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Occupancy of the Diamond-backed Terrapin (*Malaclemys terrapin*) on Coastal Islands in the Suwannee Estuary, Florida, USA

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Abstract.—**The Diamond-backed Terrapin (*Malaclemys terrapin*) inhabits coastal islands along the Gulf coast of Florida (sometimes in numbers > 100), but factors associated with terrapin occurrence on islands are poorly understood. We conducted a study of terrapin occupancy on coastal islands in the Suwannee Estuary in Florida. We used remote sensing to assess 24 discrete islands, and in 2017–2018 we conducted terrapin surveys twice per year on each island. Our results indicated that terrapin occurrence was negatively associated with increased forest coverage and positively associated with increased distance from the mainland, whereas other characteristics we measured (e.g., island size, mangrove coverage, and grass coverage) were not relevant predictors of terrapin occurrence. Overall, terrapins potentially occupy more isolated islands that are less likely inhabited by predators. Although more research is needed, this is potentially a conservation concern because these islands may lose their suitability due to sea-level rise, forcing terrapins to relocate to potentially less suitable habitats that could negatively affect nesting, survival rates, and population persistence.**

Key Words.—Bayesian; conservation; Chelonian; Florida; habitat; model; survey

Introduction

Islands vary in shape, size, isolation, ecology, and support many species of wildlife worldwide (Macarthur and Wilson 1967); however, climate change is altering the distribution of wildlife globally (Root et al. 2003). Species dependent on low-elevation islands are particularly vulnerable to sea-level rise caused by climate change, which is predicted to reshape or inundate low-lying coastal environments as seas are expected to rise between 26–82 cm by 2100 (Intergovernmental Panel on Climate Change 2014). Warmer temperatures associated with climate change further modify the vegetative composition and structure of coastal environments (Cavanaugh et al. 2014), altering the distribution of coastline-dependent species (Chen et al. 2019; Taillie and McCleery 2021). Understanding the habitat associations and occupancy of these coastline-dependent species is vital to their conservation in an era of climate change.

The Diamond-backed Terrapin (*Malaclemys terrapin;* hereafter terrapin) inhabits low-lying coastal environments, including islands, from Massachusetts to Texas (Ernst and Lovich 2009). Terrapins are the only brackish water specialist species of turtle in North America and are largely confined to estuarine habitats (Ernst and Lovich 2009). Terrapins face a variety of threats including habitat loss, road mortality, nest predation, boat strikes, and bycatch mortality in crab traps (Butler et al. 2006). Terrapins have exhibited local population declines throughout their range (Seigel and Gibbons 1995; Dorcas et al. 2007). Several states have listed terrapins as threatened or a species of special concern; however, their conservation status remains unclear partially due to a lack of population assessments in many areas of their range (Kennedy 2018).

Terrapins maintain a semiterrestrial existence on certain coastal islands along the Gulf coast of Florida (Suarez et al. 2021); however, the factors contributing to terrapin island occupancy are poorly understood. Identifying factors associated with terrapin occurrence on coastal islands is needed to better understand their regional distribution and population status. Therefore, we conducted a study investigating terrapin occupancy on coastal islands in the Suwannee Estuary in Florida. The objectives of our study were to assess the distribution of terrapins across the islands of the Suwannee Estuary and to investigate associations between terrapin occurrence and island characteristics.

Based in part by findings from other studies in the Florida panhandle that found terrapins inhabiting small, grass dominated islands (see Suarez et al. 2021), we hypothesized that island size, vegetation characteristics, and distance from the mainland affect the occupancy and abundance of terrapins. We predicted that terrapins would select smaller, grassy islands that were farther from the mainland. Findings from this study could provide resource managers and stakeholders with information to predict islands that are more likely to be occupied, which may help focus population studies, protection, and allow for spatially focused management strategies that could enhance the conservation of this species. Likewise, knowledge of terrapin habitat associations is necessary to predict and possibly ameliorate the effects of climate change on this already vulnerable species.

Materials and Methods

Study site.—The Suwannee River flows approximately 378 km from its headwaters in southern Georgia, USA, downstream to the Gulf of Mexico in Florida, USA, creating the Suwannee Estuary (Hornsby et al 2000). This river accounts for 60% of the total freshwater inflow into the Big Bend region of Florida (Montague and Odum 1997). The surge of freshwater from the Suwannee River influences much of the region, and for this study we considered the greater Suwannee Estuary to range from the Pepperfish Keys south to Cedar Key (approximately 54 km; Fig. 1). The Suwannee River is deltaic (Day et al. 1989) and contains an extensive intertidal area that can range in salinity from freshwater to nearly seawater (Hornsby 2000). The regional coastline is shallow, with low wave energy and is sediment starved (Hine et al. 1988, Hine 2009).

Island assessment.—We used remote sensing to examine characteristics of coastal islands. We identified 36 candidate islands based on the following criteria: (1) separated by water from the inland marsh at low tide; (2) not inundated at mean high tide; and (3) possessed characteristics associated with insular terrapin populations (e.g., emergent vegetation, sand). We randomly selected 24 of the 36 islands to survey for terrapins, which was the maximum number we believed to be logistically feasible.

We measured sand, grass, mangrove, and forest coverage (m^2) for each surveyed island via remote sensing. We obtained true color (red, blue, and green bands) aerial imagery with 0.15-m resolution from the online Land Boundary Information System repository of the Florida Department of Environmental Protection (https://www.labins.org/mapping_data/aerials/aerials.cfm). We used the most recent imagery available (either 2016 or 2013) and employed an unsupervised classification approach to classify land cover in ArcGIS (version 10.1, Esri, Redlands, California, USA) based on spectral reflectance. We considered forest as an area that was comprised of upland trees (e.g., oaks, *Quercus* sp., pines, *Pinus* sp., and junipers, *Juniperus* sp.). The

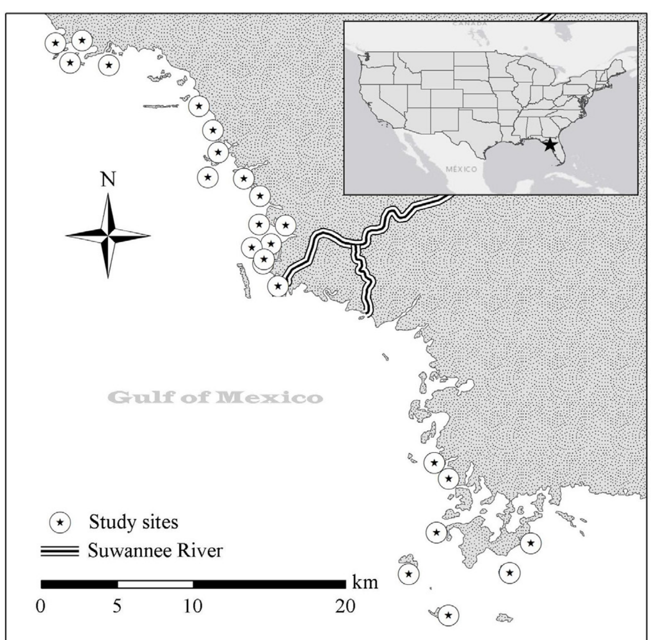

Figure 1. Study area in the Suwannee Estuary, Florida, USA, showing 24 islands surveyed for the Diamond-backed Terrapin (*Malaclemys terrapin*) twice per year during the active season (March-September) in 2017 and 2018.

unsupervised classification could not differentiate between Black Mangrove (*Avicennia germinans*), White Mangrove (*Laguncularia racemosa*), and Red Mangrove (*Rhizophora mangle*), therefore, we created a single measure of total mangrove coverage combined. Similarly, we lumped all grassy groundcover (e.g., Saltmarsh Cordgrass, *Spartina alterniflora*, and Saltgrass, *Distichlis spicata*) into a single category. We used ground truthing of the unsupervised classification estimates by generating 100 random points for 10 randomly selected islands (from the group of 24) in ArcGIS. We used a handheld GPS (model GPSmap 64st; Garmin, Olathe, Kansas, USA) to visit each random point to visually inspect and classify ground cover. Finally, we measured the shortest distance (m) between the perimeter of each island and the nearest part of the mainland along with island size (total area m^2) in ArcGIS.

Terrapin surveys.—In 2017–2018, we surveyed for terrapins twice each year on each of the 24 islands (i.e., four surveys on each island) during the active season for terrapins (March to September). We hand-captured terrapins using the methods described in Suarez et al. (2021) and similarly decided not to include specific techniques here due to concerns with illegal take. We marked each captured individual with a PIT (Passive Integrated Transponder) tag.

Data analyses.—We assessed island characteristics potentially associated with terrapin occurrence using a Bayesian Occupancy Modeling approach. This approach enabled us to model occupancy while accounting for imperfect detection (Dorazio et al. 2011). We recorded a binary measure of detection (1 = observed, 0 = not observed) for each survey of each island. We fitted a series of single-variable models inclusive of variables that we *a priori* believed might influence terrapin occurrence or detection. We created single-variable models because our variables of interest were highly correlated ($r > 0.70$; see Dormann et al. 2013; Table 1).

Table 1. Correlation between variables of interest included in single-variable occupancy models of habitat of the Diamond-backed Terrapin (*Malaclemys terrapin*) measured across 24 islands in the Big Bend/Suwannee River Estuary region of the Gulf Coast of Florida, USA. Excessive correlation (> 0.7) necessitated the creation of single-variable occupancy models, rather than additive models.

	Distance	Forest	Grass	Mangrove	Total area
Distance (m)		0.82	0.37	0.79	0.78
Forest (m^2)			0.33	0.96	0.86
Grass (m^2)				0.31	0.76
Mangrove (m^2)					0.83
Total area (m^2)	0.78	0.86	0.76	0.83	

We tested for relationships between terrapin occurrence and island-specific total area (m^2), grassy coverage (m^2), distance from the mainland (m), forest coverage (m^2), and mangrove coverage (m^2). We accounted for the potential influence of variable effort on terrapin detection probability by modeling detection probability as a function of the average per-survey time (minutes) spent surveying each island each year. We estimated the posterior distributions of each parameter using Markov chain Monte Carlo (MCMC) sampling implemented in WinBUGS (version 1.4.3) using the R package R2WinBUGS (Sturtz et al. 2005). We used uniform (uninformative) priors (Gelman et al. 1995; Gilks et al. 1996) and generated three chains of 100,000 iterations with a burn-in of 20,000 iterations and a thinning rate of 10, retaining 24,000 samples. We assessed MCMC convergence with trace plots and the Gelman-Rubin diagnostic (*Rhat*), where values < 1.1 indicated convergence (Gelman and Hill 2007). We present the effect size (on the logit scale) and 95% Bayesian credibility interval (*CRI*) associated with each covariate. Statistical analyses were conducted in R (version 4.1.2; R Development Core Team 2018).

Results

Our habitat classification was highly accurate for most metrics (Table 2), and ground truthing surveys revealed no misclassifications for grass, mangrove, and forest. Our classification of sand was only 52% accurate, however, due to incidental inclusion of oyster beds and shell fragments, so we removed sand from subsequent analysis. Island-specific total area (m^2), grassy coverage (m^2), distance from the mainland (m), forest coverage (m^2), sand coverage (m^2), and mangrove coverage (m^2) varied between islands (Table 3).

We captured 13 terrapins during surveys, and we found only three islands to be occupied during our study. In 2017, we captured five terrapins on three islands, and in 2018, we captured seven terrapins on the three same islands. Overall, terrapin detection probability was 0.80 and naïve occupancy (i.e., number of islands where

Table 2. Results from ground truthing habitat classes determined through unsupervised classification in ArcGIS of the Diamond-backed Terrapin (*Malaclemys terrapin*) measured across 24 islands in the Big Bend/Suwannee River Estuary region of the Gulf Coast of Florida, USA. All classes were highly accurate except for sand, which was removed from subsequent occupancy analyses.

Habitat Class	Predicted	Actual	Accuracy (%)
Grass (m^2)	31	31	100%
Forest (m^2)	14	14	100%
Mangrove (m^2)	34	34	100%
Sand	21	11	52%

Table 3. Island-specific total area (m^2), grassy coverage (m^2), distance from the mainland (m), forest coverage (m^2), sand coverage (m^2), and mangrove coverage (m^2) measured across 24 islands with the Diamond-backed Terrapin (*Malaclemys terrapin*) in the Big Bend/Suwannee River Estuary region of the Gulf Coast of Florida, USA.

	Mean	Minimum	Maximum
Distance (m)	578.29	35.40	2,863.3
Forest (m^2)	24,352.2	0.00	210,203.0
Grass (m^2)	35,217.2	394.4	271,386.9
Mangrove (m^2)	10,877.0	0.00	78,421.5
Sand (m^2)	13,026.8	217.4	59,981.7
Total area (m^2)	83,477.5	611.8	405,971.4

terrapins were detected/total number of islands) was 0.125. Terrapin detection was not associated with the average amount of time spent surveying each year in any model (Table 4). Terrapin occurrence was negatively associated with increased forest coverage and positively associated with increased distance from the mainland (Table 4; Fig. 2). Grass coverage, mangrove coverage, and total area were not relevant predictors of terrapin occurrence (Table 4).

Discussion

Although it is difficult to draw any strong conclusions from our models due to the uncertainty around our estimates, we found some associations between terrapin occupancy and certain island characteristics. Specifically, we found terrapins were negatively

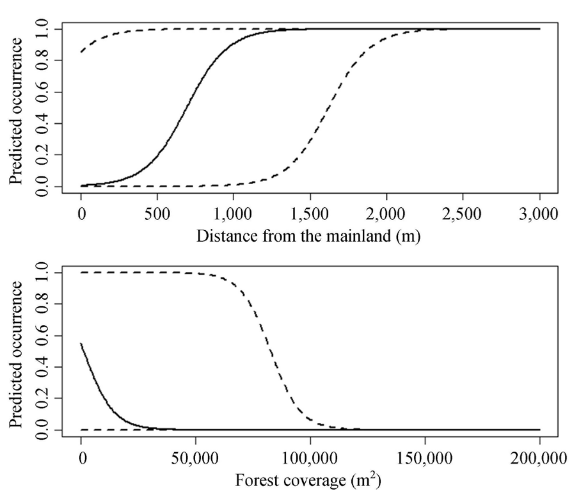

Figure 2. Results from single-variable occupancy models showing the predicted relationship between Diamond-backed Terrapin (*Malaclemys terrapin*) occurrence and distance from the mainland (top) and forest coverage (bottom) in the Big Bend/Suwannee River Estuary region of the Gulf Coast of Florida, USA. The solid line is the expected, mean value while the dotted lines depict the 95% Bayesian credibility interval.

Table 4. The mean effect of the estimated parameter (Mean), Bayesian credibility interval (CRI), and Gelman-Rubin diagnostic (Rhat), which indicates convergence when < 1.1, for models investigating terrapin occupancy (ψ) while accounting for imperfect detection (p).

Model	Mean	CRI	Rhat
ψ(distance), p(effort)	5.37	0.13–14.23	1.00
ψ(forest), p(effort)	-9.36	-23.57, -0.50	1.00
ψ(grass), p(effort)	-0.71	-2.62–0.50	1.00
ψ(mangrove), p(effort)	0.49	-2.34–13.09	1.02
ψ(total area), p(effort)	-1.03	-3.51–0.46	1.00

associated with forest cover, which potentially may be related to the presence of predators. Forests on coastal islands likely provide resources, such as shelter or food, which may be important to terrapin predators. In the presence of predators, prey often respond by changing their habitat use (Cooper 1984; Lima et al. 1985; Power et al. 1985). Thus, the presence of predators may be the ultimate driver of terrapin occupancy on coastal islands. Raccoons (*Procyon lotor*) are a major predator of terrapins and their nests (Butler et al. 2018). Although raccoon population estimates are lacking in our study region, we did notice raccoon tracks on all surveyed islands that possessed forest habitat. Interestingly, we found that terrapin occupancy decreased as forest cover approached the size of known raccoon home ranges on islands ($\geq$ 60,000 m^2; Lotze 1979). Thus, it is possible that raccoon occurrence may be a predictor of terrapin absence on coastal islands, and raccoon occurrence could be related to the presence and size of forest habitat. Future studies should explore factors influencing occupancy of raccoon and other meso-mammal predators on coastal islands.

Our results indicated that the proximity of islands to the mainland may make closer islands less preferable to terrapins because they are likely more accessible to terrapin predators. Raccoons are capable swimmers known to swim distances of a few hundred meters (Zeveloff 2002). Interestingly, islands occupied by terrapins in west Florida were > 500 m from the mainland (Suarez et al. 2021). Although terrapins occur on the mainland with Racoons, they may not exhibit the same loitering behavior as on isolated and predator free islands. We suggest that insular terrapin studies, surveys, and conservation actions should prioritize estuarine islands that are relatively distant from the mainland, as these islands may be more likely to maintain terrapin populations.

We did not find any association between terrapin occurrence and mangroves. Yet, terrapins are known to inhabit mangroves in south Florida (Mealey et al. 2014). The location of our study area was at the northern boundary of mangrove distributions, having only recently become climactically hospitable for mangrove persistence (Stevens et al. 2006). Mangroves did not occur on the northern islands in our study area and were not dominant on any of the surveyed islands. The recent arrival of mangroves could result in a lag effect during which terrapins learn how to navigate and exploit resources within the unique structure of mangroves. Alternatively, mangroves may not represent optimal habitat, but instead may be used in south Florida out of necessity due to their dominance of low-energy shorelines. As climate change continues to facilitate the northward progression of mangroves further into the range of terrapins, more research is needed to elucidate the relationship between mangrove distribution and terrapin habitat selection.

Interestingly, our occupancy models did not indicate island area as an important predictor of terrapin occupancy. Likewise, a past study found a large terrapin population estimated at > 1,000 individuals on a series of small islands of the coast of western Florida (Suarez et al. 2021). We expected similar findings; however, the islands in our study region are substantially different (i.e., vegetation composition, substrate) than those described in Suarez et al. (2021). Perhaps the most important factor for terrapin occurrence is not island size, but the previously mentioned factors related to isolation from predator communities.

Our study had low capture success compared to other studies conducted on islands using similar techniques (Suarez et al. 2021; Christopher Boykin, unpubl. report). This could be due to several factors such as terrapins in the Suwannee Estuary could be more dispersed, in lower abundance, or terrapins could be using different areas, such as saltmarsh, creeks, or tidal flats. The Big Bend region of Florida supports an expansive tidal marsh system in contrast to the panhandle region (Hine 2009). Nevertheless, the terrapins we did capture were using islands that are vulnerable to inundation by sea-level rise and destruction by increased storm severity. This is cause for concern as these islands may currently be losing their suitability and in many cases their availability. Many smaller, low-lying islands could be lost entirely, and as these islands are lost, terrapins in our study area and other insular populations will be forced to relocate to potentially less suitable habitats, which could lead to decreases in survival rates and terrapin persistence in these areas. Therefore, there is a need to conserve, manage, and even restore these important isolated islands to ensure these insular populations persist in a changing climate.

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