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Research Article

Effects of Roads and Crabbing Pressures on Diamondback Terrapin Populations in Coastal Georgia

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ABSTRACT Human activities, including the harvesting of natural resources and land development, place substantial pressure on wildlife. The diamondback terrapin (*Malaclemys terrapin*) is a small, estuarine species of emydid turtle in decline and at risk due to a suite of human activities. Vehicle-induced mortality from increasing coastal traffic and bycatch mortality in crab pots have been recognized as 2 of the primary conservation concerns for terrapins. We used mark-recapture estimates of terrapin density and sex ratio from repeated seining samples of 29 randomly stratified selected tidal creeks to evaluate the current relationships between road and crabbing pressures and the abundance, sex ratio, and size distribution of terrapin populations along the Georgia coast. We obtained 2005 captures of 1,547 individual terrapins among 29 tidal creeks sampled. Population density estimates ranged from 0 to 1,040 terrapins/km among tidal creeks with a median density of 65 terrapins/km. Among all sites, terrapin density declined with increasing crabbing activity within the creek, but was not related to proximity to roads. Sex ratios did not vary significantly with crabbing activity or proximity to roads; however, we found a significantly larger proportion of smaller-sized terrapins in creeks with no crabbing activity. Although roads may have significant localized effects on terrapin populations, we found no measurable association between proximity to roads and current variation in terrapin density along the Georgia coast. However, we did find that terrapin density and the proportion of smaller sized individuals within the population were negatively associated with crabbing activities. Bycatch from commercial and recreational activities threaten many species. We add to a growing body of research showing crabbing activities are affecting diamondback terrapin populations across much of the species' range. States committed to the conservation of terrapins and coastal species should focus on reducing bycatch risk; for example by regulating soak times and locations, requiring the use of bycatch reduction devices, and removing abandoned or lost crab pots from coastal habitats.

KEY WORDS crab trap, diamondback terrapin, *Malaclemys terrapin*, mortality, roads, turtle.

Overexploitation and habitat loss and degradation are primary causes of wildlife population declines and species losses in the continental United States (Diamond 1984, Venier and Fahrig 1996, Mitchell and Klemens 2000, Guthery et al. 2001). In marine environments, both negative impacts and relative stability are well documented for commercial and non-commercial species (Lewison et al. 2004). In particular, some marine fisheries appear to sustain stable target populations, perhaps reflecting steady and well established harvesting pressure. In contrast, development of coastal environments is increasing rapidly. Recreational activities associated with that development are known to impact a number of marine species, so coastal development may represent an increasing threat to near-shore marine wildlife (Hazel and Gyuris 2006, Laist and Shaw 2006). In addition, coastal areas are identified as having high and increasing road development that is likely to have negative ecological impacts on wildlife (Riitters and Wickham 2003, Fahrig and Rytwinski 2009). Understanding how various human activities contribute to the current and future status of wildlife is important for developing effective, long-term management strategies.

The diamondback terrapin (*Malaclemys terrapin*) is an emydid turtle and estuarine specialist whose populations have experienced significant declines throughout their range (Seigel and Gibbons 1995, Dorcas et al. 2007). Among aquatic turtles generally, human activities including recreation (Garber and Burger 1995, Hoyle and Gibbons 2000, Moore and Seigel 2006), commercial fishing (Seigel and Gibbons 1995, Cole and Helser 2001, Roosenburg 2004,

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Báez et al. 2007), land development (Bowen et al. 2004), and vehicular road mortality (Wood and Herlands 1997, Steen and Gibbs 2004, Aresco 2005) have all been documented as negatively impacting turtle populations. Bycatch in commercial and recreational crab pots has been empirically linked to declining terrapin populations (Roosenburg et al. 1997, Hoyle and Gibbons 2000, Roosenburg and Green 2000, Dorcas et al. 2007). Commercial crabbing efforts are regulated by most states through the distribution of commercial crabbing licenses, so crabbing pressures on terrapin populations are likely to remain stable. By contrast, mortality by vehicles is also proposed as a significant contributor to terrapin population declines and is expected to increase with increasing development and use of coastal areas (Seigel and Gibbons 1995). Unlike crabbing, no studies have linked vehicular mortality to local changes in terrapin abundance or shown that variation in terrapin abundance is related to increasing traffic levels or road development.

Although both crabbing and vehicle-induced mortality may cause terrapin population declines, the 2 processes likely have different effects on size or age distributions and sex ratios of diamondback terrapin populations. Vehicle-induced mortality is known to disproportionately affect female turtles who emerge to nest on elevated areas, such as causeways that pass through coastal marshes (Gibbs and Shriver 2002, Gibbs and Steen 2005, Szerlag and McRobert 2006); therefore, terrapin populations affected by vehicle mortality are predicted to be male biased. Conversely, commercial crab pots disproportionately kill small terrapins, particularly males, that do not outgrow the gape limitation of commercial wire crab pots; therefore, terrapin populations impacted by commercial crabbing are expected to be increasingly larger and older and increasingly female biased (Szerlag and McRobert 2006, Dorcas et al. 2007). Whereas commercial crabbing is known to negatively affect terrapin populations, factors such as vehicle-induced mortality that selectively decrease adult female survival are hypothesized to have larger negative effects on terrapin population growth (Congdon et al. 1993). Therefore, evaluating the relative importance of crabbing and road pressures on terrapin populations will be important for identifying and managing current and future threats to the species.

Our objectives were to assess the independent and additive or interactive effects of commercial crabbing and roads on the local abundance, sex, size, and age structure of diamondback terrapins in estuarine tidal creeks along the Georgia coast. Specifically, we tested the hypotheses that 1) terrapin abundance was negatively related to road density or proximity and crabbing activity, 2) terrapin sex ratios (M/F) are positively related to road density or proximity and negatively related to crabbing activity, and 3) the proportion of terrapins within a tidal creek composed of smaller and younger individuals would decline with increased crabbing and incline with increased road density or proximity.

STUDY AREA

We performed our study at randomly selected tidal creeks within the salt marsh ecosystem of coastal Georgia (Fig. 1). Coastal Georgia stretches approximately 160 km from its northern border with South Carolina to its southern border with Florida, encompassing six counties (Bryan, Camden, Chatham, Glynn, Liberty, and McIntosh counties), eight clusters of barrier islands (Tybee, Wassaw, Ossabaw, St. Catherines, Sapelo, St. Simons, Jekyll, and Cumberland islands) and roughly 2,000 km^2 of tidal marsh habitat (Fig. 1, Schoettle 1996). This area experienced semidiurnal

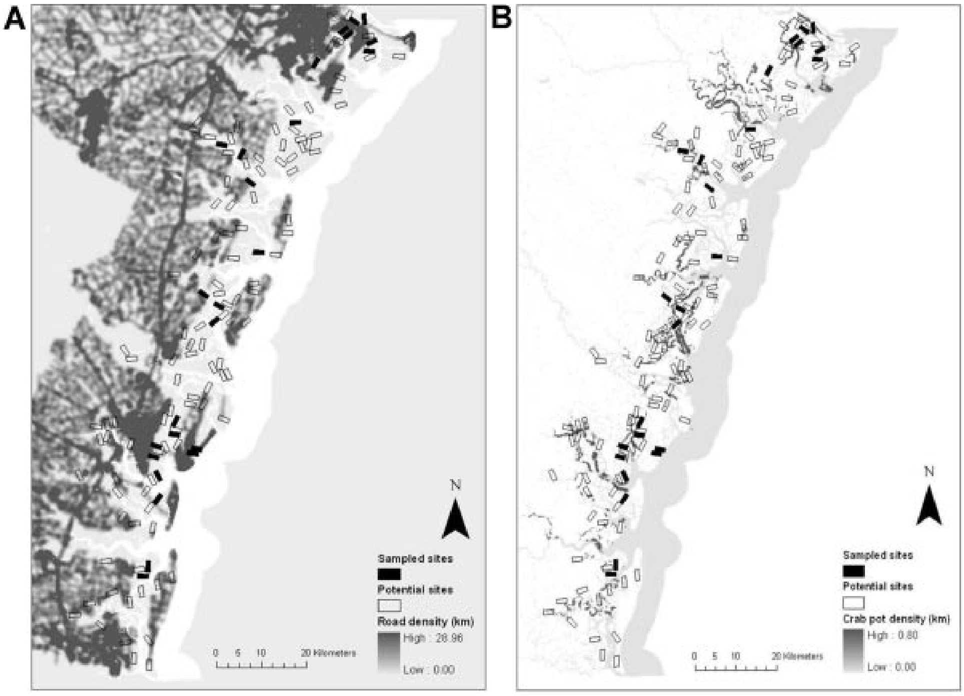

Figure 1. Possible sites for sampling diamondback terrapins (2007–2008) derived from site selection database including A) road densities of Coastal Georgia, USA from existing Geographic Information Systems (GIS), and B) crab pot densities (B. Winn, Georgia Department of Natural Resources, unpublished data).

tidal fluctuations, which were commonly between 2 and 3 m. Water temperature ranged from 18 °C to 32 °C and salinity averaged about 25 part per thousand (ppt).

METHODS

Site Selection

We chose study sites using a stratified random design. We identified 138 potential tidal creeks along the Georgia coast that were $\geq$1.5 km in length and large enough to appear in existing Geographic Information System (GIS) data layers of coastal tidal creeks, but accessible by a small boat and shallow enough to be seined manually at low tide (Fig. 1). Once we identified potential creeks, we classified each creek using two parameters available from GIS data: road density and number of commercial crab pots. We calculated road density as the linear kilometers of road (as depicted on 1:12,000 scale Georgia Department of Transportation roads depicting interstates, state highways, county roads, and city streets) within 0.5 km of either side of each tidal creek (expressed as km/km^2).

To estimate crabbing activity, we used geographically referenced data of the locations of commercial crab pots from 2003 to 2006 (obtained from the Georgia Department of Natural Resources [GA DNR], Coastal Resources Division, Brunswick, GA). We plotted the frequency of creeks along axes of crabbing activity and road density and, based on observed distributions, considered any creek with a road density >2 km/km^2 within 0.5 km as a high road-density creek and any creek with $\geq$3 commercial crab pots a high crabbing creek; therefore, we ultimately assigned all 138 creeks into one of four treatments based on their corresponding road density and crabbing pressure: high roads—no crabbing, high roads—high crabbing, low roads—high crabbing, and low roads—no crabbing (Fig. 1). From the pool of 138 sites, we randomly selected six creeks from each of the four classes. During sampling, when we failed to capture a terrapin during the first 2 capture (sampling) periods, we considered terrapins absent from the site (density = 0), and we selected another site within the same treatment to sample. Though not included in our original random sample of creeks, we sampled a creek along the Downing-Musgrove Causeway to Jekyll Island at the request of GA DNR. The Jekyll Causeway was a documented hot-spot for adult female terrapin vehicular mortality ($\geq$250 nesting females killed annually in 2007 and 2008; T. Norton, The Georgia Sea Turtle Center, unpublished data). We sampled 29 creeks in total.

We verified our measure of crab pot density with direct counts of crab pots during our sampling. Although there was slight variability between the initial crab pot density layer and direct counts of crab pots, all treatments and their corresponding replicates remained the same. We used actual crab pot numbers in our analyses and, based on observed patterns of crabbing activity, further refined crabbing classifications to no crabbing, low crabbing (1–2 pots/creek; only 1 creek had 2 pots), and high crabbing ($\geq$3 pots/creek).

Because existing GIS road density layers included all paved surfaces in Georgia (e.g., subdivisions, parking lots) and were therefore not necessarily indicative of vehicular pressure, we additionally measured the distance (km) to the closest biologically relevant road from each creek. We defined biologically relevant roads using digital photographs of each creek and our best judgment as to the closest road that could sustain traffic (i.e., higher traffic volume streets, and not subdivision roads) and could be accessed by terrapins, accounting for barriers such as sea walls (Fig. 2). Once we determined the nearest biologically relevant road, we plotted

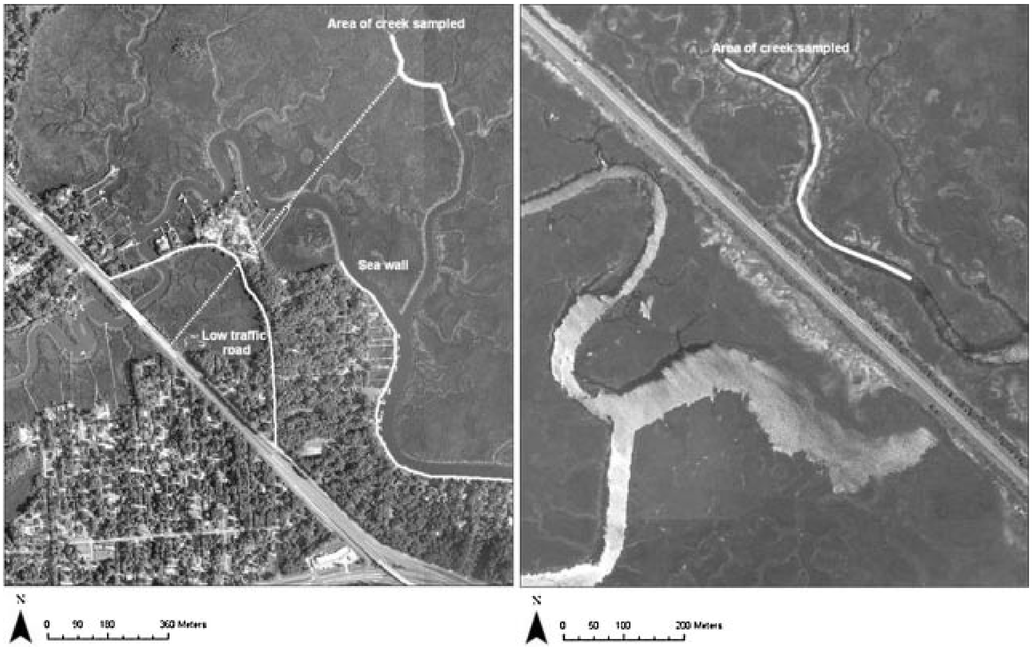

Figure 2. Examples of determination of distance to nearest relevant road (represented by the dotted line) for two diamondback terrapin study creeks in coastal Georgia (2007–2008), accounting for potential barriers (sea wall) and low traffic roads.

the distribution of all creek distances to a road and, based on that distribution, classified all sites as being proximate (within 1.2 km of a road) or distant (>2.3 km from the nearest road).

Estimating Terrapin Density

We used repeated seining and individual mark-recapture to estimate terrapin density in focal creeks. We seined each creek on five occasions using two 10-m, 2.54-cm-mesh seines with a bag (following the methods of Dorcas et al. 2007). We did not use trammel nets. Seining occurred at low tide and we pulled seines from the start of each sampling area until we reached the end of the creek, occasionally pulling the seines onto the mud bank to remove captured terrapins and bycatch. Depending on width and depth of creeks, we either pulled seines in tandem or side-by-side to maximize the area sampled. We seined each creek upstream and downstream during each visit. To reduce the potential effects of temporal changes in capture probability, we sampled all creeks once in each of five 20-day intervals between 1 April and 30 June, which is the most effective period for capturing terrapins in our study region (Gibbons et al. 2001). Following capture, we sexed, measured (carapace length, plastron length, shell width and depth), weighed (g), aged when possible (Sexton 1959), and uniquely marked all turtles using marginal scute notches (Cagle 1939). All sampling activities followed approved University of Georgia Animal Care and Use Committee Protocols (AUP no. A2007-10031-0).

We used a modified approach to estimate terrapin abundance for each study creek. We recognize that capture probabilities are not a species-level attribute and that when estimating population abundance at multiple sites, it is ideal to estimate terrapin capture probabilities for each study site (MacKenzie and Kendall 2002, Mazerolle et al. 2007). However, because we failed to recapture terrapins of one or both sexes in creeks with few individuals, it was not possible for us to estimate sex-specific capture probabilities for terrapins for all study creeks. Therefore, we assumed that terrapin behavior with regard to capture and recapture probabilities was similar among creeks. We pooled all data into two data sets, one for males and one for females, and then we used each data set to estimate capture and recapture probabilities for each sex. We used Program CAPTURE (White and Burnham 1999) to determine the most appropriate model for measuring sex-specific terrapin capture probabilities. We used sex-specific capture probabilities and the mean number of each sex captured over the five sampling periods to generate male and female closed population abundance estimates for each creek. We summed these estimates to generate a total density and sex ratio for each creek.

Statistical Analysis

We conducted two sets of analyses to test our hypotheses. First, we used analysis of variance (ANOVA) to test the hypotheses that terrapin density was negatively related to crabbing activity and proximity to a road. We used road proximity (proximate or distant) and crabbing activity (none, low, or high) as fixed factors. We used the same model to test the hypotheses that terrapin sex ratio (M/F) was positively related to road proximity and negatively related to crabbing activity. We also used general linear models combined with model selection (Akaike's Information Critertion [AIC]) to examine specific linear relationships among crabbing, road density, and proximity measures to terrapin densities and sex ratios. In addition to providing an additional test of hypotheses, linear models could be useful for management purposes in relating specific habitat measures to terrapin population metrics. We square-root transformed density estimates to meet model assumptions, and we used a $\log_{10}$ (ratio + 1) transformation for sex ratio analyses. To test the hypothesis that terrapin size distributions differed between creeks with and without crabbing, we used a one-way ANOVA to compare percentage of diamondback terrapins <107 mm plastron length among creeks with different crabbing activity classifications. We conducted all analyses in STATISTICA v8.0 (StatSoft, Inc., Tulsa, OK).

RESULTS

Among all 29 creeks, we had 2,005 captures of terrapins consisting of 1,547 individuals. Capture numbers were consistent among creeks sampled in 2007 and 2008. In 2007, we had 977 terrapin captures consisting of 783 individuals, and in 2008 we had 1,028 terrapin captures consisting of 764 individuals. We captured a median number of 6 terrapins during each visit (25–75% quartiles = 2–13 individuals). Overall captured individuals were male biased, with 77% males and 23% females. We observed 87 terrapin road mortalities, all but one of which were females making nesting migrations. We also observed 153 terrapins, approximately 10% of all live terrapins we observed in study creeks, drowned in 5 crab pots within study creeks. Of drowned terrapins 83% were males, and mean plastron length of drowned terrapins was 107 mm (median = 102 mm; 25–75% quartiles = 97–110 mm).

Terrapin density declined with increasing crabbing activity (ANOVA, $F_{2,23} = 3.933$, $P = 0.034$; Fig. 3) but did not differ measurably as a function of creek proximity to roads (ANOVA, $F_{1,23} = 0.082$, $P = 0.777$). There was no measurable interaction between crabbing activity and road proximity (ANOVA, $F_{2,23} = 0.120$, $P = 0.888$; Fig. 3). Sex ratio was not measurably related to crabbing activity (ANOVA, $F_{1,25} = 1.164$, $P = 0.219$; Fig. 3), road proximity (ANOVA, $F_{1,25} = 2.667$, $P = 0.118$), or an interaction between the two factors (ANOVA, $F_{1,25} = 2.180$, $P = 0.155$). Sex ratios were based on 1,500 individual captures (No crabbing: $n = 1{,}167$; Low: $n = 217$; High: $n = 116$). Generalized linear models results based on actual measures of crabbing activity and road density or distance to the nearest road were consistent with ANOVA results. The best model based on AIC included the single factor of number of crab pots in the creek. This model was statistically significant and showed a negative relationship between the number of crab pots and terrapin density (Likelihood ratio $\chi^2 = 9.060$, df = 1, $P = 0.003$). The model including both number of crab pots and distance to the nearest road was within 2 AIC of the top model and also significant (Likelihood ratio $\chi^2 = 9.244$, df = 2, $P = 0.010$); however,

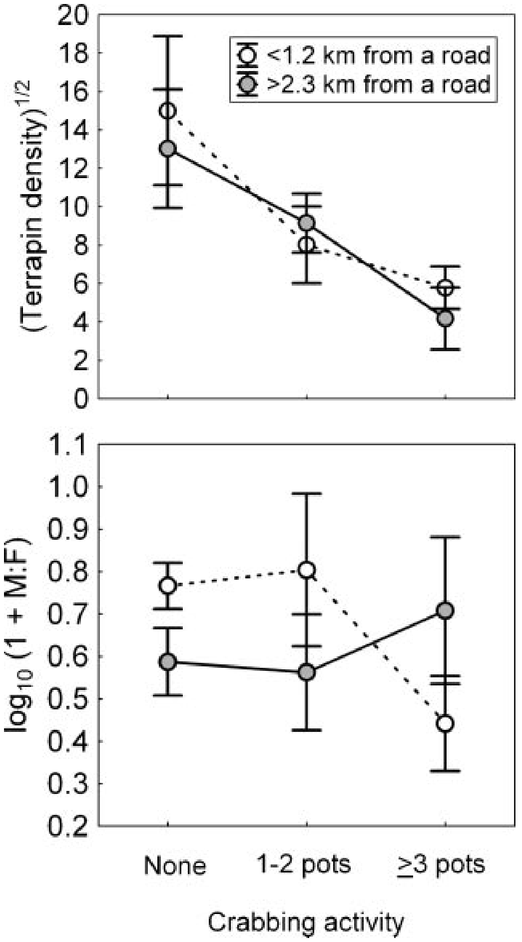

Figure 3. Mean diamondback terrapin density (upper panel) and sex ratio (lower panel) as a function of crabbing activity and proximity to a road, from sampling conducted in 2007–2008 in coastal Georgia. We square root transformed density values, and we $\log_{10}$(ratio + 1) transformed sex ratio values. Error bars represent ± 1 standard error.

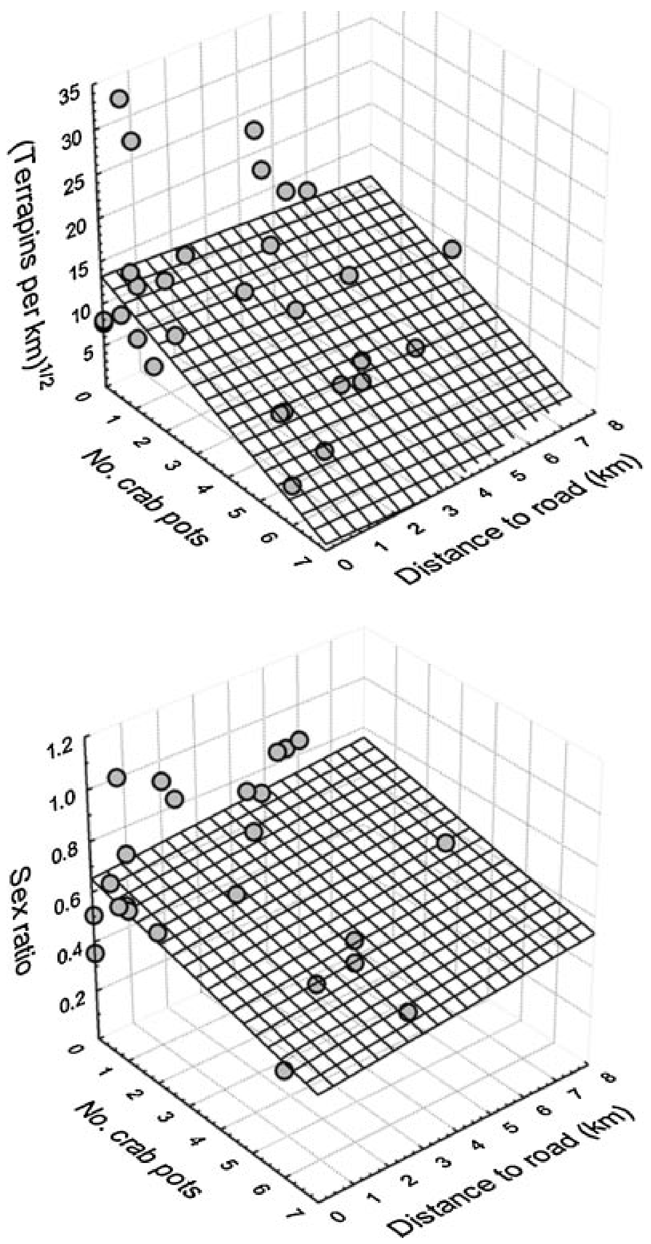

Figure 4. Multiple linear regression relationships between the number of crab pots in a tidal creek in coastal Georgia (2007–2008) and the distance to the nearest relevant road and diamondback terrapin density (upper panel) or sex ratio (lower panel). The model for terrapin density was significant with only the number of crab pots as a significant factor. The model for sex ratio was not significant. Plane represents multiple linear regression.

only the number of crab pots was identified as a significant factor in that model (Wald statistic = 5.625, $P = 0.018$; Fig. 4). Distance to the nearest road was not a significant factor (Wald statistic = 0.152, $P = 0.696$). The best model for predicting sex ratio only included crab pot number; however, that model was generally indistinguishable from models including multiple factors and was not statistically significant (Likelihood ratio $\chi^2 = 1.823$, df = 1, $P = 0.177$). The model that included both crab pot number and distance to nearest road was not significant (Likelihood ratio $\chi^2 = 2.499$, df = 2, $P = 0.287$), and neither crab pot number (Wald statistic = 2.073, $P = 0.150$) nor distance to nearest road (Wald statistic = 0.683, $P = 0.409$) was significant within the model (Fig. 4).

The percentage of terrapins <107 mm plastron length varied among our three crabbing classes, though this effect was marginally non-significant (ANOVA; $F_{2,21} = 2.871$; $P = 0.079$). Although mean percentage of terrapins <107 mm plastron length was lower among creeks with crabbing activity (None: $\bar{x} = 66\%$, SE = 0.042; Low: $\bar{x} = 53\%$, SE = 0.053; High: $\bar{x} = 52\%$, SE = 0.057), it did not differ significantly between creeks with high or low crabbing activity. However, when we combined crabbing activity classes (No crabbing: $\bar{x} = 66\%$, SE = 0.041; Crabbing: $\bar{x} = 52\%$, SE = 0.038), mean percentage of terrapins <107 mm plastron length between creeks with and without crabbing activity differed (ANOVA; $F_{1,22} = 5.994$; $P = 0.023$).

DISCUSSION

Our research shows that commercial crabbing, which is a known cause of terrapin mortality in other parts of the species range (Roosenburg 2004) and which we observed, is linked to patterns of low terrapin abundance along the Georgia coast. This appears to be another in a growing list of examples of the negative impacts of commercial fisheries on non-commercial marine wildlife (Lewison et al. 2004). Contrary to our expectations, road proximity or density was not related to terrapin abundance. This result contradicts most studies using similar approaches, which have found a negative associate between roads and animal abundance, particularly among reptiles (Fahrig and Rytwinski 2009).

Though most studies report negative effects of roads on animal abundances, there are some studies that report neutral or positive effects. Fahrig and Rytwinski (2009) propose four types of animal species that should respond negatively to roads: 1) species that are attracted to roads and are unable to avoid individual cars, 2) species with large movement ranges, low reproductive rates, and low natural densities, and 3) and 4) small animals whose populations are not limited by road-affected predators and either avoid habitat near roads due to traffic disturbance or show no avoidance of roads or traffic disturbance and are unable to avoid oncoming cars. Terrapins have several of the vulnerable characteristics described above including showing no avoidance of roads, inability to avoid cars, and low reproductive rates. Therefore, our failure to find a relationship between road proximity or density and terrapin abundance is not likely a result of terrapin characteristics and is more likely a reflection of current road and traffic patterns in coastal Georgia. Georgia has a rural coastal region with several barrier islands with little or no vehicle traffic. Of the 29 randomly selected sites we studied 16 (55%) were located >2.3 km from a biologically relevant road, contrasting sharply with patterns throughout the United States where 50% of land lies within 0.38 km of a road (Riitters and Wickham 2003). Riitters and Wickham (2003) identified coastal regions including the southeastern United States as vulnerable to the impacts of roads because 60–80% of land lies within 0.38 km of a road; however, that may not accurately reflect road proximity to estuarine habitats. Further, most of Georgia's coastal roads sustain low levels of traffic. Therefore, it is possible that density and traffic volume near Georgia's coastal estuaries is not yet sufficient to currently affect terrapin abundance across the Georgia coast.

We caution that where high traffic roads come near marshes, road mortality may be a significant factor affecting local terrapin abundance. It is widely accepted that turtle populations cannot sustain substantial increases in adult female mortality (Heppell 1998). There is ample evidence of adult female terrapin mortality on coastal roads that bisect or closely parallel marshes. For example, in 7 years in southern New Jersey, >4,000 terrapins were killed when attempting to cross causeways leading from the Garden State Parkway to barrier islands of the Cape May Peninsula (Wood and Herlands 1997). Within Georgia, 405 nesting female terrapin mortalities were reported on the Tybee Island causeway between 2005 and 2007 (J. Gray, Armstrong Atlantic University, unpublished data), and 442 terrapin mortalities (99% nesting females) were documented on the Jekyll Island causeway between 2007 and 2008 (T. Norton, unpublished data). Our study included three creeks within 30 m of a high traffic road, including one creek along the Tybee Island causeway and one along the Jekyll Island causeway. Terrapin density estimates in all three creeks were below the median value among all sites. We believe it is likely that road mortality is having localized effects along causeways in coastal Georgia.

We also must acknowledge that several factors may have limited our ability to measure any general impact of roads on terrapin populations. The number of roads near creeks can include many driveways and low traffic streets in dense residential areas that pose little risk of vehicle mortality to turtles, which is the case for the two most dense terrapin populations we documented. Although these sites were among the highest for road density, the area was highly residential and most of the area that constituted roads posed no long-term risk to terrapin populations. Determining the distance to the most relevant road requires a subjective criteria as to whether a road is biologically relevant, in most cases without any information about whether female terrapins nest near that road. Further, we used straight-line distances from creeks to roads. We do not know whether terrapins make straight-line, over-marsh migrations to nest sites, or whether they swim along creeks until they near nesting areas. So, straight-line distances may not reflect actual migration distance. Finally, other studies show that traffic volume and speed play a large role in how roads affect wildlife populations (Rosen and Lowe 1994, Fahrig et al. 1995, Forman 2000, Trombulak and Frissell 2000). Annual average daily traffic (AADT) data was not available for most of our study sites, and for others the available data reflect an annual average. Because many of the roads are used to reach coastal beaches, traffic volume is likely high during the summer and low during the remaining 9 months. Terrapins nest from mid-May to mid-July, which coincides with peak traffic volumes. Measures of traffic levels during this period might provide a better metric for evaluating road impacts on terrapin populations.

Contrary to expectation, we failed to find evidence that road density or proximity or crabbing effort was associated with variation in terrapin sex ratio. Because females migrate out of the water to nest, road mortality has been consistently documented to be higher among adult female turtles (Gibbs and Shriver 2002, Gibbs and Steen 2005, Szerlag and McRobert 2006). Consequently, turtle populations in areas of high road density or greater road proximity are often more male biased than populations in areas that are more distant from or have fewer roads (Steen et al. 2006). Our own observations of terrapin road mortality showed vehicle-induced mortality was biased toward adult female terrapins; however, we found no correlation between road density or proximity and terrapin sex ratios. Tucker et al. (2001) suggest that females may have a slightly lower natural survival rate due to their increased vulnerability during nesting migrations (i.e., high risk of boat strikes, predators). Therefore, vehicular mortality may be replacing other natural or anthropogenic sources of mortality and not lead to a measurably large shift in terrapin population sex ratio. The absence of an effect on sex ratio may also be further evidence that terrapin road mortality rates are not yet sufficient in coastal Georgia to have affected terrapin abundance or sex ratio. Finally, other factors that affect sex-specific mortality or births may be compensating for road mortality effects on terrapin sex ratio. We did not find road proximity or density interacted with crabbing activity to affect sex ratio, indicating the lack of road effects was not a product of compensatory mortality by male terrapins in crab pots. Terrapins do exhibit temperature dependent sex determination (Roosenburg and Kelley 1996), and features of roads such as less vegetation and mowing by roadsides might result in warming nest temperatures and the biased production of females.

In contrast to our road density results, our data show a measureable association between crabbing and terrapin abundance; however, we still found no association between crabbing effort and terrapin population sex ratio. Because mortality in crab pots is male biased, we expected high crabbing creeks to be more female biased. In contrast to our finding, Dorcas et al. (2007) documented an increase in mean terrapin size associated with crabbing, which was attributed to the selected survival of large adult females. One explanation for our failure to detect an association between terrapin sex ratios and crabbing was that terrapin abundance declined significantly with increased crabbing activity. Fewer terrapins captured in high crabbing creeks increases the error associated with estimating sex ratio. This error would confound efforts to measure a relationship between crabbing and terrapin sex ratios.

Because commercial crabbing is an important industry to coastal communities within the terrapin's range, effective management requires finding ways to minimize the impact of this industry on terrapin populations. We know some of the factors that determine whether a particular crab pot poses a significant risk to terrapins. When wire crab pots were introduced to commercial crab fisheries in the 1930s, early testing demonstrated significant numbers of terrapins captured in pots placed in shallow waters from April to June (Davis 1942). This time period coincides with peak activity of terrapins in the water in shallow tidal creeks. In South Carolina, Bishop (1983) reports 93% of terrapins caught in commercial crabbing gear were caught in shallow creeks during April, May, and June and primarily in wire pots. Bishop (1983) also found that peeler pots (standard wire crab traps using live male blue crabs as bait to capture molting soft shell female crabs) captured more adult terrapins than wire pots baited with fish. Hart (2005) noted that pots placed in shallow waters close to shore in April and May capture more terrapins, and she raised concern that peeler pots, which tend be fished in shallow waters in the spring may present a particular risk to terrapins. Our observations are consistent with those reported in earlier studies. The crab pots that we observed killing many terrapins were generally located far up in shallow tidal creeks that were only accessible by boat at high tide and were more likely to be neglected as evidenced by the growth of epibenthos and partial burial (Grosse et al. 2009). Restrictions on where crab pots may be placed, at least between April and June, could substantially reduce terrapin mortality. We also concur with other studies that conclude that crab pots that are over-soaked, neglected, abandoned, or lost pose the greatest risk to terrapin populations. When wire crab pots are checked daily, only 10% of captured terrapins drown (Bishop 1983). The proportion of terrapins found dead in crab pots increases to 40% if pots are checked every 1–2 days (Hart 2005), and we found nearly 100% mortality in pots visibly neglected for long periods of time. Currently, Georgia has no regulation limiting soak times for commercial crab pots (Code of Georgia 2009). A defined and enforced short soak time for crab pots could reduce the bycatch mortality of terrapins by up to 90%. Furthermore, efforts to clean up abandoned or lost pots, and education and enforcement about the responsible recreational use of commercial crab pots would be meritorious conservation actions.

Requiring bycatch reduction devices (BRDs) on commercial crab pots, particularly those fished in shallow waters, is another mechanism to reduce terrapin mortality rates due to crabbing. We are aware of 12 studies published in peer-reviewed journals, theses or the gray literature addressing the effectiveness of BRDs on reduction of terrapin capture rates and on blue crab capture numbers and sizes (Roosenburg 2004, Hart 2005). Generally, all these studies tested rectangular wire or plastic frames placed across the larger circular openings of standard commercial wire crab pots. Bycatch reduction device dimensions range from 4 cm to 5 cm × 8 cm to 12 cm. Nearly all studies found a reduction of terrapin capture numbers in crab pots modified with BRDs. A few studies reported minor reductions in blue crab size or numbers for the smallest BRDs (4–4.5 cm narrowest dimension); however, these reductions were negligible and not consistently observed. Further, several studies using slightly larger BRDs report increased numbers of crabs in modified pots; however, these larger BRD pots occasionally still capture terrapins. Hart (2005) modeled the potential effect of BRD reductions for small BRDs that may reduce blue crab harvest and large BRDs that still capture smaller terrapins but found no negative effect on blue crab catch. Those estimates suggest that small BRDs could increase terrapin population growth rates (λ) by 18–22% and large BRDs could increase population growth rates by 11–13%.

MANAGEMENT IMPLICATIONS

Although evidence for the negative effects of crabbing on terrapin populations is documented and generally known within the wildlife management community, crabbing is not explicitly identified as a potential factor affecting the conservation of terrapins in states such as Georgia. We estimated that mean terrapin abundance was an order of magnitude lower in creeks with active commercial crabbing. Though not an objective of this study, we also found that state records significantly underestimate the numbers of coastal tidal creeks being commercially crabbed. We have discussed a number of factors that could be used to reduce the bycatch impact of terrapins in commercial crab pots, most notably regulating soak times and locations for commercial crab pots in combination with requiring bycatch reduction devices on commercial pots. We found that road mortality impacts on terrapins may be limited to local effects, particularly on causeways that bisect marshes and provide access to barrier islands. Future research should focus on estimating the local impacts of road mortality on terrapin populations, and developing management tools for reducing mortality in those specific hotspots.

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LITERATURE CITED

Aresco, M. J. 2005. The effect of sex-specific terrestrial movements and roads on the sex ratio of freshwater turtles. Biological Conservation 123:37–44.

Báez, J. C., R. Real, C. García-Soto, J. M. de la Serna, D. Macías, and J. A. Camiñas. 2007. Loggerhead turtle by-catch depends on distance to the coast, independent of fishing effort: implications for conservation and fisheries management. Marine Ecology Progress Series 338:249–256.

Bishop, J. M. 1983. Incidental capture of diamondback terrapin by crab pots. Estuaries 6:426–430.

Bowen, K. D., P. L. Colbert, and F. J. Janzen. 2004. Survival and recruitment in a human-impacted population of ornate box turtles, *Terrapene ornata*, with recommendations for conservation and management. Journal of Herpetology 38:562–568.

Cagle, F. R. 1939. A system of marking turtles for future identification. Copeia 1939:170–173.

Code of Georgia. 2009. Use of crab traps; identification of boats or vessels; closure of salt waters authorized. 27-4-151.

Cole, R. V., and T. E. Helser. 2001. Effect of three bycatch reduction devices on diamondback terrapin *Malaclemys terrapin* capture and blue crab *Callinectes sapidus* harvest in Delaware Bay. North American Journal of Fisheries Management 21:825–833.

Congdon, J. D., A. E. Dunham, and R. C. van Loben Sels. 1993. Delayed sexual maturity and demographics of blanding's turtles (*Emydoidea blandingii*): implications for conservation and management of long-lived organisms. Conservation Biology 7:826–833.

Davis, C. C. 1942. A study of the crab pot as a fishing gear. Publication number 53. Chesapeake Biological Laboratory, Solomons, Maryland, USA.

Diamond, J. M. 1984. Historic extinctions: a Rosetta stone for understanding prehistoric extinctions. Pages 824–862 *in* P. S. Martin and R. G. Klein, editors. Quaternary extinctions: a prehistoric evolution. University of Arizona Press, Tucson, USA.

Dorcas, M. E., J. D. Willson, and J. W. Gibbons. 2007. Crab trapping causes population decline and demographic changes in diamondback terrapins over two decades. Biological Conservation 137:334–340.

Fahrig, L., and T. Rytwinski. 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecology and Society 14:21.

Fahrig, L., J. H. Pedlar, S. E. Pope, P. D. Taylor, and J. F. Wenger. 1995. Effect of road traffic on amphibian density. Biological Conservation 73:177–182.

Forman, R. T. T. 2000. Estimate of the area affected ecologically by the road system in the United States. Biological Conservation 14:31–35.

Garber, S. D., and J. Burger. 1995. A 20-Yr study documenting the relationship between turtle decline and human recreation. Ecological Applications 5:1151–1162.

Gibbons, J. W., J. E. Lovich, A. D. Tucker, N. N. Fitzsimmons, and J. L. Greene. 2001. Demographic and ecological factors affecting conservation and management of diamondback terrapins (*Malaclemys terrapin*) in South Carolina. Chelonian Conservation and Biology 4:66–74.

Gibbs, J. P., and W. G. Shriver. 2002. Estimating the effects of road mortality on turtle populations. Conservation Biology 16:1647–1652.

Gibbs, J. P., and D. A. Steen. 2005. Trends in sex ratios of turtles in the United States: implications of road mortality. Conservation Biology 19:552–556.

Grosse, A. M., J. D. van Dijk, K. L. Holcomb, and J. C. Maerz. 2009. Diamondback terrapin mortality in crab pots in a Georgia tidal marsh. Chelonian Conservation and Biology 8:98–100.

Guthery, F. S., M. C. Green, R. E. Masters, S. J. DeMaso, H. M. Wilson, and F. B. Steubing. 2001. Land cover and bobwhite abundance on Oklahoma farms and ranches. Journal of Wildlife Management 65: 838–849.

Hart, K. M. 2005. Population Biology of Diamondback Terrapins (*Malaclemys terrapin*): defining and Reducing Threats Across Their Geographic Range. Ph.D. Dissertation. Duke University, Durham, North Carolina, USA.

Hazel, J., and E. Gyuris. 2006. Vessel-related mortality of sea turtles in Queensland, Australia. Wildlife Research 33:149–154.

Heppell, S. S. 1998. Application of life-history theory and population model analysis to turtle conservation. Copeia 1998:367–375.

Hoyle, M. E., and J. W. Gibbons. 2000. Use of a marked population of diamondback terrapins (*Malaclemys terrapin*) to determine impacts of recreational crab pots. Chelonian Conservation and Biology 3:735–737.

Laist, D. W., and C. Shaw. 2006. Preliminary evidence that boat speed restrictions reduce deaths of Florida manatees. Marine Mammal Science 22:472–479.

Lewison, R. L., L. B. Crowder, A. J. Read, and S. A. Freeman. 2004. Understanding impacts of fisheries bycatch on marine megafauna. Trends in Ecology and Evolution 19:598–604.

MacKenzie, D. I., and W. L. Kendall. 2002. How should detection probability be incorporated into estimates of relative abundance? Ecology 83:2387–2393.

Mazerolle, M. J., L. L. Bailey, W. L. Kendall, J. A. Royle, S. J. Converse, and J. D. Nichols. 2007. Making great leaps forward: accounting for detectability in herpetological field studies. Journal of Herpetology 41: 672–689.

Mitchell, J. C., and M. W. Klemens. 2000. Primary and secondary effects of habitat alteration. Pages 5–32 *in* and M. W. Klemens, editor. Turtle conservation. Smithsonian Institution Press, Washington, D.C., USA.

Moore, M. J. C., and R. A. Seigel. 2006. No place to nest or bask: effects of human disturbance on the nesting and basking habits of yellow-blotched map turtles (*Graptemys flavimaculata*). Biological Conservation 130:386–393.

Riitters, K. H., and J. D. Wickham. 2003. How far to the nearest road? Frontiers in Ecology and the Environment 1:125–129.

Roosenburg, W. M. 2004. The impact of crab pot fisheries on terrapin (*Malaclemys terrapin*) populations: where are we and where do we need to go? Pages 23–30 *in* C. Swarth, W. M. Roosenburg, and E. Kiviat editors. A Symposium on the Conservation and Ecology of Turtles of the Mid-Atlantic Region, 30–31 October 1999 Salt Lake City, Utah, USA.

Roosenburg, W. M., and J. P. Green. 2000. Impact of a bycatch reduction device on diamondback terrapin and blue crab capture in crab pots. Ecological Applications 10:882–889.

Roosenburg, W. M., and K. C. Kelley. 1996. The effect of egg size and incubation temperature on growth in the turtle, *Malaclemys terrapin*. Journal of Herpetology 30:198–204.

Roosenburg, W. M., W. Cresko, M. Modesitte, and M. B. Robbins. 1997. Diamondback terrapin (*Malaclemys terrapin*) mortality in crab pots. Conservation Biology 11:1166–1172.

Rosen, P. C., and C. H. Lowe. 1994. Highway mortality of snakes in the Sonoran desert of southern Arizona. Biological Conservation 68:143–148.

Schoettle, T. 1996. A guide to a Georgia barrier island. St. Simons Island, GA. University of Georgia Printing Department, Athens, USA.

Seigel, R. A., and J. W. Gibbons. 1995. Workshop on the ecology, status, and management of the diamondback terrapin (*Malaclemys terrapin*). Savannah River Ecology Laboratory, 2 August 1994: final results and recommendations. Chelonian Conservation and Biology 1:27–37.

Sexton, O. J. 1959. A method of estimating the age of painted turtles for use in demographic studies. Ecology 40:716–718.

Steen, D. A., and J. P. Gibbs. 2004. Effects of roads on the structure of freshwater turtle populations. Conservation Biology 18:1143–1148.

Steen, D. A., M. J. Aresco, S. G. Beilke, B. W. Compton, E. P. Condon, C. K. Dodd, Jr., H. Forrester, J. W. Gibbons, J. L. Greene, G. Johnson, T. A. Langen, M. J. Oldham, D. N. Oxier, R. A. Saumure, F. W. Schuler, J. M. Sleeman, L. L. Smith, J. K. Tucker, and J. P. Gibbs. 2006. Relative vulnerability of female turtles to road mortality. Animal Conservation 9:269–273.

Szerlag, S., and S. P. McRobert. 2006. Road occurrence and mortality of the northern diamondback terrapin. Applied Herpetology 3:27–37.

Trombulak, S. C., and C. A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14: 18–30.

Tucker, A. D., J. W. Gibbons, and J. L. Greene. 2001. Estimates of adult survival and migration of diamondback terrapins: conservation insight from local extirpation within a metapopulation. Canadian Journal of Zoology 79:2199–2209.

Venier, L., and L. Fahrig. 1996. Habitat availability causes the species abundance-distribution relationship. Oikos 76:564–570.

White, G. C., and K. P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. Bird Study 46:120–138.

Wood, R. C., and R. Herlands. 1997. Turtles and tires: the impact of road kills on northern diamondback terrapin, *Malaclemys terrapin terrapin*, populations on the Cape May Peninsula, southern New Jersey, USA. Pages 46–53 *in* J. Van Abbema, editor. Proceedings: conservation, Restoration, and Management of Tortoises and Turtles—an International Conference, 11–16 July 1993, Purchase, New York, USA.

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