Title.—Nesting success and barrier breaching: Assessing the effectiveness of roadway fencing in Diamondback Terrapins (*Malaclemys terrapin*)

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Abstract.—Roads can adversely affect animal populations by impacting nesting behavior, causing roadway mortality, and fragmenting or reducing habitat. Fences have frequently been implemented to combat direct road mortality, but at the expense of changing patterns of nesting behavior and increasing population fragmentation. I studied the effectiveness of barrier fences that were installed to reduce road mortality in nest-seeking diamondback terrapins (*Malaclemys terrapin*) along two causeways in coastal southern New Jersey. To determine whether the barriers limited roadway access, I surveyed the ground adjacent to the fences for evidence of terrapin nest holes in relation to the barrier, indicating whether terrapin nesting activity occurred on the marsh side of the fence or on the road side. As a second direct measure of effectiveness, I created a corrugated tubing arena and documented terrapin escape success to examine barrier breaching. Fences were generally effective in restricting terrapin movement: I found far fewer road-side nests than marsh-side nests, as well as a spatial clustering of road-side nests near the free ends of the fence at one field site. Additionally, the barrier breaching success was positively correlated with gap size between the fence and the ground, irrespective of terrapin body size, indicating that diligent fence maintenance is imperative. Given terrapins' high probability of road mortality, sensitive life history traits, and widespread population declines, I conclude that fences are currently essential in their conservation and may warrant greater consideration in the field of turtle conservation, particularly in species with nesting movements that intersect with roads.

Key Words.—barrier fence; habitat fragmentation; gravid females; nesting success; road mortality; turtle; wetlands conservation

INTRODUCTION

With land development and road networks constantly expanding in the United States, road construction has likely contributed to significant population declines in mammals, birds, amphibians, and reptiles (Ashley and Robinson 1996; Gibbs and Shriver 2002). Roads affect populations by impacting nesting behavior, fragmenting habitat, and causing direct road mortality (Dodd et al. 2004). Once limited by topography, roads can now expand into previously undeveloped habitats and threaten an ever-increasing number of species (Ashley and Robinson 1996).

For the last few decades, biologists and engineers have tested and developed a number of potential solutions to the problem of roadway access by dispersing or nesting animals, which often leads to direct road mortality (Dodd et al. 2004). A common mitigation strategy is the installation of temporary fence-culvert systems to prevent roadway access and facilitate dispersal (Aresco 2005; Dodd et al. 2004). Aresco (2005) installed this type of system on a section of a highway crossing Lake Jackson, Florida, and reported that mortality of turtles and other herpetofauna declined significantly after installation. Dodd et al. (2004) assessed the effectiveness of a barrier wall-culvert system built on a section of highway in Alachua County, Florida and found that snake, turtle, and alligator mortality decreased dramatically post-construction. To alleviate impacts of a highway constructed through the center of one of the largest French populations of Hermann's tortoise (*Testudo harmanni*), Guyot and Clobert (1997) relocated 300 tortoises directly affected by the construction and installed fences and a culvert-tunnel system under the road to provide for safe movement of animals across the road. Road mortality was low in the four years following highway construction, and a mark-recapture study indicated that the adult population was stable (Guyot and Clobert 1997).

In the United States, turtles may be especially impacted by roads as compared with other animals. The United States has high turtle diversity (Ernst and Barbour 1989), but all tortoises and about one third of aquatic and semiaquatic turtles currently require conservation action (Lovich 1995; Gibbs and Shriver 2002). Roads are expected to have contributed to turtle population declines because turtles have sensitive life history traits including high adult survival rates and delayed sexual maturity (Wilbur and Morin 1988; Gibbs and Shriver 2002). Turtle populations are therefore constrained in their ability to deal with additive annual mortality due to anthropogenic impacts (Gibbs and Shriver 2002), and studies indicate that only 2-3% additive annual mortality is more than most turtle species can cope with to maintain population stability (Congdon et al. 1993, 1994; Gibbs and Shriver 2002).

Barrier effectiveness is often defined by the extent to which barriers reduce road mortality or prevent animals from accessing the road (Dodd et al. 2004; Aresco 2005). The most direct measure of barrier effectiveness is documenting roadkills. However, roadkills are highly ephemeral and difficult to measure accurately as predators, scavengers, and cars can remove this form of evidence within hours, especially for small animals. In species that encounter roads when searching for nesting habitat, an alternative, longer-lasting metric of barrier efficacy involves measuring nesting characteristics in relation to the fence. When the land on both sides of the barrier is equivalent in terms of area, moisture, substrate, and vegetation, the location of the nest (i.e. habitat-side of the barrier or road-side of the barrier) is an important metric to assess barrier effectiveness, as the distribution should be equal if the fence is ineffective.

For turtles, the disposition of the observed nests (i.e. whether the nest has been predated, or attempted before abandonment) is another useful metric of barrier effectiveness. For many turtles including diamondback terrapins (*Malaclemys terrapin*), successfully laid nests are often difficult to detect due to their cryptic concealment, but high rates of nest predation within 48 hours of oviposition (as observed in various turtle species) make predated nests a useful indicator of nesting activity. Butler et al. (2004) monitored daily nesting by diamondback terrapins for two summers and found 81.9% (in 1997) and 86.5% (in 2000) of nests were predated, and Feinberg and Burke (2003) similarly recorded diamondback terrapin nest predation of 92.2%. Therefore, predated nests are a good measure of egg-laying activity and make a reasonable proxy for successful nests resulting in hatchlings. While predated nests represent a high percentage of successfully laid nests, nest abandonment before egg-laying can be as common as completing a nest (Roosenburg 1994), so additional documentation of abandoned nests gives a more complete picture of female movement during this critical nesting phase. Further, directly observing animals' barrier breaching success when faced with a fence is another useful metric to assess barrier effectiveness, providing better understanding of the conditions under which fences are likely to be breached by females of different body sizes. This pairing of nest observations with behavioral tests can thus provide robust, inclusive estimates of general fence effectiveness for adult females, which is especially important in species with sensitive life history traits like turtles.

Among all species of turtles, diamondback terrapins may be exceptionally vulnerable to anthropogenic impacts. Diamondback terrapins are a species of emydid turtle whose populations have declined range-wide due to various human activities, one of which is road construction (Seigel and Gibbons 1995; Dorcas et al. 2007; Grosse et al. 2011). Terrapins have been disproportionately impacted by habitat development and roadway construction, mainly due to their sensitive life history traits (i.e., delayed sexual maturity, low reproductive rates, long lifespans, and high home site fidelity) and unique habitat requirements (Gibbons et al. 2001; Seigel and Gibbons 1995). The species' range is several thousands of miles long but only a few miles wide, extending along the Atlantic Coast from Massachusetts to southernmost Florida and around the Gulf Coast to Texas (Ernst et al. 1994; Wood and Herlands 1997). Terrapins are the only turtle species in the world exclusively adapted to brackish water coastal salt marshes (Ernst et al. 1994; Wood and Herlands 1997). Coastal salt marshes in the United States have been heavily impacted by industrial and real estate development over the past century, thus destroying a great deal of terrapin habitat and reducing access to nesting sites (Wood and Herlands 1997).

Along the Atlantic coast of New Jersey, terrapins' natural nesting habitat (sand dunes on barrier beach islands) has largely disappeared due to human encroachment. Large numbers of terrapins now nest on the shoulders of heavily trafficked roads adjacent to salt marshes (Wood 1997), as terrapins must lay their eggs above the high tide line (Roosenburg and Place 1994; Butler et al. 2004). Nesting alongside heavily trafficked roads results in substantial roadway access and mortality within some parts of their range. Terrapins' sensitive life history traits and unique habitat requirements lead to roads disproportionately affecting the species, thus making them an ideal model system for installing barrier fences to reduce roadway access and assessing barrier effectiveness.

Terrapins' vital role in salt marsh biodiversity maintenance further qualifies them as an ideal system to test the effectiveness of barriers. Coastal salt marshes are one of the most dynamic, diverse, and productive natural systems on earth (Ashley and Robinson 1996). Terrapins play an essential role in the maintenance of salt marsh biodiversity by controlling the density of the marsh-grazing periwinkle (*Littoraria irrorata*) (Silliman and Bertness 2002). Silliman and Bertness (2002) experimentally demonstrated that the high plant production in eastern coastal salt marshes is ultimately realized through a trophic cascade, where marine predators such as terrapins limit the densities of plant-grazing snails that are capable of devastating marshes. This suggests that significant declines in terrapin populations could alter the structure and function of salt marsh habitats (Silliman and Bertness 2002).

Although anthropogenic impacts contributing to terrapin declines include commercial harvest for food (Wood and Herlands 1997; Gibbons et al. 2001), incidental drowning in crab traps (Wood and Herlands 1997; Gibbons et al. 2001; Dorcas et al. 2001), road mortality (Seigel and Gibbons 1995; Wood and Herlands 1997), habitat destruction and fragmentation (Wood and Herlands 1997), and accidental capture in storm drains (Grottola et al. 2010), road mortality is the most obvious and one of the most important contributors to terrapin mortality along the Atlantic coast of southern New Jersey. Well over 10,000 terrapin roadkills were documented between 1989 and 2011 in Cape May County, New Jersey (McLaughlin 2011). Since 2004, both scientists and community volunteers have attempted to combat this source of terrapin mortality by developing and installing various types of terrapin barrier fences designed to restrict nest-seeking females to the marsh-side of the barrier. The barrier fence installation techniques and materials have been refined over the years, first using silt, then plastic mesh, and now plastic corrugated tubing. Corrugated tubing is currently favored because it is relatively less conspicuous, easy to install, and more durable than previous fence materials. Over 12,000 feet of barrier fences have been installed along the coast of southern New Jersey (McLaughlin 2011).

Anecdotally, the barrier fences appear effective in reducing terrapin roadway access, but there had been no assessment until this study. The primary objective of my study was to assess terrapin barrier effectiveness as a means to reduce nest-seeking terrapins' access to the roads. To determine barrier effectiveness, I first surveyed the ground adjacent to the fences for evidence of terrapin nest holes in relation to the barrier, indicating whether terrapin nesting activity occurred on the marsh side of the fence or on the road side. As a second measure of effectiveness, I created a corrugated tubing arena and documented terrapin escape success to determine the likelihood of barrier breaching. Determining barrier effectiveness is critical to understanding how barriers impact adult female nesting behavior, ensuring that conservation efforts and resources are being properly allocated, and identifying opportunities for improvement in barrier design to protect the species better in those parts of its range where roadkills during nesting season are a significant problem.

MATERIALS AND METHODS

Study Species.—Diamondback terrapins (*Malaclemys terrapin*) are estuarine, emydid turtles whose range extends from the northern tip of Cape Cod, Massachusetts to the Gulf Coast of the United States (Ernst et al. 1994; Wood and Herlands 1997). Within this range are seven subspecies (Wood and Herlands 1997). I focused my study on a population of the northernmost subspecies, the northern diamondback terrapin (*Malaclemys terrapin terrapin*), which is found from Massachusetts to North Carolina (Wood and Herlands 1997).

Terrapins nest for approximately six weeks from mid- late-May to mid- late-July (Goodwin 1994; Wood 1997; Butler et al. 2004). Many hatchlings emerge after a 10-11 week incubation period (Roosenburg 1991; Goodwin 1994; Butler et al. 2004), but in northern parts of their range including my study area, some remain in their nests throughout the winter and emerge the following spring (Wood 1997).

Study Site.—I studied two sections of roadway that connect the mainland to coastal barrier islands on the Atlantic Coast of southern New Jersey. Stone Harbor Boulevard (SHB), Cape May County (39.06°N, 74.77°W) and the Margate Causeway (MC), Atlantic County (39.34 °N, 74.54 °W) were chosen as representative of the many causeways in the area that cross salt marshes and have terrapins nesting on their embankments. I surveyed a 589 m section of the SHB and a 623 m section of the MC (Fig. 1). Both causeways cross salt marshes dominated mainly by saltmarsh cordgrass (*Spartina alterniflora*) and saltmeadow cordgrass (*Spartina patens*). Salinity is generally 30-32 ppt, similar to that of the nearby ocean, and tidal amplitude within the marsh is about 1.5 m (Wood and Herlands 1997).

Embankments alongside the causeways range in width from less than 1 m to 10 m in parts of the MC. The upper slopes of these embankments create a suitable nesting habitat for terrapins seeking high ground. Crabgrass and other vegetation cover the sandy embankments. These salt marshes are no longer subject to development, but the waterways and causeways passing through and across them are used heavily by humans, particularly in the summer months (Wood and Herlands 1997). There has been considerable alteration of both the mainland and barrier beach island sides of the marshes, so while some of the salt marsh has been preserved, natural terrapin nesting sites on sand dunes above the high tide line have largely been destroyed (Wood and Herlands 1997) or rendered inaccessible by bulkheading. This development has forced terrapins to seek alternative nesting habitat along the embankments of the causeways that cross salt marshes.

Field Survey: Nest Census.—I surveyed the north and south sides of the two roads, both previously fenced with six inch diameter corrugated tubing staked in place at ground level, for evidence of terrapin nesting activity. Fences were installed on the embankments such that the microhabitat characteristics and the total area of searchable nesting habitat on both sides were approximately equal. There was no noticeable difference in plant assemblage or moisture gradient. Preliminary data comparing fenced and unfenced roadways suggest that the distribution of nests across the strip of land between the road and the marsh is uniform (data not shown). During 2011, I surveyed both sides of each road once a week from 17 June through 8 July. Based on the results from 2011, I refined my methods and sampled less frequently, but more intensively, in

2012 by surveying both sides of each road twice between 7 June and 4 July. During every survey, I documented terrapin nest holes by walking along the marsh side of the fence in one direction and on the road side in the other direction to ensure that all nest holes were recorded. I randomly selected which end of the fence to begin each survey on. I completed all surveys to control for observer bias.

For each nest hole, I recorded the road name, whether it was on the north or south side of the road, whether it was on the marsh side or road side of the corrugated tubing barrier, GPS location (using a Magellan Triton), and the distance (in meters, to the nearest centimeter) from the corrugated tubing. I used a 10 m rolling tape measure to record the straight-line minimum distance (to the nearest centimeter), and I flattened vegetation that was in the way to measure more accurately.

Field Survey: Predation.—Predated and abandoned nests reflect nesting activity as they indicate where terrapins attempted to nest. Both predated (Fig. 2a) and abandoned (Fig. 2b) nests appear as shallow, circular excavations approximately 4-6 cm in diameter and 10-15 cm in depth. Abandoned nests may be smaller if they were not completed before abandonment. Terrapin nest holes are distinguishable from other depressions in the ground as they curve to the side at the base of the hole, forming a 'J' shape. Nests predated by common mammalian predators (e.g. raccoons, *Procyon lotor*; skunks, *Mephitis mephitis*; red foxes, *Vulpes vulpes*) were identified by eggshells scattered nearby. I estimated the number of eggs per predated nest by piecing together the eggshells, which were often broken into halves or thirds of the original whole eggs. However, some predators (e.g., fish crows, *Corvus ossifragus*) eat eggs whole and leave little or no evidence of their predation. There is no definitive way to recognize this type of predation, so holes without eggshells were counted as abandoned nests. To prevent double counting of nests, I filled in each hole after recording it and collected all predated eggshells. Nests do not remain visible for more than one season, as rain and flooding fill in the holes and wash away old eggshells.

Arena Experiment.—Terrapins can occasionally reach the road side of the barriers by crawling underneath the corrugated tubing in areas where gaps have formed. Gaps may be formed where corrugated tubing spans ground depressions, or they may result from vegetation growing upwards underneath the corrugated tubing. To understand how such gaps influence barrier effectiveness, I built a five m oval arena of corrugated tubing and raised a section of the tubing to various heights (0-8 cm). I placed adult female terrapins (N = 40 individuals; 74 trials) individually in the arena and observed the number of terrapins that escaped through the gap within 10 min. I measured the height of the terrapins and recorded gravidity. Gravidity was assessed by holding the terrapin on her side, placing fingers in the area just in front of her hind limbs, and palpating the oviducts for shelled eggs. I tested only adult females, as males typically never emerge from the safety of the salt marsh. This experiment was run for three consecutive summers during June and July. In 2010 and 2011, the arena was placed on a flat area of grass and a range of gap sizes (0, 2.5, 3.8, 6.4, and 7.6 cm) was tested. Based on these results, I also tested gaps of 5.1 cm in 2012 to compliment the sizes evaluated in previous years. I tested each individual for one or two gap sizes, so gap size and location within the arena were randomly selected each trial. I considered each trial to be independent. Terrapins typically crawled straight to the barrier, unsuccessfully attempted to climb over the tubing, and then proceeded to walk along the inner circumference of the tubing, occasionally attempting to crawl over or under it.

Data Analysis.—All of the nest locations were plotted on Google earth images using R package 'Google Maps' (R version 2.15.2). I combined the two years of field survey data (N=560) and three years of arena experiment data (N=40 individuals; 74 trials) for analysis. The field survey results, specifically whether the nest holes were on the marsh side or the road side of the fence, were tested for normality and homogeneity of variance using SAS 9.3 (SAS Institute 2011). I evaluated the effect of marsh vs. road side of fence, north vs. south side of causeway, and site, as well as the interactions among these variables, on the number of predated and abandoned nests using chi-square analysis in R for each comparison. I calculated the average road length by summing the distances on both sides of the road and dividing by two, and they are essentially identical for both study sites: (MC: (540.6 + 623.3)/2 = 581.9 m; SHB: (575.3 + 589.2)/2 = 582.2 m). Thus, I used raw nest counts for subsequent analyses instead of adjusting these values per km.

Furthermore, to assess barrier efficacy and test whether nests on the road side of the fence were closer to the free ends of the fenced sections than marsh-side nests, I used Monte Carlo resampling in R to compare the observed and expected distributions of road-side nest distances. I converted each nest coordinate from decimal degrees to UTM using a batch conversion worksheet in MS Excel (available at: uwgb.edu, date accessed: 27 September 2013). For each site independently, I used the UTM coordinate of each nest to calculate the shortest straight-line distance in meters between each nest and its nearest fence-end to generate an observed distribution of distances for the road side of the fence. To create a test statistic representing this distribution, I calculated the median distance within this observed distribution. I then resampled (100,000 repetitions) the full distribution of distances for each site to generate expected distributions of road-side distances with the same number of nests as the observed road-side distributions (N = 14 for SHB, N = 20 for MC) and similarly calculated the median for each simulated distribution.

I analyzed the arena experiment by logistic regression of proportional success vs. gap size and terrapin height. All statistical tests were performed using R, and I assessed significance at $P < 0.05$.

RESULTS

Field Survey: Nest Census.—I first assessed whether there was variation among sites and years to ensure that terrapin nesting behavior was similar across these variables. I found a significantly greater number of nests on Stone Harbor Boulevard than on the Margate Causeway ($\chi^2 = 146.06$, df = 1, $P < 0.001$). In terms of year, there was a weaker, yet significant effect, with slightly more nests found in 2012 than 2011 ($\chi^2 = 4.829$, df = 1, $P = 0.028$). I found no interaction between year and site ($\chi^2 = 5.032$, df = 1, $P = 0.249$). Because site effect is more biologically relevant and has a stronger statistical effect, I only consider site differences in the subsequent analyses.

Orientation (north vs. south side of road) played no role in nesting activity ($\chi^2 = 0.714$, df = 1, $P = 0.398$) when considering all data. The interaction between site and orientation was not significant (χ^2 = 1.193, df = 1, P = 0.275). When analyzing within site, orientation did not impact nesting activity on either road (MC: χ^2 = 2.110, df = 1, P = 0.146; SHB: χ^2 = 0.021, df = 1, P = 0.884).

When considering all data, I found a significantly greater number of nests on the marsh side of the corrugated tubing barriers than on the road side (χ^2 = 414.86, df = 1, P < 0.001). When analyzing within site, both roads had significantly more nests on the marsh side of the barriers than on the road side (MC: χ^2 = 68.679, df = 1, P < 0.001; SHB: χ^2 = 350.414, df = 1, P < 0.001). (Fig. 3). I separated the dataset by site in order to look at the effect on each road. Chi-square analysis of both site and fence side revealed a significantly greater number of road-side nests on the MC than on the SHB (χ^2 = 14.792, df = 1, P < 0.001).

I found that on the SHB, road-side nests were closer to the fence-ends than expected by chance (P < 0.001), but I found no such spatial effect on the MC (P = 0.131; Fig. 4).

Field Survey: Predation.—There was a site effect on predation such that nests on the SHB were more often predated than those on the MC (χ^2 = 15.085, df = 1, P < 0.001). Within-site analyses revealed that there was more abandonment than predation on the MC (χ^2 = 12.270, df = 1, P < 0.001; Fig. 5a) but marginally more predation than abandonment on the SHB (χ^2 = 3.596, df = 1, P = 0.058; Fig. 5b).

I found a year effect on predation, such that predation was more common in 2011 than in 2012 (χ^2 = 9.2897, df = 1, P = 0.002). I found an interaction between year and predation such that globally, predation was higher in 2011 than 2012 (χ^2 = 9.290, df = 1,

$P = 0.002$). However, within-site analyses showed evidence of an interaction effect with trends in opposite directions; the effect was significant on the MC ($\chi^2 = 14.433$, df = 1, $P < 0.001$) but only marginally significant on the SHB ($\chi^2 = 3.304$, df = 1, $P = 0.069$).

When all data were considered simultaneously, I found that predation and fence-side (marsh vs. road) were not related ($\chi^2 = 1.0389$, df = 1, $P = 0.308$). Similarly, neither within-site analysis showed an interaction between predation and fence side (MC: $\chi^2 = 0.573$, df = 1, $P = 0.449$; SHB: $\chi^2 = 2.170$, df = 1, $P = 0.141$).

Arena Experiment.—I fit a logistic regression to the data and found that increasing gap size below the fence was correlated with increasing escape success ($Z = 4.373$, df = 73, $P < 0.001$) (Fig. 6). I found that gravidity of the terrapin did not impact escape success ($Z = 1.227$, df = 73, $P = 0.220$). Carapace length, used as an estimate of size, was not correlated with escape success ($Z = 0.623$, df = 56, $P = 0.533$).

DISCUSSION

I found that the fences were effective in reducing terrapins' road access, but efficacy depended on microenvironmental factors, and was not constant within or between sites. These results have important implications for understanding the ecological tradeoffs associated with fences and recommendations for the management of terrapins and other wetlands species.

Barrier fences were highly effective in restricting nest-seeking terrapins to the marsh side of the barriers, and therefore substantially decreased roadway access, and its subsequent mortality, in my study sites. Given that terrapins emerge from the marsh, it is evident that the fences had an effect on roadway access and available nesting habitat; if the fences had no effect, one would expect to find equal numbers of nests on both sides of the barrier. Fences have been reported to work especially well in reducing mortality of turtles as compared with various animal groups (Boarman and Sazaki 1996; Barichivich and Dodd 2002; Dodd et al. 2004; Aresco 2005). However, fence usage is often controversial because there are ecological tradeoffs associated with fences, as they may create barriers to dispersal, migration, and gene flow (Jaeger and Fahrig 2004; Aresco 2005; Hayward and Kerley 2009). Fragmentation may be especially detrimental to terrapin populations due to their high site fidelity (Gibbons et al. 2001). Barriers to dispersal could further limit gene flow in species that already have restricted migration. Furthermore, it is important to consider the effects of fragmentation and roadway mortality on terrapins, despite only nest-seeking females being affected, as both anthropogenic impacts could have significant population-wide consequences; population model analyses for loggerhead sea turtles indicate that an annual loss of only a few hundred subadult and adult female turtles can have a profound impact on population dynamics (Heppell et al. 1996).

Jaeger and Fahrig (2004) used a simulation model to determine whether fences enhance or reduce the effect of roads on population persistence in various species, and they reported that the impact of the fence depends on an animal's degree of roadway avoidance and its probability of roadway mortality upon entering the road. For species with high traffic mortality rates, fences generally enhance population persistence, especially when populations faced additional sources of anthropogenically-induced mortality. In my study area and throughout their range, terrapins qualify as a species with a high likelihood of roadway mortality, low road avoidance, and multiple sources of mortality. Therefore, the model indicates that fences would likely enhance population persistence of terrapins despite the fragmentation tradeoff. In combination with my finding that fences are highly effective in restricting nest-seeking terrapin movement, I conclude that fences are currently necessary in maintaining terrapin populations in southern New Jersey.

Turtles may be particularly susceptible to road mortality because their life histories are characterized by high adult survivorship, delayed sexual maturity, and low annual recruitment (Congdon et al. 1993), and many species' life cycles incorporate terrestrial movements that often intersect with roads (Gibbons 1986). When this occurs, turtles are especially vulnerable to roadway mortality due to low road avoidance and low travel speed (Steen and Gibbs 2004), so barrier fencing could be a highly effective management strategy for many turtle species beyond terrapins, despite the barrier-induced fragmentation effects. Turtle life history traits limit populations' ability to absorb the loss of sexually mature adults (Brooks et al. 1991), so fences that restrict the movement of nesting or dispersing individuals may warrant greater consideration in the field of turtle conservation.

My results also indicate that fence effects and ecological tradeoffs are dependent upon site differences and local conditions. Across sites, the fences were effective in reducing overall road access, but barrier breaching varied within and between sites and depended on microenvironmental factors including elevation, flooding, and vegetation. Barrier breaching was more common on the MC, as road-side nests represented a greater proportion of total nests as compared with the SHB nests. MC had lower elevation (4 m) than SHB (6 m), greater flooding, and excess vegetation growth along its embankments (pers. obs.). Vegetation can create gaps beneath the fence and provide terrapins with a bridge over the fence. Further, MC fences were newer than SHB fences, and it has been observed that corrugated tubing barrier effectiveness increases with time, barring damage, as the fences sink into the ground and kill the vegetation underneath. New fences are light and sit on top of live vegetation, making it much easier for terrapins to crawl beneath (pers. obs.). Fence effectiveness and subsequent ecological tradeoffs depended heavily on local conditions, so management plans and maintenance should be carefully tailored to complement microenvironmental conditions.

These findings were supported by my arena experiment results, which demonstrated that barrier breaching success was positively correlated with gap size between the bottom of the fence and the ground surface, irrespective of terrapin body size. Interestingly, gravidity of the terrapins did not impact escape success, so females before and after oviposition were equally likely to breach the barriers. This unexpected result is encouraging, indicating that efforts to target adult females for protection are not being hindered by gravid female determination to overcome the barriers. Examining female body size and gravidity in relation to barrier behavior was a novel approach.

Similarly, predation and spatial placement of nests in relation to the barrier depended on local conditions. Because there was a spatial clustering of road-side nests near the free-end of one SHB fence, this suggests that the SHB fence was even more effective than the road-side nest counts indicated, as terrapins likely accessed this area by walking around the fence-end or emerging from the marsh in an unfenced section and walking to the fenced zone. This pattern was not found on MC, as road-side nests were more evenly scattered throughout the fence. The MC study site was a small island, so accessing the road from beyond fenced sections was not possible. Predation patterns also varied between sites, likely caused by microenvironmental differences in elevation, flooding, and vegetation. Further, fence side and predation were not related, so fences did not seem to be offering protection from predation or altering predator behavior. Fence-related effects seem to depend on local conditions, so it may not be possible to draw certain generalizations across sites.

Based on the results of my study, I offer a few basic recommendations for the conservation of terrapins (or other marshland specialists) subject to road mortality. This study demonstrates that significant decreases in roadway access can be achieved through simple, low-cost management practices. Corrugated tubing fences have a measurable impact and are relatively easy, inexpensive, and fast to install. In order to optimize fence effectiveness, maintenance of the fence, vegetation, and ground is imperative during nesting season. This can be accomplished via vegetation management, filling gaps beneath fences with sediment, and regularly replacing broken fence stakes. New approaches should be investigated, including strategies to modify the fence-ends to prevent the spatial clustering of road-side nests near fence-ends, as seen on the SHB. Fences should always curve outward toward the marsh at their ends and extend all the way to the water, if possible. Further studies are needed to develop new techniques for weighing down the fences and more permanently attaching fences to the ground.

Given the limited funding available in conservation management, efficient use of resources is critical (James et al. 1999). Management of wetlands species, specifically dual-environment species, can be difficult, and conservation plans must be designed within the context of how the species uses its multiple habitats (Pressey 1994; Law and Dickman 1997). If regional populations are to persist, management plans must accommodate the nesting migration and local movements of turtles and other species (Gibbs and Amato 2000; Gibbs and Shriver 2002). By focusing my study on terrestrial nesting activity, I show that fences can effectively address the problem of female-biased roadway access, and subsequent mortality, in this dual-habitat species. Protecting adult females in species with sensitive life history traits can have significant population-wide consequences (Wilbur and Morin 1988), so fences that reduce mortality of adult females represent an efficient use of conservation resources. My results are encouraging and may be useful in situations dealing with complex habitat usage, as often is found in wetlands systems. Multiple habitat usage can complicate conservation efforts, but targeted protection of adult females could significantly help long-lived species cope with additive mortality.

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LITERATURE CITED

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Figure Legends

Figure 1. Map of two study sites in New Jersey, USA. Atlantic County and Cape May County are outlined in red on the inset state map.

Figure 2. Predated and abandoned terrapin nests reflect nesting activity by indicating where terrapins chose to lay eggs. Predated nests (a) are identified by eggshells scattered nearby a shallow circular excavation. Abandoned nests (b) appear as shallow, circular excavations.

Figure 3. Distribution of terrapin nests on SHB in 2011 (a) and 2012 (b) and MC in 2011 (c) and 2012 (d). Points are randomly jittered along both axes to allow the display of overlapping data.

Figure 4. Straight-line distance to the free-ends of the fence on both roads. Distribution of Stone Harbor Boulevard marsh-side nests (a) and road-side nests (b) used to generate the expected distribution of marsh-side nest distances through Monte Carlo resampling (c). Distribution of Margate Causeway marsh-side nests (d) and road-side nests (e) used to generate the expected distribution of marsh-side nests as above (f). The vertical dashed lines in (c) and (f) represent the observed median road-side nest distance to the closest free end of the fence for each study site respectively for comparison to the simulated distributions of nest distances.

Figure 5. Number of predated and abandoned nests on the Margate Causeway in 2011 and 2012 (a) and on Stone Harbor Boulevard in 2011 and 2012 (b) show an interaction effect between year and site.

Figure 6. Terrapin escape success increases with size of gap beneath the fence. Black sections of bars represent successful terrapin escape. White sections of bars represent terrapin escape failure. Number of trials at a given size class is at the top of each bar.

Figures

Figure 1

Figure 2

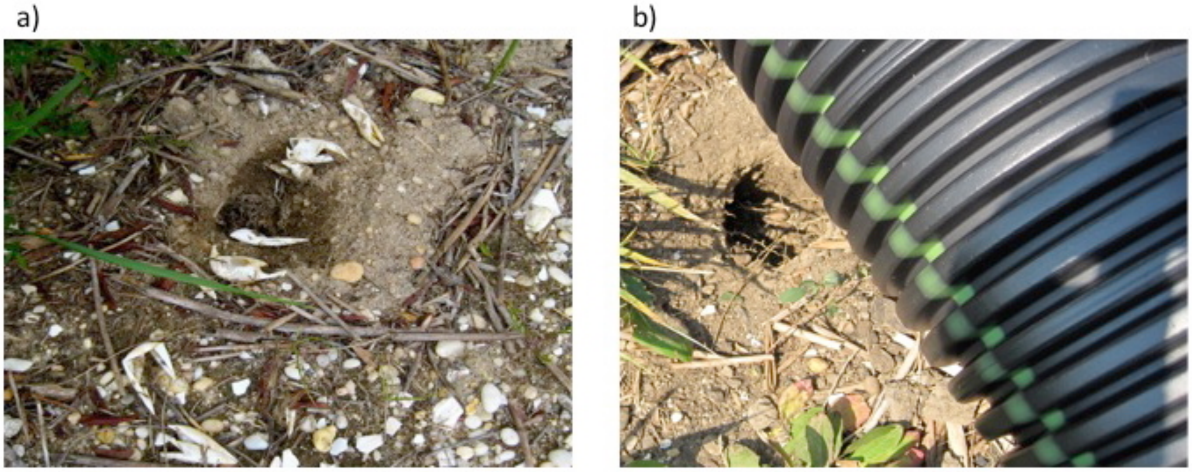


Figure 3

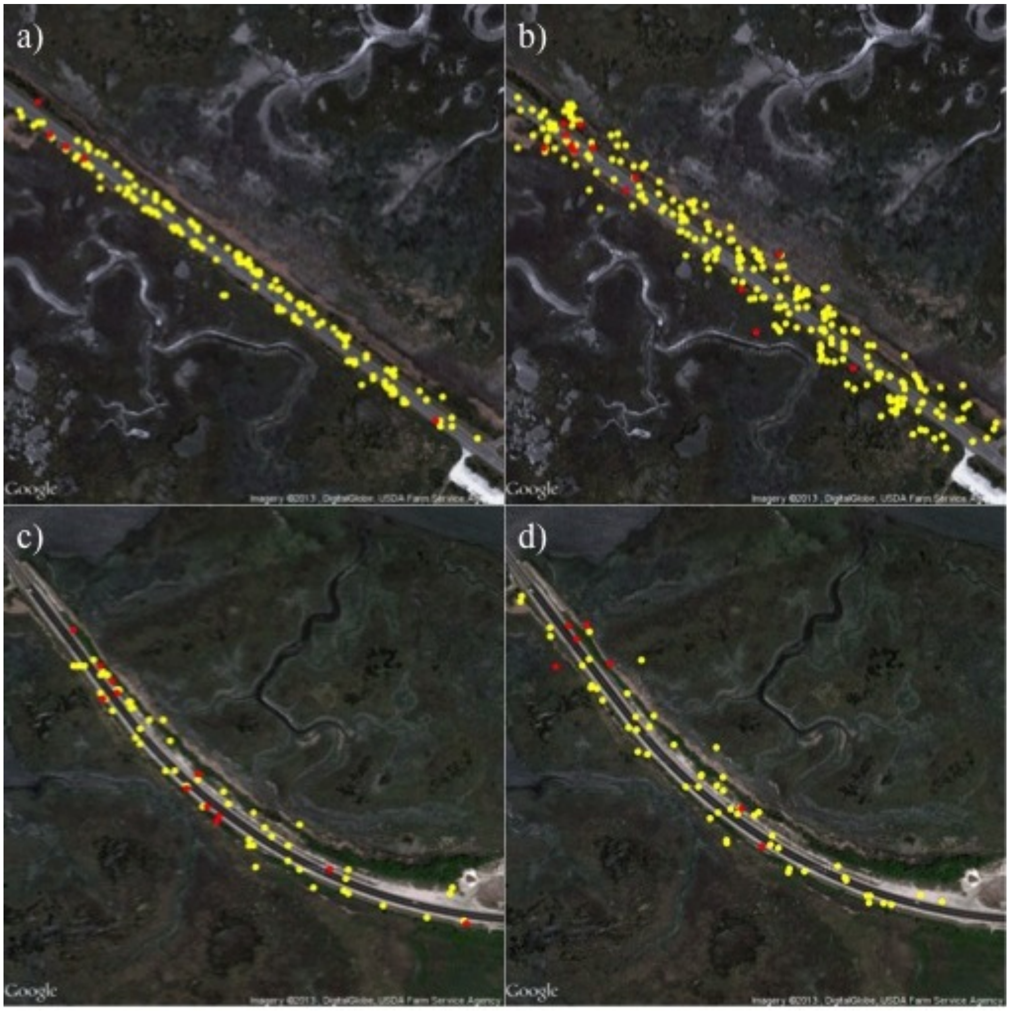
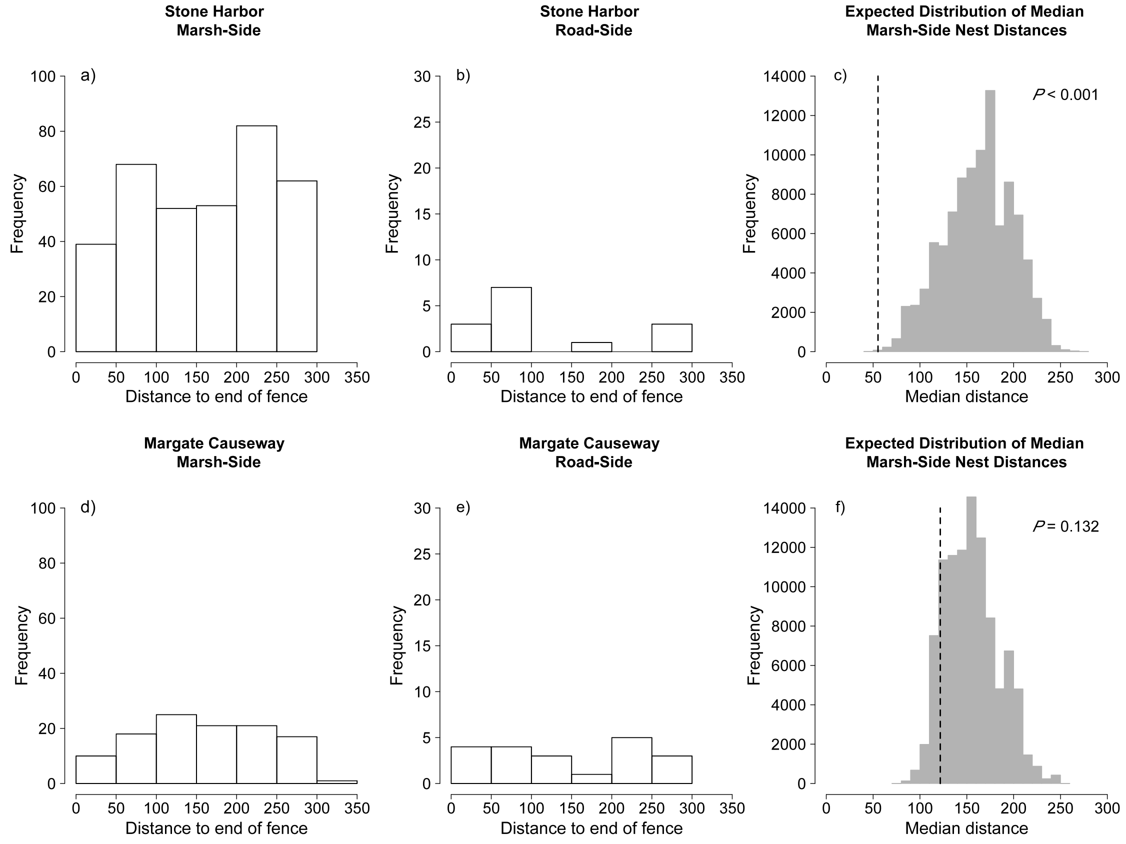

a)
b)
c)
d)
Google
Imagery ©2013, DigitalGlobe, USDA Farm Service Agency

Figure 4



Stone Harbor Marsh-Side

Stone Harbor Road-Side

Expected Distribution of Median Marsh-Side Nest Distances

Margate Causeway Marsh-Side

Margate Causeway Road-Side

Expected Distribution of Median Marsh-Side Nest Distances

Figure 5

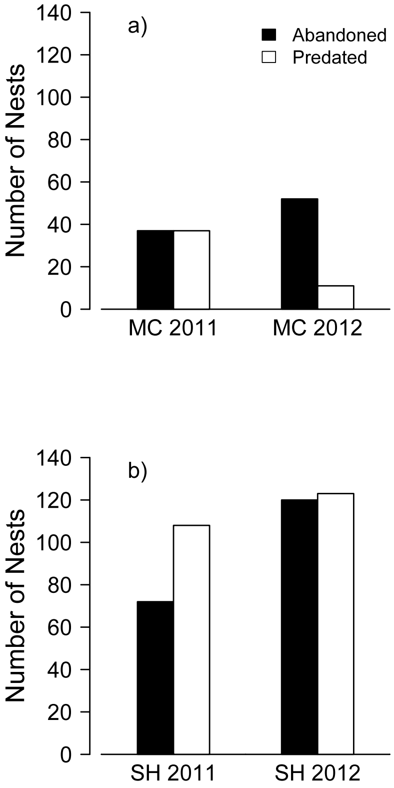


Figure 6