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Factors Limiting Reproductive Success of American Oystercatchers (*Haematopus palliatus*) in Florida's Southern Big Bend Region

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Abstract.—Florida's Big Bend region hosts the second largest concentration of breeding American Oystercatchers in the state, but reproductive success is low. Nest site characteristics and predation were examined to determine their influence on survival of nests and broods at two areas in the southern Big Bend (Cedar Key and Barge Canal). The probability of a nest surviving in Cedar Key was low ($\overline{x}$ = 0.25, CI = 0.13–0.41) and limited by nest overwash (46% of known nest attempts); survival of nests at Barge Canal was much higher ($\overline{x}$ = 0.45, CI = 0.31–0.58). However, 40% of chicks that survived to fledge (35 days) at Barge Canal died before reaching independence (60 days). Raccoon presence and hatch date were negatively correlated with brood survival at Barge Canal. Finally, chicks at Barge Canal weighed less and were smaller compared to chicks at an Atlantic Coast site, which may be related to low abundance of live oysters within 100 m of their nest sites. Efforts to enhance oystercatcher reproductive success may require different approaches for each site: habitat restoration to increase elevation of nest sites in Cedar Key and reduction of predators at Barge Canal. *Received 30 Nov 2020, accepted 16 August 2021.*

Key words.—breeding success, brood survival, disturbance, nest survival, overwash, predation, spoil islands.

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Many shorebird species are coastal ecosystem obligates and therefore susceptible to anthropogenic and naturally-occurring threats associated with this environment (Sabine *et al.* 2008; Virzi *et al.* 2016). Anthropogenic impacts to coastal habitats used by shorebird species include coastline development, recreational use, and the effects of climate change. Coastal habitat loss has contributed to large-scale declines in many coastal-dependent wildlife species and specifically shorebirds (Brown *et al.* 2001; Mazaris *et al.* 2009). Other threats to shorebirds, their nests, and chicks include high water events such as storms and predation pressure (Virzi *et al.* 2016). Although birds and predators have evolved together, the increased human occupation of coastal areas has dramatically shifted the predator landscape (Burger 2018). Habitat loss and alteration, human-related disturbance, and predation are three of the greatest limitations to recovering shorebird populations (Burger 2018). Here, we consider the factors limiting reproductive success of a shorebird in the Big Bend of Florida (Fig. 1).

Florida's Big Bend region, the region of Florida's Gulf Coast extending from the Ochlockonee Bay in the northwest to the Anclote Key in the south (Fig. 1), is largely undeveloped, with over 96 km of coastline under conservation protection. The region provides important habitat for many shorebird species (Schulte *et al.* 2010; Geselbracht *et al.* 2011) including American Oystercatchers (*Haematopus palliatus*; hereafter: oystercatcher; Cox *et al.* 1994; American Oystercatcher Working Group *et al.* 2012; Brush *et al.* 2017). Oystercatchers are state-listed as Threatened in Florida due to a small population size and historical and anticipated continued population decline (Florida Fish and Wildlife Conservation Commission 2011). Oystercatchers have high breeding site fidelity even when these sites become degraded (Schulte 2012; Murphy *et al.* 2017). High site fidelity and limited distribution in Florida suggest that all nesting habitat in the region

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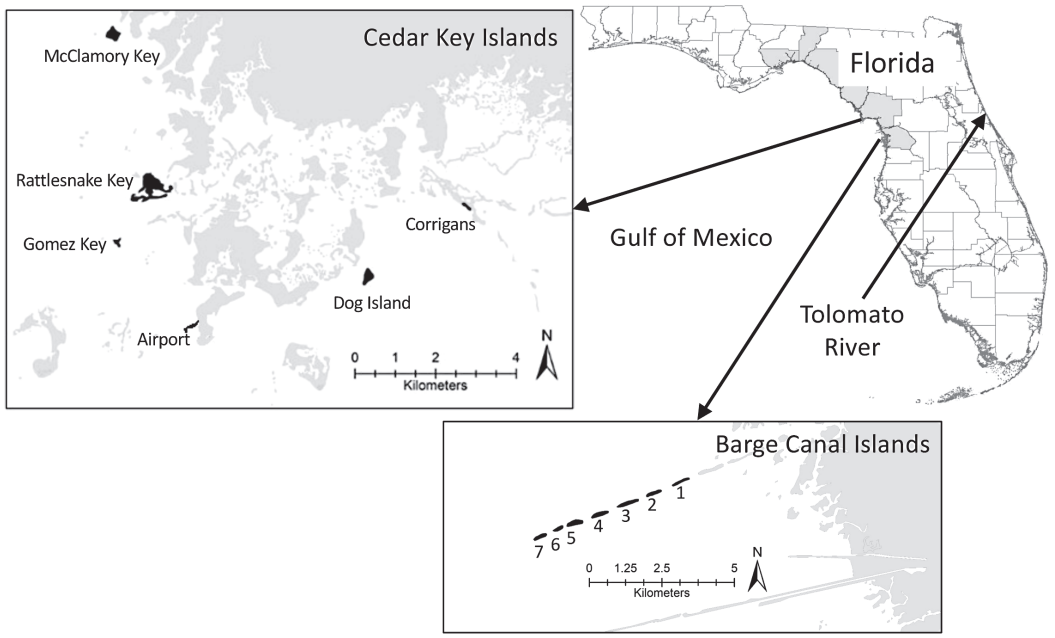


Figure 1. American Oystercatcher nesting islands within our study area located in the Big Bend region (grey highlighted counties), Florida: Cedar Key (top) and Barge Canal (bottom) islands.

is important for species recovery in the state. Nesting habitat within the southern Big Bend region is limited to a few small (< 3 ha) offshore islands, including natural and spoil islands. These islands are susceptible to habitat degradation because of extensive oyster reef loss and sea-level rise (Geselbracht *et al.* 2011; Seavey *et al.* 2011; Vitale *et al.* 2020). With the lack of barrier islands in the area to provide erosion protection, oyster reefs perform a critical role in shoreline stabilization (Piazza *et al.* 2005; Scyphers *et al.* 2011). The region has sustained significant losses in the extent of oyster reefs (88% offshore, 61% nearshore, and 50% inshore) in the last two decades (Seavey *et al.* 2011). These reefs not only play an important role in providing oystercatcher foraging habitat, but also stabilize roosting and nesting habitats.

As islands degrade, they are reduced in total area and elevation, resulting in nests becoming more vulnerable to overwash, even when nests are placed on the highest elevations possible. Effects of climate change, including sea-level rise and increased intensities and frequencies of storms (Emanuel 2005; Webster *et al.* 2005) are increasing the frequency of nest overwash events. Although overwash commonly occurs at sites that are lower in elevation and/or near the high tide line, it can also occur at nearly all coastal nesting habitats during storm and high wind events. This influence is evident in the poor reproductive success of oystercatchers in the Big Bend region, where overwash has been the largest known contributor to nest loss since the implementation of standardized monitoring at two of the three breeding areas in the Big Bend region: St. Marks National Wildlife Refuge and Cedar Key (Florida Shorebird Database 2019).

Nest overwash is not the only threat to nesting oystercatchers in this region. Some of the islands used by nesting oystercatchers in the Big Bend region are also areas where people recreate, and human disturbance is widely documented as contributing to shorebird nest failure and chick mortality (Peters and Otis 2005; McGowan and Simons 2006; Sabine *et al.* 2008). In addition, predators can have catastrophic impacts on coastal nesting species by reducing the survival of eggs, chicks, and adults (Davis *et al.* 2001; Rodewald and Kearns 2011; Newsome *et al.*

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2015). Specifically, raccoons (*Procyon lotor*) are a major source of nest and chick loss in the suite of potential predators (Davis *et al.* 2001; Schulte and Simons 2016). The presence of predators and human disturbance, as well as proximity and availability of food, can influence the ability of adults to adequately provision their chicks. Chicks with lower provisioning rates grow more slowly and have lower survival (Kersten and Brenninkmeijer 1995; Robinson *et al.* 2019), and body condition of chicks can be a limiting factor for survival to the fledgling stage (Ens *et al.* 1992; Hunt *et al.* 2017).

These conservation concerns led us to examine factors influencing reproductive success of oystercatchers using natural and human-made spoil islands for nesting in the southern Big Bend region of Florida. We predicted that all islands would be impacted by overwash, particularly natural islands, because they are lower in elevation than spoil islands. We specifically examined nest location characteristics, overwash, human use, and predation pressure with respect to nest and chick survival. Finally, we compared morphometric measurements (mass, wing chord, and exposed culmen length) as indicators of body condition, and growth of chicks from our study area to those from a site on the Atlantic Coast. Our objectives were to examine the relative influence of overwash, human presence, and predation on nest and brood survival to better inform the management of oystercatchers breeding along the Gulf Coast of Florida.

METHODS

Study Area

Our study area included two sites used by breeding oystercatchers in the Big Bend region. The first area consisted of spoil islands of the barge canal within the Marjorie Harris Carr Cross Florida Greenway (hereafter: Barge Canal). The second area included natural islands in Cedar Key (Fig. 1). These sites represent the nesting concentrations of oystercatchers in the southern portion of Florida's Big Bend region. Both areas have similar mean tidal ranges: 0.86 m (Cedar Key), 0.94 m (Barge Canal). However, the two sites differ physically (COOPS NOAA 2018).

The US Army Corps of Engineers constructed the Barge Canal islands in the mid-1960s; at present they consist of a straight line of ten islands perpendicular to the coast. Surface substrate primarily consists of limestone rock (generally 5–20 cm diameter), shell, and sand. Above the tidal range, most of the islands are vegetated by dense low shrubs, grasses, and woody vegetation. The four islands (Fig 1., islands 4, 5, 6 and 7) that currently support the largest numbers of breeding oystercatchers are posted around the perimeter with closed area signs to deter human use. Breeding oystercatchers have used six to eight of the Barge Canal islands since at least 1976, supporting approximately 15–28 pairs annually (Schreiber and Schreiber 1978; Florida Shorebird Database 2019; Vitale et al. 2020). Currently, oystercatchers use six of the 10 islands for nesting. The six islands are 2–5.75 km from the mainland and 0.1–1.5 ha in size. Wilson's Plovers (*Charadrius wilsonia*), Least Terns (*Sternula antillarum*), and a few heron species (*Ardeidae*) also nest on the islands.

The second study area consisted of seven islands around Cedar Key. Six islands are characterized by sand and shell substrates with variable amounts of vegetation including ground cover and some woody vegetation. The seventh island, Corrigan's Reef, is a large shell rake with minimal vegetation. The Cedar Key islands have supported 6–12 pairs of breeding oystercatchers annually since 2001 (Douglass and Clayton 2004; Florida Shorebird Database 2019); there are no estimates of breeding populations prior to 2001 for this area. A few of the Cedar Key islands also support breeding populations of Wilson's Plovers and Least Terns.

Nest Survival

We monitored nests at least once per week during the breeding season by direct observation in 2017 and 2018. We recorded GPS locations for breeding oystercatcher adults and nests and documented the number of eggs per nest during each survey. We monitored nests until the eggs hatched or failed. In addition to direct nest observations, we used Browning Dark OPS 940HD cameras to supplement monitoring of oystercatcher nests and determine sources of failure or hatch date. The cameras served a secondary function of detecting predators, chicks, and humans on the islands throughout the breeding season. We placed cameras on short (1 m) metal poles inserted into the ground, near dense vegetation when possible, and as far away and low as feasible while still maintaining sight of the eggs in the nest. Placement took a maximum of five minutes per camera and time near the nest was always kept to a minimum, to ensure there were not impacts due to disturbance. We placed cameras immediately following discovery of a nest. We left cameras in place until the nesting pair either failed and re-nested (in which case we moved the camera to the new nest) or until the conclusion of the breeding season in August. We left cameras in place all season to document human and predator presence and to track chicks that remained near the nest location. Cameras were set to detect motion and rapidly take three photos when triggered with a 30-second delay between triggers. Memory cards and batteries were

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replaced every three weeks on average. Review and data recording from photos were accomplished using Digikam and the R package camtrapR.

Brood Survival

Oystercatcher chicks fledge at ~35 days old but are dependent on their parents for food for at least 60 days (American Oystercatcher Working Group *et al.* 2012). Thus, we monitored broods twice per week for up to two months post-fledging to determine causes of mortality and to calculate daily survival rates. We used a combination of banded adults, location, and chick age to identify and track unique pairs. We hand-captured chicks between three weeks old and when they were flight capable. We attached two color bands engraved with a unique three-character code to each tibia and a metal U.S. Geological Survey band on the tarsometatarsus. We took morphometric measurements including wing chord (mm) using a ruler, exposed culmen length (mm) using calipers, and weight (g) using a Pesola scale. We used VHF radio telemetry to locate chicks. When chicks weighed more than 280 g, we attached a 3-g Lotek Pip Ag392 transmitter to the scapular region using cyanoacrylate glue directly on the skin and two polypropylene sutures connected to each end of the transmitter (technique developed by Loring (2016) and modified for use on oystercatchers by Susan Heath, Gulf Coast Bird Observatory (S. Heath, pers. commun.). We ensured the total weight of bands and tags remained < 3% of total chick mass. The transmitter setup was designed to stay attached and transmit for 6–8 weeks. We located transmitter-equipped chicks using Yagi antennas and a VHF receiver from a boat or by foot whenever we did not detect them visually. When chicks died, we located the remains and transmitter. We determined the cause of death in the field (e.g., predation) or via necropsy.

During our nest surveys, we documented human presence on and within 100 m (visually estimated) of each island used by nesting shorebirds by counting the number of people, boats or kayaks, and dogs. We also conducted surveys on days where we predicted human presence would be high (e.g., Independence Day and weekends with nice weather). We prioritized additional surveys to record human presence at the Barge Canal rather than Cedar Key because of the greater number of broods at the Barge Canal and because people were rarely present during our nest surveys at Cedar Key. During these additional surveys, we collected the same information as during the nest surveys, except in 10-minute intervals. These surveys provided snapshot views of human presence on or near the nesting islands throughout the season and provided a qualitative way to describe human presence and disturbance at the nesting sites.

We measured nest-site characteristics related to prey (oysters), and threats (overwash, predator access) as potential covariates in our nest and brood survival estimations. First, we used distance to mainland as a variable that could be related to the likelihood of mammalian predators accessing the nesting site. Second, we categorized oyster density within 100 m of the nest because if adults need to travel long distances for food, their broods are more vulnerable to predation and fed less often. Finally, we used tide height as a variable that is linked to the likelihood of nest site overwash. To minimize disturbance to breeding birds, we measured these characteristics after nesting was completed and the birds were no longer actively defending breeding areas. Using nest location and GIS software we measured distances (m) of nests from the mainland. We also categorized food abundance (live oysters) within a 100 m radius of each nest by surveying along transects in the intertidal zone at low tide. We categorized oyster abundance by density of live oysters at three broad levels: low (< 5 live oysters per m^2), medium (5–50 live oysters per m^2), and high (> 50 live oysters per m^2). Finally, we collected observed daily maximum tide heights (m) from the Cedar Key tide and weather station, which was within 20 km of both sites (CO-OPS NOAA 2018).

Analyses

Since 2011, Florida Fish and Wildlife Conservation Commission has reported productivity for both sites in our study area (Florida Fish and Wildlife Conservation Commission 2011), calculated as the number of chicks fledged divided by the number of known breeding pairs. We continued using this measure of productivity to compare our data with previous years; however, productivity does not account for differing detection rates associated with factors such as differences in habitat and survey effort, thus comparisons may be misleading (American Oystercatcher Working Group *et al.* 2012).

We conducted analysis by study area to incorporate site-specific variables and covariates. We calculated a daily survival rate (DSR), for oystercatcher nests and broods for each study site. We defined the nest survival period as the time from the first egg laid until the first egg hatched or 27 days, whichever was first (American Oystercatcher Working Group *et al.* 2012). We used information from nest cameras to determine hatch dates and also back-dated from hatch to determine nest initiation dates. A nest was considered successful if at least one egg survived to hatch. For broods, we calculated survival to both fledging and to independence. We considered brood survival as successful if at least one chick from a brood survived the specified period. Survival to fledging is defined in the literature as hatching to 35 days and survival to independence is defined as hatching to 60 days (American Oystercatcher Working Group *et al.* 2012). We calculated brood survival because tracking individual chicks was problematic due to low detection (Jodice *et al.* 2014; Koczur *et al.* 2014). We used nest survival models in Program Mark (Dinsmore and Dinsmore 2007), which uses a generalized linear model (GLM) approach with a logistic-exposure link function accounting for variable exposure days between checks, and uses maximum likelihood to estimate failure dates when the exposure period is greater than one day. We evaluated different models by testing all combinations of covariates that made ecological sense.

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We used weekly raccoon presence as a covariate in our survival models for Barge Canal but excluded other predators due to low detection rates. We used a hierarchical multiscale occupancy model (Nichols *et al.* 2008; Aing *et al.* 2011; Mordecai *et al.* 2011) as a data filter for our raccoon covariate to account for unknown detection rates and inconsistent effort (e.g., changes in number of cameras operating at any given time). Two sets of latent state variables were estimated from the process component: (1) permanent occupancy at sites based on the proportion of islands ever occupied and (2) temporary occupancy based on the proportion of sites occupied on a given survey, defined as a one-week period. The observation component assumes the number of daily detections of raccoons out of the total surveyed days over the one-week survey periods occurred as a binomial process. From the hierarchical occupancy model, we were only interested in the survey level occupancy probability, from which we used the median values as the covariate of weekly raccoon presence at Barge Canal in our survival models.

For model selection, we used Akaike's Information Criterion for small sample sizes (AICc). We compared survival estimates among top models, which included those within two units from the model that minimized AICc (ΔAICc $\leq$ 2; Burnham and Anderson 2004). Additionally, we used 85% confidence intervals to identify uninformative parameters and reduce model selection uncertainty. We used survival estimates from the top models to calculate period survival of nests and broods. Finally, we used the top models to examine the effect of individual covariates on survival across a range of values.

Effective sample size for adjusted survival models is determined by the total number of exposure days all nests or broods survived. No rules exist for determining minimum sample size because it depends on the amount of information provided by each nest and the level of detail in the analysis (Dinsmore and Dinsmore 2007); however, due to limited information, we only calculated a null model for DSR for Cedar Key for both nests and broods. To explain variation in the nest and brood survival at Barge Canal, we used time-related and environmental covariates in our models (Table 1). Additionally, we planned to use food abundance as a covariate in our survival models but because it was correlated with distance from mainland at Barge Canal (R_s = -0.744, $P < 0.001$) it was not included. However, we compared food abundance between Barge Canal and Cedar Key islands using a chi-square analysis.

We compared morphometrics of chicks hatched in our study area to those at another site in Florida that has high productivity to determine relative size as a proxy for body condition of chicks at our study sites. We used data from 2012 to 2018 to compare mass, wing chord, and exposed culmen length of chicks captured at Barge Canal to chicks from the Tolomato River, on the Atlantic coast of Florida (Fig 1., Florida Shorebird Database 2019). Cedar Key was excluded due to small sample size. We used an analysis of covariance (ANCOVA) to compare each morphometric measurement between sites while controlling for differences in age. We checked for normality using Levene's test and met the assumptions for an ANCOVA.

RESULTS

Nest and Chick Survival

We monitored 91 nests in 2017 and 2018. At Barge Canal, most nests survived to hatch (apparent nest survival = 58.7%, n = 63, both years combined), but at Cedar Key, only 21% of nests (n = 28) hatched. Predators were the leading cause of nest failure (31%) at Barge Canal, and overwash was the leading cause (55%) of failures for Cedar Key nests (Fig. 2). We monitored 42 broods total (Barge Canal n = 36; Cedar Key n = 6). Productivity at Barge Canal was 0.50 and 0.71 fledglings per breeding pair in 2017 and 2018, respectively, and 0.50 in Cedar Key for both years. Of chicks that survived to fledge (35 days) at Barge Canal, 40% were lost before they reached independence (60 days), whereas no chicks were lost during this period in Cedar Key.

Variation in daily nest survival (DSR, effective sample size = 828 exposure days) was not well explained by any of the covariates tested (Table 2). The null model was 2.5 AICc lower than our best performing model, and model weight was < 20% for any given model. Raccoon occupancy and tide were consistently included in our top-ranked models; however, these were uninformative parameters. Overall average DSR for all nests at Barge Canal was 0.97 (CI = 0.96–0.98), resulting in a 0.45 probability of at least one egg hatching (CI = 0.31–0.58). For Cedar Key, average DSR was 0.95 (CI = 0.93–0.97, n = 26) resulting in a 0.25 probability of hatch (CI = 0.13–0.41).

At Cedar Key islands, we detected seven species of potential predators. Detections of most predators were uncommon, except for Boat-tailed Grackles (*Quiscalus major*) that were frequently seen on two islands, and raccoons on one (Table 3). At Barge Canal we detected 13 species of potential predators during the two breeding seasons (Table 3). Two avian predators (Black-

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Table 1. Covariates used in Program MARK to determine factors influencing nest and brood survival of American oystercatchers at Barge Canal in the Big Bend region of Florida's Gulf Coast 2017–2018.

Variable	Justification	How Measured/Estimated
Nest Survival		
Lay Date	Environmental conditions throughout the season may change, influencing survival of nests laid at different times.	Estimated date first egg laid.
Nest Age	Survival generally has a positive relationship with age (Colwell *et al.* 2007; Ackerman *et al.* 2014; Schulte and Simons 2015).	Number of days since lay date.
Year	Survival has been shown to vary between years (Sabine *et al.* 2006)	—
Distance to Mainland	Related to proximity of food resources and potential influence of predators.	Shortest straight-line distance from nest to mainland.
Tide	Used as measure of nest overwash susceptibility.	Daily max water height from Cedar Key tide and weather station (COOPS NOAA 2018).
Raccoon Presence	Raccoons are frequently the source of egg loss	Camera trap detections used to create a hierarchical multiscale occupancy model.
Chick Survival		
Hatch Date	Conditions throughout the season may change influencing survival of chicks hatched at different times.	Estimated date first chick hatched.
Chick Age	Survival generally has a positive relationship with age (Colwell *et al.* 2007; Ackerman *et al.* 2014; Schulte and Simons 2015).	Number of days since hatch date.
Year	Capture variation in factors such as storm events.	—
Distance to Mainland	Related to proximity of food resources and potential influence of predators.	Shortest straight-line distance from nest to mainland.
Raccoon Presence	Raccoons are frequently the source of chick mortality	Camera trap detections used to create a hierarchical multiscale occupancy model.

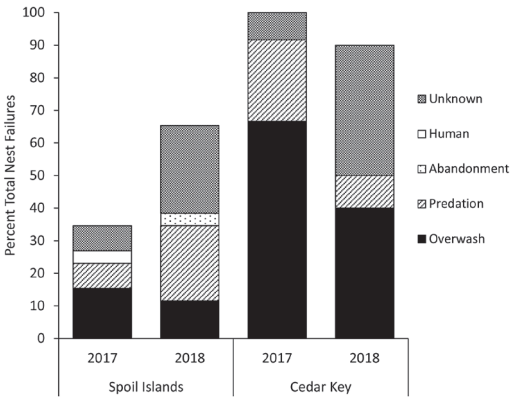


Figure 2. Causes of nest failure for American Oystercatchers at Barge Canal and Cedar Key in Florida's Big Bend region, 2017–2018.

crowned Night Herons [*Nycticorax nycticorax*] and Fish Crows [*Corvus ossifragus*]) were documented depredating oystercatcher, Wilson's Plover, and Least Tern nests at Barge Canal. Black-crowned Night Herons were documented nesting at Barge Canal in small numbers (5–15) in previous years with no observed impacts to other nesting birds. However, in both 2017 and 2018, we found >80 individuals nesting on island six and in 2018, a nest camera recorded Black-crowned Night Heron predation on nearby Least Tern nests. The camera recorded Black-crowned Night Herons walking through the Least Tern colony daily, starting shortly after terns began incubating nests; this pattern continued for two weeks until the adult Least Terns had all disappeared and eggs were presumably eaten. Additionally, we observed Fish Crows taking eggs out of oystercatcher nests in 2018. However, most camera-response times were not fast enough to document these events because the Fish Crows took eggs while remaining in flight and therefore only remained within view of the camera for a few seconds, likely resulting in low detection of these events. Hence, nest predation by Fish Crows likely represents a portion of the 2018 unknown nest failures. Raccoon use of the islands was variable between and within years. In 2017, we had an increase in detections late in the season, which corresponded with when most broods were near fledging. In 2017, we had three times the number of detections as 2018, resulting in higher survey-level use estimates from our occupancy models that season.

Four competing models describing the variation in DSR of broods at Barge Canal (effective sample size = 1450 exposure days) were top-performing models; all had similar support (ΔAICc = 1.21, model weight = 0.15–0.29, Table 4). The best model included hatch date, year, and weekly raccoon presence (Fig. 3). Hatch date had the largest effect and broods that hatched earlier had a higher survival probability (β_{hatch} = -0.05, CI = -0.08—0.02). Raccoon presence had a similar effect size; higher estimates negatively influenced brood survival ($\beta_{raccoon}$ = -5.01, CI = -10.01—0.001). Brood survival rate between years also received support by all top models (β_{2018} = 1.44, CI = -0.05–2.92). Distance from the mainland and chick age were uninformative parameters in our top models. Average DSR for broods at Barge Canal was 0.99 (CI = 0.98–0.99), giving a probability of 0.61 (CI = 0.47–0.73) for at least one chick in a brood fledging and a probabil-

Table 2. Summary of top seven models evaluating factors affecting daily nest survival (Program MARK) of American Oystercatchers at Barge Canal, in the Big Bend region of Florida's Gulf Coast 2017–2018. Models are ranked in ascending ΔAICc values, showing models that ranked as well or better than the null model. Model factors include year, nest age (NestAge), date nest was laid (laydate), weekly raccoon presence (raccoon), daily max tide height (tide), and distance to mainland (dist.land).

Model	Parameters	ΔAICc	Weight	Deviance
raccoon + tide	3	0.000	0.187	188.97
raccoon	2	0.575	0.140	191.56
tide	2	0.827	0.123	191.81
raccoon + dist.land + tide	4	1.345	0.095	188.30
raccoon + dist.land	3	1.396	0.093	190.37
raccoon + dist.land + tide + year + laydate + NestAge	7	2.171	0.063	183.04
Null	1	2.535	0.053	195.53

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Table 3. Summary data grouped by site and year of effort and potential predator species detections for all cameras set-up on American Oystercatcher nesting islands on Florida's Big Bend region, 2017–2018.

		2017		2018	
		Barge Canal	Cedar Key	Barge Canal	Cedar Key
Effort	Trap nights	1428	266	1448	437
	Camera stations	19	13	27	12
Detections*	Bald Eagle (*Haliaeetus leucocephalus*)	5	0	0	0
	Black-crowned Night Heron (*Nycticorax nycticorax)*	112	13	77	2
	Boat-tailed Grackle (*Quiscalus major*)	1	107	47	96
	Fish Crow (*Corvus ossifragus*)	32	0	42	1
	Great Blue Heron (*Ardea herodias*)	25	3	0	1
	Great-horned Owl (*Bubo virginianus*)	2	0	0	0
	Gull spp.	144	0	10	0
	Peregrine Falcon (*Falco peregrinus*)	2	0	0	0
	Yellow-crowned Night Heron (*Nyctanassa violacea*)	0	6	0	2
	Dog (*Canis lupus familiaris*)	4	0	0	0
	Raccoon (*Procyon lotor*)	93	24	19	15
	Rodent	5	9	0	0
	Snake	1	8	4	0
	Unknown	3	0	0	0
Total Predator Detections		429	170	199	117

*detections of predators are raw data and do not account for repeated detections of the same individual; therefore numbers may be biased towards individuals who spend more time in front of cameras.

ity of surviving to independence at 60 days of age of 0.42 (CI = 0.27–0.58). Average DSR for broods at Cedar Key was 0.99 (CI = 0.97–0.99, n = 6), with a probability of fledging of 0.74 (CI = 0.30–0.93) and a probability of surviving to independence at 60 days of age of 0.60 (CI = 0.13–0.88).

We attached transmitters to 12 chicks at Barge Canal in 2018. Three of the birds died before they reached 60 days old and a fourth died between 61 and 68 days old. Of the four mortalities, we found two of the transmitters below the high tide line and without any chick remains. Both transmitters still had intact sutures and feathers attached, suggesting they became detached from the bird after the bird's death, but the cause of death is unknown. The other two transmitters were located still at-

Table 4. Summary of top 12 models (Program MARK) evaluating factors affecting brood survival of American Oystercatchers at Barge Canal, in the Big Bend region of Florida's Gulf Coast 2017–2018. Models are ranked in ascending ΔAICc values, showing models that ranked as well or better than the constant model. Model factors included year, hatch date (hatchdate), chick age (ChickAge), weekly raccoon presence (raccoon), and distance to mainland (dist.land).

Model	Parameters	ΔAICc	Weight	Deviance
raccoon + hatchdate + year	4	0.000	0.280	134.16
raccoon + hatchdate + dist.land + year	5	0.224	0.250	132.37
year + ChickAge + hatchdate	4	1.156	0.157	135.32
raccoon + year + dist.land + hatchdate + ChickAge	6	1.210	0.153	131.34
hatchdate + year	3	2.323	0.088	138.49
raccoon + dist.land	3	3.938	0.039	140.11
raccoon + dist.land + year	4	5.451	0.018	139.61
dist.land	2	7.044	0.008	145.22
raccoon	2	9.041	0.003	147.22
ChickAge + hatchdate	3	13.022	0.000	149.19
Null	1	13.797	0.000	153.98

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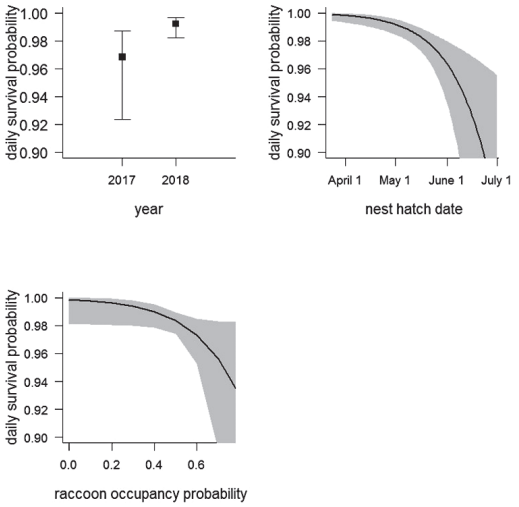


Figure 3. Daily survival probabilities of American Oystercatcher broods (black points and lines) with 95% confidence intervals (error bars and grey shaded area) at Barge Canal in Florida's Big Bend region, 2017–2018. Graphs show the three covariates for the top ranked model that included additive effects of year, hatch date, and raccoon occupancy.

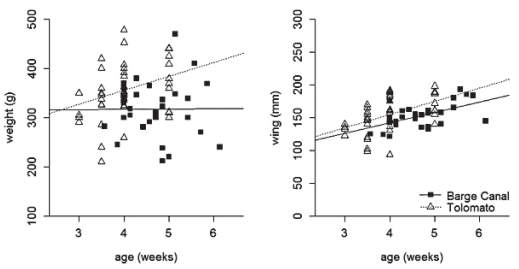


Figure 4. American Oystercatcher chick weight (left) and wing chord (right) including linear trends for chicks captured at the Barge Canal on the Gulf Coast and the Tolomato River on the East Coast of Florida from 2012–2018.

tached to intact birds with no signs of predation, scavenging, or detectable injuries. One of these birds was too decayed for a full necropsy, but starvation was the suspected cause of death. We found the other bird soon after death and sent it to Southeastern Cooperative Wildlife Disease Study, College of Veterinary Medicine at the University of Georgia, for analysis. The final diagnosis showed emaciation and bacterial sepsis (no causative bacterium was cultured) as likely causes of death.

Chick Growth

Chicks at Barge Canal were an average of 50 g (SE = 14.67) lighter ($F_{1, 73} = 11.57$, $P = 0.001$) and had slightly shorter wing chords ($F_{1, 73} = 7.697$, $P = 0.007$) than the chicks at Tolomato River, the comparison site, after controlling for age (Fig. 4). Slow and delayed growth of chicks was observed at Barge Canal. For example, one chick, which was captured twice, decreased in weight by 20 g over an 8-day period and did not fledge until 55 days of age. Our estimates of oyster abundance showed that our two sites were significantly different ($\bar{x} = 36.28$, $P < 0.001$) and Barge Canal nest sites had much lower oyster abundance compared to birds nesting at the Cedar Key islands (Fig. 5).

Human Presence

We documented infrequent human use on and around oystercatcher nesting islands for both Barge Canal and Cedar Key ($\bar{x}$ = 1.6 and < 0.1 boats per survey, respectively). Of the people detected in the area, > 80% were fishing and not directly using the islands. Despite few detections, surveys and cameras showed that there were days with high use at Barge Canal. While our survey design did not allow us to directly quantify disturbance to birds, cameras detected multiple instances of people nearly stepping on active nests. We also documented two cases of direct human-caused nest and chick fail-

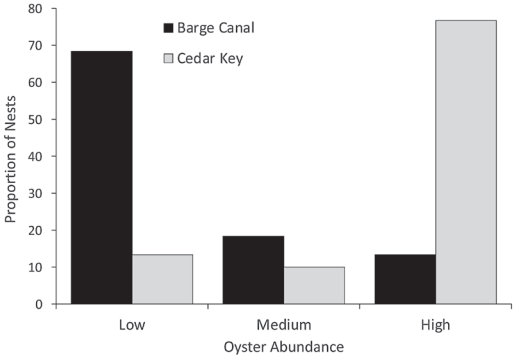


Figure 5. Proportion of American Oystercatcher nests in each food abundance category for each site, Barge Canal (dark grey) and Cedar Key (light grey), Florida's Big Bend region, 2017–2018: low (< 5 live oysters per m²), medium (5–50 live oysters per m²), and high (> 50 live oysters per m²)

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ure at Barge Canal. The first occurred in 2017, when an active nest was stepped on, crushing the eggs. The nature of this event was likely a prolonged disturbance event, which would have displaced other nesting oystercatchers that used the same area and made their nests vulnerable. The second occurred in 2018 when kayakers found two wet 6–10-day old chicks and brought them to a wildlife rehabilitator where one of the chicks died. It is possible that the chicks were wet because the kayakers had unknowingly disturbed them causing the chicks to run into the water to escape (a common behavior at oystercatcher nesting sites).

DISCUSSION

Although we predicted that overwash would be a major factor limiting productivity of oystercatchers, this was only the case at Cedar Key where productivity was limited by nest overwash; productivity at Barge Canal was limited by chick predation. Despite limitations on chick survival, Barge Canal had a higher probability of nests hatching and broods fledging (based on adjusted survival) than documented by other studies of American Oystercatchers (McGowan *et al.* 2005; Sabine *et al.* 2006; Traut *et al.* 2006; Virzi 2008; Schulte and Simons 2015). In addition, productivity (fledglings per pair) was higher in 2017 and 2018 than the previous five years (Florida Shorebird Database 2019) at Barge Canal; however, this high productivity was likely due in part to our increased survey frequency which reduced the number of unknown chick outcomes. Despite the relatively high productivity at Barge Canal, 40% of chicks that survived to 35 days (fledging) died before reaching 60 days (independence), thus post-fledging survival was low. In contrast, Cedar Key had low nest survival and because of the frequency of overwash events, we were unable to reliably evaluate other potential threats to nests and chicks at this site. However, of the few nests hatched in Cedar Key, most chicks survived to independence, suggesting that if nests survive there is a high probability of success.

We originally expected human use of Barge Canal to be a negative factor influencing reproductive success. Although we did not directly quantify the impact of human presence, we found that human use of the islands was generally low. However, even low human use may have indirect effects by attracting predators (Rodewald and Kearns 2011; Newsome *et al.* 2015). In addition, on small islands with high nesting density, impacts from human disturbance may be amplified because breeding shorebirds and chicks are unable to move away. Consequently, any level of human use in areas with breeding birds can have significant impacts, especially if birds are experiencing multiple stressors. Furthermore, although infrequent, days of high human use did occur, which can significantly decrease nest and chick survival (Ruhlen *et al.* 2003; DeRose-Wilson *et al.* 2018). Despite relatively low human use, we observed two species of nest predators (Fish Crows and raccoons) often associated with human presence (Denmon *et al.* 2013; Clay *et al.* 2014; Schulte and Simons 2016), at our study sites. Both Fish Crows and raccoons preyed upon oystercatcher eggs, and our models included raccoon presence as an important covariate related to brood survival at Barge Canal. In addition, we observed higher productivity at Barge Canal in 2018, which corresponded with fewer detections of raccoons that year.

We observed several temporal factors influencing survival at Barge Canal. First, nests that hatched earlier were more likely to successfully fledge chicks. The influence of the timing of nesting on survival can depend on many factors such as patterns in weather, human disturbance, and predator activity (Nol 1989; Rusticali *et al.* 1999; Burhans *et al.* 2002). In contrast, survival rates for shorebird chicks generally increase rapidly with age as they become more mobile and less dependent on their parents (Colwell *et al.* 2007; Ackerman *et al.* 2014; Schulte and Simons 2015). However, our most supported models either excluded chick age or, when included, indicated a potentially small negative effect on survival. The effect of chick age on survival may be confounded with

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temporal variation in survival (Dinsmore *et al.* 2002), which was detected in our models by the nest hatch date covariate. If that were the case, these two covariates may indicate late-season factors lowering brood survival, such as an increase in predators. However, because we had chicks alive to sample across nearly the entire breeding season, with chicks and broods of differing ages available throughout the season, it is unlikely that temporal variation confounded the effect of chick age on survival. Therefore, if chick age did have an independent effect and brood survival did not increase with age as our models indicated, older chicks had lower survival rates than expected. In addition, at Barge Canal, we found that of chicks that reached 35 days of age, approximately 40% did not survive to 60 days. While early dispersal or a change in detection after chicks fledged is possible, this scenario is unlikely since chicks remain dependent on their parents for at least 60 days and consequently dispersal would involve the entire family group (Palmer 1967; Kersten and Brenninkmeijer 1995; American Oystercatcher Working Group *et al.* 2012). We reliably found both adults of missing chicks during surveys and can assume chicks were lost to sources of mortality as opposed to dispersal.

Lower survival of older chicks at Barge Canal could be related to inadequate food resources needed to support their energy requirements. Oystercatchers with foraging areas adjacent to their nesting area generally have higher productivity (Ens *et al.* 1992), and chicks with higher parental provisioning rates grow faster and have higher survival rates (Robinson *et al.* 2019). We found evidence of food limitations at Barge Canal, including low abundances of oysters close to nests; most nests were located on the islands farthest from the mainland, away from areas of higher oyster abundance. In addition, we observed that many adult birds flew to other islands in the area to forage. Traveling to distant areas to forage can negatively impact chick survival due to parents being less available to be vigilant, leaving chicks more susceptible to predation (Nol 1989). In addition, even if distant foraging areas are of high quality, transport costs from these areas can outweigh the benefits gained when compared to birds with a foraging area within their nesting territory (Ens *et al.* 1992). Shorebirds have been found to consider both intake rates and cost of commuting when choosing foraging areas; Eurasian Oystercatchers (*Haematopus ostralegus*) are able to detect and select for foraging patches that are the most profitable (Van Gils *et al.* 2006; Schwemmer *et al.* 2016). Accordingly, oystercatchers would only choose to fly to distant foraging areas if nearby foraging areas are so poor that the benefits of traveling outweigh the associated costs. Finally, chicks at Barge Canal were smaller and lighter than chicks at the Atlantic Coast site. Chicks in poor body condition, regardless of age, are more likely to be lost to predation and disease (Groves 1984; Ens *et al.* 1992; Heg and van der Velde 2001). In Eurasian Oystercatchers, cause of death varied with chick age; the majority of older chicks were believed to have died from starvation or disease, whereas younger chicks were usually lost to predators (Ens *et al.* 1992). The death of at least two > 50-day-old chicks from starvation at Barge Canal supports this hypothesis.

Similar to our results, breeding oystercatchers on isolated dredge spoil islands in North Carolina had relatively high hatching success but then had poor fledging rates due to predation and suspected issues with food availability (McGowan *et al.* 2005). In contrast, in New Jersey the probability of fledging a chick per egg laid was an order of magnitude higher on spoil islands than on barrier beaches (Virzi *et al.* 2016). If managed properly, spoil islands can provide important breeding habitat for oystercatchers (American Oystercatcher Working Group *et al.*, 2012), especially as sea level and anthropogenic pressures continue to increase. However, since we found evidence suggesting food resources are influencing productivity on the Barge Canal spoil islands, further research could focus on how to improve prey availability.

Despite recent declines in the extent of oyster reefs in the Big Bend Region of Florida (Baker *et al.* 2003; Bergquist *et al.* 2006;

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Seavey *et al.* 2011), oyster density was significantly greater within 100 m of the nesting islands of Cedar Key and we assumed food availability was not a factor contributing to reproductive success. In general, foraging habitat is abundant in Cedar Key and easily supports more than 1,100 oystercatchers in winter (Brush *et al.* 2017). However, in contrast to breeding birds, wintering oystercatchers select for reefs associated with greater oyster densities, which do not overlap with the islands used for nesting (Seavey *et al.* 2011*b*; Brush *et al.* 2017). Understanding how and where additional factors such as food availability and human disturbance also drive reproductive success at these sites could help in the development of future management strategies for oystercatchers.

The effects of habitat loss, climate change, and sea-level rise will have significant long-term consequences on nesting habitat for oystercatchers in our study area as well as areas throughout their range. All oystercatcher-nesting islands in our study area have eroded over the past few decades and islands in Cedar Key have become susceptible to frequent inundation (Florida Shorebird Database 2019, Vitale *et al.* 2020). Enhancing nesting habitats to reduce overwash risk could improve reproductive success at this site. A habitat restoration strategy that uses materials to promote oyster resettlement on and near nesting islands could help to ensure long-term stability of islands as well as foraging areas for oystercatchers. These restoration efforts, combined with the addition of materials to increase the elevation of the nesting islands could decrease the probability of nest loss due to overwash. We documented overwash as the biggest threat to nest survival in Cedar Key, but reevauation of other factors that may annually influence nest and brood survival may be necessary because the impact of other threats such as predation were likely underrepresented in our study. We demonstrate that site-specific management strategies for American Oystercatchers could be beneficial; reduction of predation pressure and human disturbance may be more important at some sites, while nesting and foraging habitat restoration may be more beneficial at sites such as Cedar Key.

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