Note

Between the Bay and a Hard Place: Altered Diamondback Terrapin Nesting Movements Demonstrate the Effects of Coastal Barriers Upon Estuarine Wildlife

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ABSTRACT Human development can impede wildlife moving between complementary habitats, particularly in highly disturbed coastal ecosystems. Coastal barriers may affect the behavior of diamondback terrapins (*Malaclemys terrapin*), a salt-tolerant estuarine turtle that requires access to complementary upland habitat for annual nesting. We used telemetry to quantify terrestrial and aquatic movements of 78 nesting female terrapins in response to coastal barriers at 2 sites in Barnegat Bay, New Jersey, a heavily developed estuary. Nesting female terrapins traveled significantly greater distances with more tortuous paths or spent significantly more time in the water when their movements were obstructed than females nesting at beaches with no obstructions. We hypothesize that the additional effort and displacement associated with reproduction where obstructions exist will reduce terrapin fitness and potentially contribute to population declines. Our study demonstrates a unique approach to quantifying effects of barriers on organisms requiring complementary habitats, and improves our understanding of the impacts of shoreline hardening on estuarine wildlife threatened by encroaching coastal development. © 2015 The Wildlife Society.

KEY WORDS Barnegat Bay Estuary, biotelemetry, coastal barriers, diamondback terrapin, nesting behavior.

Most animals require complementary habitats to facilitate their movement, migration, growth, or reproduction (Moran 1994). Life-stage-specific physiological constraints or resource needs often necessitate changes in morphology, physiology, or behavior associated with movements between complementary habitats (Wilbur 1980, Dunning et al. 1992). For example, the transition of herbivorous tadpoles to terrestrial carnivorous adult frogs, or anadromous fish migrations between rivers and oceans are well-known cases of organisms requiring more than 1 habitat within an individual's lifetime. Roadways, dams, agricultural conversion, and building developments are common forms of anthropogenic barriers to species movement between complementary habitats, and may threaten the conservation of wildlife (Hamer and Organ 2008, Kemp and O'Hanley 2010, Mandelik et al. 2012, Crawford et al. 2014). Turtles require complementary habitats, often traversing the aquatic-terrestrial ecotone to complete their life cycle (Bennett et al. 1970). Most aquatic turtles spend the majority of time in water, but because they have a cleiodoic egg, successful embryo development requires laying eggs on land. Choice of nesting habitat can affect egg survival and sex ratio (Mitchell et al. 2014); therefore, turtles are generally faithful to specific nest locations (Roosenburg 1996, Szerlag-Egger and McRobert 2007, Sheridan et al. 2010, Crawford et al. 2014). However, accessibility to suitable nesting habitats is deteriorating because of the persistence of anthropogenic barriers in the coastal complementary habitat (Hinrichsen 1998).

The loss and degradation of estuaries is the leading threat to coastal ecosystems worldwide (Lotze et al. 2006). The United States mid-Atlantic coast is experiencing rapid coastline development (Kennish 2002), causing a major challenge to the conservation of estuarine habitats and the species that depend on them (Peterson and Lipcius 2003). This degradation is likely to continue, with the current costal population in the United States projected to grow 25% by the year 2028 (Scavia et al. 2002). Over the past 30 years, Barnegat Bay Estuary, New Jersey, has lost the largest percentage of natural shoreline of any mid-Atlantic estuary because of coastal development (Jivoff 2007, Lanthrop and Haag 2007). Coastal development generally leads to increased bulkheading. Also known as rip-rap, revetments,

seawalls, groins, and jetties, these barriers protect terrestrial areas from wave damage, erosion, and flooding. The effect of these coastal barriers on the movement of wildlife along coastal habitats is in need of further study (Roosenburg 1991, Witherington et al. 2011).

We used the diamondback terrapin as a model to determine the impacts of coastal barriers on wildlife that use the aquatic-terrestrial interface. Terrapins are in decline throughout much of their range due to anthropogenic activities affecting both aquatic and terrestrial habitats (Gibbons et al. 2001, Cecala et al. 2008, Harden et al. 2009, Grosse et al. 2011, Hart and Crowder 2011). Roosenburg (1991, 1994) identified coastal bulkheading and other barriers to terrapin migration from aquatic to terrestrial nesting habitats as a threat to terrapin conservation. Nonetheless, there has been little effort to quantify the effects of nesting barriers on terrapin behavior or performance.

The purpose of this study was to measure the impacts of barriers on the behavior of diamondback terrapins during nesting. We measured distance traveled and tortuosity on land, as well as time spent in the water near nesting beaches to quantify behavioral changes in reproductive female terrapins in relation to shoreline barriers. We predicted that female terrapins encountering barriers while nesting would travel farther and spend more time in both aquatic and terrestrial habitats versus those encountering an unobstructed nesting habitat.

STUDY AREA

Our study areas included 2 terrapin nesting sites in Barnegat Bay, New Jersey, USA (39°47'N, 74°9'W): Sedge Island, 1 km west of Island Beach State Park, and Conklin Island, within the Edwin B. Forsythe National Wildlife Refuge (Fig. 1A). We chose these sites based on their historically high levels of nesting activity (Wnek 2010, H. Avery, The College of New Jersey, unpublished data). Although similar in their valuable nesting habitat, Conklin and Sedge Islands vary in their size and shape (Fig. 1A). Conklin Island is more

remote, whereas Sedge Island houses an active educational facility. Because of the differences in size, shape, and levels of human activity, we refrained from making statistical comparisons of terrapin behavior between Sedge and Conklin Islands.

METHODS

Experimental Manipulation
We identified the 2 beaches with the highest nesting activity at each site (Conklin and Sedge Islands) based on Wnek (2010) and results of unpublished nest surveys from 2006 to 2012 (H. Avery, personal communication). We selected beaches at each site based on similar sediment type (sand), terrapin accessibility (open beach), water depth along the immediate shoreline (0.2–0.5 m), beach length (Conklin: 245–275 m, Sedge: 65–90 m), and prominent vegetation surrounding the nesting habitat (*Spartina* spp. and *Phragmites* spp.). At 1 beach at each site, we installed Yodock[TM] plastic construction barriers (The Yodock Wall Company, Inc., Bloomsburg, PA; Model 2001M (Metropolitan), 182 cm × 45 cm × 81 cm) parallel to the vegetation line at the high water mark, central to the area of highest reported nesting emergence. Barriers lined equal proportions of the beach at each site, representing 25% of the total beach length (Conklin: 67.7 m, Sedge: 20.1 m). The second designated beach remained unobstructed and served as a control beach (Fig. 1B).

Terrapin Nesting Survey and Biotelemetry
We conducted daily 6-hour surveys simultaneously at experimental and control beaches on Sedge and Conklin Islands over 29 days in July 2010 and 48 days between June and July 2011. Investigators sat inconspicuously among *Phragmites* sp. in the nesting habitat to allow for unobstructed observation. We observed both aquatic and terrestrial terrapin behaviors within 100 m of investigator locations, focused toward the shoreline of the nesting habitat.
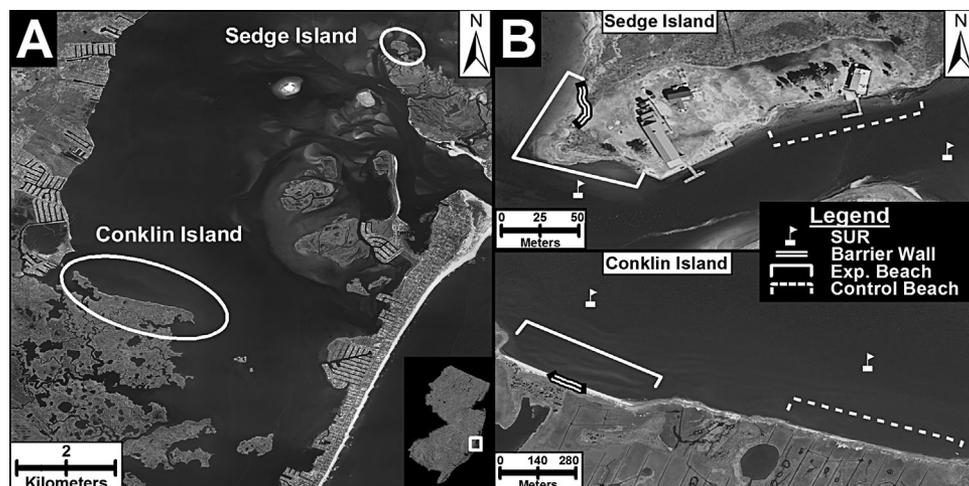
Figure 1. Study site (A) in Barnegat Bay, New Jersey with terrapin nesting survey sites, and experimental design (B) demonstrating beaches with experimental barriers (exp.) without barriers (control), and locations of submersible underwater receivers (SUR) for aquatic monitoring at both Sedge and Conklin Islands.

We collected nesting terrapins after 1 minute of attempted oviposition and brought them to the laboratory overnight. We measured, x-rayed, and marked each terrapin (Sheridan et al. 2010). We considered gravid females likely to return to nest, and thus outfitted them with both radio (Sirtrack, Hawkes Bay, New Zealand; 2-stage very high frequency [VHF], 20 g, 164 MHz–166 MHz) and acoustic (Sonotronics, Tucson, AZ; IBT-96-5, 3.2 g, 40 kHz) transmitters on their carapace using epoxy and monofilament tethers. We designed radio transmitters with a 45° spring antenna to ensure exposure when the terrapin was at the surface breathing. We wrapped radio antennas in orange electrical tape to increase visibility. After outfitting, we re-released terrapins at their original capture location. This study was approved under annually issued Scientific Collecting Permits and Scientific Holding Permits by New Jersey's Department of Environmental Protection, and annual Special Use Permits by the Edwin B. Forsythe National Wildlife Refuge. All research protocols were approved by Drexel University's Institutional Animal Care and Use Committee.

Radio receptions facilitated our subsequent measurement of terrapin nesting activity. We used telemetry to confirm the identity of individuals seen in the water or emerging on land and to measure individual aquatic surfacing rates. Consistent receptions indicated a female emerging onto a nesting beach and allowed us to measure terrestrial displacement. When a transmittered terrapin emerged to nest, we recorded the point of emergence, points along their path, and point of oviposition with a global positioning system (GPS; Garmin, Olathe, KS; error ≤ 5 m), and calculated total path distance.

We used passive acoustic telemetry to measure the time terrapins spent in the aquatic habitat near but prior to their point of emergence. We mounted submersible underwater receivers (SUR; Sonotronics, SUR-2) to partially submerged 2.5-m polyvinyl chloride (PVC) poles, and placed them within 75 m of each beach's shoreline. When a telemetered female swam into the area adjacent to the nesting habitat, the SUR units recorded time of acoustic reception. This documented the amount of time each telemetered female remained in the water adjacent to the nesting area until emergence onto land.

Aquatic and Terrestrial Measures

Terrestrial movement and displacement measures.—We measured total distance, net displacement, and tortuosity to quantify terrapin's terrestrial movements. Total distance included an individual terrapin's point of emergence, each path point, and the point of oviposition. Equivalent to the measure path length or L (Benhamou 2004), total distance in our study represented the sum of distances between each location point (or GPS coordinate). Net displacement represented distance between point of emergence and point of oviposition. Equivalent to a straight-line measurement, D (Benhamou 2004), net displacement was the distance between the initial and final fixes of a terrapin's random search path (Claussen et al. 1997). Tortuosity was the ratio between net displacement and total distance or D/L (Benhamou 2004). This ratio is an index of the directness

of an animal's path (Batschelet 1981, Benhamou 2004). Fractal measures can also be used to estimate tortuosity of movement paths; however, D/L was more appropriate for our study because the index allowed us to determine orientation (Emlen 1969), and to compare pathways of animals exposed to novel situations (Sinsh 1988, Claussen et al. 1997).

For each terrestrial movement measure, we considered experimental terrapins as those that made contact with or walked around the barrier upon emergence. Avoid terrapins were any other terrapin that nested within the boundaries of the study beach but did not come in contact with the barriers. We designated control terrapins as those emerging to nest within the designated control beach habitat. We collected terrestrial responses to barriers only in 2011.

To calculate the distance for each terrestrial measure, we mapped GPS coordinates for an individual terrapin's nesting attempt in ArcGIS v10.0 (ESRI, Redlands, CA) and then used the pointdistance function in Geospatial Modeling Environment v0.7.1.0 (Spatial Ecology LLC, ©Dr. Hawthorne L. Beyer). We compared distances to transect tape measurements for accuracy, confirming a +/− 5-m confidence with geospatially referenced locations.

Aquatic behavior and displacement measures.—We measured individual surfacing frequency, total surfacing frequency, and SUR presence to quantify the amount of time terrapins spent in the aquatic habitat before emerging to nest. Individual surfacing frequency was the number of surfacing observations per unique, identifiable terrapin. Because we could not always identify each surfacing terrapin head as that of a unique individual, we also measured total surfacing frequency, which was the cumulative number of turtles seen surfacing per observation period. For both measures, experimental surfacing included all observations of turtles surfacing in the water within 100 m of the experimental barrier. Control surfacings included all observations of turtles in the water within 100 m of the designated control beach. We used SUR presence as our measure of the amount of time a turtle spent in the water immediately prior to nesting. We counted the number of SUR receptions for each outfitted terrapin, and then calculated each individual's ratio of time at the SUR using the following equation:

$$\text{SUR presence} = \frac{\text{total receptions}}{\text{potential receptions}}$$

Total receptions is the number of SUR receptions from an individual terrapin. Potential receptions is the total seconds between a terrapin's transmitted release until recapture (time in water) divided by 7 because a SUR scans for transmissions approximately once every 7 sec (Sonotronics, personal communication).

Data Analysis

We examined each measure for normality and homogeneity of variances before statistical analyses using R 2.15.0 (The R Foundation for Statistical Computing, Vienna, Austria). We log-transformed total distance and net displacement for a 1-way analysis of variance (ANOVA) to determine differences in travel distance between turtles in experimental, avoid, and

control groups at each site. We used Tukey's honest significant difference test to determine which groups were different from one another with regards to each response variable. Tortuosity is a purely descriptive measure (Batschelet 1981); thus, it did not require statistical analysis. We calculated tortuosity as $1 - D/L$ to facilitate interpretation of the paths taken by terrapins. Tortuosity values approaching 0 indicated a path closest to a straight line, whereas those near 1 signified a more tortuous, wavering path.

We modeled differences between individual and total surfacing frequency at each treatment beach per site using Poisson regression. Time of year contributes to the probability of a terrapin being present in the aquatic habitat proximal to a nesting beach. To control for this factor in each surfacing frequency Poisson model, we calculated terrapin nesting probability over the course of a season using 2005–2008 Sedge Island data (Wnek 2010). In addition to this nesting probability variable, we also included total survey hours (effort) and year in our model as random effects. The average SUR presence values from 2010 and 2011 were not significantly different (Student's t test, $P = 0.142$), and hence we combined and arcsine transformed the 2 years of data. We used a Kruskal–Wallis test to determine whether statistically significant differences occurred in SUR presence between treatment beaches at each site. We used an alpha level of 0.05 for all statistical tests.

RESULTS

Terrestrial Movements and Displacement

Total distance was not different between terrapins in experimental ($n = 8$), avoid ($n = 26$), or control ($n = 17$) groups at Sedge Island ($F = 0.85$, $P = 0.28$), nor was net displacement ($F = 0.38$, $P = 0.77$). However, at Conklin Island, nesting terrapins encountering barriers ($n = 7$) traveled approximately 5 times farther than avoid ($n = 16$), and 3 times farther than control ($n = 4$) terrapins ($F = 12.79$, $P \leq 0.01$; Fig. 2A). Also, net displacement was 150% greater for experimental than avoid terrapins ($F = 6.18$, $P \leq 0.01$; Fig. 2B). At Sedge Island, tortuosity levels were similar among the 3 terrapin groups ($\mu = 0.53$, 0.43, and 0.37 for experimental, avoid, and control, respectively). At Conklin Island, terrapins exposed to barriers had paths that were 5–9 times more tortuous than paths of terrapins that avoided barriers or emerged on control beaches ($\mu = 0.53$, 0.11, and 0.06 for experimental, avoid, and control, respectively; Fig. 2C).

Aquatic Behavior and Displacement

Individual surfacing frequency ($Z = 3.20$, $P \leq 0.01$) and total surfacing frequency ($Z = 6.67$, $P \leq 0.01$) for both 2010 and 2011 were greater in the aquatic habitat proximal to barriers ($n = 57$) than at the control beach ($n = 54$) on Sedge Island. At Conklin Island, barriers did not have an effect on individual surfacing ($n_{\text{experimental}} = 59$, $n_{\text{control}} = 56$, $Z = -0.19$, $P = 0.85$) or total surfacing ($Z = -1.43$, $P = 0.16$; Fig. 2D) in 2010 or 2011. Terrapin SUR presence was 2 times greater at experimental versus control treatments at Sedge Island ($n = 22$, $\chi^2 = 6.63$, $P \leq 0.01$) but not different

between treatments at Conklin Island ($n = 11$, $\chi^2 = 0.52$, $P = 0.47$; Fig. 2E).

DISCUSSION

At Conklin Island, barriers on nesting beaches can displace terrapins, cause them to travel farther on land, and increase the tortuosity of nesting migrations. Similarly, painted turtles (*Chrysemys picta*) travel farther when nesting in developed versus less altered habitats (Baldwin et al. 2004). Traveling farther on land resulted in greater exposure to roads, and subsequently, higher mortality rates within the painted turtle nesting population (Baldwin et al. 2004). Studies have demonstrated mammalian predators, such as raccoons (*Procyon lotor*), can be a substantial threat while terrapins are nesting (Seigel 1980, Feinberg and Burke 2003, Butler et al. 2004). Thus, by causing greater migration distances, nesting barriers may directly affect turtles by increasing stress and mortality through increased exposure to predators. Barriers such as roads and bulkheading can also lead terrapins to nest in marginal habitats (Roosenburg 1994) such as backyards and driveways. Such displacement is of particular concern as human development increases because it may lead to lower nest success (Roosenburg 1996, Roosenburg et al. 2014) and population declines.

We found that terrapins interacting with nesting barriers at Conklin Island also exhibited more tortuous movements. Studies of tortuosity in freshwater turtles suggest that more tortuous paths indicate lack of orientation (Caldwell and Nams 2006). When nesting, terrapins typically orient directly upslope from the marsh to an area above the high tide line (Burger 1977). Based on their increased tortuosity, terrapins facing barriers may be less likely to find appropriate nesting conditions. The increased travel distance, time on land, and disorientation caused by barriers may also increase exposure to higher levels of thermal stress (Crawford et al. 2014).

On Sedge Island, we found that barriers blocking direct access to nesting beaches increase the amount of time terrapins spend in the water and increase their surfacing frequency before nesting. These results suggest that nesting females at Sedge Island could see the barriers, and this affects their behavior prior to emerging onto land. Studying terrapin behavior in the aquatic habitat prior to emergence is important towards understanding their nesting ecology (Szerlag-Egger and McRobert 2007). Increased time swimming before nesting may increase energy expenditure and fatigue or stress females prior to nesting. When combined with increased tortuosity on land, anthropogenic impediments to nesting could significantly increase the stress females experience while trying to nest in suitable habitat. In addition, increased time spent surfacing in areas of high boat traffic may increase rates of boat strikes to mature females (Cecala et al. 2008, Lester et al. 2013). We cannot rule out the possibility that differences in the shape of our study beaches on Sedge Island (and not the presence of the barrier) caused the differences in terrapin aquatic behavior. The experimental beach on Sedge Island was round, whereas the control beach was more linear, with shallower water.
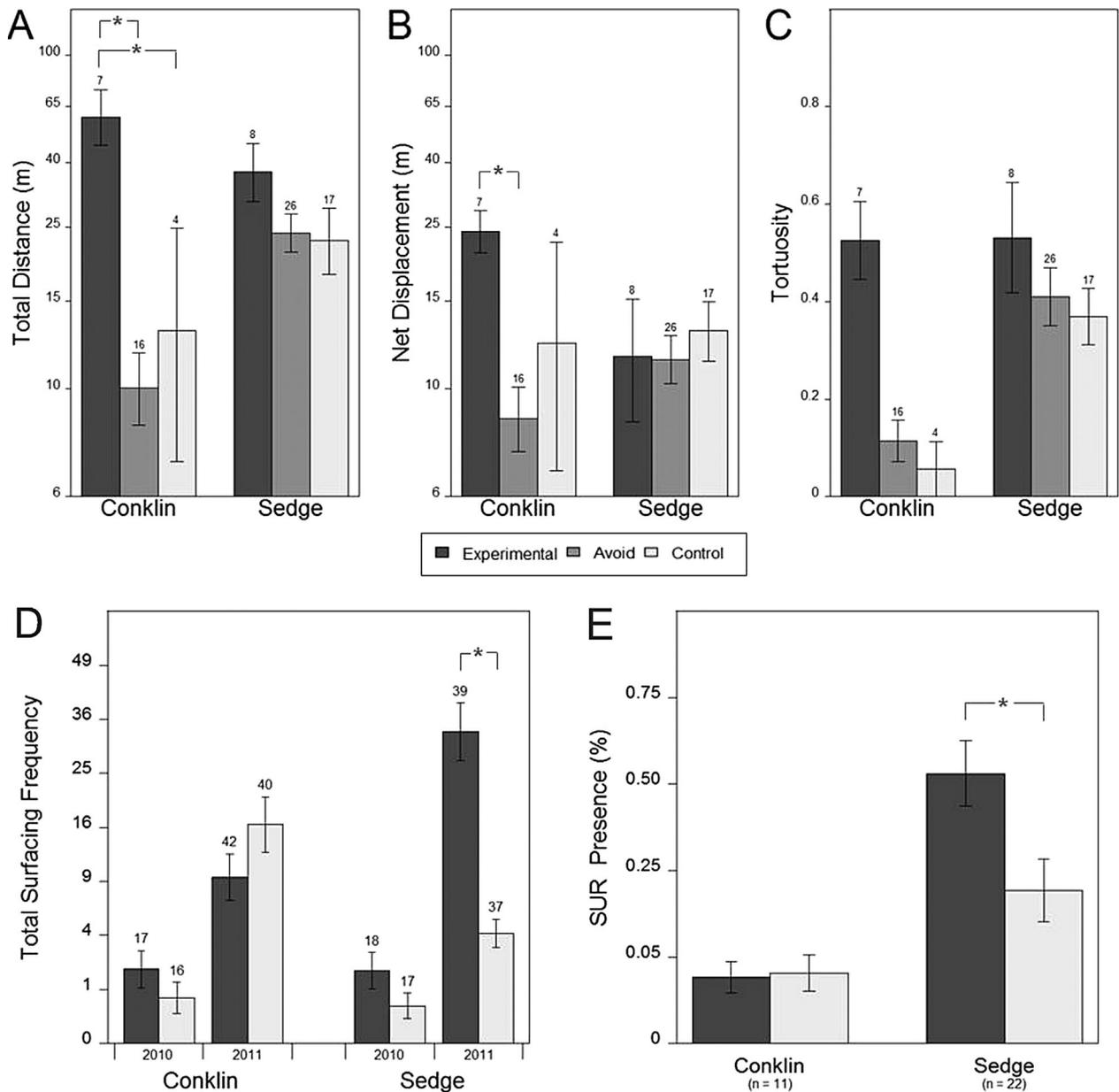
Figure 2. Terrestrial and aquatic measures of total distance (A), net displacement (B), tortuosity (C), total surfacing frequency (D), and submersible underwater receiver (SUR) presence (E) of nesting diamondback terrapins in experimental, avoid, and control groups on Sedge and Conklin Islands in Barnegat Bay, New Jersey in 2010 and 2011. Numbers document sample size. Asterisks indicate statistical significance at $P < 0.01$. Bars represent 1 standard error. A and B are shown on a log axis. D is transformed on a square-root axis. E is presented on an arcsine axis.

However, we consider the long barriers a more likely cause of changes in terrapin behavior than beach shape.

Although our results suggest that barriers affect the terrestrial and aquatic behavior of terrapins, we did not observe both effects at each study site. At Conklin Island, terrapins traveled farther on land but did not spend more time in the water in response to barriers. At Sedge Island, terrapins were in the aquatic habitat longer but did not travel farther on land. As discussed earlier, Conklin and Sedge Island's respective nesting habitats vary in size, shape, and levels of human activity. With this in mind, we ensured that experimental manipulation was as consistent as possible between sites. Barriers blocked equivalent proportions of

shoreline and the distance to alternative available nesting beaches was similar. Thus, observing terrapins' responses to barriers as either exclusively aquatic or terrestrial at a site is most likely due to the site's habitat type, size of nesting area, or anthropogenic factors. Conklin and Sedge Islands are representative of 2 different, yet common terrapin nesting habitats. Despite inherent site differences, our findings may apply to any terrapin population nesting in habitats of high human development.

Although our study provides quantified support that even partial barriers can increase the tortuosity of nesting for diamondback terrapins, the barriers in our study may not fully represent coastal barriers that terrapins face. Terrapins

may often encounter larger and longer barriers than occurred at our study sites, particularly in areas of extensive bulkheading. In these areas, terrapin paths may be more tortuous and nesting displacement is likely greater than we observed. Larger and longer barriers also have the potential to eliminate movement between some aquatic and terrestrial areas that are essential to the terrapin life cycle. Our results indicate that terrapins may exert more energy, experience greater stress, and incur greater risk from predation because of manmade structures at the aquatic-terrestrial interface. We recommend future studies quantify the impacts of such barriers on individual terrapin fitness and population abundance.

MANAGEMENT IMPLICATIONS

With the rapid rate of population growth and subsequent development of coastal infrastructure (Kennish 2001), it is imperative that we quantify the impacts of manmade barriers on wildlife movement between complementary habitats. Our results show that barriers between estuaries and terrestrial nesting habitats increase the time, distance, and tortuosity of terrapin nesting migrations. These findings are consistent with multiple observations of human–wildlife interactions within mid-Atlantic estuaries (Carney and Sydeman 1999, Moore and Perrin 2007, Seavey et al. 2011). Considering wildlife will not likely change their migrations, humans can protect wildlife by preserving important terrapin nesting habitats including the management of efficient nesting migration routes. Manmade structures, such as bulkheads or coastal walls, should include gaps or other design features that allow terrapins to emerge from the estuary. The creation of artificial nesting habitats could also be used to offset the creation of barriers to natural nesting areas (Baldwin et al. 2004). For example, Roosenburg et al. (2014) describe the restoration of an offshore island within the Chesapeake Bay, Maryland that has created productive nesting habitats for terrapins away from the complex threats present around mainland nesting sites. Knowing that terrapins will use artificial nesting habitats, we recommend their development in Barnegat Bay from washed dredge soils (Wnek et al. 2013). By recognizing and addressing manmade barriers as a contributing threat to terrapins, better management strategies can be developed to conserve the species.

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