Disturbance and Recovery of Sooty Tern Nesting Colony in Dry Tortugas National Park

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Abstract:

The sooty tern (*Onychoprion fuscatus*), an abundant pelagic seabird common throughout tropical waters, is an important ecological indicator for the health of the world's oceans due to its widespread distribution and long life history. The nesting colony on Bush Key, Dry Tortugas National Park has been the subject of a 16-year monitoring effort to track changes in nesting population and plant community present on the island. A devastating hurricane season in 2005 reduced available nesting habitat by over 70%. By 2013, available habitat had recovered to 92% of pre-disturbance levels. Recovery of nesting pairs continues to lag with an estimated 16,000 in 2016, compared to 40,000 in 2001. Plant community composition remains significantly altered. This analysis is vital to park managers charged with protecting the natural resources of our National Parks. Continued monitoring will be necessary to assess emerging threats to marine resources, such as climate change and increased anthropogenic pressures.

Contents

Introduction:

The sooty tern (*Onychoprion fuscatus*) is a medium-sized pelagic seabird of the family Sternidae. It is found throughout the tropical and subtropical oceans and nests in dense colonies on rocky or coral islands (Schrieber et al. 2002). Sooty terns are ground-nesting seabirds and usually breed in open areas (Schrieber et al. 2002). However, colonies exposed to aerial predators have been found to change their behavior and nest under vegetative cover (Feare et al. 1997; Colchero et al. 2010). Although sooty terns are currently not a threatened species, their global distribution and life history makes them an important ecological indicator, reflecting the health of the world's oceans.

The nesting colony on Bush Key in Dry Tortugas National Park is estimated to support between 50,000 and 75,000 sooty terns each year (Tennesen 2007). Terns begin to arrive up to 2 months before the first eggs are laid. Nests consist of a shallow scrape in the sand, either in the open or under vegetative cover. Accounts from the 1960's indicate that sooty terns arrived to breed in the Dry Tortugas in April. In recent years, however, the terns have begun nesting late in January (Colchero et al. 2010). The cause of this major shift in breeding behavior remains unknown. Pressures from overfishing and climate change are considered potential causal agents of the observed shifts in nesting behavior. Due to this shift in timing, the sooty terns on Bush Key are exposed to aerial predators that winter on the islands. It is thought that increased aerial predation has caused the terns to prefer nesting in vegetated areas (Colchero et al. 2010).

The island is closed to visitors during the nesting season to protect the birds from human disturbance. Despite this protection, the colony faces threats of habitat loss due to storm events and sea level rise. Hurricanes typically strike the Dry Tortugas every five to six years, and can cause severe impacts (Port 2014). Because hurricanes typically approach from the southeast, the islands are hit hardest by initial prevailing winds out of the northeast, which tends to cause westward movement of sediments (Port 2014).

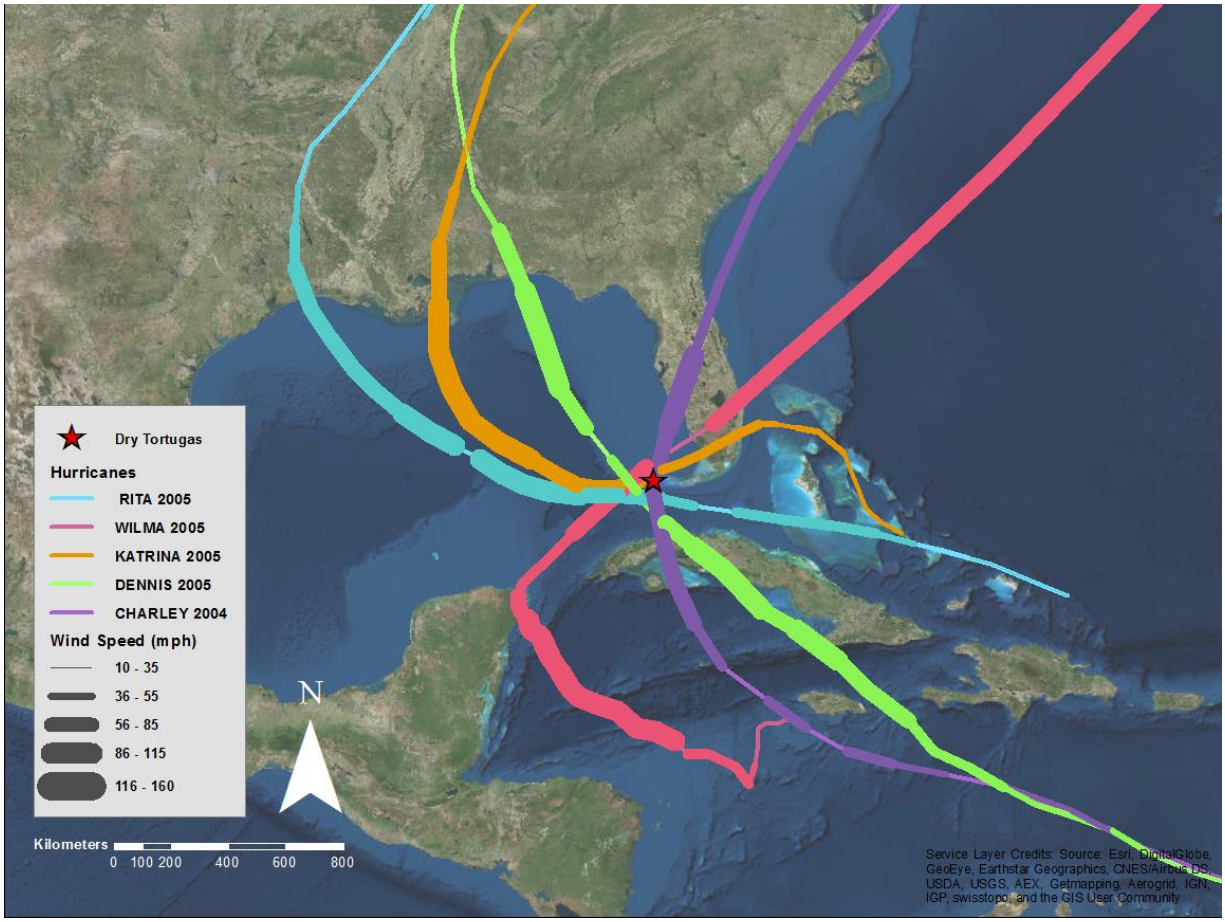

Figure 1: Storm tracks for hurricanes affecting Dry Tortugas National Park in 2004 and 2005.

In 2004 and 2005, an unusually large number of hurricanes affected the islands. Hurricane Charley passed directly over the islands in 2004. In the following year, Dennis, Katrina, Rita and Wilma hit consecutively, causing major damage to park resources (Fig. 1). Over-wash from these storms stripped Bush Key of most of its vegetation. The estimated total number of nests on Bush Key dropped from 28,000-34,000 during 2001-2005, to about 4,000 nests in 2007, with recovery evident by 2008 (approximately 18,000 nests) (Colchero et al. 2010).

In addition to severe disturbance from hurricanes, the sooty tern colony is vulnerable to more gradual coastal processes, including erosion and sea level rise, which may reduce suitable habitat for nesting. Because of their low-elevation and gentle coastal slope, the islands of the Dry Tortugas are vulnerable to rising sea level. The northern shore of Bush Key is highly vulnerable to sea-level rise, while the south shore was classified as low-vulnerability due to accretion and low wave energy (Pendleton et al. 2004). Mean sea level has risen at approximately 2.33 millimeters per year at Key West over the past 100 years (NOAA).

The National Parks Service is mandated to protect and manage all natural resources within our National Parks. In light of climate change predictions, the Parks Service is particularly interested in understanding how disturbance events affect vegetation and island morphology, as well as the ability of the terns to recover from disturbance. This knowledge will be crucial to the successful management of the colony. As hurricanes in the Atlantic are predicted to intensify due to climate change (Knutson et al. 2010; Holland and Bruyère 2014), storms will continue to impact the breeding habitat of sooty terns on Bush Key. Management will be further complicated by the added threat of increased rates of sea-level rise (Levitus et al. 2012). The identification of management strategies will become increasingly important to the preservation of the sooty tern as the effects of climate change reduce their breeding habitat worldwide.

As part of joint initiative by the Florida Fish and Wildlife Conservation Commission and the National Parks Service, the breeding colony at Bush Key has been the subject of a long-term data collection project tracking the changes in vegetation and breeding behavior on the island. The goal of this study is to use these surveys to assess the impacts of large disturbances on sooty tern nesting habitat and nesting numbers. In order to accomplish these goals, I first use geospatial analysis to assess changes in island geomorphology and available nesting habitat. I then analyze changes in both vegetation cover and nesting effort over the past 16 years. Finally, I develop a model to describe vegetation preference for sooty tern nest sites. In addition, I identify areas of further research that may aid the National Park Service in protecting the integrity of the breeding colony.

Methods:

Study Site:

The Dry Tortugas lie approximately 113km west of Key West and are the most remote of the Florida Keys. The small, atoll-like islands represent less than 1% of the total area of Dry Tortugas National Park, which encompasses 262 km^2 of primarily pristine marine habitat,

including coral reefs, sandy shoals and seagrass beds. Located near the southern edge of the Florida Platform, the islands formed during the Holocene as a result of wave action and a rise in sea-level which produced mounds of carbonate sand (Pendleton et al. 2004). The archipelago is highly dynamic, with islands constantly changing in size and shape, and occasionally disappearing or emerging completely due to hurricane impacts.

Bush Key is home to the only Sooty Tern nesting colony in the continental United States. It is located directly east of Garden Key, the site of the nineteenth century Fort Jefferson, and is connected to Long Key at the northeastern tip in most, but not all years. The island has changed in size and shape, becoming more elongated in an east-west orientation over the past 60 to 70 years (Port 2014). In more recent years, significant erosion has occurred on the eastern and northern shores, while the southern shore has shown moderate accretion. Compared to the other islands, Bush Key is moderately stable, with the western side remaining relatively unchanged over the past 16 years. Sediment transport in this area is generally to the west, causing Bush Key to move gradually closer to Garden Key (Port 2014). A sand bar intermittently forms to connect these two islands as a result of storm events. Land cover on the island includes dune associated vegetation communities and shrubland on the western side, and predominantly sparse vegetation-sand cover on the central isthmus and eastern side (Luciani et al. 2011).

Data Collection:

From 2001 to 2016 we surveyed the Sooty Tern colony on Bush Key each year during the nesting period. We generated a random set of survey plots by overlaying a grid of 20 m^2 cells on a 2000 image of Bush Key and randomly selecting a point within each cell. At each of the 133 points, we surveyed a circular plot with a radius of 2.65 m, effectively sampling approximately 5% of total island area. Plots were located at 3m apart so as not to overlap with adjacent sampling areas. We marked the location of the points with PVC pipes and the same plots were sampled each year, unless lost to erosion or inaccessible due to dense cactus coverage. Rising water levels destroyed 12 plots by 2016. The total number of plots sampled

each year ranged from 116 to 133, except in 2008, 2010, and 2013 when logistical restraints led to sample sizes of 78, 87, and 87, respectively.

In each plot, we used a modified Braun-Blanquet cover scale to estimate cover of vegetation species with the following percent intervals: <5, 2-25, 25-50, 50-75, 75-95, >95 (Mueller-Dombois and Ellenberg 1974). We then calculated the interval midpoint for each cover type and values were normalized so that cover in each plot summed to 100%. In addition, we counted eggs, depredated eggs, and total nests at each plot. Any egg shells present within the plot were counted as "depredated".

Statistical Analysis:

I used a linear model to test the effect of plant species on sooty tern nest density. I assessed main effects of plot, sampling year, and common plant species on the total number of nests recorded at each plot. Plot and sampling year were treated as categorical factors. To assess vegetation preferences, I used the normalized midpoint value for the 8 most common plant species. I performed all statistics using RStudio Version 0.98.1073.

Geospatial Analysis:

Using satellite imagery for five years spanning 2001-2013, I generated estimated shoreline profiles (Table 1). The 2016 shoreline profile was recorded in the field using a Trimble Juno handheld GPS unit. In order to estimate total island area and available habitat area, I produced an unsupervised maximum likelihood classification of the raster images using the Iso Cluster tool in ArcGIS with default parameters. I then reclassified the raster into sand and vegetation and summed the area to estimate total area and vegetated habitat area. I used ArcGIS 10.3.1 for all spatial analysis.

Table 1: Year, source and resolution of imagery used for shoreline and island area estimates.

Year	Source	Resolution (m^2)
2001	IKONOS Satellite Imagery	4
2003	QuickBird Satellite Imagery	1
2007	National Agriculture Inventory Program	1
2010	National Agriculture Inventory Program	1
2012	USGS High Resolution Orthoimagery	0.15
2013	National Agriculture Inventory Program	1

Results:

Island Change:

Erosion is evident on both the eastern and northern shoreline of Bush Key, while the southern shore remains relatively stable (Fig. 2). The spit connecting Bush and Garden keys, while completely washed out in 2005, has grown to be substantially wider than pre-hurricane years (Fig. 2). Total island area has declined slightly over the 16-year period, with an anomalous year in 2010, when the island reached a maximum size of 73,500 m^2 (Fig.3). As expected, total vegetated area was greatly reduced in the years following the hurricanes. Vegetation cover was reduced by approximately 60% in 2007 to 15,500 m^2, compared with an estimated 38,500 m^2 in 2003. By 2013, plant cover had recovered to pre-hurricane conditions, with approximately 42,200 m^2 of vegetated habitat (Fig. 3).

Nesting Effort:

The average number of nests per plot fluctuated between 11.4 and 13.0 during the period from 2001 to 2005, followed by sharp decline in 2006 and 2007 (5.2 and 1.7 average nests per

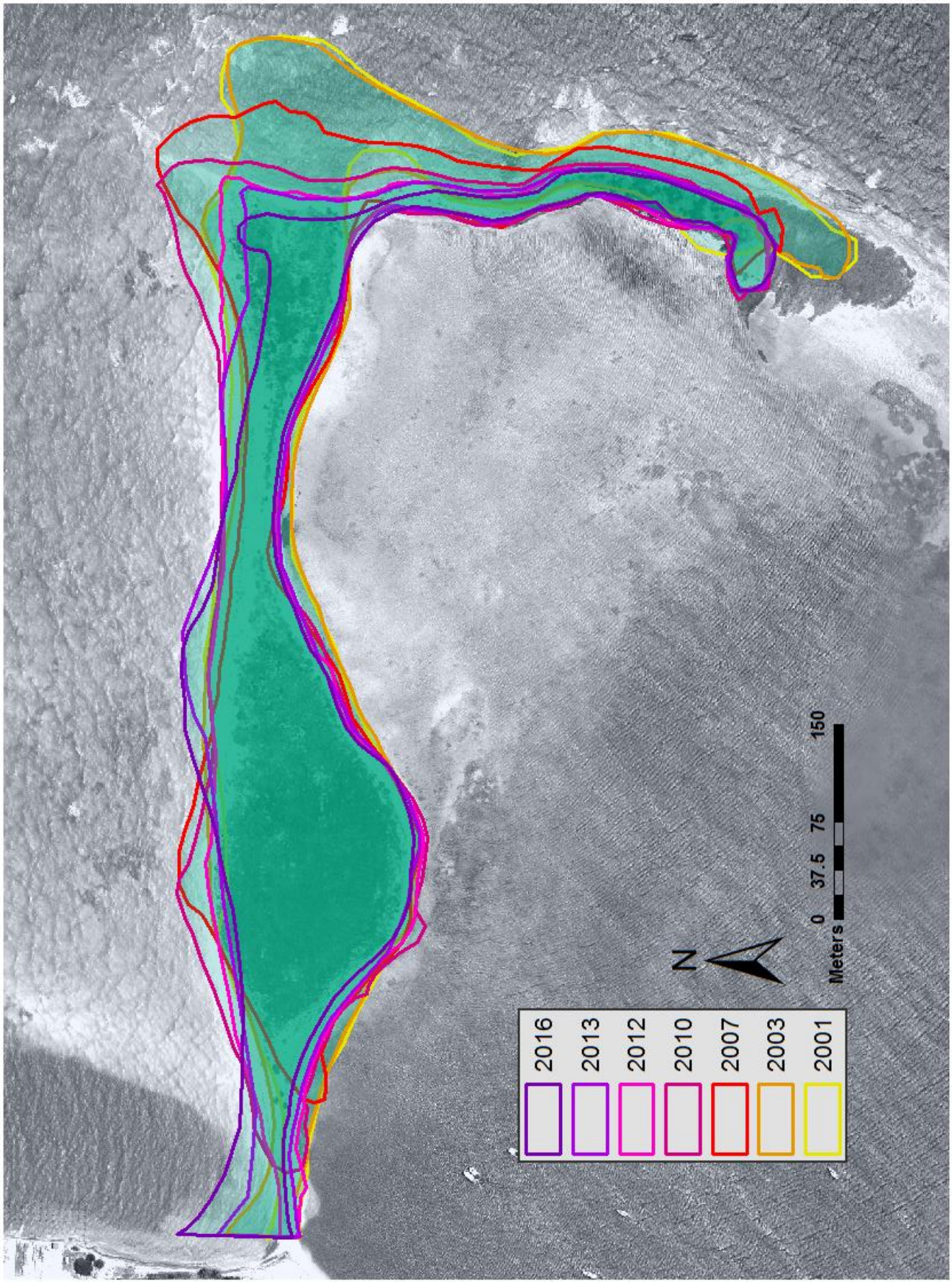

Figure 2: Movement of Bush Key from 2001 to 2016. Image from 2012.

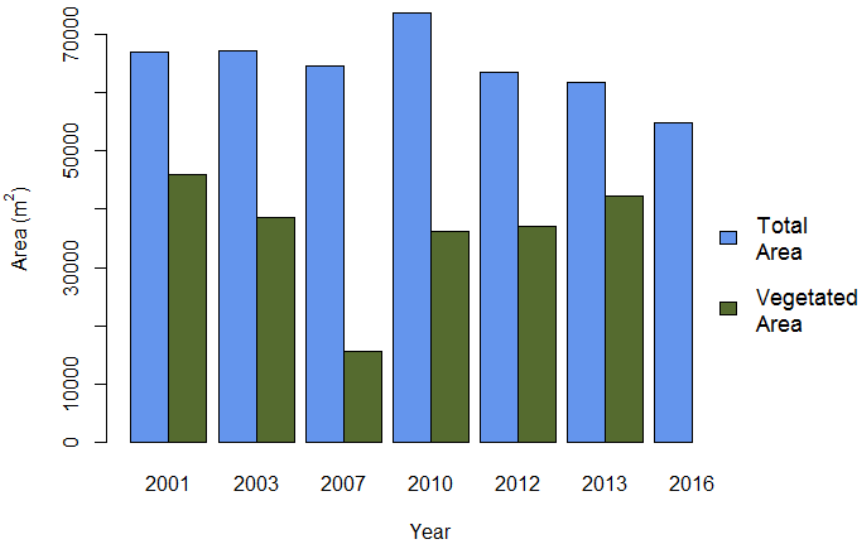

Figure 3: Total island area and area of available vegetated habitat present on Bush Key from 2001 to 2016.

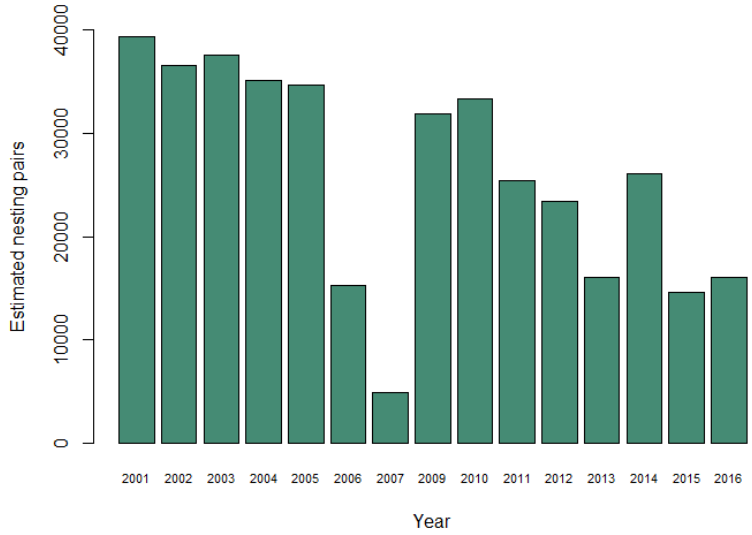

Figure 4: Average total nesting pairs for each year of the nesting survey. Data from 2008 omitted due to missing values.

plot, respectively). Nesting effort has since recovered, although it remains below pre-hurricane levels, with average nests per plot ranging between 5.7 and 10.0 from 2009-2016. We calculated the total number of sooty nesting pairs by multiplying the average nest density per year by the total area sampled, and scaling up to the entire available area. Nesting pairs have declined from an average of 36,685 in pre-hurricane years to an average of 20,285 pairs in the past five years (Fig. 4).

Vegetation Trends:

The hurricanes of 2004 and 2005 had significant and lasting effects on the plant community present on Bush Key. Vegetation cover was severely reduced in 2006 and species composition changed significantly post-disturbance (Fig. 5). Species evenness appears to be lower post-hurricane, with sea rocket dominating (Fig. 5). Diversity was also greatly reduced post-disturbance. In 2005, twelve different species represented at least 1% of average cover per plot, falling to only 6 species in 2006. Both evenness and richness appear to be recovering in recent years (Fig. 5), with 8 species representing at least 1% of average cover in both 2015 and 2016.

Mangrove species were completely eradicated from the island as a result of the hurricanes, while bay cedar (*Suriana maritima*), prickly pear (*Opuntia stricta*), and sea purslane (*Sesuvium portulacastrum*) were greatly reduced. Sea rocket (*Cakile lanceoata)* cover increased from an average of 1.2% from 2001-2005 to 26.4% since 2009, becoming the predominant vegetation type on the western side of the island (Figs. 6 & 7).

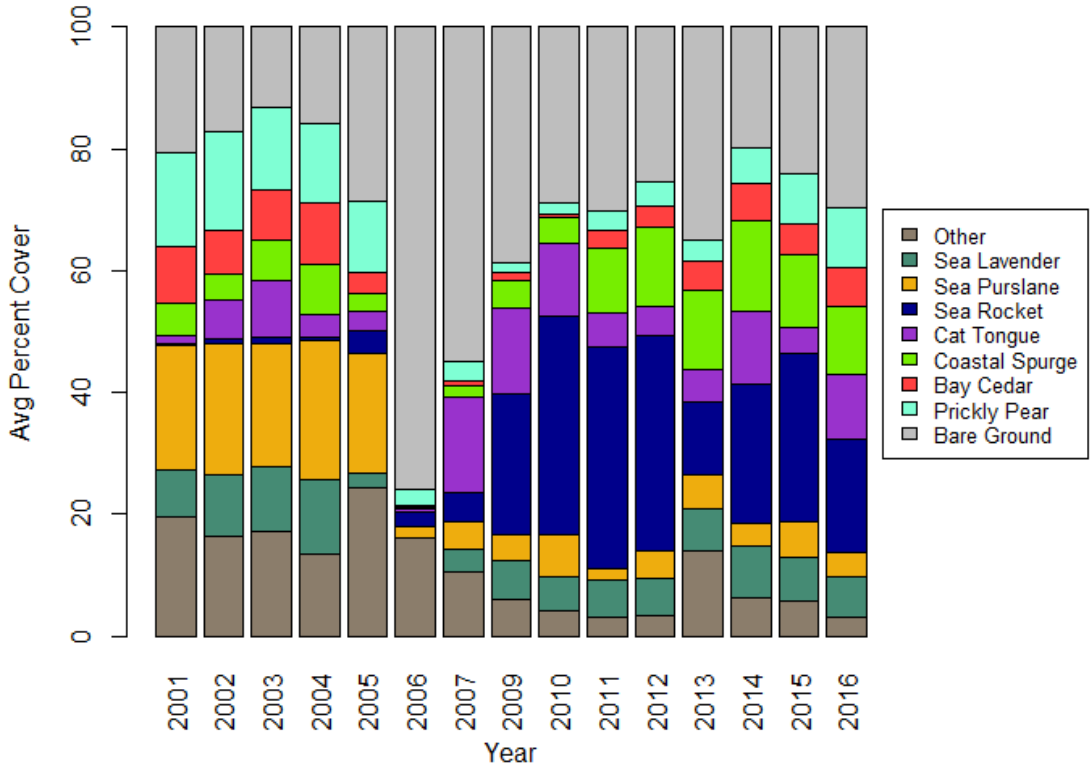

Figure 5: Average percent cover of vegetation and bare ground cover types per year. Data from 2008 omitted due to missing values.

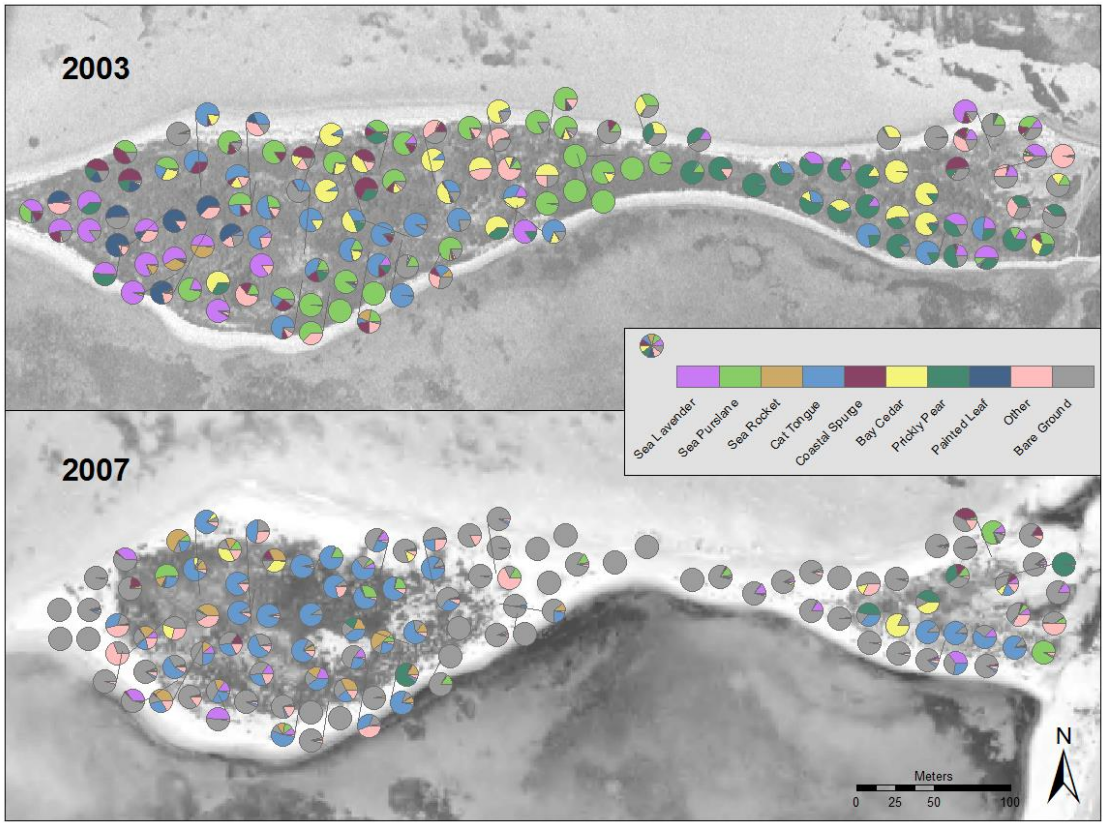

Figure 6: Percent cover of bare ground and vegetation types for 2003 and 2007. Images from 2003 (top) and 2007 (bottom).

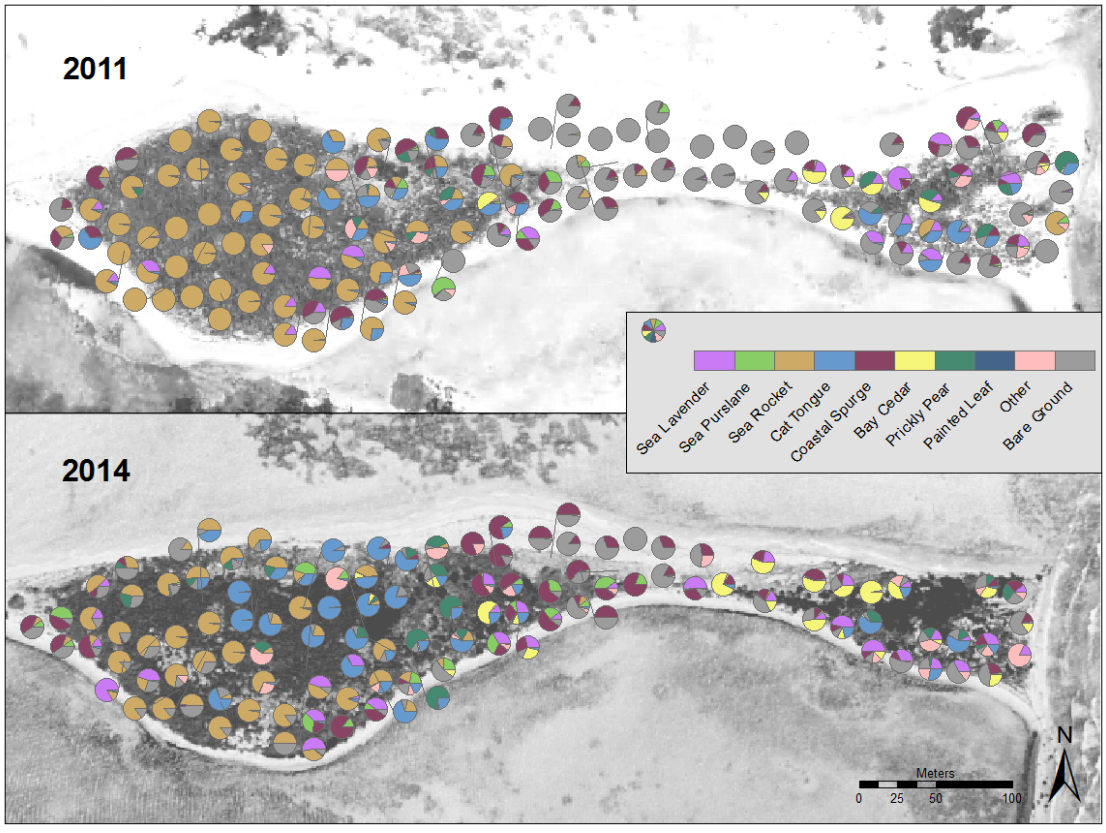

Figure 7: Percent cover of bare ground and vegetation types for 2011 and 2014. Images from 2010 (top) and 2013 (bottom).

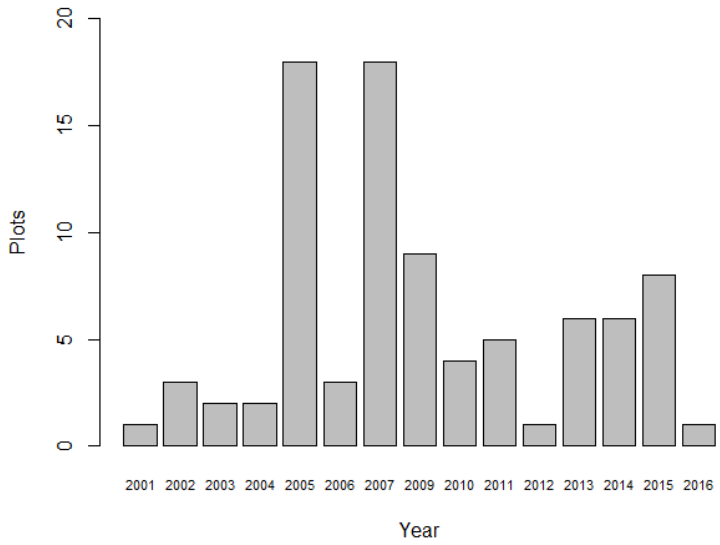

Figure 8: Occurrences of crowsfoot grass in survey plots from 2001 to 2016

In contrast, sea purslane cover decreased from an average of 20.9% during pre-hurricane years to 4.6% since 2009 (Figs. 6 & 7). In general, plant cover recovered more rapidly on the western side of the island (Fig. 7).

Crowsfoot grass (*Dactyloctenium aegyptium)*, an invasive species of particular concern to park managers, was found in 18 plots in both 2005 and 2007, the highest number recorded over the 16-year study period (Fig. 8). Its presence on the island has since declined, with only one occurrence in plots sampled in 2016.

Nesting Preference:

Nesting habitat preference appears to correspond to patterns in vegetation cover. In the years prior to the hurricanes, nesting effort was spread across Bush Key, with terns nesting on the both the western and eastern ends of the island (Fig. 9). Following the low nesting numbers in 2006 and 2007, nesting effort increased, with terns appearing to prefer areas of highest vegetation cover (Fig. 10). Interestingly, the terns appear to avoid the eastern end of the island completely in the majority of years following the storms, even after vegetative cover recovered significantly.

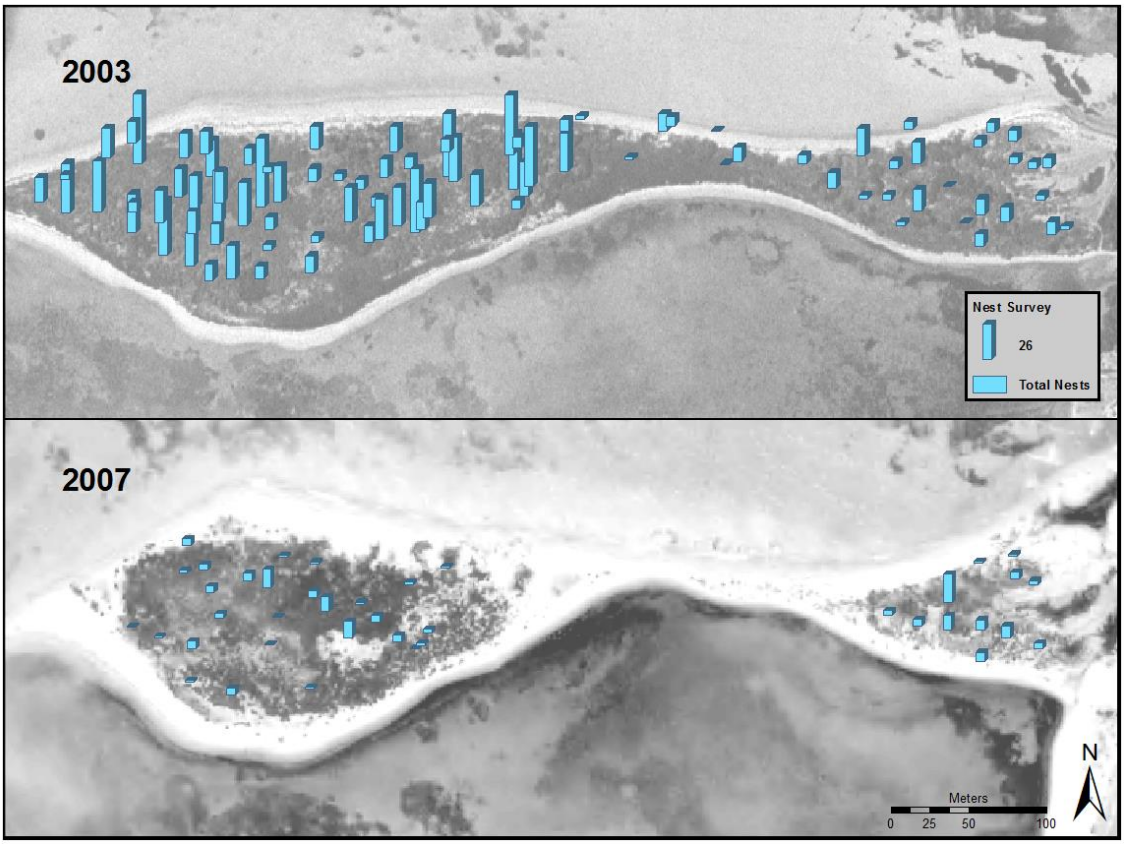

Figure 9: Total nests per plot for 2003 and 2007. Images from 2003 (top) and 2007 (bottom).

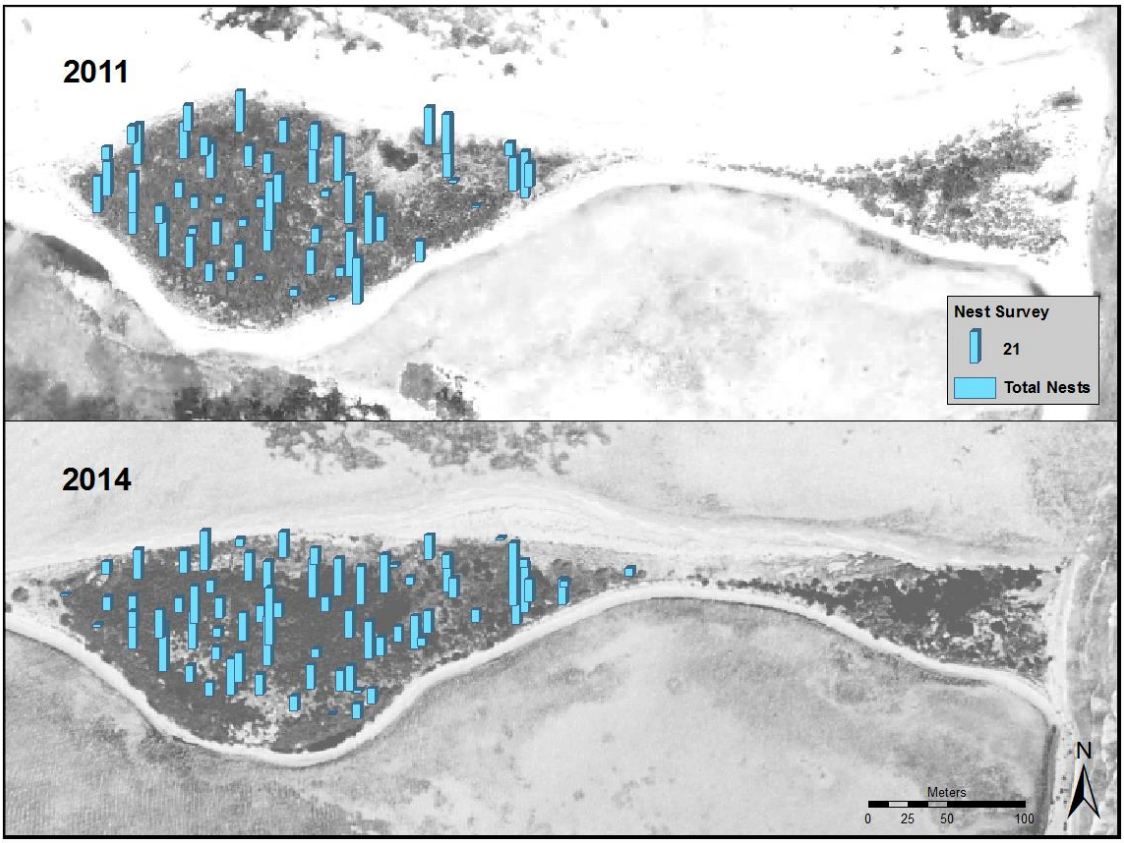

Figure 10: Total nests per plot for 2011 and 2014. Images from 2010 (top) and 2013 (bottom).

Results of the linear model showed significant main effects for plot, year, and all common vegetation types except bay cedar and coastal spurge (Adjusted $R^2 = 0.42$, $F_{156,1673} = 9.624$, $p < 0.001$) (Table 2). Sea lavender (*Argusia gnaphalodes*) and cat's tongue (*Melanthera aspera*) were shown to have a positive effect on nest density, with a 1% increase in coverage producing an increase of 0.07 and 0.05 nests, respectively. Bare ground and sea purslane were found to have the largest negative effect on nest density, with a 1% increase in coverage producing a decrease of 0.13 and 0.18 nests, respectively.

Table 2: Effect size, t-value, and significance from the ANOVA model assessing vegetation preference for sooty tern nests.

	Coefficient Estimate	**t-value**	**Significant ($\alpha < 0.05$)**
Sea Lavender	0.07	3.34	*
Sea Purslane	-0.17	-10.50	*
Prickly Pear	-0.07	-3.70	*
Bare Ground	-0.13	-8.68	*
Cat's Tongue	0.05	2.66	*
Coastal Spurge	-0.06	-2.44	
Sea Rocket	-0.09	-5.68	*
Bay Cedar	0.001	0.03	

Discussion:

Nesting Habitat:

Bush Key has remained relatively stable over the past 16 years. The observed westward shift is consistent with documented sediment transport patterns. Continued erosion of the eastern end of the island, as well as the westward shift of vegetated habitat, may eventually force terns to nest closer to Garden Key and, therefore, closer to disturbance from park visitors.

In general, we find that the nesting colony ecosystem is resilient to disturbance. Despite an almost complete loss of vegetative cover immediately following the strong hurricane season, total available habitat recovered within 5 years. However, changes in the magnitude, duration and frequency of disturbance regimes have been shown to make ecosystems more vulnerable to shifts to an undesired state (Folke et al. 2004). Increased intensity and frequency of hurricanes in the Atlantic (Knutson et al. 2010; Holland and Bruyère 2014) may shorten the recovery interval between large disturbances and suppress the ability of the island to recover following disturbance. This could potentially reduce the available nesting habitat for sooty terns in the future.

Nesting Effort:

While nesting effort recovered somewhat following the hurricane season in 2005, our survey suggests an overall decline in the number of nesting pairs on Bush Key. This decline, despite the complete recovery of vegetation on the island, suggests that other factors are affecting the birds either on their feeding grounds or along their migratory route. Food availability is a major factor controlling seabird populations during the breeding season (Ashmole 1963, Oppel et al. 2015). Recent literature suggests that climate change may produce changes in the timing and abundance of upwelling events and forage fish productivity, leading to bottom-up effects on marine food webs (Snyder et al. 2003). In 2005, an anomalous weather pattern caused delayed upwelling and zooplankton blooms off the coast of California, leading to a failure of the breeding colony of Cassin's auklets due to reduced foraging success at the breeding site (Sydeman et al. 2006). Further investigation into the feeding ecology of the sooty tern population are needed to identify the mechanisms that might be responsible for this decline in nesting effort and to predict how climate change will impact the species.

The lack of nests on the eastern end of the island is likely due to a temporal delay in nest establishment, rather than a lack of suitable habitat on this end of the island. In recent years, terns have been observed to nest later (early to mid-April) on the eastern side, which may have resulted in a temporal mismatch in the survey. Because the survey is conducted in early

to mid-March, this mismatch may be skewing our estimates of breeding pairs. The observed decline in nesting effort could be explained, in part, by the exclusion of late-nesting terns in the nesting pair estimates.

Vegetation Preferences:

Our survey results suggest that sooty terns prefer to nest in sea lavender and cat's tongue, while they avoid bare ground and sea purslane. Both sea lavender and cat's tongue tend to grow as short shrubs, while sea purslane is a succulent that often covers the ground in a dense mat. Our findings are consistent with Colchero's previous work, which found that sooty terns on Bush Key prefer nesting under shrubs as compared to forbs and bare ground. Sea lavender and cat's tongue allow the terns to nest on bare sand, while providing a refuge from aerial predators such as magnificent frigatebirds and peregrine falcons, which are common on the island during the breeding season. In contrast, dense patches of sea purslane prevent access to sandy substrate and provide no protection from predators. These results highlight the importance of plant morphology. Sooty terns prefer a certain type of plant structure , but are not necessarily reliant upon one or more specific species of plant for nesting habitat. The invasive crowsfoot grass, a tufted annual grass, is likely poor nesting habitat and its decline represents a decreased threat to the tern colony. Continued monitoring for this and other invasive species is essential to protect the integrity of the nesting colony.

Conclusions:

Bush Key provides a stable and resilient habitat for sooty terns during the breeding season. While terns prefer to nest in shrub-like species, they appear resilient to shifts in the composition of the plant community on the island. Further research is needed to identify the cause of the recent decline in nesting pairs. Follow-up nesting surveys in April would help determine whether or not this decline is an artifact of a temporal mismatch. In addition, a

more complete understanding of sooty tern migratory routes and diet would provide insight into the effects of conditions outside the breeding colony.

Furthermore, continued monitoring is essential to ensure that impacts from developing threats are minimized. Anthropogenic impacts, such as the introduction of invasive species and disturbance from park visitors, will need to be reassessed as park attendance increases and the island shifts closer to higher trafficked areas. As a result of climate change, increased rates of disturbance and changes in ocean dynamics are predicted throughout the world's marine ecosystems, and threaten to alter both the terrestrial and pelagic habitats that sooty terns rely upon. Further research into the ecology and behavior of sooty terns will provide a better understanding of how these threats will affect the species, as well as provide insights into the health of the world's ocean.

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