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# Response of a Reptilian Ecosystem Engineer to Large-scale Dune Construction: Implications for Coastal Wildlife

By

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## Abstract

Response of a Reptilian Ecosystem Engineer to Large-scale Dune Construction: Implications for Coastal Wildlife

Scott A. Martin

Climate change-induced sea-level rise is a major threat to coastal habitat worldwide. Current management aimed at reducing beach erosion often focuses on protecting human structures, and research on the impacts of management on wildlife is lacking. I evaluated how a reptilian ecosystem engineer, the Gopher Tortoise (*Gopherus polyphemus*), colonized human-constructed dunes along coastal scrub at the Merritt Island National Wildlife Refuge in Central Florida. Over two years I surveyed tortoise populations along natural dunes and two constructed dunes (completed in 2012 and in 2014) and estimated tortoise density each summer and winter. My models indicate that tortoise density along the 2014 dune was similar to that of the natural dunes (means ranging from 0.9 to 9.66 tortoises per hectare), and density peaked at a mean of 36 tortoises per hectare along the 2012 constructed dune. Overall, Gopher Tortoises rapidly colonized constructed dunes, and dune construction may represent effective management to reduce habitat loss for this species.

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## Introduction

Climate change is one of the largest threats to biodiversity (Sala et al. 2000, Thomas et al. 2004). Most management plans for species and land conservation will need to address potential impacts from the effects of climate change in order to account for evolving threats to wildlife (Staudinger et al. 2013). Coastlines are particularly vulnerable to the impact from climate change, as they are facing both a rise in sea level and a potential increase in the strength of hurricanes and tropical storms (Scavia et al. 2002, Nicholls et al. 2007, Overpeck and Weiss 2009, Zhang et al. 2013). Often, coastal management to protect against beach erosion focuses on protecting human interests, while the effects on wildlife are understudied (Schlacher et al. 2007, Harris et al. 2015).

Most management aimed at protecting coastal interests use methods such as dune construction, sediment supplementation, and hard sea walls (Klein et al. 1998). Sea walls have been shown to increase overall coastal erosion by causing a large loss in beach area in front of the walls and worsening erosion along their edges (Bernatchez and Fraser 2011). If the goal is to protect coastlines and conserve natural beaches, the construction of hard wall structures may cause a loss of both habitat and biodiversity that would discourage construction in certain areas, and should be considered a last resort to manage beaches (Schlacher et al. 2007, Harris et al. 2015).

One common alternative to hard walled sea structures is beach nourishment; a ‘soft engineering’ form of management aimed at preserving natural features. Often beach nourishment involves the construction of dunes to help prevent or reduce overwash erosion where storm surges transport water and beach sediment over dune crests (Klein et al. 2001). Beach nourishment in this form is seen as a minor disturbance from which the ecosystem can rapidly recover (Harris et al. 2015). Constructed dunes can be part of management strategies to protect wildlife, increase coastal resilience to storms, and reduce coastal erosion (Nordstrom et al. 2000). In areas at risk from climate change-induced sea-level rise beach nourishment or supplementation may be part of larger management plans to protect biodiversity in coastal areas (Schlacher et al. 2007, Nicholls and Cazenave 2010). However, research is needed to assess how native wildlife are affected by different shoreline management strategies (Schlacher et al. 2007, Spalding et al. 2014).

Climate change is one of the leading threats to reptile biodiversity, and is expected to cause range contractions in up to 85% of chelonian species (Gibbons et al. 2000, Ihlow et al. 2012). Turtles possess a unique suite of life history traits, such as high adult survivorship, low hatching survivorship, delayed reproduction, and temperature-dependent sex determination, which puts them at increased risk to disturbance-induced declines leading to this clade-wide impact (Congdon et al. 1993). Tortoises (Family: Testudinidae) are likely to be hit especially hard as they exhibit low dispersal ability, high generation time, low fecundity, and low phenotypic plasticity, traits correlated with negative impacts under climate change scenarios (Staudinger et al. 2013, Rostal et al. 2014). Therefore, I evaluated the response of Gopher Tortoises (*Gopherus polyphemus*), a candidate species for listing under the Endangered Species Act and a threatened species in Florida, to soft engineering in the form of dune construction aimed at mitigating the impact of sea-level rise (Rostal et al. 2014).

Habitat loss is one of the leading threats to the genus *Gopherus*, which is likely to increase even in protected areas due to climate change, and research on potential management methods is needed (Rostal et al. 2014). By evaluating colonization rates and local population sizes on constructed dunes, I sought to test if Gopher Tortoises utilized constructed dunes similar to surrounding natural dunes.

**Materials and Methods**

*Study Site.* - Due to range-wide declines over the past century, an estimated 80% of the remaining populations of Gopher Tortoises in the US live in Florida (Auffenberg and Franz 1982). Additionally, Florida is a major biodiversity hotspot in North America, and sea-level rise combined with increased storm surges creates a major threat to both developed and protected areas as no part of the state is greater than 120 km from a coastline (James 1961, Reece et al. 2013, Zhang et al. 2013, Noss et al. 2015). The John F. Kennedy Space Center (KSC) and Merritt Island National Wildlife Refuge (MINWR) are one of the largest protected wildlife habitats along the Atlantic coast of Florida and is an area rich with biodiversity (Breininger et al. 1994a). Climate change-induced sea level rise is the leading threat to KSC, and in the past decades, overwash events have contributed to large (25-60 m wide) erosion along the coastline (Rosenzweig et al. 2014).

*Dune Construction*. - Following Hurricane Sandy in 2012, NASA proposed construction of new dunes along sections of the beach with the worst erosion in order to reduce overwash and to protect government assets (Fig. 1). NASA constructed one 214 m long dune in early 2012 (2012 constructed dune) and finished construction on another dune in March 2014 (2014 constructed dune) extending 445 m north and 1088 m south of the 2012 constructed dune (Rosenzweig et al. 2014). In total, the constructed dunes are 1.77 km long, 18.3 m high, and 24.4 m wide and help minimize overwash during storms (Fig. 2).

*Study Species.* - Gopher Tortoises create characteristic burrows that provide a stable microclimate, refuge from disturbances such as wildfires, and reduce the energy requirements on smaller burrowing animals that dig offshoots from the main Gopher Tortoise burrow tunnel (Diemer 1986, Lips 1991, Kinlaw and Grasmueck 2012). Gopher Tortoises are considered an ecosystem engineer due to the cascading effects of their burrows, and studies have shown that over 300 invertebrate and 60 vertebrate species use Gopher Tortoise burrows as commensals including several state and federally protected species such as the Eastern Indigo Snake (*Drymarchon couperi*), Southeastern Beach Mouse (*Peromyscus polionotus niveiventris*), Gopher Frog (*Lithobates capito*), and Eastern Hognose Snake (*Heterodon platirhinos*) (Hubbard 1893, Young and Goff 1939, Jackson and Milstrey 1989, Lips 1991, Witz et al. 1991).

Prior to dune construction all Gopher Tortoises found at the site were captured using bucket traps and relocated to the surrounding coastal scrub (R. Bolt, pers. comm.). Each dune was planted with native grasses and other herbaceous vegetation propagated from the surrounding area in order to aid colonization by wildlife and to stabilize the dunes.

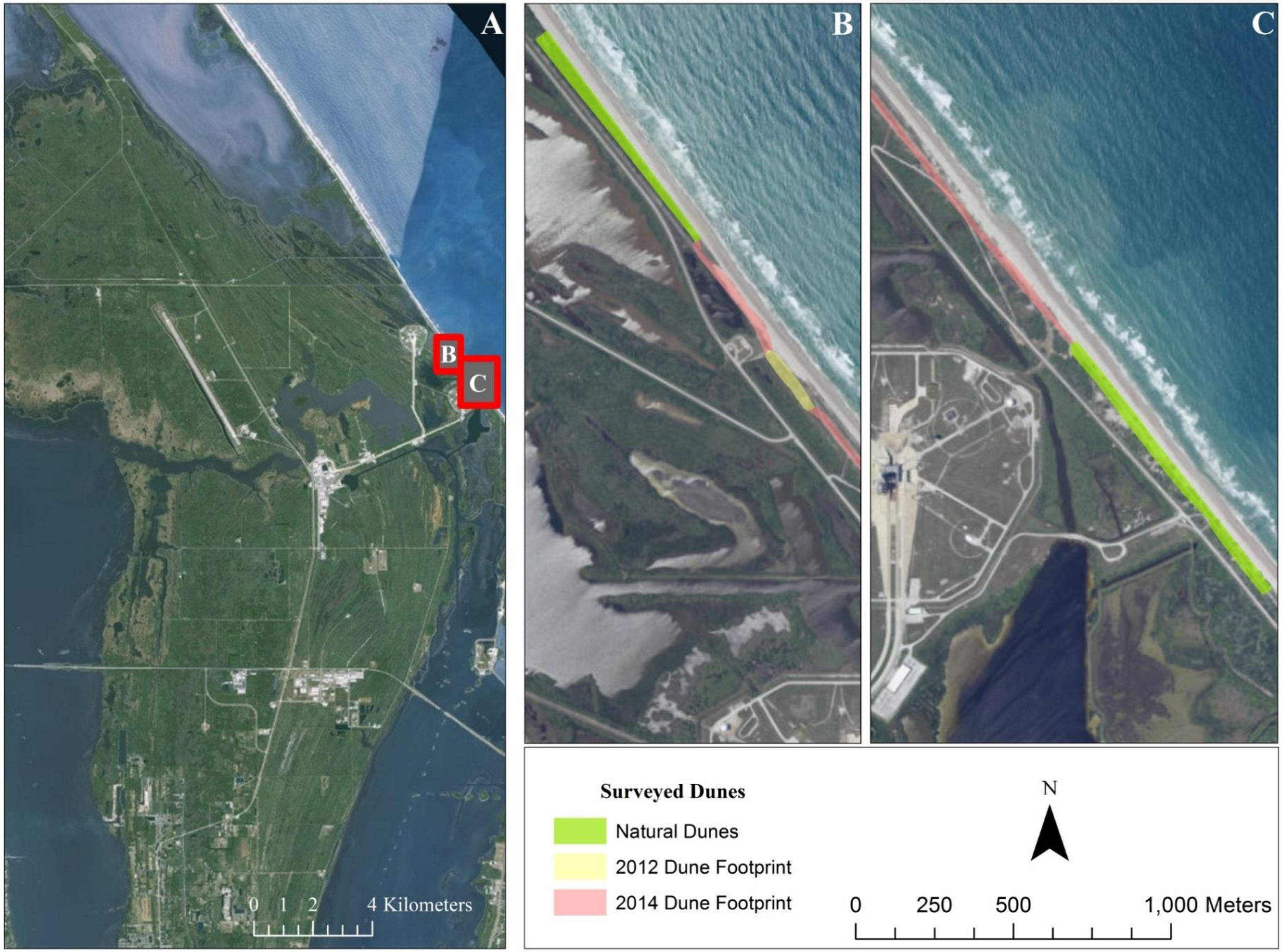


Figure 1: Map of the John F. Kennedy Space Center (A) and constructed dune footprints (B and C).

Figure 2. Vegetation along northern section of the 2014 dune with the 2012 constructed dune visible behind temporary silt fencing.

Gopher Tortoises rely on forbs and grasses to make up the majority of their diet, but are otherwise generalist herbivores, with foraging taking place from March through October in much of their range. Most foraging occurs within 30 m of their burrows (Rostal et al. 2014). Each tortoise maintains two to nine burrows in a loose social aggregation with six to twelve other tortoises (Rostal et al. 2014). Eggs are laid in late spring to early summer with each female laying only a single clutch of five to nine eggs per year, often at the entrance to the burrow (Rostal et al. 2014). Gopher Tortoises exhibit annual survival rates similar to other chelonian species with high hatchling and juvenile mortality rates (up to 90% in the first six years) that steadily declines with age down to 1-2% annual mortality for adult tortoises (Pike and Seigel 2006, Rostal et al. 2014).

*Population estimation*. - I used transect-based distance sampling in order to estimate adult tortoise burrow density along the 2012 constructed dune, the north and south sections of the 2014 constructed dune, and two natural dunes immediately north and south of the construction area (Anderson et al. 2001, Nomani et al. 2008). Dune crest lines were surveyed for the entire length of the constructed dunes, and 800 m of each natural dune was surveyed for tortoise burrows. During each survey, the seaward side of the dune and then the inland side of the dune crest were surveyed in order to meet the assumption of 100% detection for line-transect surveys at zero distance. Surveys were performed twice in the summers of both 2014 and 2015, and once in January 2015 and January 2016. This allowed me to evaluate colonization over two years and potential seasonal changes in density. For each located burrow with an entrance diameter greater than 25 cm a GPS coordinate was taken using a handheld eTrex 30 GPS (Garmin, Olathe, KS, USA), and all points were later imported into ArcMap version 10.1 (ESRI, Redlands, CA, USA).

During each winter field season, a random subset of burrows along each dune (N=20 or all burrows if less than 20 were found) were "scoped" by inserting a camera attached to a flexible conduit into the burrow to determine whether the burrow was occupied by a tortoise (Buskirk and Fiedler 1986, Breininger et al. 1991, Smith et al. 2005). These data were used to calculate the average tortoise burrow occupancy for each dune. Burrows were only scoped in winter, as this is the period of lowest activity for tortoises, and minimized the chances of falsely declaring a burrow as unoccupied (Eubanks et al. 2003, Rostal et al. 2014). Burrows were placed in one of three categories: Empty (end of burrow was seen, no tortoise present), Occupied (tortoise was observed), or Unknown (burrow became too small for adequate detection by the scope). Burrows classified as unknown were later removed from analysis in order to accurately assess occupancy rates; this method was designed to address the limitations discussed by Nomani et al. (2008) relating to incorrectly calculating tortoise occupancy rates. All parameters and density estimates are reported with one standard error.

Straight-line distance from each burrow to transect was calculated using the "Distance" tool in ArcMap. Habitat coverage on each transect was calculated by intersecting land cover data with 100 m buffer zones around each transect in order to estimate the surrounding land cover as 100 m is the area of secondary foraging for Gopher Tortoises and covers most of the land between the ocean and the inland salt marsh (Fig. 1) (Rostal et al. 2014). Percent land cover for each cover type was calculated by dividing the area of each type by the total buffer area to standardize land cover values; while the arcsine transformation is commonly used for percentage data, I did not apply it here since it may result in interpretational issues (Warton and Hui 2011). Distances for each burrow and percent habitat coverage for each transect were imported into R (R version 3.2.0, http://www.R-project.org, accessed 31 Aug 2013) using RStudio (RStudio version 0.99.441, https://www.rstudio.com, accessed 31 Aug 2013). Percent habitat coverages were then checked for correlation between covariates; percent ocean and percent infrastructure were removed from final analysis based on high correlation ($r > |0.6|$) with other covariates.

Burrow densities were estimated using the package ‘Unmarked’ to test 25 *a priori* competing hierarchical models based on land cover and categorical covariates of Gopher Tortoise burrow density and detectability; models tested are listed in Table 1, covariates and their descriptions are listed in Table 2 (Fiske and Chandler 2011). Hierarchical models use multiple component models (detection and density in this study) to explicitly describe variation due to both ecological processes and imperfect observations, each with different conditional probability structures (Royle and Dorazio 2008, Royle et al, 2014). This differs from classical multi-level modeling as each component model has an explicit biological basis (Royle et al. 2014). I included all burrows when calculating burrow density, as I only scoped burrows during the winter due to concerns over active periods causing me to falsely declare burrows unoccupied. While this methods goes against the recommendations given by Castellón et al. (2015), burrow occupancy rates in coastal environments tend to be much lower than those reported by Castellón et al. (2015), and most burrows are relatively straight and easy to scope leading to few cases of unknown burrow status (<1%).

| Model (~Detection Component Model ~Density Component Model) | ΔAIC |
|---|---|
| ~1 ~ BEACH * CONSTRUCT + INWATER + STRAND + PEPPER + RUDHERB + SCRUB | 0 |
| ~1 ~ Dune + Orientation | 59.34 |
| ~1 ~ BEACH + CONSTRUCT + STRAND + PEPPER + RUDHERB + SCRUB | 71.22 |
| ~1 ~ BEACH + CONSTRUCT + INWATER + PEPPER + RUDHERB + SCRUB | 72.26 |
| ~1 ~ BEACH + CONSTRUCT + INWATER + STRAND + PEPPER + RUDHERB + SCRUB | 72.32 |
| ~1 ~ BEACH + CONSTRUCT + INWATER + STRAND + PEPPER + RUDHERB + SCRUB + BARREN | 73.94 |
| ~1 ~ BEACH + INWATER * STRAND + PEPPER + RUDHERB + SCRUB + CONSTRUCT | 74.02 |
| ~1 ~ BEACH + CONSTRUCT + INWATER + STRAND + PEPPER + RUDHERB + SCRUB + MANGROVE | 74.04 |
| ~1 ~ BEACH + STRAND + PEPPER + RUDHERB + SCRUB + CONSTRUCT * INWATER | 74.27 |
| ~1, ~ BEACH + CONSTRUCT + INWATER + STRAND + PEPPER + RUDHERB + SCRUB + RUDWOOD | 74.32 |
| ~1 ~ BEACH * INWATER + STRAND + PEPPER + RUDHERB + SCRUB + CONSTRUCT | 74.32 |
| ~1 ~ BEACH + INWATER + STRAND + PEPPER + RUDHERB * SCRUB + CONSTRUCT | 74.32 |
| ~1 ~ BEACH + INWATER + STRAND + PEPPER + RUDHERB + SCRUB * CONSTRUCT | 74.32 |
| ~1 ~ OCEAN + CONSTRUCT + INWATER + STRAND + PEPPER + RUDHERB + SCRUB | 96.74 |
| ~1 ~ Dune | 147.79 |
| ~1 ~ BEACH + CONSTRUCT + INWATER + STRAND + RUDHERB + SCRUB | 154.87 |
| ~1 ~ Dune + Year | 358.06 |
| ~1 ~ Type | 454.61 |
| ~1 ~ Season | 457.03 |

| | |
|---|---|
| ~ Season ~ 1 | 459.94 |
| ~1 ~BEACH + CONSTRUCT + INWATER + STRAND + PEPPER + RUDHERB + SCRUB + YEAR | 529.76 |
| ~1 ~ Dune + Year + Orientation | 537.15 |
| ~1 ~Type * Year + Orientation | 666.11 |
| ~1 ~Year + Orientation | 752.65 |
| ~Season ~ Year + Orientation + STRAND + BEACH + PEPPER + CONSTRUCT + RUDHERB + INWATER + SCRUB | 934.68 |

Table 1. Burrow density models and ΔAIC scores. Tilde "~" represents the start of each components model statement, and component models are reported by detection, then density model statements.

| Covariate | Description |
|---|---|
| Type | Dune category: Natural, Construction or Older Construction |
| Dune | Unique ID for each dune |
| Year | Test for colonization over time effect |
| Season | Effect of survey timing (Summer/Winter) |
| Orientation | Seaside or inland dune face |
| BEACH | Percent of land cover classified as beach |
| STRAND | Percent of land cover classified as coastal strand |
| OCEAN | Percent of land cover classified as open ocean |
| INFRA | Percent of land cover classified as infrastructure |
| PEPPER | Percent of land cover classified as Brazilian Pepper |
| MARSH | Percent of land cover classified as marsh |
| CONSTRUCT | Percent of land cover classified as constructed |
| RUDHERB | Percent of land cover classified as ruderal herbaceous plants |
| RUDWOOD | Percent of land cover classified as ruderal woody plants |
| INWATER | Percent of land cover classified as open inland water (salt or fresh) |
| SCRUB | Percent of land cover classified as oak or saw-palmetto scrub |
| MANGROVE | Percent of land cover classified as mangrove marsh |
| BARREN | Percent of land cover classified as barren or seasonally flooded |

Table 2. Covariates and their descriptions. Land cover percentages were calculated using coarse-grain land-cover maps.

Four potential distributions (half-normal, hazard rate, negative exponential, and uniform) for detectability as a function of distance were tested using null models, with the top performing models selected using Akaike's Information Criterion (AIC) values (Akaike 1973). AIC values are based on finding the most parsimonious model by taking model likelihood and applying a penalty that increases with the number of parameters (Burnham and Anderson 2002). AIC values are reported here as hierarchical models combine multiple models into a single model; this leads to uncertainty in choice of sample size to use the alternative AIC*c* sample size based selection method. Models are considered to have equal likelihood if they are not separated by an AIC score greater than six; the more common standard of selecting the top models separated by an AIC score of two or less may lead to incorrect inferences and exclusion of important parameters (Richards 2005, 2008, Grueber et al. 2011). Model fit was assessed using a chi-squared goodness of fit test with 10,000 bootstrap samples using the package "AICcmodavg" in R (Mazerolle 2015). Confidence intervals of burrow density were then calculated using iterative bootstrapping of model predictions. Profile confidence intervals were calculated for all parameters, as this likelihood-based method does not rely on any distributional assumptions for calculating interval size (Venzon and Moolgavkar 1988).

Occupancy rates between dunes and years were tested by using generalized linear models in R using the "lme4" package to calculate average occupancy and test the effects of different dunes with year as a random effect (Bates et al. 2015). Tortoise occupancy rates for each dune were calculated by using both top models and the "predict" function in R to calculate 95% confidence intervals for burrow density and burrow occupancy rates, which were then multiplied to estimate current tortoise density along each dune. In order to increase precision, I kept the inland and coastal sides of each transect separate when calculating final tortoise density.

**Results**

The top model for burrow detectability was the null model fitted using a negative exponential function, and the top model for burrow density included percent coverage of the following landcover variables for each transect; beach, constructed dune, inland water, coastal strand, Brazilian pepper, ruderal herbaceous, scrub, and an interaction factor between beach and constructed area for burrow density. ΔAIC values for all models are listed in Table 1.

Based on the predicted distribution of values for the top burrow density model, the observed values were not significantly different than the predicted for the top model ($P$ = 0.253), and $\hat{c}$ equaled 1.08, indicating only slight overdispersion with good overall model fit. Back-transformed covariate parameters and 95% profile confidence intervals for the top model are listed in table 3.

| Parameter (SE) | Lower 95% | Mean | Upper 95% |
|---|---|---|---|
| Intercept (0.532) | -2.45 | -1.93 | -1.01 |
| Percent Beach (2.072) | 16.41 | 18.05 | 20.31 |
| Percent Construction (8.557) | 71.28 | 75.65 | 82.91 |
| Percent Inland Water (13.771) | -103.04 | -99.51 | -96.70 |
| Percent Strand (1.272) | -7.37 | -6.30 | -4.96 |
| Percent Brazilian Pepper (3.655) | -23.92 | -22.38 | -20.67 |
| Percent Ruderal Herbaceous (15.704) | 115.98 | 119.30 | 122.64 |
| Percent Scrub (38.268) | -135.69 | -128.30 | -117.87 |
| Interaction Beach:Construction (54.585) | -421.13 | -403.13 | -390.08 |

Table 3. Parameters estimates and 95% confidence intervals from the top model for Gopher Tortoise Burrow Density.

| Burrow Occupancy Models | ΔAIC |
|---|---|
| ~ Type | 0 |
| ~ (1\|Year) + Type | 2.02 |
| ~ Dune | 3.67 |
| ~ (1\|Year) + Dune | 5.67 |
| ~ 1 | 6.06 |

Table 4. Models for Gopher Tortoise Burrow Occupancy and their ΔAIC values.

Of the model set evaluated for burrow occupancy, all but the null model fell within 6 ΔAIC values of the top model (Table 4). A Wald test found a significant difference ($\chi^2$ =18, $P \leq$ 0.001) between the 2012 constructed dune occupancy and that of the natural dunes, whereas the occupancy rates of the 2014 constructed dunes did not significantly differ from either group.

Predictors accounting for differences between the older constructed dune and the natural dunes were included in all competing top models, so varying occupancy rates based on the lowest AIC value model were incorporated into the Gopher Tortoise density estimation. Final estimated Gopher Tortoise densities for each dune are given in Table 5, and burrow occupancy rates are listed in Table 6. The 2012 constructed dune had the highest overall density of all dunes, and only the southern natural inland dune had higher tortoise density than the seaward sections of the 2014 constructed dunes. Burrow occupancy rates were also higher along the constructed dunes, and highest along the 2012 constructed dune.

| Dune Face | 95% Lower CI | Mean | 95% Upper CI |
|---|---|---|---|
| North Natural Seaward | 0.04 | 0.13 | 0.37 |
| North Natural Inland | 0.01 | 0.09 | 0.67 |
| North 2014 Construction Seaward | 1.53 | 3.20 | 6.37 |
| North 2014 Construction Inland | 1.84 | 3.92 | 7.91 |
| 2012 Construction Seaward | 12.53 | 22.91 | 38.96 |
| 2012 Construction Inland | 20.51 | 35.64 | 57.57 |
| South 2014 Construction Seaward | 0.10 | 0.28 | 0.71 |
| South 2014 Construction Inland | 5.18 | 8.67 | 13.81 |
| South Natural Seaward | 1.76 | 3.41 | 6.33 |
| South Natural Inland | 5.56 | 9.66 | 16.10 |

Table 5. Gopher Tortoise density estimates (Tortoises per hectare) and their confidence intervals for each transect of each dune.

| Type (SE) | Lower 95% CI | Estimate | Upper 95% CI |
|---|---|---|---|
| Natural (0.234) | 0.191 | 0.272 | 0.371 |
| 2014 Constructed (0.233) | 0.288 | 0.390 | 0.502 |
| 2012 Constructed Dune (0.278) | 0.403 | 0.538 | 0.668 |

Table 6. Gopher Tortoise burrow occupancy rates along each dune.

**Discussion**

Based on parameter estimates for the top model, overall tortoise density was low throughout most of the study area, but increased in constructed and ruderal herbaceous areas and slightly increased near the beach. The first burrow on the 2014 dune was found approximately three months post-construction, with a rapid increase in burrows prior to the first transect being completed in the area. All three habitat types positively associated with tortoise density (beach, construction, and ruderal) had a higher proportion of open areas and herbaceous vegetation compared to the other land cover types. The negative association with other habitat types may be caused by a lack of fire management along the dunes, leading to a proliferation of woody scrub and invasive plants such as saw-palmetto, cabbage palm, sea grape, and Brazilian pepper throughout the area (Diemer 1986, Menges 2007).

My results match those of Breininger et al. (1994b), who found tortoise density at KSC to be positively associated with an increase in disturbed, herbaceous areas. Lau and Dodd (2015) also found a significant, positive relationship between herbaceous cover and coastal tortoise burrow density. My study is the first to focus on the effects of newly-created habitat, while prior studies only evaluated natural land cover types and habitat disturbed by past roadway or building construction. When looking at the parameter estimates for constructed habitat it should be noted that while beach and construction are both open areas positively associated with density, their interaction is negatively associated with density and may be due to lack of a source population of Gopher Tortoises. A lack of any nearby founding populations of tortoises is also likely why areas of inland water have strong negative associations with burrow density in the surrounding areas.

Results from this study reinforce previous studies linking open habitat areas to increasing densities of coastal Gopher Tortoises in Florida.

Although my study was not designed to estimate density of hatchling and yearling tortoises, several ($N \approx 6$) young individuals were encountered along the constructed dunes implying that constructed habitat was being utilized by smaller size classes of tortoises as well as adults (Fig. 3). I did not perform surveys for commensals along the beach, but Southeastern Beach Mice (*Peromyscus polionotus niveiventris*) were regularly documented on game cameras in the area indicating use of burrows along the constructed dunes by vertebrate commensals (S. A. Martin unpublished data).

Overall, dune construction was positively associated with higher Gopher Tortoises populations at this site, with burrow density rapidly equaling and surpassing the density compared with the natural dunes. The extremely high density along the 2012 constructed dune may be a response by Gopher Tortoises to a lack of open areas in other areas along the beach, indicating the potential for further habitat improvement along the natural dunes (Breininger 1994b). At KSC, the lack of long term fire management due to concerns over man-made structures is responsible for the proliferation of woody vegetation through the area; recent efforts to remove the invasive Brazilian pepper as part of coastal scrub habitat restoration is likely to improve the surrounding natural coastline for Gopher Tortoises at this site. Further management to improve habitat through introducing small controlled burns in order to promote the growth of herbaceous vegetation would also help to improve forage without negatively impacting other species in the area (Diemer 1986, Breininger and Smith 1992, Ashton et al. 2008). In areas where burns are not feasible due to the proximity to man-made structures, mechanical removal or reduction of woody vegetation may be a potential management option, but more research is needed on the impacts of such methods.

Coastal Gopher Tortoise populations have historically been understudied compared to their inland counterparts, and are likely to be under greater pressure to habitat loss range-wide as climate change induced sea-level rise erodes coast lines (Lau and Dodd 2015). As the effects of climate change increase, further work will be needed to assess the potential impacts on Gopher Tortoises and their commensals, including how rising temperatures may impact sex ratios among hatchling tortoises and the ability of tortoises to disperse from degrading habitat. In situations where coastal tortoise populations are threatened with rapid loss of habitat, beach nourishment through dune construction represents both a potential management strategy to mitigate habitat loss and also improvement coastal habitat.

Managing dunes has long been focused on their relationship to human settlements. I demonstrated that dune construction can also have a positive impact on Gopher Tortoises, and should be considered a potential management tool for reducing habitat loss in coastal environments. With this shift in purpose, several considerations need to be taken into account when designing management plans. Traditionally, damage to dunes following local erosion and overwash from storms was rapidly repaired, but recent efforts to utilize a more ‘dynamic management’ method has shown that constructed dune left unrepaired developed better long term vegetation profiles, and do not show any long term negative impact on dune growth (De Jong et al. 2014). By accepting the principles of dynamic management for dunes, long term costs are also reduced since construction equipment and sediment will not be needed following every storm event, and variance in native vegetation profiles will be promoted by the formation of local microhabitats due to erosion (De Jong et al. 2014). The size of constructed dunes will also greatly alter their potential longevity. Dunes greater than 30m in width are likely to last several decades in most coastal environments, while medium dunes between 5-30m showed greater variance in long term persistence, and dunes less than 5m wide lasted only a few years in previous studies (Nordstrom et al. 2000).

**Management Implications**

Managing areas for coastal resilience is a major challenge in the 21st century as climate change-induced sea level rise worsens world-wide. I have demonstrated that constructed dunes could help mediate the impact of increasing sea levels on coastal wildlife populations while also protecting man-made structures. The construction of new primary and secondary dunes in heavily eroded coastal areas to reduce erosion can also be an opportunity to increase both available habitat area and overall habitat quality in the process. This study showed that Gopher Tortoises (*Gopherus polyphemus*) responded positively to the construction of dunes in the coastal environment of a barrier island, and tortoise density along both 2012 and 2014 dunes were equal to or far greater than tortoise densities in the nearby natural dunes. Management plans utilizing constructed dune systems must decide how breach and overwash events following storms will be addressed; by allowing natural erosion to occur, natural variation in vegetation communities will be promoted and long term dune persistence will likely increase. Dynamic management also reduces the potential for major recurring costs involved in acquiring and moving sediment under traditional management. In order to minimize the rate of erosion, construction should occur outside of storm season, and dunes should be pre-planted in order to help stabilize the dunes via root systems. Short term monitoring of plant communities to remove any invasive plants either through mechanical or chemical means will also help the establishment of functional native communities.

Figure 3. Hand captured Gopher Tortoise along the southern section of the 2014 dune. The tortoise was measured then released at capture site.

**Appendix A**

TOWSON UNIVERSITY

## IACUC PROTOCOL: 03312014RS-01

To: Richard Seigel, PhD

From: Towson University Institutional Animal Care and Use Committee
Louis DeTolla, VMD, PhDl, DACLAM, IACUC Chairperson
Jack Shepard, PhD, IACUC Member
Eric Scully, PhD, IACUC Member

Date: March 31, 2014

RE: **IACUC PROTOCOL # 03312014RS-01**
***Is managed retreat a feasible option for Gopher Tortoise populations impacted by projected sea level rise in Florida***

Office of Sponsored Programs
& Research
Towson University
8000 York Road
Towson, MD 21252-0001
t. 410 704-2236
f. 410 704-4494
www.towson.edu/ospr

This is to certify that the Institutional Animal Care and Use Committee has reviewed your protocol and granted FULL APPROVAL. The approval date for this protocol is March 31, 2014.

Your protocol is approved for a period of 3 years; an annual report must be submitted to the IACUC six weeks before each anniversary of the protocol. Please note your protocol will expire March 30, 2017. If you need to extend the protocol beyond this date, you must submit an Animal Care and Use form at least three months prior to the expiration.

If you have any questions, please do not hesitate to contact the IACUC Coordinator by email (ospr@towson.edu) or by phone (410.704.2236).

X

Louis J. DeTolla, VMD, PhD, DACLAM
Chairman, IACUC

**Appendix B**

```
library(unmarked)
library(AICcmodavg)
library(aod)
library(ggplot2)
library(Rcpp)
library(lme4)
covs<-read.csv("~/R files/ThesisCov.csv")
dists<-read.csv("~/R files/ThesisDistances.csv")
transectlengths<-read.csv("~/R files/ThesisTransects.csv")
occudata<-read.csv("~/R files/burrowoccumodel.csv")
length<-transectlengths[,2]
#Checking covariates for correlations
correlations<-cor(covs[,7:13])
summary(correlations)
#don't use ocean, don't have strand and infra in same model
breaks<-seq(0,30,0.8)
yDat<-formatDistData(dists,distCol="distance",transectNameCol="transect",dist.breaks=breaks)
umf<-unmarkedFrameDS(y=as.matrix(yDat), siteCovs=covs,survey="line",
dist.breaks=breaks,tlength=length,unitsIn="m")
hist(umf, xlab="distance (m)", main="", cex.lab=0.8, cex.axis=0.8)

#Sandy North had no burrows season 1
#Null model distribution testing
haz_Null<-distsamp(~1 ~1,umf, keyfun="hazard",output="density",unitsOut="ha")
halfnorm_Null<-distsamp(~1 ~1,umf, keyfun="halfnorm",output="density",unitsOut="ha")
exp_Null<-distsamp(~1 ~1,umf, keyfun="exp",output="density",unitsOut="ha")
uni_Null<-distsamp(~1 ~1,umf, keyfun="uniform",output="density",unitsOut="ha")
summary(uni_Null)
summary(exp_Null)
summary(haz_Null)
summary(halfnorm_Null)

#Hazard and exp almost identical AIC scores
#different model testing
global<-distsamp(~SEASON ~YEAR+ORIENTATION+STRAND+BEACH+PEPPER+
        CONSTRUCT+RUDHERB+INWATER+
        SCRUB,umf, keyfun="exp",output="density",unitsOut="ha")
fm1<-distsamp(~SEASON ~1,umf, keyfun="exp",output="density",unitsOut="ha")
#Season doesn't seem important for detection. Null model better
```

```
#Broad categorical models
fm2<-distsamp(~1 ~DUNE,umf, keyfun="exp",output="density",unitsOut="ha")
fm3<-distsamp(~1 ~DUNE+YEAR,umf, keyfun="exp",output="density",unitsOut="ha")
fm4<-distsamp(~1 ~TYPE*YEAR+ORIENTATION,umf,
keyfun="exp",output="density",unitsOut="ha")
fm5<-distsamp(~1 ~YEAR+ORIENTATION+INWATER+CONSTRUCT,umf, keyfun="exp",
        output="density",unitsOut="ha")
fm6<-distsamp(~1 ~DUNE+YEAR+ORIENTATION,umf,
keyfun="exp",output="density",unitsOut="ha")
fm7<-distsamp(~1 ~TYPE,umf, keyfun="exp",output="density",unitsOut="ha")
fm8<-distsamp(~1 ~DUNE+ORIENTATION,umf,
keyfun="exp",output="density",unitsOut="ha")
fm9<-distsamp(~1 ~SEASON, umf, keyfun="exp", output="density", unitsOut="ha")

#Habitat based models
fm10<-distsamp(~1 ~BEACH+CONSTRUCT+INWATER+STRAND
        +PEPPER+RUDHERB+SCRUB, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm11<-distsamp(~1 ~BEACH+CONSTRUCT+STRAND
        +PEPPER+RUDHERB+SCRUB, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm12<-distsamp(~1 ~BEACH+CONSTRUCT+INWATER
        +PEPPER+RUDHERB+SCRUB, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm13<-distsamp(~1 ~BEACH+CONSTRUCT+INWATER+STRAND
        +PEPPER+RUDHERB+SCRUB+MANGROVE, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm14<-distsamp(~1 ~BEACH+CONSTRUCT+INWATER+STRAND
        +PEPPER+RUDHERB+SCRUB+RUDWOOD, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm15<-distsamp(~1 ~BEACH+CONSTRUCT+INWATER+STRAND
        +PEPPER+RUDHERB+SCRUB+BARREN, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm16<-distsamp(~1 ~BEACH+CONSTRUCT+INWATER+STRAND
        +PEPPER+RUDHERB+SCRUB+YEAR, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm18<-distsamp(~1 ~OCEAN+CONSTRUCT+INWATER+STRAND
        +PEPPER+RUDHERB+SCRUB, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm19<-distsamp(~1 ~BEACH+CONSTRUCT+INWATER+STRAND
        +RUDHERB+SCRUB, umf,
        keyfun="exp", output="density", unitsOut="ha")
fm20<-distsamp(~1 ~BEACH*CONSTRUCT+INWATER+STRAND
        +PEPPER+RUDHERB+SCRUB, umf,
        keyfun="exp", output="density", unitsOut="ha")
```

```
fm21<-distsamp(~1 ~BEACH*INWATER+STRAND
            +PEPPER+RUDHERB+SCRUB+CONSTRUCT, umf,
            keyfun="exp", output="density", unitsOut="ha")
fm22<-distsamp(~1 ~BEACH+INWATER+STRAND
            +PEPPER+RUDHERB*SCRUB+CONSTRUCT, umf,
            keyfun="exp", output="density", unitsOut="ha")
fm23<-distsamp(~1 ~BEACH+INWATER*STRAND
            +PEPPER+RUDHERB+SCRUB+CONSTRUCT, umf,
            keyfun="exp", output="density", unitsOut="ha")
fm24<-distsamp(~1 ~BEACH+INWATER+STRAND
            +PEPPER+RUDHERB+SCRUB*CONSTRUCT, umf,
            keyfun="exp", output="density", unitsOut="ha")
fm17<-distsamp(~1 ~BEACH+STRAND
            +PEPPER+RUDHERB+SCRUB+CONSTRUCT*INWATER, umf,
            keyfun="exp", output="density", unitsOut="ha")

fmlist<-
fitList(global,fm1,fm2,fm3,fm4,fm5,fm6,fm7,fm8,fm9,fm10,fm11,fm12,fm13,fm14,fm15,fm16,
fm18,fm19,fm20,fm21,fm22,fm23,fm24,fm17)
modSel(fmlist)
#testing fit
fitfm20 <- Nmix.gof.test(fm20,nsim=100,plot.hist=TRUE)
fitfm20
#fm20 is top model and works well, c-hat is fine and fit good
#Trying to get confidence intervals and back transform

paracoef<- coef(fm20, type='state')
#calculate asymtotic profile CI, more accurate
paraciint <- confint(fm20, type='state', method = 'profile')
#need to back transform from arcsine using (sin(x))^2

#Rate for detection exponential model
rate<-backTransform(fm20, type='det')

#This will plot out the detection function
modelrate<-coef(fm20, type='det')
plot(function(x) gxexp(x, rate=modelrate[1]), 0, 30,
    xlab="Distance (m)", ylab="Detection prob.")

#backtransform to get density, made one set of new data matching conditions on each side of
each dune
NNB<- data.frame( BEACH= 0.199, CONSTRUCT= 0,INWATER =0,STRAND=0.38,
PEPPER=0, RUDHERB=0.0,SCRUB=0.0)
NNI<- data.frame( BEACH= 0.002, CONSTRUCT= 0,INWATER =0.01,STRAND=0.51,
PEPPER=0.198, RUDHERB=0.079,SCRUB=0.0)
```

```
SNB<- data.frame( BEACH= 0.161, CONSTRUCT= 0.193,INWATER =0,STRAND=0.15,
PEPPER=0, RUDHERB=0.0,SCRUB=0.0)
SNI<- data.frame( BEACH= 0, CONSTRUCT= 0.146,INWATER =0.211,STRAND=0.086,
PEPPER=0.088, RUDHERB=0.14,SCRUB=0.0)
PB<- data.frame( BEACH= 0.129, CONSTRUCT= 0.222,INWATER =0,STRAND=0.301,
PEPPER=0, RUDHERB=0.0,SCRUB=0.0)
PI<- data.frame( BEACH= 0, CONSTRUCT= 0.156,INWATER =0,STRAND=0.117,
PEPPER=0.61, RUDHERB=0.073,SCRUB=0.0)
SSB<- data.frame( BEACH= 0.221, CONSTRUCT= 0.069,INWATER =0,STRAND=0.234,
PEPPER=0, RUDHERB=0.0,SCRUB=0.0)
SSI<- data.frame( BEACH= 0, CONSTRUCT= 0.192,INWATER =0,STRAND=0.339,
PEPPER=0.382, RUDHERB=0.01,SCRUB=0.0)
SB<- data.frame( BEACH= 0.356, CONSTRUCT= 0,INWATER =0,STRAND=0.312,
PEPPER=0, RUDHERB=0.0,SCRUB=0.0)
SI<- data.frame( BEACH= 0, CONSTRUCT= 0,INWATER =0.006,STRAND=0.609,
PEPPER=0, RUDHERB=0.136,SCRUB=0.049)

northnatB <- predict(fm20,newdata=NNB, type = "state")
northnatI <- predict(fm20,newdata=NNI, type = "state")
sandynorthB <- predict(fm20,newdata=SNB, type = "state")
sandynorthI <- predict(fm20,newdata=SNI, type = "state")
pilotB <- predict(fm20,newdata=PB, type = "state")
pilotI <- predict(fm20,newdata=PI, type = "state")
sandysouthB <- predict(fm20,newdata=SSB, type = "state")
sandysouthI <- predict(fm20,newdata=SSI, type = "state")
southnatB <- predict(fm20,newdata=SB, type = "state")
southnatI <- predict(fm20,newdata=SI, type = "state")


#Burrow Occupancy data from scoping
occudata$year<-factor(occudata$year)
occudata$dune<-factor(occudata$dune)
occudata$type<-factor(occudata$type)
occumodel<-glm(occu~dune,family="binomial", data=occudata)
occuboth<-glm(occu~(year)+dune,family="binomial", data=occudata)
occunull<-glm(occu~1,family="binomial", data=occudata)
occutype<- glm(occu~type, family ="binomial", data=occudata)
occutypelmer<- glm(occu~type + (year), family ="binomial", data=occudata)
confint(occumodel)
#tests for significance of dune overall
wald.test(b = coef(occutype), Sigma = vcov(occutype), Terms = 1:2)
exp(cbind(OR = coef(occutype), confint(occutype)))
predictdata<-with(occudata,data.frame(type=factor(1:3)))
predictdata$duneP <- predict(occutype, newdata = predictdata, type = "response")
occupredict <- cbind(predictdata, predict(occutype, newdata = predictdata, type="link",
se=TRUE))
```

```
occupredict <- within(occupredict, {
  PredictedProb <- plogis(fit)
  LL <- plogis(fit - (1.96 * se.fit))
  UL <- plogis(fit + (1.96 * se.fit))
})
```

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Curriculum vitae

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**EDUCATION**

MS in Biology, GPA: 4.0 — Expected Spring 2016
Towson University, MD
Thesis title: Response of an Ecosystem Engineer to Large-scale Dune Construction: Implications for Coastal Wildlife and Management
Advisor: Richard A. Seigel

BSc in Mathematics — 2011
University of Texas at Austin

**PUBLICATIONS AND GRANTS**

New Passive Survey Technique for Herpetofauna: Combining Drift Fences with Game Cameras (manuscript in preparation)

Explorers Club of Washington — 2014
Research Grant — $2,156

Towson Graduate Student Association — 2014
Student Travel Grant — $200

**AWARDS AND HONORS**

Gopher Tortoise Council — 2014
2nd Place Student Presentation
Student Travel Award — $100
Wildlife Society of MD/DE Chapter — 2015
1st Place Student Poster

**CONFERENCE ACTIVITY**

Wildlife Society of MD/DE Chapter (September 2015) — 2015
Student Poster: Remote Surveying for Reptiles and Amphibians: New Applications for Game Cameras

Gopher Tortoise Council Annual Meeting (October 2014) — 2014
Student Presentation: Usage of Man-made Dunes by Gopher Tortoises (*Gopherus polyphemus*) in Central Florida: Preliminary results.

**TEACHING EXPERIENCE**

Towson University

Fall-Spring, 2013-2016; Head TA 2014-2016 Principles of Biology (Lab)

Sole-taught lab sections and oversaw training for incoming TAs

**RESEARCH EXPERIENCE**

John F. Kennedy Space Center, FL 2013-2015

Managed Retreat in Gopher Tortoises

PI: Richard Seigel and Chris Parkinson

Smithsonian Biological Conservation Institute 2012-2013

Lowland Leopard Frog gene expression

PI: Anna Savage

Assisted in captive rearing and monitoring of Lowland Leopard Frogs to assess population specific immune gene expression following exposure to chytrid fungus.

Panamanian Golden Frog commensal fungus trials

PI: Brian Gratwicke

Assisted in captive rearing and monitoring of Panamanian Golden Frogs to assess potential for symbiotic skin fungus to ward off chytrid infection

Brackenridge Field Laboratory, University of Texas 2009-2011

Supervisor: John Abbott

Sorted and identified specimens for collections, and aided in public outreach programs.

**UNIVERSITY SERVICE**

Towson Biology Graduate Student Association 2014-2015

Treasurer/Founding Member 2014

Coauthored introductory guide to R for graduate students 2014

**RELATED PROFESSIONAL SKILLS**

Software proficiency: R/RStudio, ArcGIS, GENPRESS

Statistical Skills: Model Selection, Distance modelling, Detectability and Occupancy, Multivariate analysis

Field Skills: Radio-telemetry, Distance sampling, Small mammal trapping, Herpetofauna surveys