satellite telemetry transmitters, revealing some of the variation in individual habitat use and challenges still to overcome with tracking small semi-aquatic species.

Methods

Data collection

St. Joseph Bay is located in northwest Florida in the northern Gulf of Mexico and covers approximately 260 km^2 (Fig. 1). Seagrass beds, dominated by *Thalassia testudinum*, cover approximately one-sixth of the bay (43 km^2) and are most abundant in the shallow southern end [25]. Tidal marshes cover approximately 3 km^2 and are comprised primarily of black needlerush (*Juncus roemerianus*) and smooth cordgrass (*Spartina alterniflora*).

Because terrapins are frequently taken by poachers, we do not provide specific capture methods or locations. We conducted monthly surveys for terrapins at five sites in St. Joseph Bay from March to November 2018–2021 as part of a long-term mark-recapture program. The five capture location sites (A–E, Additional file 1: Table S1) ranged from 2.0 to 10.9 km apart and were located on the east side of St. Joseph Bay.

We measured straight plastron length (SPL) and weighed all captured terrapins following [5], then sexed and aged each individual following processing protocols outlined by [26]. To allow individual identification, we individually marked each turtle with unique notches in their marginal scutes [27, 28]. We also inserted a passive integrated transponder (PIT) behind the left bridge of each terrapin after first cleaning the application site with isopropyl alcohol [29].

We adhered satellite transmitters (Wildlife Computers SPOT-275 86 mm x 17 mm x 18 mm; SPOT-387 59 mm x 29 mm x 23 mm) to the anterior carapace using fast-setting epoxy (Superbond). Briefly, the anterior portion of the carapace was cleaned using rough grit sandpaper to remove dirt and epibionts, and to create more surface area for tag adhesion. A small amount of epoxy (approximately 15 g) was then placed on the carapace either directly along the midline of the vertebral scutes or slightly off-set near the margin of the vertebral and costal scutes, depending on the individual carapace (i.e., how well the tag fit on the carapace). After letting the epoxy set for approximately 15 min, we placed the tag into the epoxy and then covered most of the tag (except necessary sensors) with a thin coating (i.e., another approximately 15 g) of epoxy. Because we were initially concerned about possible antenna damage, the transmitter on the first satellite tagged terrapin was deployed with the antenna facing the posterior of the terrapin. All subsequent transmitters were deployed with the antenna facing the terrapins' anterior. The combined mass of the transmitter and epoxy was less than 5% of terrapin mass. Each tag was programmed to be active for 24 h d^{-1} and to transmit 250 transmissions d^{-1}. We released all tagged individuals at the site of capture.

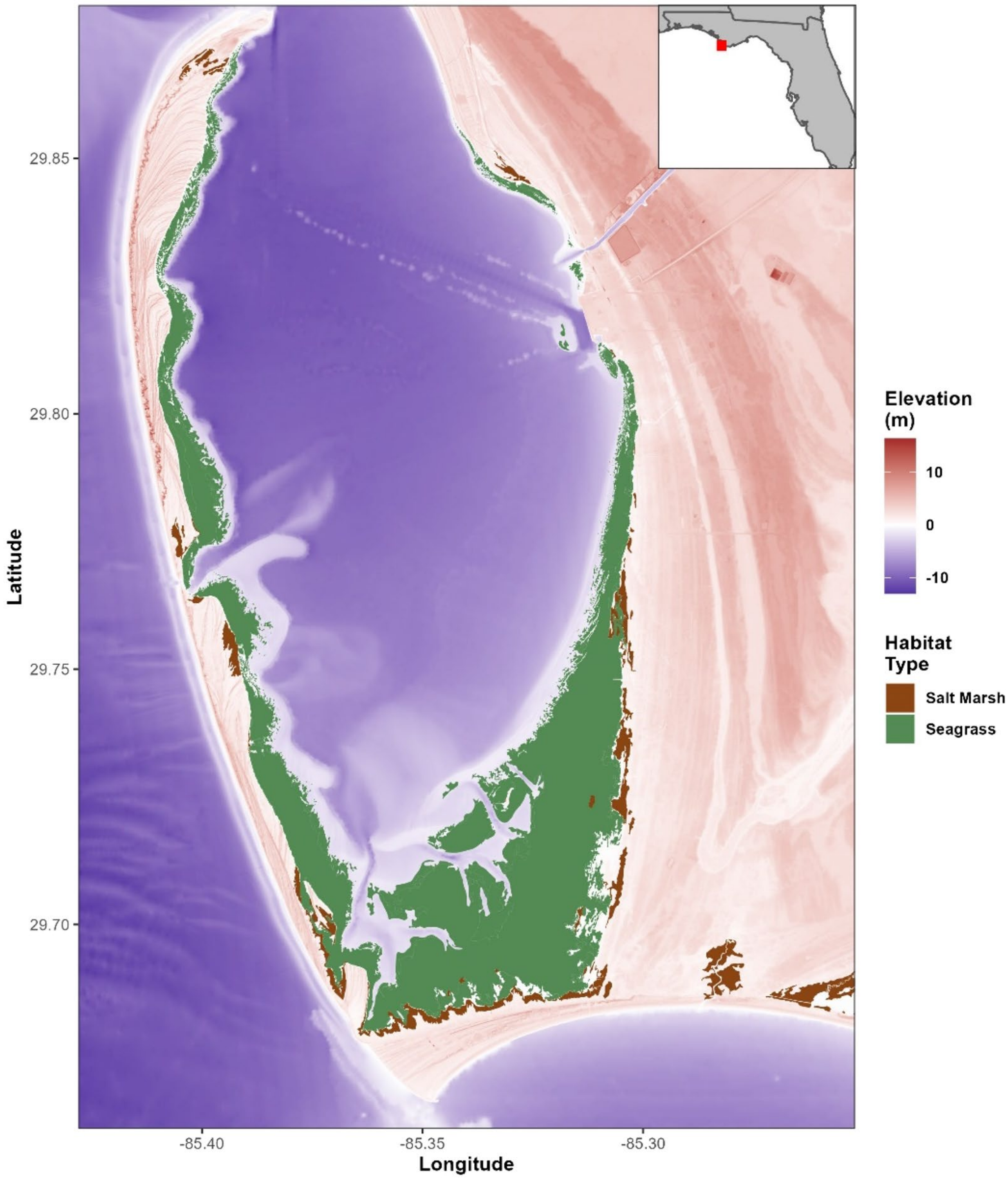

Fig. 1 Habitat map of St. Joseph Bay, FL, including polygons of salt marsh and seagrass habitat overlain on a digital elevation model (DEM) raster

Analysis

Location information was downloaded from Wildlife Computers Inc. which uses the satellite-based Argos system to generate locations and assign location quality based on accuracy estimates using Kalman filtering. When a satellite tag's antenna breaks the surface of the water, a saltwater switch signals the tag to send messages. Those messages are used to estimate locations and the number of messages successfully received affects the error associated with each location. Argos assigns accuracy estimates for locations ranging from < 250 m for the most accurate location class (LC 3) to > 1500 m for LC 0. The estimated accuracy is unknown for LCs A and B and locations failing Argos's plausibility test are assigned to LC Z ([30, 31]. We filtered out all LC equal to Z. Similarly, large temporal gaps in location data at the beginning or end of some terrapin tracks lead to greater uncertainty in ssm locations. Thus, we censored the head or tail end of the data for some individuals when satellite communications failed for more than 5 days, generally removing transmissions that occurred after November for four terrapins and before May 22 for one terrapin. This time period coincides with the portion of the year when terrapins have limited activity and are brumating in mud [6]. An exception was made for PTT 176033 which had very sparse data throughout the tag duration and is likely due to the posterior-facing antenna on this one individual.

In addition to error associated with Argos locations generated from satellite tags, these telemetry data also often contain large temporal gaps. Filtering these data is often insufficient to account for the location errors and may require dropping a significant amount (e.g., 80%) of transmitted locations. Bayesian hierarchical state-space models are frequently used to smooth Argos tracking data and account for LC error ([32, 33]). Similarly, we used the 'bsam' package [34, 35] in R (version 4.2.1; R Core Team 2022) to estimate a location for each individual every 24 h using a Bayesian hierarchical state-space model ('fit_ssm' function). Terrapin tracks were fitted using a hierarchical first difference correlated random walk (hDCRW) to improve movement parameter estimates by estimating them jointly across all individuals. Two independent MCMC chains were run in parallel by calling JAGS (package rjags; [36] using 10,000 adaptive samples and 30000 samples drawn from the posterior distribution and thinned by 20 to reduce within chain autocorrelation. We assessed for convergence using the 'diag_ssm' function in the 'bsam' package which utilizes Gelman and Rubin's shrink factor [37, 38]. Applying the state-space model (ssm) to the Argos-derived location data refines estimates by accounting for location class error and reduces the autocorrelation inherent in movement data.

We estimated seasonal space use using the daily locations generated from the ssm to calculate minimum convex polygons (MCP) and kernel density estimates (KDE) for each individual using the 'adehabitatHR' [39] R package. We used the least-squares cross-validation method to determine the bandwidth of the utilization density, ensuring convergence for each individual. As a consequence of their size and speed, terrapins occupy relatively small areas characterized by mostly tortuous movements which, combined with the error structure inherent in Argos-derived positions, tend to result in an overestimation of home range metrics [40–42]. While the ssm appeared to account for much of that error, the output presented some uncertainty with several outlying location estimates for a few individuals. For this reason, we estimated MCPs using 95% of the locations closest to the centroid to define individual space use areas. Using all locations within each 95% MCP, we determined which point was farthest from individual centroids. For each terrapin, we then calculated the distance of each location along a terrapin's track from the associated farthest location to assess patterns of directed movements for each terrapin.

We estimated polygon area overlap of each MCP and KDE with seagrass and salt marsh habitat [43, 44]. We also summarized elevation use within each MCP and KDE area from cells (3 m x 3 m) within a digital elevation model (DEM) of St. Joseph Bay [45]. We tested the relationship between space use area (MCP and KDE) and terrapin size (mass and SPL), as well as the relationship between tracking duration and terrapin size, capture location, and capture day (i.e., day of year) using linear regression and bivariate Pearson's correlation coefficient. In addition, we tested site fidelity using "adehabitatLT" [39] by generating 1000 correlated random walks starting from the true first location of each individual, then randomizing turn angles and step distances, and returning the same number of relocations as the ssm-derived original track. We then ran a one-sided Monte-Carlo test from the "ade4" R package [46] to determine whether the terrapin movement tracks were more spatially constrained than random by computing the "less" alternate hypothesis p value using both 95% MCP and 95% KDE from randomized and observed values.

Results

We captured and tagged 10 terrapins between July 13, 2018 and July 22, 2021 (Additional file 1: Table S1). Terrapins ranged in size from 13.7 to 16.4 cm SPL and in mass from 670 to 1200 g. We obtained 14,018 locations from satellite data, after censoring 212 locations and two Z LCs, which provided a mean tracking duration of 125 d (range 39–186 days). There was no relationship between tracking duration and terrapin size, tagging date, or capture location within the bay. Though we censored all location data after November, most tags (n = 7) ceased transmitting between October and December. One tag (PTT 202456) that was deployed in May 2020 continued transmitting until February 2021, while another (PTT 202455) only transmitted for 40 days from June to July. Resultant censored location data still included a high proportion of LC B (68.6%) to LC 3 transmissions (10.3%, highest class), but large temporal gaps in location data were removed to improve the certainty in estimates (Additional file 1: Table S1).

Three terrapins were more mobile than expected, undertaking long-distance, directed movements, two of which (PTT 202453 and PTT 202458) traveled in a cyclical pattern (i.e., traveling repeatedly between two approximate locations) with a mean periodicity of 13 (6–20) days (Fig. 2). Mean seasonal space use area was 9.4 (3.1–14.8) km^2 and 8.1 (0.5–17.1) km^2 for 95% MCP and 95% KDE, respectively, with a core area (i.e., 50% KDE) mean of 1.3 (0.0007–2.79) km^2 (1, Fig. 3). There was no

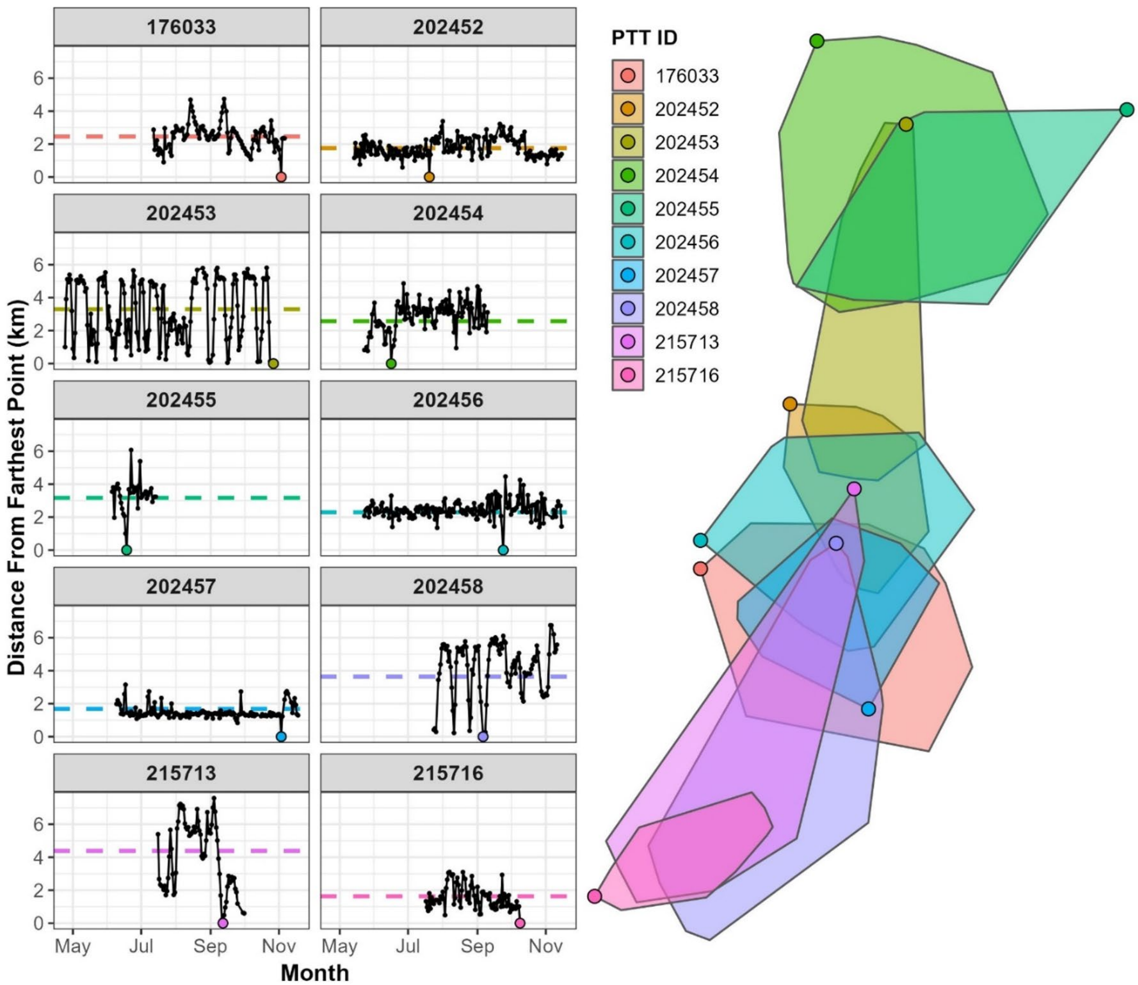

Fig. 2 Calculated 95% MCPs for ten terrapins and the associated farthest ssm estimated relocation point from the centroid. Distance from the farthest point from the centroid of the 95% MCP based on ssm estimated relocations for each of ten terrapins. The colored point represents the farthest location and the dashed line represents the centroid distance from the farthest location. The black points represent the distance of each relocation point from the farthest point traveled by each turtle over time (black line)

relationship between terrapin size or mass and space use area; however, the largest terrapin (PTT 202457) used the smallest area, calculated using KDE (50% and 95%), while the smallest terrapin (PTT 215716) used the second smallest area. The resulting terrapin 95% MCPs and 95% KDEs were more constrained than random for each individual ($p < 0.01$), indicating that all terrapins in this study exhibited site fidelity during the study period.

Seagrass habitat was present in all space use areas, comprising 10.3–94.1% (mean: 55.8%) and 8.9–91.1% (mean: 58.0%) of terrapin 95% MCP and 95% KDE areas, respectively. Whereas terrapin core use areas encompassed a greater percentage of seagrass, ranging from 21.7% to 98.2% (mean: 70.7%). In general, the percentage of seagrass area overlap increased as kernel density areas reduced from 95% to 50%, except for terrapin PTT 202457 which had a very small (< 0.0008 km^2) core area comprised primarily of one isolated patch that included 50.4% of salt marsh habitat. Salt marsh made up a smaller portion of each terrapin area than seagrass, largely due to availability (~3 km^2 total area, or 1% of St. Joseph Bay), which included 0.28–6.15% (mean: 3.0%) and 0.18–6.48% (mean: 3.4%) of 95% MCP and 95% KDE terrapin use areas, respectively. Core use areas included 0–50.4% (mean: 6.7%) salt marsh habitat. The percentage of salt marsh present in each core use area was positively correlated (rho: 0.76) with terrapin mass ($p < 0.05$).

Derived from DEMs that were calibrated to mean high water, mean elevations used by terrapins were all below sea level at − 0.13 m (± 2.3), − 0.35 m (± 2.5), and − 0.27 m (± 1.19) for 95% MCP, 95% KDE, and 50% KDE, respectively. Two terrapin space use areas, belonging to PTT 202454 and PTT 202455, encompassed a wide range of positive and negative values with 95% of pixels

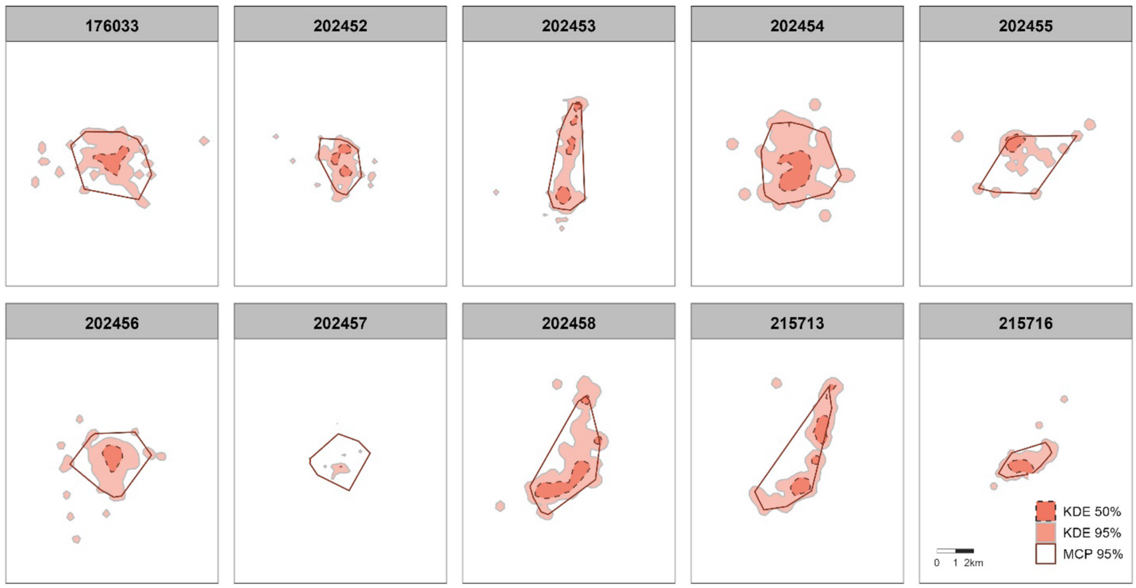

Fig. 3 Calculated 95% MCPs, 95% KDE, and 50% KDEs for ten terrapins on the same spatial scale. The black polygon represents the 95% MCP, light red represents the 95% KDE, and darker red outlined with a dashed line represents the 50% KDE (core area)

between − 7.01 and 6.77 m, while 95% of elevations used by the other eight terrapins were between − 4.91 and 2.52 m, with a core area composition between − 0.91 and 0.42 m. Excluding PTT 202454, PTT 202455 and PTT 202457 (50% KDE only due to use of a small, isolated patch), the most frequently used elevation was -0.30 to -0.61 m, accounting for an average of 49.3% (± 19.3) of pixels within each terrapin space use area (Fig. 4).

Discussion

Satellite telemetry provided broad-scale spatiotemporal movement and space use data for diamondback terrapins inhabiting a coastal bay in Northwest Florida; however, because they are small, slow-moving semi-aquatic animals that often seek cover in vegetation or are submerged, the error inherent in Argos-derived telemetry data produced considerable noise in the location data relative to true terrapin movement [47, 48]. In addition, there were punctuated periods of missing information during sheltering or inactivity, especially from November to February when terrapins most likely remain buried in the mud [21]. Though the ssm appeared to perform adequately in estimating most terrapin locations, some locations did not seem biologically realistic (e.g., in water > 6 m deep in the center of the bay as opposed to crossing a channel to access additional salt marsh sites) and not all tags appeared to perform with the same precision in Argos locations, possibly due to the inclusion of November locations which appeared to have more error. Moreover, these satellite tags contain a saltwater switch that triggers the tag to transmit location messages when removed from the water (i.e., as the animal surfaces). When submerged in freshwater (e.g., if a terrapin temporarily moves into a freshwater source), the tag will continually transmit messages even when underwater thereby resulting in poor location quality and reduced battery life, as was most likely observed with PTT 202454 and PTT 202455, where their home ranges included a large freshwater source (Wildlife Computers SPOT User Guide v.202004; https://static.wildlifecomputers.com/SPOT-User-Guide-5.pdf). Despite these challenges, we were able to estimate reasonable broad-scale habitat use areas for 10 individuals captured within St. Joseph Bay. Because area overestimation remains a possibility [49], we included three habitat use metrics (i.e., 95% MCP, 50% KDE, and 95% KDE) for comparison and limited our MCP analysis to 95% of ssm estimated locations nearest to the centroid.

While there were two general movement patterns exhibited by terrapins in this study, stationary and migratory, when we attempted to run the behavioral hierarchical first difference correlated random walk (hDCRWS) switching model, it was unable to differentiate movement parameters between the two groups given the small movements of terrapins relative to the large error in Argos-derived telemetry data (i.e., directed movements contained short step-lengths and positional noise similar to stationary behaviors). However, when examining movement patterns based on distances relative to the farthest individual location

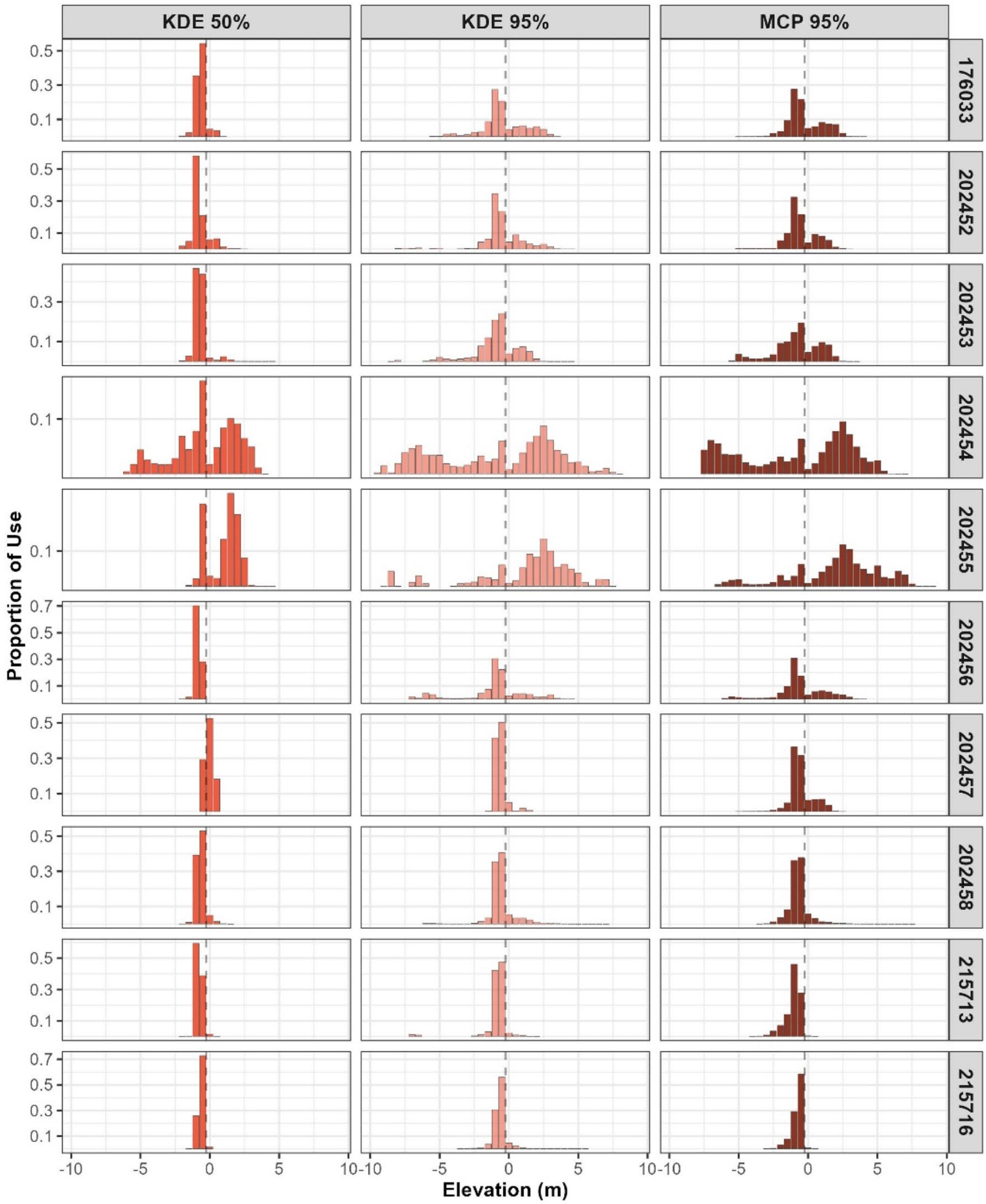

Fig. 4 Proportion of elevation (DEM raster) cells (3 × 3 m) contained within each space use area and binned at a 0.5 m resolution

(Fig. 2), three terrapins made long-distance (3–7 km), directed movements. For two of those migratory individuals, those long-distance movements were repeated multiple times, separated by fairly short time periods (6–20 days) within the tracking season.

Female terrapins are known to undertake relatively long-distance movements during the nesting season [12, 21, 24, 50]; however, the movements we documented occurred through October, whereas in most locations in the Gulf of Mexico, terrapins only nest through

August [51, 52]. The extent of the terrapin nesting season in Northwest Florida is unknown, so perhaps these are indeed late-season nesting movements. Alternatively, these individuals could be making movements to freshwater sources [53, 54] or in search of prey. The predominate osmoregulatory strategy used by terrapins are behavioral adjustments, such as basking or terrestrial shuttling [53, 54]. This may explain movement patterns undertaken by some of our tagged terrapins (e.g., PTT 202454, PTT 202455) who appeared to spend considerable time in or near freshwater sources. The use of freshwater is a challenge to satellite tags that are built for the marine environment, and this may have contributed to poor tag transmission quality for PTT 202454 and lower tracking durations for PTT 202455 (Additional file 1: Table S1). Importantly, movements of this scale and frequency would unlikely be observed if using traditional VHF tracking. Although the remaining seven individuals did not exhibit the same directed movement, all 10 appeared to oscillate at consistent distances around the centroid of each 95% MCP (Fig. 2) and exhibited site fidelity, suggesting that the space use information collected encompasses the extent of seasonal home ranges for these terrapins.

The comparatively large home ranges documented in this study support preliminary findings presented by [24] who suggested terrapins in St. Joseph Bay may use larger areas than previously documented in other locations [20, 21, 23]. Although, despite reporting smaller home ranges, terrapins in those studies were reported traveling 1.5–12.5 km from known locations [12, 20, 21, 55]. Similarly, home ranges of aquatic turtles are typically estimated to be small at < 1 km^2 [56–59], while home range size may increase with latitude [56] or waterbody size [60] and in less productive habitats, where turtles must roam to find resources [57]. Estimates of home range size are also affected by tracking methods. Home ranges of yellow-spotted river turtles (*Podocnemis unifilis*) tracked using VHF telemetry were 10 × smaller than those tracked using satellite telemetry [61, 62], and green turtle (*Chelonia mydas*) home ranges were also smaller when data were collected using active acoustic telemetry (i.e., manual tracking; [15] than satellite telemetry [18]. It is possible that the limited frequency of location fixes obtained via hand-telemetry using VHF and acoustic tags may result in underestimates of home range size; these species may thus have larger home ranges than currently believed. This underestimation could impact conservation decisions; for example, when quantifying appropriate habitat for management decisions [63, 64] or ranking threats to terrapins [11]. Conversely, the use of satellite telemetry has the potential to overestimate habitat use areas [40–42]. Thus, it is important to consider the scientific questions being addressed when deciding which method to use to gather location information for smaller species [47]. Satellite telemetry in this study provided valuable information on broad-scale terrapin use of the bay but is not sufficient for addressing fine-scale ecological concerns (Tables 1, 2 and 3).

Although home ranges were larger than expected, terrapins in St. Joseph Bay remained within the bay throughout the entire tracking period, using a small amount of the bay. Despite using a small proportion (1–16% of 95% MCP) of available salt marsh (~ 3 km^2), this habitat covers only 1% of the entire bay and patches were centralized within the 95% MCPs or 95% KDEs of all terrapins in this study. This is not surprising as terrapins use salt marsh for thermoregulation, salinity regulation, and predator avoidance [20, 54, 65] and typically forage on salt marsh species, particularly the periwinkle snail (*Littornia* sp; [66–68]. In fact, in our study, heavier terrapins had a greater proportion of salt marsh in their home ranges. It

Table 1 Use area calculations for ten terrapins, including percentage of area overlap with salt marsh and seagrass habitats

Capture			Area (km^2)			Seagrass Overlap %			Salt Marsh Overlap %		
PTT	SPL	Wgt	MCP95	KDE95	KDE50	MCP95	KDE95	KDE50	MCP95	KDE95	KDE50
176033	15.4	980	12.2	10.0	1.33	54.3	52.0	89.7	4.02	4.35	3.93
202452	15.9	1000	5.0	4.9	0.81	56.0	58.5	79.6	6.15	6.48	6.63
202453	14.9	790	8.0	6.9	1.15	37.8	49.8	89.2	4.72	3.34	0.28
202454	14.5	760	14.8	17.1	2.79	10.3	9.5	27.5	0.28	0.30	0.54
202455	14.4	830	10.4	5.6	0.68	10.6	8.9	21.7	0.39	0.18	0.35
202456	15.3	820	9.9	8.4	1.07	50.8	56.3	98.2	4.25	3.88	0.00
202457	16.4	1200	6.0	0.5	0.00	71.1	90.4	23.3	6.10	4.95	50.36
202458	15.9	990	13.2	13.1	2.58	81.9	76.7	87.4	2.62	2.43	2.04
215713	14.2	800	11.7	10.4	1.88	90.9	91.1	98.0	0.40	2.35	1.31
215716	13.7	670	3.1	4.5	0.78	94.1	86.6	92.7	0.96	5.44	1.92

Table 2 Summary of elevation cells within terrapin space use areas, including the mean and quantiles (0.025, 0.975)

PTT	KDE50 (m)			KDE95 (m)			MCP95 (m)		
	Mean	2.50%	97.50%	Mean	2.50%	97.50%	Mean	2.50%	97.50%
176033	− 0.4 (±0.3)	− 1.0	0.7	− 0.2 (±1.5)	− 3.9	2.8	0 (±1.2)	− 2.0	2.5
202452	− 0.4 (±0.5)	− 1.5	0.9	− 0.2 (±1.4)	− 2.8	2.9	− 0.3 (±1.1)	− 2.0	1.8
202453	− 0.4 (±0.5)	− 1.1	1.3	− 0.6 (±1.5)	− 4.8	1.8	− 0.5 (±1.7)	− 4.7	2.0
202454	0 (±2.3)	− 5.0	3.3	− 0.6 (±4.2)	− 7.7	5.8	− 0.6 (±3.9)	− 7.2	5.1
202455	1.3 (±1.1)	− 0.5	2.8	1.5 (±3.5)	− 8.2	6.9	2.3 (±3.1)	− 5.3	7.2
202456	− 0.6 (±0.1)	− 0.9	− 0.4	− 0.8 (±2.2)	− 6.4	3.2	− 0.3 (±1.6)	− 5.0	2.9
202457	0.2 (±0.3)	− 0.4	0.7	− 0.4 (±0.4)	− 0.7	1.0	− 0.2 (±0.8)	− 1.6	1.6
202458	− 0.4 (±0.3)	− 0.7	0.3	− 0.3 (±1.0)	− 1.7	2.1	− 0.4 (±0.7)	− 1.8	1.4
215713	− 0.5 (±0.1)	− 0.7	− 0.2	− 0.6 (±0.9)	− 1.9	0.3	− 0.8 (±0.5)	− 2.2	− 0.2
215716	− 0.4 (±0.1)	− 0.6	− 0.1	− 0.4 (±0.4)	− 1.3	0.7	− 0.5 (±0.4)	− 1.6	− 0.1

Table 3 Space use by diamondback terrapins at sites across the southeastern U.S., including results presented in [24] for a female terrapin tracked in St. Joseph Bay (also included in this study) and in Santa Rosa Sound, FL

Study	Sex	Tracking	Analysis	Mean home range (km^2)	Location
Spivey et al. 1998	Female	VHF	KDE	2.52 (±0.39)	Core Sound, North Carolina
	Female	VHF	MCP	3.05 (±0.65)	Core Sound, North Carolina
	Female	VHF	KDE core use areas	0.34 (±0.08)	Core Sound, North Carolina
	Female	VHF	MCP core use areas	0.083 (±0.02)	Core Sound, North Carolina
Butler 2002	Female	VHF	MCP	0.54 (±0.55)	Northeast Florida
Harden and Williard 2012	Male/female	VHF	MCP	0.53	Southern North Carolina
	Male/female	VHF	MCP	0.26	Southern North Carolina
Lamont et al. 2021	Female	Satellite	KDE	69.8	St. Joseph Bay, Florida
		Satellite	KDE	167.3	Santa Rosa Sound, Florida
This study	Female	Satellite	MCP	9.4 (±3.8)	St. Joseph Bay, Florida
	Female	Satellite	KDE	8.1 (±4.8)	St. Joseph Bay, Florida
	Female	Satellite	KDE core use	1.3 (±0.9)	St. Joseph Bay, Florida

has been suggested that the diamondback terrapin is an area-sensitive species that requires a minimum proportion of salt marsh area within its home range [64]. Areas with disjunct fringing marshes may support dispersing individuals or individuals making long-distance movements but not be sufficient for core terrapin habitat [64]. This may explain the disparity in home range sizes between this and other studies, as habitats in other studied regions are generally dominated by salt marsh and are confined, tidal waterway systems [20, 21, 23]. Although salt marsh is distributed along the coastline throughout the southern end of St. Joseph Bay, most of the mainland marshes are multi-species assemblages [69] comprised of some species that are not favored by periwinkle snails [70] and also increasingly invaded by expanding mangrove habitat [71]. Terrapins in St. Joseph Bay may more heavily use marsh patches that are dominated by *Spartina alterniflora* most likely because it is preferred by periwinkle snails [72]. In addition, the configuration (i.e., narrow fringe) of salt marsh in the bay does not make a large amount of it available to terrapins relative to the size of terrapin home ranges. Interestingly, the core use area for the largest female in this study contained 50% salt marsh habitat; however, she also used the smallest areas (50% and 95% KDE).

Although considered an estuarine species, seagrass habitat comprised a large portion of the terrapin home ranges in St. Joseph Bay. The southern end of the bay is dominated by seagrasses and as such, any movements away from salt marsh habitat would take terrapins over seagrasses. Our data do not provide the resolution necessary to determine how, or if, terrapins are using seagrass habitat, other than as corridors; however, it is likely that terrapins use seagrass habitat as protection from predators, similar to small green turtles [73]. In addition, terrapins are considered foraging generalists [67, 74] and may select prey in seagrass beds or forage directly on seagrass [75]. In the Chesapeake Bay, terrapins foraged on eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*; [75]), which is likely also occurring with *Thalassia testudinum* that dominates St. Joseph Bay [25]. In fact, terrapins may help disperse eelgrass seeds thereby contributing to the maintenance of seagrass habitats [76, 77]. If a similar process occurs in St. Joseph Bay, the relatively large home ranges we documented in this study would allow for increased seed dispersal distances by terrapins, and as such, would highlight another important role diamondback terrapins play in maintaining coastal habitats.

Conclusion

Understanding the spatial needs of coastal species is critical to their conservation, particularly as human populations increase in these regions and climate change threatens coastal habitats [78]. Urbanization and landscape alteration can constrain landward migration of coastal habitats due to sea-level rise [79], thereby reducing available habitat for terrapins. Anthropogenic structures such as bulkheads and riprap block the connection between the terrestrial and estuarine environment and can prevent terrapin movements [64]. Using a variety of movement ecology tools (e.g., satellite telemetry) can provide invaluable data that lead to conservation actions, such as establishing Marine Protected Areas [80, 81], defining critical habitat [82], and implementing activity closures, such as commercial fishing or vessel activity [83, 84]. However, the choice of satellite telemetry, particularly with smaller species, such as diamondback terrapins, needs to be made with project objectives in mind [13, 85]. Although there are satellite tags that can document locations with submeter accuracy (e.g., [86]), the large size required for such data collection prohibit their use with small species. Development of such tags would provide the ability to identify relationships between terrapin movements, environmental parameters, and habitat characteristics; data that are necessary for design of effective conservation actions to benefit terrapins. While terrapin home ranges in this study were considerably larger than in previous studies, it is unclear whether those sizes were due solely to the method of data collection or whether reduced habitat quality and sparse marsh distribution combined with anthropogenic spatial limitations, forced terrapins to cover larger areas to meet life history requirements. Moreover, there is a growing concern that as mangrove habitat expands northwards [71] it will alter or out-compete salt marsh habitat in this area, displacing many of the plant and prey species relied upon by diamondback terrapins.

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Supplementary Information

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Additional file 1: Table S1.: Terrapin capture date and satellite transmitter deployment information, including the first and last day transmissions were received from the tag, for 10 diamondback terrapins tracked using satellite telemetry in St. Joseph Bay, FL. PTT = Platform Terminal Transponder, SPL = straight plastron length; Argos location classes = number of transmissions (after data were censored) in each location class.

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Author contributions

ML acquired resources for this project. ML and DC designed the study and conducted field investigations. ML, DC, and MP conceptualized manuscript objectives. MP analyzed data. ML and MP led writing of the manuscript. All authors contributed to revisions and final submission approval.

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Availability of data and materials

Because diamondback terrapins are an exploited species, the authors will not release location information publicly. Data requests can be sent to the lead author at: USGS Wetland and Aquatic Research Center, 7920 NW 71st St., Gainesville, FL 32653 or via email at mlamont@usgs.gov.

Declarations

Ethics approval and consent to participate

All turtle handling and sampling was conducted under State of Florida Scientific Collection Permits #33447 and #73692 and performed according to the Institutional Animal Care Protocol USGS/WARC/GNV 2019–15 and USGS/WARC.GNV 2018–04.

Competing interests

The authors declare no competing or conflicts of interests.

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