EVALUATING THE USE OF DRONES FOR MONITORING WATERBIRD NEST ABUNDANCE AND NEST SURVIVAL

A Thesis

by

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BS, Humboldt State University, 2014

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in

BIOLOGY

Texas A&M University-Corpus Christi
Corpus Christi, Texas

December 2022

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This thesis meets the standards for scope and quality of
Texas A&M University-Corpus Christi and is hereby approved.

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December 2022

ABSTRACT

Surveys of colonial waterbirds are used to monitor species' population dynamics, contaminant levels, and to derive metrics that can be used to assess wetland ecosystem restoration and management. Previous studies have found that drone surveys provide accurate estimates of nest abundance and survival for ground-nesting waterbird species such as terns (Laridae Spp.), but drones have not been used to estimate survival for waterbirds nesting in a canopied marsh habitat, and potential sources of bias in drone surveys have not been examined in depth. We examined potential visibility biases associated with using a drone to survey colonies of wading birds (Ciconiiformes and Pelecaniformes) in marsh habitat in Florida in 2020 and 2021. Monthly nest counts and survival were compared between traditional (combination of fixed-wing aircraft and ground surveys) and drone survey methods. Ground-based and drone nest transect surveys were conducted to estimate survival and detection probabilities of each species and plumage color. Generalized linear mixed-effects models were used to quantify the degree to which visual occlusion of nests influenced detectability. Estimates of white-colored waterbird nests were significantly greater for drone surveys than those derived from traditional survey methods but estimates of dark-colored waterbirds from drone surveys were biased low. Variation in detection was best explained by canopy cover, plumage color, and nest stage. Overall, there was no difference between survival estimates from either method. However, drone-derived estimates of dark-colored waterbirds had lower accuracy. Our results suggest that drone surveys are a viable method to conduct monthly nest surveys and estimate survival of waterbirds breeding in marsh habitat, but researchers should consider their study area and species before choosing a survey method.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dale Gawlik, for his support and guidance. I would also thank Michael Starek and Greg Stunz for serving on my committee, and Michelle Petersen for providing a substantial amount of expertise and feedback during field work.

This project wouldn’t have been possible without the contributions of the volunteers and technicians, fellow graduate students, and members of my lab (Biodiversity and Conservation Lab at the Harte Research Institute): David Essian, Antonio Cantu, Alex Sharp, Jacqueline Evans, and Lars Nelson.

I would also like to thank my family for their love and support, and the numerous gas stations surrounding my study site that provided the majority of my caloric intake during the field season.

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CHAPTER I

Introduction

Wildlife species are commonly the focus of ecological monitoring programs and are used as indicators to gain information about the state of an ecosystem and how it changes over time. This is because wildlife species are visible, reactive, can be easily measured, and often hold a deep intrinsic value to members of the public (Stolen et al., 2005). When selecting a wildlife species as an indicator of environmental conditions and ecosystem functioning, how the species responds to specific changes in the ecosystem must be well understood, there must be baseline data to compare past, current, and future trends, and it must be possible to measure how a species responds to target parameters (Lindenmayer and Likens 2011).

Because waterbirds respond closely to hydrologic variation, their distribution, abundance, and nest counts are often used as metrics of wetland ecosystem function (Crozier & Gawlik 2003, Hafner 1993, Kingsford et al. 1999). (Vos et al. 2000, Crozier & Gawlik 2003, Frederick et al. 2009). Accurately assessing these metrics is difficult because waterbirds often breed in colonies that are inaccessible by land, are spaced large distances apart, and contain several species breeding sympatrically (Frederick et al. 1996). To detect these often widely-spaced and inaccessible colonies and to accurately count numbers of nests of each species therein, surveyors have previously used fixed-wing aerial and ground-based monitoring methods (Frederick et al. 1996). Collectively, fixed-wing aerial and ground-based monitoring methods are referred to as traditional survey methods for the remainder of this paper. Ground-based surveys are used to estimate nest abundance of waterbird species that are difficult to observe aerially and obtain productivity measures such as nest survival and brood size at fledging. Although ground surveys allow for estimation of productivity measures, ground monitoring techniques are expensive and the significant disturbance they can cause to birds may impact reproduction (Frederick et al. 1996, Werschkul et al. 1976, Tremblay and Ellison 1979). Fixed-wing aerial survey methods are used to monitor the size, composition, and status of colonially breeding waterbirds (Gibbs et al. 1988, Tremblay and Ellison 1979, Frederick et al. 1996). Whereas fixed-wing aerial surveys are crucial in monitoring colonially breeding waterbirds, they are expensive and have been shown to have significant observer and detection bias (Frederick et al. 2003; Frederick et al. 1996; Rodgers et al. 2005). Fixed-wing aerial surveys have also not been proven to reliably identify and track individual nests, which is needed to estimate nest survival and fledging success.

Recently, there has been an increased interest in the use of drones for environmental and wildlife monitoring applications (Elraham et al. 2005, Jones et al. 2006, Chabot et al. 2015). Drones have proven effective in several wildlife applications, most notably in monitoring several avian species (Bevan et al. 2018, Vermeulen et al. 2013, Elraham et al. 2005, Jones et al. 2006, Chabot et al. 2015). Drones may be less disturbing to birds than traditional survey methods (Chabot et al. 2015, Vas et al. 2015) and have higher detection rates of some colonially nesting birds than fixed-wing aerial surveys (Afán et al. 2018, Chabot et al. 2015, Mcevoy et al. 2016). Given recent advances in drones and post-processing technology, it is now possible to program drones to fly fully autonomous missions, capturing images in specified locations with automatic or preset camera settings (Floreano and Wood 2015).

A precursor to counting birds or nests in drone-derived imagery is to combine individual phots captured with the drone into a single orthomosaic image of an entire waterbird colony. An orthomosaic image is an accurate photo representation of a specific area, created from overlapping photos stitched together and geometrically corrected for accuracy (Floreano and Wood 2015). Orthomosaic images can be crafted with survey-grade accuracy when drones are used in conjunction with a high-accuracy GPS and ground control points (Agüera-Vega et al. 2016). With the increasing improvement in cameras utilized by some models of drones, orthomosaic images can be produced with remarkably high resolution. Whereas there are still limitations regarding max flight time and transmission range of currently available drones, the ability to produce orthomosaic images with survey-grade accuracy and high resolution may prove useful in monitoring waterbird breeding colonies (Afán et al. 2018, Garner et al. Unpublished).

Aerial images taken with a drone can provide more precise counts of waterbirds than ground observations (Hodgson et al. 2016). Similarly, drone-derived photographic surveys sometimes produce higher detection rates of colonial nesting birds compared with traditional fixed-wing aerial surveys, depending on species and habitat (Afán et al. 2018, Chabot et al. 2015, Mcevoy et al. 2016). For example, Chabot et al. (2015) observed detection rates up to 97% for white-colored Common Terns nesting on coastal island with no canopy cover, whereas Bar et al. (2018) observed detection probability of just 53% for decoys dark-colored Black Skimmers in similar habitat. Additionally, Bar et al. (2018), found very low detection probabilities for both white and dark-colored waterbird decoys in areas with high canopy cover. Understanding the relative accuracy of nest counts, and the effect of potential sources of bias related to those nest counts, is a necessary precursor to evaluating the utility of drones for surveying waterbirds and becoming an accepted tool for long-term monitoring of bird populations. Thus, the objective was to quantify the detection probabilities and sources of bias related to counting colonial waterbird nests from aerial imagery taken with a drone. We conducted surveys of colonially nesting waterbirds during the 2020 and 2021 breeding season in South Central Florida, USA to (1) quantify the relative accuracy of drone-derived nest counts as compared to Traditional surveys, and (2) examine the effect of plumage coloration, species, nest stage, nest substrate characteristics, gust speed, and cloud cover on detectability.

Study Area

Data on wading bird nesting were collected February-July of 2020 and 2021 at Lake Okeechobee, Florida, USA (Fig. 1). Lake Okeechobee (hereafter referred to as the lake) is a large ($1730\ km^2$), shallow (mean depth of 2.7m), eutrophic lake that lies at the center of the Greater Everglades Watershed in South Central Florida (26º560'28"N, 80 º510'32"W) (Johnson et al. 2007).

Waterbirds typically nest within the littoral zone of the lake, on natural and anthropogenic islands (SFWMD 2021). Within the littoral zone, plant communities are dominated by emergent marsh (Milleson 1987). Dense stands of willow (*Salix caroliniana*), common reed (*Phragmites australis*) and pond apple (*Annona glabra*) are scattered on elevated ridges throughout the littoral zone and on several spoil islands (Langeland and Jacono 2012).

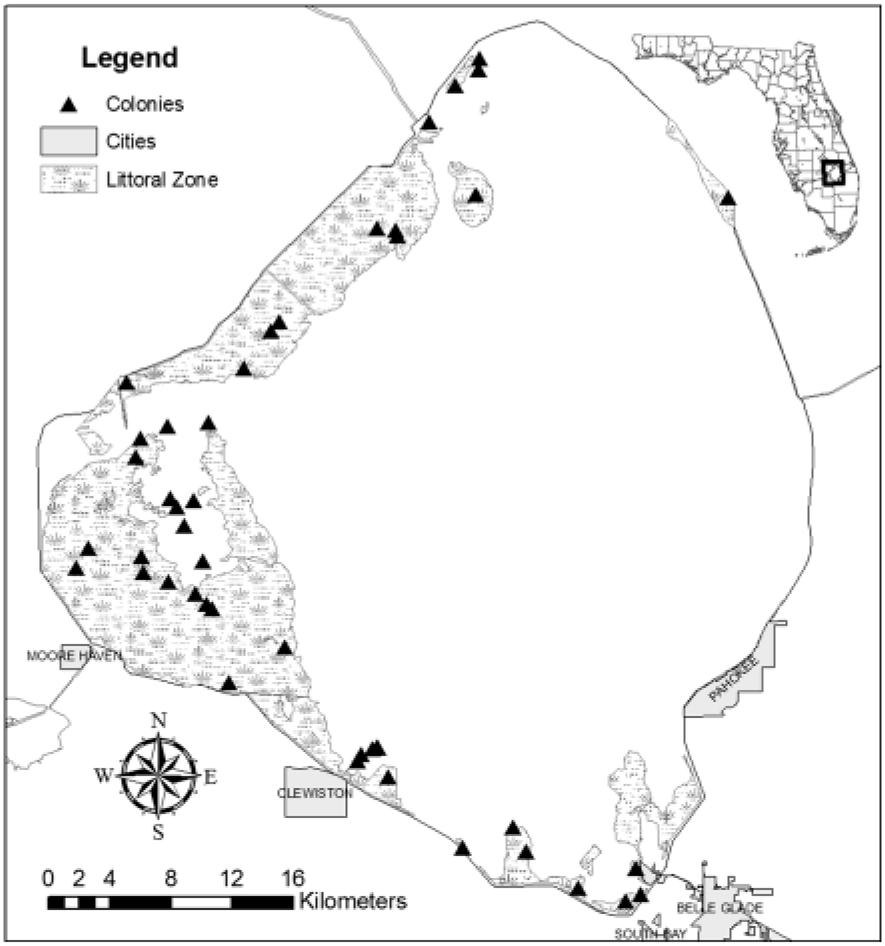


Figure 1. Map of all waterbird colonies observed in the littoral zone of Lake Okeechobee, Florida from 1957 to 2021

Methods

Traditional Fixed-wing Aerial Surveys

Traditional Survey Methods consist of conducting censuses of colonially nesting waterbirds through fixed-wing aerial surveys, often using a fixed-wing aircraft to count and photograph breeding colonies, and ground surveys, which often uses data on the proportion of species observed in colonies through nest transects (Frederick et al. 1996, Werschkul et al. 1976, Tremblay and Ellison 1979).

To calculate waterbird nest abundance, Fixed-wing aerial surveys were conducted monthly during the 2020 and 2021 waterbird breeding season (February-June) (Fig. 1). All fixed-wing aerial surveys were conducted with two observers from a fixed-wing Cesna 182 aircraft. Pre-survey training was provided to observers prior to conducting all fixed-wing aerial surveys if they had not conducted aerial surveys previously. Pre-survey training consisted of ground and in-flight identification of the focal species to improve the accuracy of species identification during fixed-wing aerial surveys (Frederick et al. 1996). Breeding colony locations were located from previously documented colony locations and by flying transects recorded in GIS. Any new colonies located were recorded for future surveys. After locating a colony, the fixed-wing aircraft circled the entire colony several times at an altitude (≈100 m) low enough to differentiate between the individual species on their nest. During surveys, observers counted and recorded nesting waterbirds to species. The colony was then photographed with a Nikon D500 and a 75-300 mm lens. Following each flight, the observer systematically examined photographs to manually count and identify nesting waterbirds in the photos to species. Raw counts were the number of adult birds converted to numbers of nests according to stage of nesting. If the colony was courtship or nestbuilding, both members of the pair were likely to be present, and raw counts were divided in half to estimate numbers of nests. If in incubation, the number of birds observed were considered roughly equivalent to numbers of nests (Frederick et al. 1996, Frederick et al. 2002).

Traditional Ground Surveys

To calculate waterbird nest abundance, traditional ground surveys were conducted monthly during the 2020 and 2021 waterbird breeding season (February-June) (Fig. 1). Because ground-based monitoring techniques are considered the “standard” for deriving counts of smaller wading bird breeding colonies (Buckley and Buckley 1976, Frederick et al. 1996, Rodgers et al. 2005), they were compared to the accuracy of drone-derived estimates. If the best possible estimates of nesting were assembled using information from a combination of survey methods, the number of nests derived from this combination of survey methods were used as the number from which drone nest count survey estimates were compared (Frederick et al. 1996). Raw counts of adult birds were included as mentioned in traditional fixed-wing aerial surveys (see above). Ground-based monthly nest counts were taken 0-3 days after a fixed-wing aerial survey was conducted. The Ground Survey method used in this study was similar to methods used in the Florida Everglades (South Florida Wading Bird Breeding Report 2020). The colony was approached with an airboat and at least twoobservers conducted flightline counts of birds, simultaneously, for 30 minutes. The proportion of each species was recorded and used to determine the proportion of birds in the colony that are more difficult to observe from aerial surveys (i.e., dark-colored waterbird species).

Drone Nest Count Surveys

To calculate waterbird nest abundance, drone nest count surveys were conducted monthly with a consumer-grade drone (Inspire 2, DJI, Shenzhen, Guangdong, China) equipped with a 24 mega-pixel RGB camera (Zenmuse x7, DJI, Shenzhen, Guangdong, China). The Inspire 2 is operated by a single researcher, has the ability to launch from almost any surface, and is operated using an inelaborate ground station (iPad device and remote control, [Apple Inc., Cupertino, CA]).

The max wind speed at which a DJI Inspire 2 is rated to fly is 38 kph, and to ensure the safety of both drones and researchers, the max wind speed at which the drone was operated was 38 kph at the altitude missions were flown (77 m). The Drone was flown at an altitude of 61 m. and achieved a Ground Sampling Distance (GSD) of 0.8cm. Gusts often went above 38 kph during surveys, and to ensure surveys were appropriately spaced apart, it was necessary to pilot the drone with gusts up to 46 kph. Weather projections were accessed daily using a third-party app (UAV Forecast), and if the wind exceeded this limit, surveys were called off.

All drone nest count surveys were conducted within 0-3 days of fixed-wing aerial surveys. While surveying a colony with a drone, a location over 183 m from the colony was selected as the “Home Base”, and the drone was programmed to photograph a breeding colony with a third-party app (DJI GS Pro). The drone then began its mission, flying at an altitude of 76.20 m, and capture images at predetermined intervals of distance. The drone continued capturing images of the colony until it has recorded the entire colony. Upon the completion of the survey, images were processed through Agisoft Metashape, and rectified via a digital elevation model and stitched into Orthomosaic images. Orthomosaic images were converted to JPEGs and nesting birds were manually counted in the same manner as fixed-wing aerial survey photographs.

Ground-based Nest Transects

To calculate waterbird productivity, ground-based nest transects were conducted at 4 breeding colonies on Lake Okeechobee, FL, USA, during the 2021 breeding season. I established two parallel 50-m transects, 30 m apart at each monitored colony (e.g., Chastant and Gawlik 2018). Transects were 3-m in width. During each nest transect survey, a total count of nests within a transect, as well as species, contents (i.e., eggs and nestlings), nestling age, and fate were measured. The origin of the first transect was randomized by selecting a random distance and bearing from the boat. If a selected random bearing ran through unsuitable nesting habitat or extended past the edges of an island (spoil islands), the start and direction of each transect was adjusted.

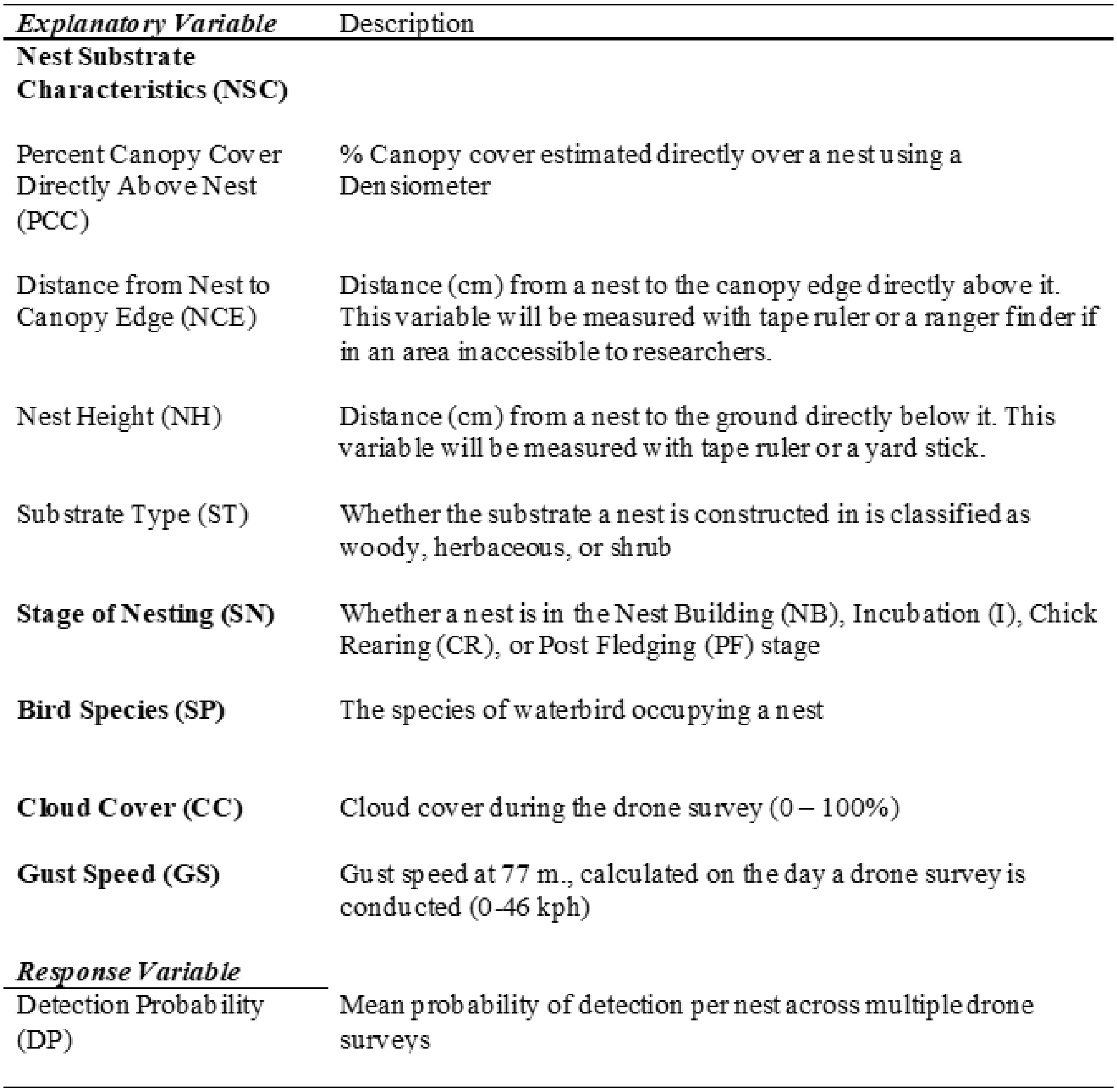
Ground-based nest surveys were conducted every 2-7 days. All nests within a 1.5-m perimeter on both sides of the transect were flagged and assigned an identification number. If the sample size was less than 50 per species, nests outside of the 1.5-m buffer were marked. Species, contents, nestling age, and fate were recorded for each marked nest. The estimated age of each nestling was used to determine hatch date. The hatch date was back-calculated for nestling A, and served as the nest hatch date. If a nest reached at least 14 days old (±2 days), the nest was considered successful, and the brood size was recorded for brood size at fledging (Frederick and Collopy 1989, Parsons and Master 2000). Due to the infrequency of colony visits and the difficulty of assigning some 14-day old chicks to their original nest, the addition of a two-day threshold around the fledging age resulted in increased data retention. A GPS waypoint of each nest location was also be taken using a Leica GS07 GNSS RTK Rover. The name associated with each GPS waypoint denoted the transect, colony, and number associated with each nest. All GPS waypoints were imported to an orthomosaic image produced in Agisoft Metashape (see below). Notes of where nests were located based on their orientation in the transect, as well as ground photographs, were also used to positively identify individual nests.

Nest and Nest Substrate Characteristics

All Nest Substrate Characteristics (NSCs) were collected on the ground during ground-based nest transects (see below). Nest substrate characteristics in this study refer to measures or descriptions directly associated with the makeup and/or location of a nest. used in this study resemble those used in May et al. (2018). These characteristics include the Percent Canopy Cover Directly Above a Nest (PCC), Distance from the Nest to the Canopy Edge (NCE), Nest Height (NH), and Substrate Type (ST) (Table 1.). Percent Canopy Cover Directly Above a Nest was recorded as the percent of canopy cover directly over a nest and was measured using a

Densiometer. Distance from the Nest to the Canopy Edge was recorded as the distance (cm) between the base of a nest, to the nearest edge of the canopy, and was measured using a tape measure. Nest Height was recorded as the distance (cm) from a nest to the ground directly below it and was measured with tape ruler. Substrate Type was recorded as whether the substrate a nest was constructed in was classified as woody, herbaceous, or shrub.

Table 1. Variables used to test hypotheses regarding the degree to which visual occlusion of nests influences detectability.



Explanatory Variable	Description
Nest Substrate Characteristics (NSC)	
Percent Canopy Cover Directly Above Nest (PCC)	% Canopy cover estimated directly over a nest using a Densiometer
Distance from Nest to Canopy Edge (NCE)	Distance (cm) from a nest to the canopy edge directly above it. This variable will be measured with tape ruler or a ranger finder if in an area inaccessible to researchers.
Nest Height (NH)	Distance (cm) from a nest to the ground directly below it. This variable will be measured with tape ruler or a yard stick.
Substrate Type (ST)	Whether the substrate a nest is constructed in is classified as woody, herbaceous, or shrub
Stage of Nesting (SN)	Whether a nest is in the Nest Building (NB), Incubation (I), Chick Rearing (CR), or Post Fledging (PF) stage
Bird Species (SP)	The species of waterbird occupying a nest
Cloud Cover (CC)	Cloud cover during the drone survey (0 – 100%)
Gust Speed (GS)	Gust speed at 77 m., calculated on the day a drone survey is conducted (0-46 kph)
Response Variable	
Detection Probability (DP)	Mean probability of detection per nest across multiple drone surveys

Given the high densities of nesting waterbirds, distance between colonies used in the study, and the limited duration of time researchers were permitted to conduct ground-based nest transects in a colony (2 hours), it was not possible to record the Nest Substrate Characteristics on the first date a nest was observed. Instead, Nest Substrate Characteristics were recorded after the date in the season at which willows (*salix*) leafed out (April 14). Recording the nesting substrate after this date helped standardize the vegetative cover and reduce bias associated with the time in the breeding season at which the nest site characteristics were recorded.

Due to logistical constraints, Nest Substrate Characteristics were recorded for only 73% of nests observed in the study Nests were selected by numbering nests from one onward in each transect and using a random number generator to select from those nests. If a nest had been selected and failed or had been abandoned before Nest Substrate Characteristics were recorded, researchers placed a flag with a unique color to denote the nest was no longer active, a GPS waypoint was taken for the nest, and nest substrate characteristics were recorded as close to the date the nest had failed as possible.

Stage of Nesting (SN) and Bird Species (SP) were also recorded for each nest, and Cloud Cover (CC), and Gust Speed (GS) were recorded for the date, time, and location of each transect survey. Stage of Nesting was recorded as whether a nest was in the Incubation (I), Chick Rearing (CR), or Post Fledging (PF) stage of nesting. Bird Species was recorded as the species of wading bird occupying a nest. Cloud Cover and Gust Speed were recorded daily, at the time and location of each drone nest count surveys, using a third-party app (UAV Forecast). Cloud cover was measured as a percent, and Gust Speed was measured in KPH at the altitude at which drone nest count surveys were flown (77m).

Drone Productivity Survey

Drone productivity surveys were conducted with a DJI Inspire 2 paired with a zenmuse x7 camera. Drone productivity surveys adhered to the same wind limit stated in “Drone nest count surveys s” above (< 38.7 kph; see above).

Drone productivity surveys were conducted every 2-7 days and took place approximately 1 hour before the ground-based nest transect survey. Before drone productivity surveys took place, five Ground Control Points (GCPs) were placed in each colony. GCPs are marked points on the ground with known coordinates (Liu et al. 2022). The coordinates of the GCPs are used to increase the geospatial accuracy of orthomosaic images that have been “stitched” together during post-processing. The Ground Control points used in this study were constructed of 2-foot by 2-foot water resistant plywood that had been painted to resemble a small section of a checkerboard. GCPs were placed atop steel pipes (1.2 m to 3.0 m long) that had been hammered vertically into the ground and were unobstructed by canopy or vegetation. Four GCPs were spread evenly on the outer edges of a colony, and one GCP was placed in the middle of the colony. A GPS waypoint of each GCP was taken using a Leica GS07 GNSS RTK Rover. During Ground Surveys, GCPs were checked to ensure no vegetative litter or other debris was obstructing their vertical presentation.

While conducting a drone productivity survey, a location over 183 m from the colony was selected as the “Home Base”, and the drone was programmed to photograph the transect using a third-party app (DJI GS Pro). The drone then began its mission, flying at an altitude of 76.20 m, and capturing images at a 78º angle, at intervals with the appropriate overlap (90% front overlap and 90% side overlap). The drone continued capturing images of the transect until it recorded the entire transect. Upon the completion of the survey, images were processed through Agisoft Metashape, and “stitched” into Orthomosaic images. GCPs were marked during post-processing to ensure increased geospatial accuracy of the orthomosaic image.

The location of nesting waterbirds was recorded by photointerpretation using Agisoft Metashape, and nesting pairs were identified and tracked using the post-processing software’s Orthomosaic window feature. After producing an orthomosaic image, the area of the transect was zoomed in to a scale of 1:20, and the colony was systematically searched in a grid pattern. In some cases (n=29), new nests appeared in the same location as old nests, after not being detected during previous weeks. Those nests were considered new nests and were given a unique identification number.

After a nest was determined to be active through ground-based nest transect surveys, GPS coordinates taken for a nest using the RTK Rover (see above) were imported into Agisoft Metashape. Nests observed in the orthomosaic image were matched to nests marked through ground-based nest transects (see above). The location of nests that were identified through ground-based nest transects but were not observed through drone productivity surveys, were marked in the orthomosaic image to confirm the nest had been accounted for and had not been mistaken for another nest.

Active nests detected through Drone transect surveys were tracked throughout the nesting season and Bird Species, Stage of Nesting, contents, nestling age, and fate were recorded. A record of whether a nest was detected was also recorded for each survey. Nest were tracked using the “Filter Photos by Marker” function in Agisoft Metashape. After locating a nest through drone productivity surveys, a georeferenced “reference marker” was placed directly over the location nest, and the reference marker was then selected using the function “Filter Photos by Marker” in Agisoft Metashape. This function allows the user to access every photo that includes the location of a referenced marker, and will automatically zoom to the same magnification, in same location, in every image. I went through every image containing the nest, and the image with the highest resolution and clearest view of the contents of a nest was used to record Bird Species, Stage of Nesting, contents, nestling age, and fate (Fig. 2.).

Nest Stage was determined based on the contents of a nest that were observable during drone transect surveys. Until nestlings were visible in an image of a particular nest, the nest would be classified as being in the Incubation (I) or Nest Building (NB) stage. The NB stage is the period of time in which a pair of nesting waterbirds is in the process of constructing a nest, whereas the I stage is the period of time that a pair of nesting waterbirds are actively incubating eggs, but no nestlings have hatched. After observing a nestling in a nest, the nest would be classified as being in the Chick Rearing (CR) stage until the nestlings were believed to be at least 14 days old (±2 days). The CR stage is the period of time in which a pair of nesting waterbirds are on a nest in which one nestling is present, and the nest has not reached fledging (first nestling to hatch reaches 14 ± 2 days old; see below).

To determine the age of a nest using drone-derived photographic counts, the nest was tracked through drone-derived orthomosaic images from the date it was first detected. If a nest failed or was abandoned before chicks were observed, the first date a nest was observed was marked as day zero, with the number of days in-between subsequent surveys added to its initial age. If a nestling was observed within a nest during a drone productivity survey, the date of the survey would be marked and used to back-calculate the age of the nest. Because I was unable to positively ascribe a nestling to a certain age given the resolution of the imagery, the nestling would be marked as 0 days old during its first observation, and the age of the nest would be back-calculated based on the incubation period for a particular species [Great egret (*Egretta* *alba)* = 25 days, Snowy Egret (*E. thula*) = 22 days, Tricolored Heron (*E. tricolor*) = 22 days, White Ibis (*Eudocimus albus*) = 22 days, Cattle Egret (*Bubulcus ibis*) = 23 days, Glossy Ibis (*Plegadis falcinellus*) = 21 days) (Birds of the World 2022). If back-calculating the age of a nest resulted in ascribing the age of a nest in previous surveys to a negative number, the nest was detected was marked as 0 days old. This can happen when nestlings aren't observed in a nest when they are very young and/or the nest was first detected and tracked close to the date the first egg was laid. Because I was unable to determine the precise age of nestlings using images captured in this study, I often needed to track nests past the age of fledging used in prior literature. Chicks are highly mobile past the age of fourteen days old and may leave the nest before investigators can record them (Billerman et al. 2020). Thus, fledging has been recorded at fourteen days ± two days in prior literature (Chastant et al. 2017; Frederick et al. 2002). Because drone productivity surveys do not require investigators to directly approach nests, it was possible to reliably distinguish chicks to a nest past 14 days old. On the date a nest was determined to have reach fledging using drone productivity surveys, the nest was marked as successful and no longer tracked in subsequent surveys.

Statistical Analysis

Monthly Nest Count Comparison. Statistical analyses were performed in Program R (R Core Development Team 2016). Combined information from both traditional fixed-wing and ground surveys (see above) was used to produce the best estimates of nest counts. The size and species composition of waterbird breeding colonies observed on the lake using drones survey techniques alone was compared with that derived from the best combination of traditional aerial and ground surveys. I considered the combined information from both fixed-wing aerial and ground counts as the best estimate of the number of nests initiations in any given year (Frederick et al. 1996). I then calculated and noted the percent difference, standard error (SE), and n for each species, total number of birds, white birds, and dark birds between survey methods (Fig. 2.). I used paired t-tests to examine the null hypothesis of no difference (α=0.05) in the mean estimated number of breeding pairs for total birds, white birds, and dark birds between survey methods (e.g., Gibbs et al. 1988). Finally, I calculated 95% confidence intervals for total birds, white birds, and dark birds between survey methods (Table 3.)

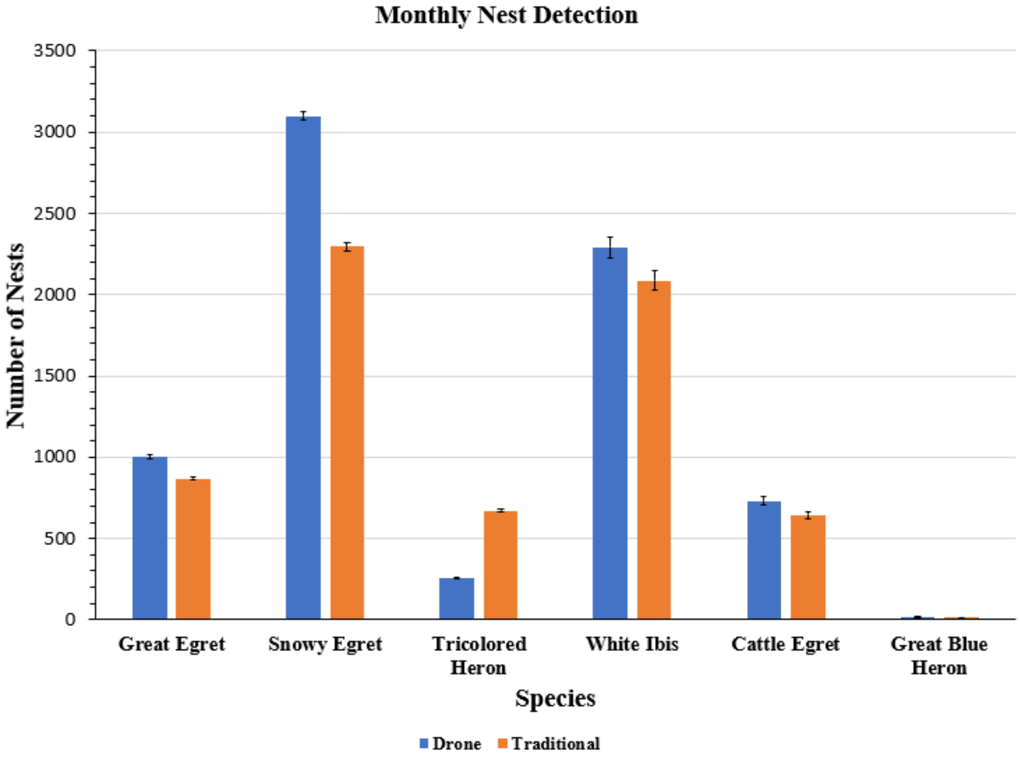


Figure 2. Comparison between total estimates of nesting waterbirds derived from monthly drone nest count surveys and traditional survey methods in Southern Florida, USA during the 2020 and 2021 breeding season; Standard error is presented as a vertical standard error bar.

Table 2. Best estimates of nests using traditional survey methods (aerial plus ground counts) and colonies[1] of wading birds during 2020 and 2021 on Lake Okeechobee, with best estimates of drone-derived counts.

Year	Survey Method	Parameters	GREG[2]	SNEG	CAEG	GLIB	TRHE	WHIB	GBHE	Total White Birds	Total Dark Birds[3]	Total Birds
2020 & 2021	Aerial Plus Ground	Number of Nests	868	2294	644	399	672	2088	13	5894	1087	6981
	Drone	Number of Nests	998	3097	728	92	255	2255	20	7132	370	7470
	Drone	Drone Accuracy[4]	1.15	1.35	1.13	0.23	0.38	1.08	1.52	1.21	0.34	1.07
	Drone	Mean Colony Accuracy[5]	0.81	1.45	1.43	0.73	0.34	1.11	1.5	1.35	0.66	1.23
	Drone	SD	0.22	0.49	0.51	1.25	0.23	0.31	1.15	0.35	0.84	0.42
	Drone	95% CI	[18.44, 34.72]	[30.59, 54.25]	[-18.70, 28.06]	[-63.13, -38.87]	[-27.03, -16.45]	[-6.14, -16.45]	[-0.80, 2.36]	[43.29, 84.49]	[-44.57, -30.58]	[5.31, 47.84]

[1] 10 wading bird breeding colonies were surveyed; [2]GREG = Great Egret (*Ardea alba*), SNEG = snowy Egret = (*Egretta thula*), WHIB = (*Eudocimus albus*), TRHE = Tricolor Heron (*Egretta Tricolor*), GBHE = Great Blue Heron (*Ardea Herodias*) CAEG = Cattle Egret (*Bubulcus ibis*), GLIB = Glossy Ibis (Plegadis falcinellus) ; [3]Total Dark Birds and Total Birds include the addition of Little Blue Heron (*Egretta caerulea*); [4]Drone Accuracy = number of nests detected using a drone /number of nests detected using Aerial Plus Ground; [5]Mean Colony Accuracy = average accuracy of drone estimates per colony/aerial plus ground estimates per colony

Visibility Bias Associated with Drone Surveys. I used generalized linear mixed-effect models (GLMMs) with a Binomial log-link function and error distribution to analyze the factors determining nest detection (Harrison et al. 2018). I preserved correspondence among nests within each colony by specifying a nested random effects structure where nest ID was nested within colony. Nest detection was a binomial dependent variable (nests detected or not), and Nest Substrate Characteristics', Bird Species (n = 6), Stage of Nesting (n = 3), Cloud Cover (0-100%), and Gust Speed (0- 46 kph) were the independent variables. Given the large degree of variation in Distance from the Nest to the Canopy Edge of individual nests, Distance from the Nest to the Canopy Edge was scaled. Color, Bird Species, and Stage of Nesting were treated as categorical predictors in the model (see methods section), whereas Distance from the Nest to the Canopy Edge, Percent Canopy Cover Directly Above a Nest, Cloud Cover, Gust Speed were treated as numeric predictors. I also included the interaction between Percent Canopy Cover Directly Above a Nest and Distance from the Nest to the Canopy Edge as a predictor variable. All predictor variables were examined for collinearity before inclusion in any models. Models with Cloud Cover and Nest Height failed to converge, so these variables were removed from further model selection. Given that the majority of monitored nests were constructed on *Salix* (.99), Substrate Type was also removed from further model selection.

The GLMMs were constructed and analyzed using the lme4 package for program R (R Development Core Team 2022, version 4.2.0). I ran a model selection analysis to examine *a priori* hypotheses that Bird Species, color, Stage of Nesting, Nest Substrate Characteristics, Cloud Cover, and Gust Speed affected detection. I then used the chosen global model to estimate six candidate models that included all supported *a priori* hypotheses, as well as a null model. ΔAICc values were calculated for each of the candidate models to reflect differences from the best candidate model (i.e., the model with the lowest AICc). Candidate models were then ranked based on ΔAICc values to choose the best-fitting and most parsimonious models. An ΔAICc < 4 was chosen as the threshold to compare against the best model. Relative support of candidate models was obtained through scaling models according to their AICc weight of evidence (Burnham and Anderson 2002). Conditional and marginal R^2 values were calculated for each model to assess goodness-of-fit (Nakagawa and Schielzeth 2013). Conditional R^2 assesses fit for the combined fixed and random effects, whereas marginal R^2 is a measure of fit (i.e., the proportion of variance explained by the model) for fixed effects (Nakagawa and Schielzeth 2013). I did not use model averaged function from the MuMin Package (Bartón 2009) to average candidate models based on information criterion. To demonstrate the level of effect each fixed parameter had on detection, I constructed a odds ratio forest plot with 95% CI (Fig. 4.)

Results

Monthly Nest Survey Comparison. I conducted 19 total monthly nest surveys of 10 individual colonies across 6 months in 2020 and 2021 on the lake. I found that the use of the drone survey methods for monthly nest counts gave estimates for the number of nests of 8 species that were 107% of the total derived from traditional survey methods (range 82 – 185% among individual months, Fig. 2.). The accuracy of drone-derived monthly nest count estimates varied considerably among the 8 species (range for drone accuracy of nest counts among species was 38 – 152%, see Table 3). Means of species-specific monthly nest count accuracies averaged across white-colored species (White Ibis [*Eudocimus albus*], Cattle Egret (*Bubulcus ibis*), Great Egret [*Ardea albus*], Snowy Egret [*Egretta thula*]) was 121% of the total derived from traditional survey methods (range 108 – 135% among individual species). Means of species-specific monthly nest count accuracies averaged across the dark-colored species (Great Blue Herons

[*Ardea herodias*], Tricolored Herons (*Egretta Tricolor*), Little Blue Herons (*Egretta caerulea*), and Glossy Ibises [*Plegadis falcinellus*]) was 34% of the total derived from traditional survey methods (range 23 – 152% among individual species).

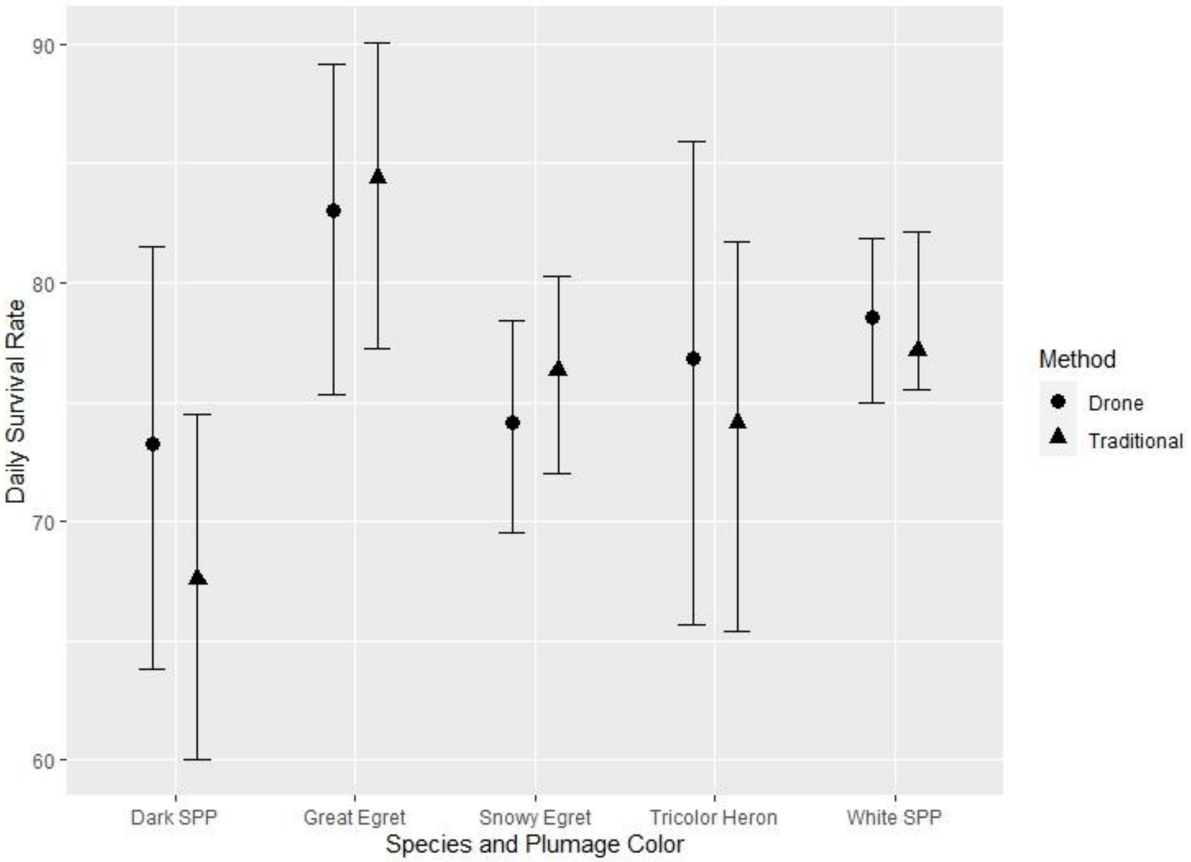


Figure 4. Comparison between Traditional Survey Methods and Drone Survey Methods of (Dark SPP) mean (± 95% CI) daily survival rate of nests for 3 dark-colored waterbird species [Tricolor Heron, Glossy Ibis, Little Blue Heron]; Great Egret) mean (± 95% CI) daily survival rate of nests for Great Egret; (Snowy Egret) mean (± 95% CI) daily survival rate of nests for Snowy Egret; (Tricolor Heron) mean (± 95% CI) daily survival rate of nests for Tricolor Heron; (White SPP) mean (± 95% CI) daily survival rate of nests for 3 white-colored waterbird species [Great Egret, Snowy Egret, White Ibis]

The 18 individual colonies surveyed during monthly nest counts using drone survey methods (M = 394.0, SD = 332.36, see Table 3.) compared to the same 18 individual colonies surveyed using traditional survey methods (M = 367.42, SD = 323.15) demonstrated greater estimates of total nests (Table 3.). Drone-derived estimates of white-colored waterbird nests were significantly greater than estimates obtained through traditional survey methods, although this was constant across species and plumage color. For example, drone-derived monthly nest estimates greater for the Great Egret and Snowy Egret but there was no difference in detection of the Cattle Egret and White Ibis nests (Table 3). Drone-derived estimates of the total number of dark-colored waterbirds was biased low, but there was a marginally significant decrease in detection of Glossy Ibis nests (Table 3.). Unlike other dark-colored waterbird species examined in this study, there was found to be marginally significant increase in Great Blue Heron nest estimates using drone survey methods compared to traditional survey methods (Table 3.).

Visibility Bias Associated with Drone Surveys. I conducted 104 total drone and traditional nest transect surveys, across 8 individual nest transects, in 4 breeding colonies, on the lake during the 2021 waterbird breeding season. A total of 538 individual nests were included in our analysis. Detection probability varied across all 8 species included in this study. There was a noticeable difference between the proportion of dark and white colored waterbird species detected using drone transect surveys compared to ground-based nest transect surveys (Fig. 5). Mean Snowy Egret detection probability was 91.6% (n=292), mean Great Egret detection probability was 99.7% (n=60), mean White Ibis detection probability was 85.7% (n=30), and mean Cattle Egret detection probability was 99.2% (n=22), whereas mean Tricolor Heron detection probability was 62.5% (n=83), mean Glossy Ibis detection probability was 55% (n=49), and mean Little Blue Heron detection probability was 96% (n=6) (Fig. 5). White-colored waterbird species that regularly nest on top of the canopy (e.g., Great Egret) were found to have the highest detection probability (Fig. 5).Percent Canopy Cover Directly Above a Nest of all nests ranged between 0 - 95% (Mean Snowy Egret PCC = 0.69, mean Great Egret PCC = .47, mean Tricolor Heron PCC = 0.71, mean Glossy Ibis PCC = 0.65, mean White Ibis PCC = .86, mean Cattle Egret PCC = 0.54, mean Little Blue Heron PCC = 0.52), Nest Height of all nests ranged between 30.48 – 256.1 cm (Mean Snowy Egret NH = 145.04 cm, mean Great Egret NH = 160.07 cm, mean Tricolor Heron NH = 137.87 cm, mean Glossy Ibis NH = 168.67 cm, mean White Ibis NH = 138.76 cm, mean Cattle Egret NH = 159.98 cm, mean Little Blue Heron NH = 155.21 cm), Distance from the Nest to the Canopy Edge of all nests ranged between 0 – 248.92 cm (Mean Snowy Egret NCE = 90.82 cm, mean Great Egret NCE = 82.34 cm, mean Tricolor Heron NCE = 120.04 cm, mean Glossy Ibis NCE = 153.84 cm, mean White Ibis NCE = 130.73 cm, mean Cattle Egret NCE = 90.82 cm, mean Little Blue Heron NCE = 117.07 cm), Cloud Cover during all flights ranged between 0–91%, and Gust Speed during all flights ranged between 0 – 46 kph.

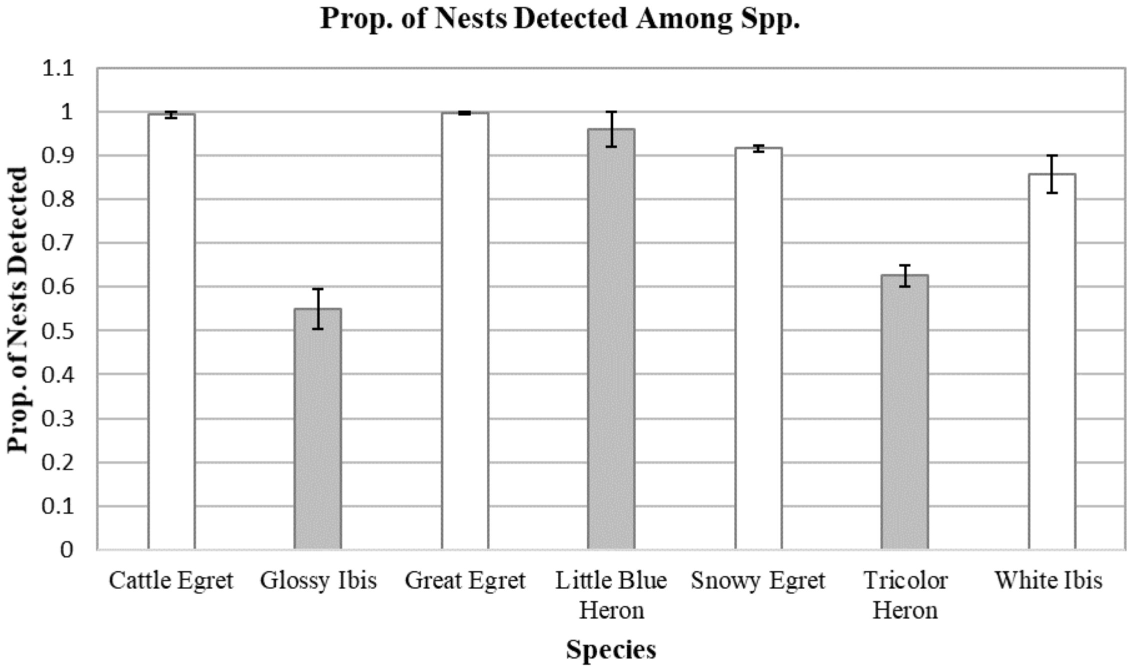


Figure 5. Average proportion of nests detected, among species, through Drone Productivity Surveys, compared to Ground-based Nest Transect Surveys, for Cattle Egret, Glossy Ibis, Great Egret, Little Blue Heron, Snowy Egret, Tricolored Heron, and White Ibis; Standard error is presented as a vertical standard error bar for each species; White bars denote white-colored species, and dark bars denote dark-colored species.

All top models ($\Delta AICc < 4$) explaining variation in the detection of waterbird nests in breeding colonies on Lake Okeechobee, FL, USA, contained terms for Percent Canopy Cover Directly Above a Nest, the interaction between Percent Canopy Cover Directly Above a Nest and Distance from the Nest to the Canopy Edge, Color, and Stage of Nesting (Table 2.). These models supported three of our ten *a priori* hypotheses. Differences among the top models were due to inclusion of bird species and gust speed as predictor variables, and the inclusion of colony as a random variable (Table 2.). Species, plumage color, nest stage, percent canopy cover directly over a nest, the interaction of percent canopy cover directly over a nest, and the distance from a nest to the canopy edge were included in the best candidate models ($\Delta AIC > 4.00$). Nest ID was included as the random variable. Our second-most supported model ($\Delta AICc = 0.32$) was similar in structure to our best supported model, with the removal of species. Our third most supported model ($\Delta AICc = 1.66$) was our global model, which stated that nest detection using drone surveys was best explained by all the predictor variables included in our most well supported model, with the inclusion of gust speed as a predictor variable, and colony as a random variable. Because our top three models were found to have $\Delta AICc < 4$. 95% CIs of model-averaged parameters (β) were computed on the logit scale as $\beta \pm 1.96$ (SE). Estimates were back-transformed to the real scale using the inverse-logit function and plotted by rank (fig.5). All fixed effects used in the best fitting model, with the exception of Bird Species, did not overlap 0, suggesting that models containing these fixed effects have useful predictive value (Burnham and Anderson 2002). Because the best fitting model had one additional parameter, only received a modest increase in AIC_c score than the second-best fitting model (Best Fitting Model $AIC_c = 974.6$, Best Fitting Model $AIC_c = 974.9$, Table 2.) and deviance did not change substantially between the models (Best Fitting Mode df Residual = 950.5, Deviance = 2501; Second Best

Fitting Model df Residual = 960.9, Deviance = 2515), the CI of the regression coefficient was examined. Every species had a 95% CI that overlapped zero, with standard errors that were close to, or larger, than coefficient estimates. This implies that species is a "pretending variable" and its addition did not improve the model fit from the second-best fitting model (Anderson 2010).

Table 3. Selected Generalized Linear Mixed Models assessing nest detection of 8 species of nesting waterbirds from drone-derived aerial imagery. Missions conducted and imagery collected March through May 2021, Florida, USA.

Model(1)	K	ΔAIC	LL2	R^2_m (3)	R^2_c (4)	$\hat{c}$(5)	W_i
Detection ~ Color + Species + (1|nest) + Nest Stage + Percent Canopy + Percent Canopy * Distance to Canopy Edge	12	0.0	-475.24	0.59	0.88	0.52	.437
Detection ~ Color + (1|nest) + Nest Stage + Percent Canopy + Percent Canopy * Distance to Canopy Edge	7	0.32	-480.44	0.58	0.88	0.52	.372
Detection ~ (1|colony/nest) + Species + Color + Nest Stage + Percent Canopy + Distance to Canopy Edge + Percent Canopy * Distance to Canopy Edge + Gust Speed	13	0.190	-475.6	0.59	0.88	0.52	.190

Detection ~ Color + (1|nest) + Nest Stage + Percent Canopy + Distance to Canopy Edge + Gust Speed	6	17.53	-489.53	0.72	0.92	0.53	0
Detection ~ Color + (1|nest) + Nest Stage + Percent Canopy + Distance to Canopy Edge	5	18.03	-490.05	0.72	0.92	0.53	.0
Detection ~ Species + Color + (1|Nest) + Nest Stage + Percent Canopy + Distance to Canopy Edge	6	18.03	-485.26	0.74	0.92	0.53	.0
Detection ~ Color + (1|Nest) + Nest Stage + Percent Canopy + Distance to Canopy Edge + gust	5	18.50	-485.26	0.74	0.92	0.53	.0
Detection ~ Color + (1|Nest) + Percent Canopy + Distance to Canopy Edge	4	20.22	-492.39	0.72	0.92	0.53	.0
Detection ~ Species + (1|Nest) + Percent Canopy + Distance to Canopy Edge	4	20.50	-488.50	0.74	0.92	0.53	.0
Detection ~ (1|nest) + Percent Canopy + Percent Canopy * Distance to Canopy Edge	5	129.37	-546.97	0.26	0.93	0.51	0
Detection ~ (1|colony/nest)	2	1161.1	-577.56	0	0.97	0.50	0

(1)Models variables are *Species* (Great Egret, Snowy Egret, Tricolor Heron, White Ibis, Glossy Ibis, Cattle Egret, Little Blue Heron), *Color* (plumage dark or white), *Nest Stage* (incubation, chick rearing, post fledging), *Percent Canopy* (percent canopy cover directly over a nest), *Distance to Canopy Edge* (distance in cm from a nest to the nearest canopy opening), *Gust Speed* (wind speed in KPH at the time and date a drone transect survey was conducted, (Percent Canopy * Distance to Canopy Edge) the interaction of canopy cover directly over a nest and distance from a nest to the nearest canopy opening. (Colony) and (Nest) represent the random effects of the colony an individual nest was observed and the individual nest, respectively. I tested a full global model with both random effects against a reduced model without the colony effect by likelihood ratio test (LRT).

(2)Log-likelihood of the model.

(3)Marginal R^2, the percent of variance explained by the fixed effects in the model.

(4)Conditional R^2, the percent of variance explained by both the fixed effects and random effects (i.e., among-colony and among-nest) combined

(5)Dispersion Parameter

Discussion

Monthly Nest Count Comparison. Drone-derived monthly nest count estimates of total waterbirds in marsh and spoil island breeding colonies were significantly larger than estimates from traditional survey methods (Fig. 2). Overall, drone estimates of monthly nest counts were over 7% larger than from traditional survey methods and estimates of white-colored waterbirds were over 21% greater (Range 108 – 135%). Detection biases due to cryptic plumage color are well documented on fixed-wing aerial surveys (Pollock and Kendall 1987, Frederick et al. 1996, Rodgers et al. 2005, Barr et al. 2018) and this study shows the same is true of drone surveys.

However, that bias was less for drones than that observed in previous studies examining nest detection of dark-colored waterbird using traditional fixed-wing aerial surveys alone. Rodgers et al. (2005) was unable to detect five species (Tricolored Heron, Reddish Egret [*E. rufescens*], Black-crowned Night Heron [*Nycticorax nycticorax*], Yellow-crowned Night Heron [*Nyctanassa violaceus*], and Glossy Ibis, using traditional fixed-wing aerial surveys in southern Florida, USA, whereas Frederick et al. (1996) found that the use of traditional fixed-wing aerial surveys alone produced nest estimates that ranged between 0-27.6% among five dark-colored species (Little Blue Heron, Tricolor Heron, Glossy Ibis, and Black-crowned Night Heron) species, compared to ground-based counts. Total nest detection for dark-colored waterbird species using drone nest count surveys averaged 44% of that derived from traditional survey methods, and detection ranged between 34-73% among species (see below).

The higher detection of white-colored waterbird species using drones compared to traditional survey methods is likely due to the contrast of plumage color on the surrounding habitat, the resolution of orthomosaic images, and the ubiquitous coverage of images captured during a drone nest count survey. Chabot and Bird (2012) found reduced variability in detection of snow geese (*Anser caerulscens*) compared to Canada Geese (*Branta canadensis*), which they attributed to the contrast of white plumage on a dark background. Waterbirds on the lake typically nest within the littoral zone, which is dominated by green emergent marsh. The white plumage of Great Egret, Snowy Egret, Cattle Egret, and White Ibis contrasts highly against the green background of the emergent marsh, and likely makes the white-colored birds easier to distinguish. Studies have also noted the importance of image resolution to correctly identify nesting birds to species. Dulava et al. (2015) recommended an image resolution of ~ 0.50 cm/pixel to correctly identify nesting waterfowl. While the image resolution of maps produced for this study were 0.8 cm/pixel, the impressive resolution of the 24 mega-pixel RGB camera used in this study likely helped in detecting nesting waterbirds. Additionally, when mapping a large colony, I was far more likely to capture higher resolution images of the entire colony through drone surveys than with traditional survey methods. Because the drone was programmed to capture images over the entire colony, at the same altitude, it was very unlikely that sections of the colony would be missed unless researchers ran out of batteries or were time limited. While the 21 mega-pixel RGB Nikon D500 camera and 75-300-mm lens used for traditional fixed-wing aerial surveys was impressive, manually selecting portions of the colony to photograph and adjusting the camera and lens likely leaves greater room for error. Researchers also did not have time to go over images captured during fixed-wing aerial surveys in real time due to logistics. Whereas a researcher should be confident that they photographed the entire colony during a traditional fixed-wing aerial survey, it was unlikely that a researcher could verify that all the images captured were in focus and were taken at the appropriate magnification to identify birds to species.

Unlike white-colored waterbird species, detection of dark-colored waterbird species was biased low, with the exception of Great Blue Herons, which had the greatest increase in detection estimates using drone-derived survey methods compared to traditional survey methods (152%; Table 3, Fig. 2). This may be because larger herons like Great Blue Herons typically nest atop the canopy (Rodgers et al. 2005), which likely makes them easier to view aerially. Smaller dark-colored waterbirds such as Tricolor Herons, Glossy Ibis, and Little Blue Herons typically nest below the canopy, which likely makes them difficult to distinguish from aerial photos. Overall, drone estimates of monthly nest counts for dark-colored waterbirds were ~ 66% lower than estimates derived from traditional survey methods and constituted a significant decrease in detection. The discrepancy between drone-derived dark and white-colored waterbird detection is likely the result of the low contrast of dark colored birds under dense canopy cover. While dark-colored waterbirds may show high contrast to the green emergent marsh, below the canopy, they may blend into the darker substrate of the lake or be mistaken for shadows. Previous studies examining the effects of canopy on waterbird detection have reported similar results of low detection (Frederick et al. 2003, Conroy et al. 2008, Bar et al. 2018), and this was reinforced with the GLMM models (see below).

The results of our GLMM models show that several variables play an important role in waterbird nest detection using drone-derived photography (Table. 2.). Percent Canopy Cover Directly Above a Nest, Distance from the Nest to the Canopy Edge, Bird Species, color, Stage of Nesting, and the interaction between Percent Canopy Cover Directly Above a Nest and Distance from the Nest to the Canopy Edge were included in all our top models. Of those variables Percent Canopy Cover Directly Above a Nest, color, Stage of Nesting, Distance from the Nest to the Canopy Edge, and the interaction between Percent Canopy Cover Directly Above a Nest and Distance from the Nest to the Canopy Edge did not overlap 0 (Fig. 3), suggesting that models containing these fixed effects have useful predictive value (Burnham and Anderson 2002). I included color within our models due to its importance in previous studies examining detection of waterbird nests using drone-derived imagery (Sarda'-Palomera et al. 2012, Chabot et al. 2015, Barr et al. 2018). Given the contrast between the color of nesting birds and the substrate of the lake (see above), it's likely that researchers are better able to distinguish white-colored nesting birds to species, whereas dark-colored birds may blend into the darker substrate of the lake or be mistaken for shadows. Percent Canopy Cover Directly Above a Nest was included in our models because previous studies examining the effects of visual occlusion of nests found canopy cover to play a pivotal role in explaining variation in nest detection using aerial-based surveys (Frederick et al. 2003, Conroy et al. 2008). Our findings were similar to those from previous studies, and the effect of Percent Canopy Cover Directly Above a Nest was found to have useful predictive value in explaining the variation inherent in drone-derived nest detection. Distance from the Nest to the Canopy Edge and the interaction between Percent Canopy Cover Directly Above a Nest and Distance from the Nest to the Canopy Edge were included in our models to account for variation in canopy cover above and around a nest. Because Percent Canopy Cover Directly Above a Nest was measured as percent canopy cover directly over a nest, it was possible that the measure did not account for the full effect of visual occlusion of nests from canopy cover. An example to illustrate this is a nest that is under full canopy, but on the edge of the canopy. While this nest may not be visible using an orthomosaic image stitched together using images captured at 90º, it may be possible to detect the nest if using an orthomosaic image stitched together from images captured at oblique angles or from individual pictures captured during the survey. Because the nest is on the edge of the canopy, the nest may be easily detected from an oblique view, despite having high canopy cover. Alternatively, a nest that is a far distance from the canopy edge may have low Percent Canopy Cover Directly Above a Nest and may be easy to view aerially. If a waterbird nest had high Percent Canopy Cover Directly Above a Nest and Distance from the Nest to the Canopy Edge, I hypothesized the interaction of the two predictor variables may be important in explaining variation in detection. Model estimates suggest this was likely the case (Table 2.). Finally, I included Stage of Nesting as a predictor variable because I believed an increase in number of birds in a nest may aid in detecting said nest. If a nest has high Percent Canopy Cover Directly Above a Nest and is difficult to view from oblique angles, I believed there may be a greater chance of detecting the nest if nestlings were present inside or just outside the nest. This was supported by the results of our GLMM (Table 2.).

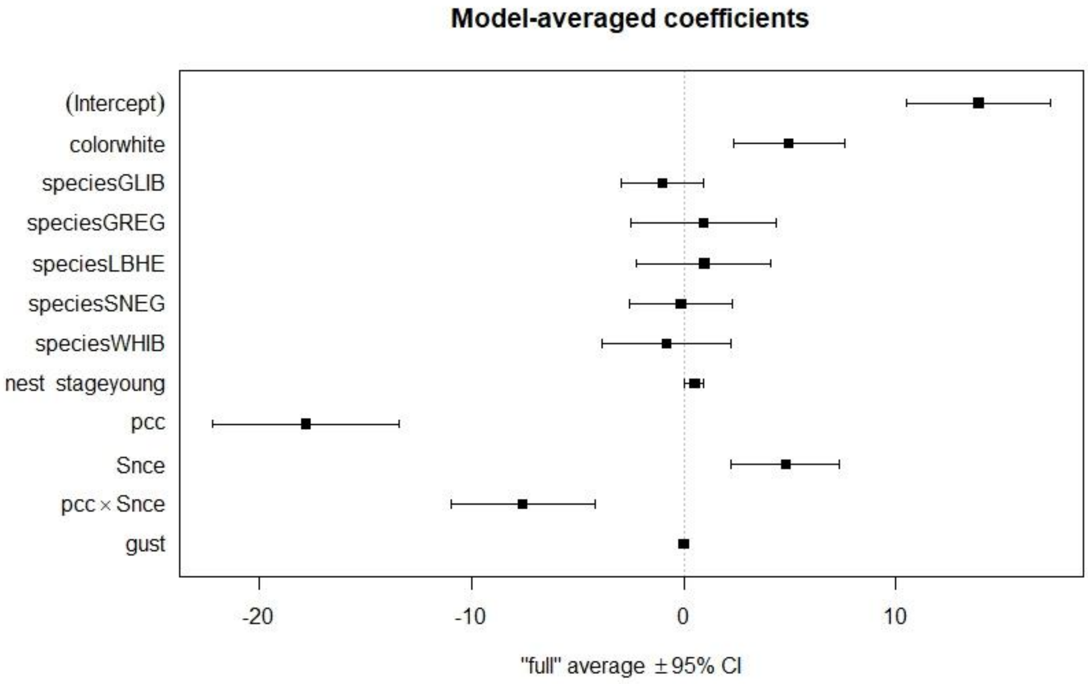


Figure 3. Standardized regression coefficients (β) (±95% CI) for averaged GLMM models (ΔAIC < 4) of waterbird nest detection. Model terms include (colorwhite) Plumage Color (i.e. dark or white-colored), (speciesGLIB) Glossy Ibis, (speciesGREG) Great Egret, (speciesLBHE) Little Blue Heron, (speciesSNEG) Snowy Egret, (speciesWHIB) White Ibis, (nest stageyoung) nest stage of waterbird nests, (pcc) percent canopy cover directly over a nest, (Snce) distance from a nest to nearest canopy edge, (pcc x Snce) the interaction between percent canopy cover directly over a nest and the distance from a nest to the nearest canopy edge, (gust) speed at the time a drone nest transect survey is conducted.

Whereas drone-derived estimates of the Snowy Egret, Great Egret, and white-colored birds overall were significantly greater than estimates from traditional survey methods, there was no difference between survey methods for the Cattle Egret and White Ibis. The lack of an observed difference between survey methods for these two species were likely due to battery limitations of the drone, poor weather conditions. When constructing an orthomosaic image, it is imperative that individual pictures are taken with the appropriate amount of overlap. We found that an overlap of 80% front and 80% side overlap was necessary to produce high resolution orthomosaic images given the drone and camera used in this study (DJI Inspire 2 and Zenmuse x7 camera). Increasing the overlap of images increases the amount of time and sets of batteries a drone must use to complete a mission. Although I had three sets of batteries and a charging system during the course of this study, there was one individual monthly survey in which the drone was not able to capture images of an entire colony due to battery limitations and poor weather conditions. Large estimates of White Ibis (n = 199) Cattle Egret (n = 444) were detected using traditional survey methods, and when this individual survey was removed from the dataset, there was a marginally significant increase between survey methods for the Cattle Egret (t = 1.71, p = 0.08, df = 4) and White Ibis (t = 1.74, p = 0.09, df = 17). Whereas lack of an observed difference between survey methods for Cattle Egret and White Ibis may be in part due to poor weather conditions and battery limitations, additional data is needed to validate this.

The overall finding of this study is that drone-derived imagery is equal to, or more effective than, traditional fixed-wing aerial surveys and ground counts, particularly for abundance estimates of white-colored colonial waterbirds. Drone-derived nest counts provided under-estimates for dark-colored waterbirds that nest in the sub-canopy, however, this may be remedied by supplementing drone surveys with ground-based surveys. Results from the model selection used in this study found that canopy cover, plumage color, and nest stage were found to be important predictor variables in explaining variation in detection. The use of drones for environmental and wildlife monitoring applications is growing, and advancements in GPS accuracy, camera resolution, and flight time are developing rapidly (Elraham et al. 2005, Jones et al. 2006, Chabot et al. 2015). It’s likely that drones will be a frequently used tool by conservation managers and biologists going forward, but researchers should take into account the species and study and evaluate whether a drone is the appropriate tool to meet their objective

CHAPTER II

Introduction

Survival of nests has traditionally been a difficult demographic parameter to measure because it requires repeated assessments on the fate of individual nests across the breeding period. This is especially true when estimating nest survival for waterbird breeding colonies, which often nest in dense aggregations over a relatively short duration of time (Furness and Monaghan 1987). Nest survival is defined as the proportion of successful nests where ≥ 1 egg hatches in a sample (Dinsmore et al. 2002). This often necessitates repetitive researcher intrusion into a colony to monitor breeding pairs, their distribution, and estimating breeding measures (Kildaw et al. 2005).

Traditionally, waterbird populations have been surveyed using fixed-wing aerial and ground-based monitoring methods, each of which has its own limitations and biases. Ground surveys are currently the only survey method proven to accurately estimate productivity measures of most waterbird species; however, ground monitoring techniques are expensive and may cause disturbance resulting in negative effects to reproduction (Frederick et al. 1996, Werschkul et al. 1976, Tremblay and Ellison 1979). Fixed-wing aerial surveys are crucial in monitoring colonially nesting waterbirds; however, they are expensive and have been shown to have significant observer and detection bias (Frederick et al. 2003; Frederick et al. 1996; Rodgers et al. 2005). While fixed-wing aerial surveys are crucial in monitoring colonially breeding waterbirds, they’re expensive and have significant observer and detection bias. Also, fixed-wing aerial surveys have are not reliable for identifying and tracking individual nests, which is vital in estimating productivity and survival measures.

Recently, there has been an increased interest in the use of drones for environmental and wildlife monitoring applications (Elraham et al. 2005, Jones et al. 2006, Chabot et al. 2015). Drones have proven effective in several wildlife applications, most notably in monitoring several avian species (Bevan et al. 2018, Vermeulen et al. 2013, Elraham et al. 2005, Jones et al. 2006, Chabot et al. 2015). Drones may be less disturbing to birds than traditional survey methods (Chabot et al. 2015, Vas et al. 2015) and have produced higher detection rates of some colonially nesting birds than fixed-wing aerial surveys (Afán et al. 2018, Chabot et al. 2015, Mcevoy et al. 2016).

Given recent advances in drones and post-processing technology, it is now possible to use drone-derived aerial imagery to relocate individual nests on subsequent surveys, allowing researchers to track individual nests throughout the season (Lachmen et al. 2020). Because drones can be programed to fly fully autonomous missions, capturing images in specified locations with automatic or preset camera settings (Floreano and Wood 2015), images may be combined into a single orthomosaic image of an entire waterbird colony. An orthomosaic image is an accurate photo representation of a specific area, created from overlapping photos stitched together and geometrically corrected for accuracy (Floreano and Wood 2015). Orthomosaic images can be crafted with survey-grade accuracy when drones are used in conjunction with a high-accuracy GPS and ground control points (Agüera-Vega et al. 2016). Because orthomosaic images can be produced with survey-grade accuracy, it’s now possible to identify and track individual nests and juvenile birds throughout the breeding season. This allows estimates of productivity measures like nest survival to be recorded. Lachmen et al. (2020) used drones to model nest survival of Western Grebes (*Aechmophorus occidentalis*) and Scarton and Valle (2020) used drones to model nest survival of Gull-billed Terns (*Gelochelidon nilotica*), but to date, no one has used drones to estimate nest success and productivity of mixed-species waterbird breeding colonies in an area with high canopy cover. Thus, the objectives of this study were to (1) quantify the relative accuracy of drone-derived photographic counts to estimate nest survival and (2) test for a difference between survival estimates derived from drone surveys and traditional ground-based surveys.

Study Area

Fieldwork was performed on Lake Okeechobee throughout the waterbird breeding season (March-June) of 2020 and 2021. Lake Okeechobee (hereafter referred to as the lake) is a large ($1730\ km^2$), shallow (mean depth of 2.7m), eutrophic lake that lies at the center of the Greater Everglades Watershed in South Central Florida (26º560'28"N, 80 º510'32"W) (Johnson et al. 2007). Lake Okeechobee has served as an important South Florida waterbird population since National Audubon Society Game Wardens started patrolling the area during the 1930s (David 1994). While management increases in lake levels from 1978-2007 reduced the overall presence of breeding waterbirds on the lake by 60%, the adoption of the Lake Okeechobee Regulation Schedule 2008 (LORS2008) has increased the presence of breeding waterbirds on the lake (Essian et al. 2022). The lake currently supports the second largest nesting aggregation of nesting birds in south Florida, typically producing approximately 10% of all nests in the area each year (SFWMD 2020).

Waterbirds typically nest within the littoral zone of the lake, which is predominantly located on the lake’s western edge, and man-made spoil islands (SFWMD 2020). Within the littoral zone, plant communities are dominated by emergent marsh (Milleson 1987). Dense stands of willow (*Salix caroliniana*), common reed (*Phragmites australis*) and pond apple

(*Annona glabra*) are scattered on elevated ridges throughout the littoral zone and on several spoil islands used by nesting waterbirds on the lake (Langeland and Jacono 2012).

Methods

Ground-based Nest Transects

At each monitored colony, two parallel 50-m long, 3 m wide transects, spaced 30 m apart, were established (e.g., Chastant and Gawlik 2018). Species, contents (i.e., eggs and nestlings), nestling age, and fate were recorded for each marked nest during each nest transect survey. A randomized bearing and distance from the boat were used to select the origin of the first transect. The start and direction of each transect was adjusted if a random bearing extended beyond the edges of an island (spoil islands) or passed through unsuitable nesting habitat.

Ground-based nest surveys were conducted every 2-7 days. Within a 1.5-m perimeter on both sides of the transect, nests were flagged and assigned an identification number. If the sample size was below 50 per species, nests outside of the 1.5-m buffer were marked. Contents, nestling age, species, and fate were recorded for each marked nest. Hatch date was determined from the estimated age of each nestling. The hatch date for nestling A was back-calculated and used as the nest hatch date. Nests were considered successful, and the brood size was recorded for brood size at fledging, when a nest reached at least 14 days old (±2 days) (Frederick and Collopy 1989, Parsons and Master 2000). Nest success [defined as the probability of fledging at least one nestling (Frederick and Collopy 1989)] for wading bird species has been recorded at 14 days old (±2 days) because after the age of fourteen days old, chicks are highly mobile and cannot be attributed to any particular nest (Billerman et al. 2020). As a result, Nest success for wading birds has been defined as a nest with chicks that reaches fourteen days ± two days in prior literature (e.g., Chastant et al. 2017; Frederick et al. 2002). The addition of a two-day threshold around the fledging age was used to due to the difficulty of assigning some 14-day old chicks to their original nest, the infrequency of colony visits, and resulted in increased data retention. A Leica GS07 GNSS RTK Rover was used to take GPS waypoints of each nest location. The transect, colony, and number associated with each nest were denoted in the name associated with each GPS waypoint.

All GPS waypoints were later imported to the orthomosaic image produced for the survey in Agisoft Metashape (see below). Notes of nest locations based on their orientation in the transect, and ground photographs, were also used to positively identify individual nests.

Drone Transect Surveys

Drone transect surveys were conducted with a commercially available drone (Inspire 2, DJI, Shenzhen, Guangdong, China) paired with a 24 mega-pixel RGB camera (Znemuse x7, DJI, Shenzhen, Guangdong, China). The Inspire 2 may be operated by a single researcher, launched from almost any surface, and is operated using a modest ground station (iPad device and remote control, [Apple Inc., Cupertino, CA]).

The DJI Inspire 2 is rated to fly at a max wind speed of 38 kph, and to ensure the safety of researchers and drone, we intended to only operate the drone when wind speeds were ≤ 38 kph at the altitude missions were flown (77 m). Gusts commonly exceeded 38 kph during drone transect surveys, and to ensure surveys were conducted at appropriate time intervals, it was necessary the increase the max wind speed during surveys to ≤ 46 kph at the altitude missions were flown (77 m). Weather projections were accessed before each survey using a third-party app (UAV Forecast), and if the wind exceeded 46 kph, surveys were called off.

At the start of the season, and before any drone surveys took place, five Ground Control Points (GCPs) were placed throughout each monitored colony. GCPs are marked points on the ground with known coordinates (Agüera-Vega et al. 2016). The coordinates of the GCPs often have high geospatial accuracy and are used to increase the geospatial accuracy of orthomosaic images “stitched” together during post-processing. Ground Control Points consisted of 2-foot by 2-foot water resistant plywood which had been painted to resemble a small checkerboard target. GCPs were placed atop steel pipes (1.2 m to 3 m long) that had been positioned vertically into the ground in areas of each colony which were unobstructed by canopy or vegetation. Five GCPs were placed throughout each monitored colony. GPS waypoints were taken for each GCP using a Leica GS07 GNSS RTK Rover. GCPs were regularly checked to ensure no debris was obstructing their vertical presentation.

A “home base” ≥ 183 m from the colony was selected to launch the drone while conducting drone transect surveys, and the drone was programmed to photograph the transect using a using a drone mapping app (DJI GS Pro). The drone then flew to an altitude of 76.20 m and captured images of the transect at intervals with the appropriate overlap (90% front overlap and 90% side overlap). The drone continued capturing images until it recorded the entire transect. Upon the completion of the survey, images were imported to Agisoft Metashape, rectified via DSM/DEM, and “stitched” into Orthomosaic images. During post-processing, GCPs were marked to ensure high geospatial accuracy of the orthomosaic image.

Waterbird nests were identified and tracked by photointerpretation using Agisoft Metashape’s orthomosaic window feature. Upon constructing an orthomosaic image, the nest transect was systematically searched in a grid pattern at a scale of 1:20. Active nests were distinguished following Sardà-Palomera et al. (2012). Because the orthomosaic images used in this study were produced by stitching together individual images captured using a seventy-eight-degree angle, it was not always possible to positively distinguish birds below the canopy as being on nests when using an orthomosaic image alone. Instead, due to the angle of the image and the amount and location of canopy cover over a nest, it was possible that a researcher was only able to view the back of a bird and not an actual nest. These nests were labeled as probable nests and a georeferenced "reference marker" was placed directly over the location of a suspected nesting bird. The reference marker of the probable nest was then selected using the function "Filter Photos by Marker" in Agisoft Metashape. This function automatically selects every photo containing a referenced marker, and automatically zooms to the same magnification in every image. We went through every image containing a referenced marker and recorded whether the bird could be confirmed as on a nest from an individual image captured during the survey, or was in the same location in images captured throughout the survey. If it was not possible to confirm nesting through an individual image captured during the survey, a nest was assumed to be active if the individual did not move locations in consecutive images taken during the survey, at an interval between 15 and 45 min between the time images were captured. Nests classified as active were tracked throughout the season. There were 29 instances when new nests were constructed on top of old nests, after not being detected during previous weeks. Those nests were considered new nests and were marked with a unique identification number.

Once a nest was confirmed active through ground-based nest transects, GPS coordinates of the nest's location recorded with the RTK Rover (see above) were imported into Agisoft Metashape. Nests observed in Agisoft Metashape were then matched to nests marked through ground-based nest transects (see above). The GPS coordinates of nests observed during ground-based nest transects, but not detected through drone surveys, were marked in the orthomosaic image to ensure the nest had been accounted for and had not been mistaken for another nest.

Active nests observed through drone surveys were tracked throughout the nesting season using the “Filter Photos by Marker” function in Agisoft Metashape. Nests were tracked throughout the season, and a record of whether a nest was detected, bird species, stage of nesting, contents, nestling age, and fate were recorded. After looking through every image containing a nest, the image with the clearest view of the contents of a nest and highest resolution was used to record bird species, nestling age, contents, and fate.

The contents of a nest observable through drone transect surveys were used to determine Nest Stage. The nest would be classified as being in the I or NB stage until nestlings were visible in an image of a particular nest. A nest would be classified as being in the CR stage once a nestling was observed in a nest, until the nestlings were believed to be at least 14 days old (±2 days).

To determine the age of nests, nests were tracked from the initial date they were observed. If a nest was abandoned or had failed before chicks were observed, the initial date the nest was observed was marked as day zero. The number of days in-between subsequent surveys was then added to its initial age. If a nestling was confirmed to a nest, the date of the survey was marked and used to back-calculate the age of the nest. Given the resolution of the imagery, we were unable to positively ascribe a nestling to a certain age. Thus, nestlings were marked as 0 days old during their first observation, and the age of the nest was back-calculated based on incubation periods for each species [Snowy Egret (Egretta thula) = 22 days, Great egret (Ardea alba) = 25 days, Tricolored Heron (E. tricolor) = 22 days, Cattle Egret (Bubulcus ibis) = 23 days, White Ibis (Eudocimus albus) = 22 days, Glossy Ibis (Plegadis falcinellus) = 21 days) (Birds of the World 2022). If the age of a nest in previous surveys was ascribed to a negative number because of back-calculating, the initial date the nest was detected was marked as zero days old.

This may occur if nestlings are not observed in a nest until they are several days old and/or the initial date a nest was first detected and tracked was close to the date the first egg was laid. Given the resolution of the imagery, we were unable to determine the precise age of nestlings using images captured in this study and often needed to track nests past the age of fledging used in prior literature. Past the age of fourteen days old, chicks are highly mobile and may leave the nest before researchers can record them (Billerman et al. 2020). As a result, fledging has been recorded at fourteen days ± two days in prior literature (Chastant et al. 2017; Frederick et al. 2002). Because researchers do not have to directly approach nests while conducting drone surveys, chicks could reliably be distinguished to a nest past 14 days old (researchers were not able to reliably track nests past the age of 21 days old, as chicks were often far enough away from the nest that they could not be successfully matched to their nest). On the date a nest was determined to have reach fledging using drone surveys, the nest was marked as successful and no longer tracked in surveys.

Statistical Analysis

Nest Survival Between Survey Methods. All estimates were computed in program R (R Development Core Team 2022, version 4.2.0). To account for biases resulting from variation in the initial nest ages at monitored nests, Daily nest survival (proportion of nests that fledge ≥ one nestling) was calculated using logistic exposure models (Shaffer, 2004, SFWBR, 2021). Generalized linear models were fitted with a loglink distribution function. The model estimates daily survival rate (DSR). DSR can be converted to overall survival rate ($\text{DSR}^{\text{interval length}}$). Separate models were developed for the nestling and incubation periods because there were clear differences in survival rates between the two nest stages. Appropriate Interval lengths for incubation and nestling periods were used for each species (see above).

Estimates of Overall daily survival rate of nests tracked using ground-based nest transect surveys were compared to overall daily survival rate estimates of nests tracked using drone transect surveys. Overall daily survival rate was estimated for the Snowy Egret, Tricolor Heron, Great Egret, white-colored waterbirds, and dark-colored waterbirds. Means of each species and grouping were then compared using paired t-tests to the null hypothesis that there is no difference in the mean survival of Snowy Egret, Tricolor Heron, Great Egret, white-colored waterbirds, and dark-colored waterbirds between survey methods. To visually display the difference of survival estimates between survey methods, a box plot of means and 95% confidence intervals of estimates of daily survival rate for each species and grouping were paired by surveying method (fig 2.).

Results

During the 2021 waterbird breeding season, over which I compared overall survival nest survival rate between ground-based and drone nest transect survey methods, I followed the fates of 563 different nests using ground-based nest transect surveys, with a total of 2,813 individual observations (Table 4). This included 307 Snowy Egret, 83 Tricolor Heron, 24 Cattle Egret, 49 Glossy Ibis, 30 White Ibis, and 6 Little Blue Heron nests (Table 4.).

Not every nest observed in ground-based nest transects surveys was observed in drone nest transect surveys, nor did both survey methods have an equal number of observations per nest. As a result, the dataset used for either method was composed of only those nests observed through the associated survey method. Thus, the dataset used for drone nest survival estimates was not the same as the dataset used for traditional nest survival.

I followed the fates of 510 different nests using drone nest transect surveys, with a total of 2,432 individual observations (Table 4.). This included 300 Snowy Egret nests, 64 Great

Egret, 65 Tricolor Heron, 24 Cattle Egret, 25 Glossy Ibis, 28 White Ibis, and 6 Little Blue Heron (Table 4.).

Grouping	Method	Nests	Total Observations	Mean Detections per Nest	SD
CAEG	Drone	24	140	5.83	1.67
	Traditional	24	141	5.88	1.62
GLIB	Drone	25	76	3.04	2.16
	Traditional	49	148	3.02	1.81
TRHE	Drone	65	249	3.83	2.2
	Traditional	83	407	4.9	2.49
SNEG	Drone	300	1482	4.94	2.35
	Traditional	307	1613	5.25	2.32
WHIB	Drone	28	68	2.43	0.74
	Traditional	30	79	2.63	1.03
GREG	Drone	64	389	6.08	2.63
	Traditional	64	390	6.09	2.65
LBHE	Drone	6	28	4.67	1.37
	Traditional	6	28	4.67	1.37
Dark	Drone	96	352	3.67	2.17
	Traditional	138	582	4.22	2.39
White	Drone	416	2080	5	2.43
	Traditional	425	2224	5.23	2.4
Total	Drone	510	2432	4.77	2.43
	Traditional	563	2813	5	2.43

Table 4. Comparison between the total number of nests observed (Nests), the total number of observations per nest (Total Observations), and mean detections per nest observed through drone productivity surveys and ground-based nest transect surveys for (CAEG) Cattle Egret, (GLIB) Glossy Ibis, (GREG) Great Egret, (LBHE) Little Blue Heron, (SNEG) Snowy Egret, (TRHE) Tricolor Heron, (WHIB) White Ibis, (Dark) all dark-colored waterbird species, (White) all white-colored waterbird species, and (Total) the total number of nests, for all species, pooled together; SD denotes the standard deviation for mean detections per nest.

Nest Survival Derived from Ground-Based versus Drone Surveys. Mean overall survival rate of nests (Fig.2) for waterbird species did not vary significantly between drone and ground-based nest transect surveys (Paired t test, t = 2.53, df = 4, P = 0.54, one-tailed), but variation was not constant among individual groupings and species. The difference in the overall survival rate between survey methods for white and -dark colored warbirds was relatively low, with noticeable variation between species (difference between survival estimate for white-colored waterbirds: 1.41%, 95% CI [9.46, 2.26], difference between survival estimate for Great Egret: -1.37%, 95% CI [-1.89%, -0.90%], difference between survival estimate for Snowy Egret: -0.51%, 95% CI [3.19%, -1.36%], Fig. 4). The difference in the overall survival rate between survey methods for Tricolor Heron and dark-colored waterbirds was greater than that observed with white-colored waterbird species (difference between survival estimate for Tricolor Heron: 2.68%, 95% CI [9.46%, 2.26%], difference between survival estimate for dark-colored waterbirds overall: -5.73, 95% CI [3.77%, 7.33%].

Discussion

The use of drones provided a non-invasive means to estimate the date eggs were laid in nests, productivity, and nest survival. This is notable because the ability to accurately estimate daily and overall nest survival is dependent on the ability to record and reconstruct nest histories (Rotella 2017).

Recording and reconstructing nest histories of the seven waterbird species used in the analysis was made possible with the machine characteristics of the model used in this study, (DJI Inspire 2), implementation of GCPs into waterbird colonies, and analyzing both the orthomosaic image and individual pictures. The machine characteristics of model of drone used in this study (DJI Inspire 2) was instrumental in conducting the individual surveys necessary to estimate survival. With a max flight time of 27 minutes, max transmission distance of 7 km, and the ability to fly fully autonomous missions and capture images in specified locations, the machine characteristics of the DJI Inspire 2 was instrumental in conducting nest transect surveys. Waterbird breeding colonies are often located far distances apart and are inaccessible by land (Frederick, 1996). Because our study area was composed of large, often inaccessible tracks of thick emergent marsh, spaced far distances apart, it was not always possible to set up home base for a mission within 183 m stated previously. Instead, missions were often initiated up to 0.75 km from the nest transect, albeit still within line of site of the survey area. The use of a drone with a greater flight time and transmission distance was necessary to conduct drone transect surveys. Additionally, the use of a quadcopter, as opposed to a fixed-wing drone, was essential in capturing images with the resolution needed to identify individual nests to species. Previous studies have noted difficulties in identifying nesting birds to species with lower resolution orthomosaic images (Bar et al. 2018). I was able to achieve a pixel resolution of 0.8 cm, which was sufficient to identify nests to species. It would likely not have been possible to achieve this level of resolution, given the camera used in this study (Zenmuse x7), without the use of a quadcopter drone. Because quadcopter drones have the flexibility and maneuverability to fly at lower speeds and altitudes than a fixed-wing models (Siebert and Teizer 2014), I was able to capture images with greater magnification and overlap. Greater magnification of individual images increases the resolution of the resulting orthomosaic images, whereas greater overlap is necessary to stitch together images during the initial stages of post-processing. Quadcopter drones are also generally smaller and lighter than most fixed-wing models, which gives them the capability to take off and land vertically; these features permit greater diversity of launch locations than many fixed-wing drones (Siebert and Teizer 2014), which was necessary to conduct missions on the lake.

The use of GCPs was another vital component in tracking individual nests. Because individual nests must be tracked from orthomosaic image to orthomosaic image, establishing GCPs with precise, known coordinates allowed me to georeference and align orthomosaic images with a greater degree of accuracy. Georeferencing orthomosaic images with the same GCPs allowed researchers to horizontally and vertically align orthomosaic images. This facilitated coordinates of individual nests from one orthomosaic image to be imported directly into another orthomosaic image, while minimizing associated error. This is necessary to efficiently track nests throughout the season, particularly in areas of a breeding colony with high nest density (Lachman et al. 2020).

The use of drone technology and the methodology used in this study allowed us to successfully estimate survival for several waterbird species, with low variation observed between estimates derived from traditional survey methods (Fig. 4.). Drone surveys detected 0.91 of total waterbird nests, ~ 97% of white-colored waterbird nests, and 0.73 of dark colored waterbird nests detected through traditional surveys.

Despite the previously mentioned strengths of our study, I found several limitations inherent to studies using drone imagery to investigate waterbirds. Notwithstanding the low level of variation between survival estimates of ground-based and drone nest transect surveys, variation was not constant across groupings. Whereas drone estimates of overall survival including all groupings of waterbirds included in our analysis (Great Egret, Snowy Egret, Tricolor Heron, dark-colored waterbird species, and white colored waterbird species) was not found to differ significantly from estimates obtained through ground-based nest transect surveys, there were clear differences between estimates of dark-colored and white-colored waterbirds. The overall survival rate between survey methods for Snowy Egret, Great Egret, and white-colored waterbirds was relatively low (Difference between survival estimate for white-colored waterbirds: 1.41%, 95% CI [9.46, 2.26], Difference between survival estimate for Great Egret: -1.37%, 95% CI [-1.89%, -0.90%], Difference between survival estimate for Snowy Egret: -0.51%, 95% CI [3.19%, -1.36%], Fig. 4.), whereas the difference in the overall survival rate between survey methods for Tricolor Heron and dark-colored waterbirds was noticeably larger (difference between survival estimate for Tricolor Heron: 2.68%, 95% CI [9.46%, 2.26%], difference between survival estimate for dark-colored Waterbirds Overall: -5.73, 95% CI [3.77%, 7.33%], Fig. 4). This pattern is consistent with Frederick et al. (2003) and Bar et al. (2018) where dark-colored waterbird nests were detected significantly less than white-colored waterbird nests in the same colony. The discrepancy between drone-derived dark and white-colored waterbird estimates is likely the result of the low contrast of dark colored birds under dense canopy cover (Chabot and Bird 2012, Bar et al. 2018). Whereas dark-colored waterbirds may show high contrast to the green emergent marsh, below the canopy, they may blend into the darker substrate of the lake and mistaken for shadows. Additionally, it was far more difficult to view dark-colored waterbird nestlings under canopy cover than a white-colored nestling, as the nestling may be mistaken for shadows from the canopy and/or the attending parent.

The methodology used to track individual nests after post-processing was also very time consuming. Unlike previous studies examining waterbird breeding colonies (Chabot and Bird 2012, Sandra-Palomera et al. 2017, Bar et al. 2018), nests were not only tracked with a single orthomosaic image, but through every individual image containing the nest that was incorporated into the orthomosaic image. Using the post-processing software (Agisoft Metashape), the reference marker created for a particular nest was selected using the function “Filter Photos by Marker”, and every photo that contained the location of said reference marker was analyzed for demographic traits of the nest by researchers (see above). Unless an unobstructed, clear view of a nest and its contents was observed in one of the pictures, the researcher manually inspected every picture containing the nest during the associated survey. This often included several dozen individual pictures. As a result, whereas other studies have noted a shorter duration of time necessary to conduct nest surveys of waterbirds using a drone compared to traditional survey methods, I found that opposite to be true.

Finally, although this study examines nest survival, I did not investigate nest success or brood size at fledging, which represent important productivity measures (Kildaw et al. 2005). Although I observed relatively little variation between survival estimates derived from traditional and drone surveys, its unlikely I would have observed the same level of variation for nest success and brood size at fledging. Nestlings were infrequently observed at very young ages during drone surveys, and not every nestling in nest was observed at the time of fledging. Because I was unable to discern the age of chicks based off individual photos, I recorded the first date a chick was observed as day zero for chick A. This results in a lower estimate of nest age for drone-derived estimates than those derived from traditional survey methods. If nestlings are only describable at several days old, and subsequent surveys are not conducted frequently enough, it's possible nestlings will have fledged and left the nest before drone surveys can successfully the nest as successful and record brood size.

Very few studies have measured nest survival of waterbirds using drone-derived photogrammetry. Of those that have, none have conducted ground-based surveys simultaneously to compare survival estimates between survey methods (Sandra-Palomera et al. 2017, Lachman et al. 2020, Scarton and Valle 2021). This makes it difficult to compare results between different studies, but also highlights the importance of this line of research. Because nest survival measures are often the most effective way of evaluating avian conservation and management practices, they must be as reliable and communicative as possible (Etterson et al. 2011). Ideally, new methodology should be validated by comparing estimates against independently collected data (Williams et al. 2002, Jehle et al. 2004). This highlights the importance of future studies aimed at comparing nest survival estimates derived from drone and traditional survey methods. The use of drones in wildlife biology is expanding rapidly, and several studies have documented their merits for nest counts (Chabot et al. 2015; Hodgson et al 2016, 2018; Lyons et al. 2019). Our study demonstrates the use of drones to document demographic traits of large breeding colonies of waterbirds. Our ability visit transects with greater frequency allowed us to track the fates of individual nests and estimate nest survival with high relative accuracy. Using a quadcopter drone equipped with a high-resolution camera, as opposed to the fixed-wing drones used in other studies (Chabot et al. 2015, Sarda-Palomera 2017), I was able to fly at the low speeds and altitudes and launch missions from our research vessel. This allowed our study to construct orthomosaic images with greater temporal and spatial resolution than has been reported in prior studies (Sarda-Palomera 2017, Lachman et al. 2020). Finally, the images recorded through the methodology used in this paper (see above) allowed for improved visualization of parents, nests, and nest contents.

Drones are a rapidly advancing technology, but ground-based research is beneficial to understand the dynamics of productivity measures within a colony (i.e., all nest stages; Callaghan et al. 2019). the advantages of using drones over other methods likely depends on the specifics of the habitat being surveys, nesting species, and parameters that researchers wish to record. Technological advancements in GPS accuracy, camera resolution, and flight time are developing rapidly, and its likely drones will become an even more useful tool for conservation managers and wildlife biologists going forward.

CHAPTER III

Overall Conclusion

The drone technology and methodology used in this study allowed researchers to estimate species abundance and composition, as well as productivity measures like daily survival, for waterbirds nesting in woody vegetation within marsh habitat. There was clear variation between the accuracy of estimates for birds with dark and white plumage color suggesting that drone-derived imagery is equal to or more effective at measuring species abundance and composition for white colored waterbirds than traditional survey methods. Drone-derived nest counts provided under-estimates for dark-colored waterbirds that nest beneath the canopy, such as Tricolor Herons (Fig 2.). Results from GLMM model selection found plumage color, canopy cover, and nest stage to be important predictor variables in explaining variation in detection. Additionally, we were able to successfully estimate survival for several waterbird species, with low variation observed between estimates of drone-derived and ground-based survey methods (Fig. 4.). Drone nest transect surveys detected 93.35% of white-colored waterbird nests, 62.38 % of dark colored waterbird nests, and 86.95% of total waterbird nests detected through traditional surveys (Fig. 5.). Although the results of this study suggest drones have the potential increase the accuracy and volume of available data on waterbird reproductive measures, researchers interested in surveying nesting waterbirds with a drone should consider limitations regarding current drone technology, and the immediate demand for rigorous comparative testing of survey methods.

The use of quadcopter drones for avian research has several considerations researchers should account for, including the initial cost of equipment and additional labor requirements necessary for pre-survey preparation and post-survey data processing. The price for consumerlevel drones has fallen substantially over the last several years, with a range of drones accessible for many research budgets (Crutsinger et al. 2016); although, there’s an initial expenditure for equipment, as well as the cost associated with training. The cost of the drone package used in this study (DJI Inspire 2 paired with a Zenmuse x7 camera) was approximately $12,000 when new, whereas there are now drone packages available from ~ $300 to well over $50,000. In addition to monetary investment, researchers must consider the flight time, lens magnification, image quality of the associated camera system, ease of use, and the size of a drone model intended for a project. Generally, drones and cameras that are more expensive provide better image quality, which is typically required for accurate species recognition (Orengo et al. 2021). One must also consider the flight time associated with missions, given the GSD necessary for a study. Previous studies have found ground resolution should be ≤ 1 cm/pixel for accurate species identification of waterbirds (Drever et al. 2015). If the model of drone under consideration for a study is limited to a single camera and lens, and permits require researchers to fly above a certain altitude, it may not be possible to achieve the GSD necessary for a study unless the camera is compatible with a higher magnification lens. When limited to a single mission altitude, previous studies focusing on waterbird identification have noted difficulties in species identification if surveys were conducted with a drone was equipped with a single lens, and the resulting GSD was above the threshold necessary for object identification (Han et al. 2017). Additionally, if the camera used with a drone is compatible with a higher magnification lens, one must consider the increased flight time and battery requirements of increasing GSD. Given a static front and side overlap, a higher magnification lens and a decreased GSD will increase the flight time of a mission (Raoult et al. 2020). This will likely necessitate the use of additional drone batteries, which vary in price based on specific drone models. The area of breeding colonies observed in this study ranged from 0.1 km^2 to 0.94 km^2, requiring several sets of fully charged batteries when conducting surveys of the larger colonies. To achieve this, we used tractor batteries and a high-capacity inverter (EverStart 1000-Watt Inverter). If recharging batteries while in the field is not as option, researchers should consider recharging batteries at a facility near the study area or purchasing enough batteries to negate the issue. The size and capabilities of the drone are also an important consideration. If a study is limited to using a boat to launch a drone, researchers must consider whether there is sufficient room to land and launch the drone, as well as the flight capabilities of the drone itself. Larger drones are typically rated to higher wind speed speeds (Krishna, 2017; Jayaweera and Hanoun, 2021), and this may dictate which models of drone are applicable to a particular study area. Finally, researchers should consider the ease of use associated with a drone and camera. If the autonomous camera settings of a drone are not sufficient to maximize the resolution of images, researchers must be able to manipulate the camera settings manually. This may determine if a drone and camera are suitable for a project. For example, throughout this study, flight missions were often conducted during the middle of the day, such that the sun was directly overhead. Because many of the breeding colonies surveyed were located near or directly over water, the reflection of the sun was often a problem. To negate this, we obtained and used a polarizing lens filter. This did help negate issues associated with sunglint, but the camera (DJI zenmuse X7) was unable to employ autonomous settings properly, and researchers were forced to select the camera settings manually each day. If a researcher is unfamiliar with how and why to select proper camera settings given the conditions for an induvial survey, this may be a limiting factor in whether a drone would be beneficial.

The growing excitement and use of drones by ecologists and waterbird researchers necessitates an immediate need for further research. While the 0.8 cm/pixel GSD achieved by surveys conducted during this study were sufficient to identify waterbirds to species and track individual nests throughout the breeding season, there is a general lack of information on the effect of lowering GSD. Whereas Dulava et al. (2015) recommended a GSD of ~ 0.50 cm/pixel to correctly identify nesting waterfowl, and previous studies have found ground resolution should be ≤ 1 cm/pixel for accurate species identification of waterbirds (Drever et al. 2015), the GSD necessary to identify many avian species and groupings is unknown. Future studies should emphasize determining what GSD is necessary to identify particular species and track them throughout the breeding season. Furthermore, the effect of sun elevation angle and sun azimuth on nesting surveys should be evaluated in more depth. Angle of the sun has been shown to have a substantial influence on the detection of waterbird species such as whooping cranes (Grus aericana), where detection probability increases three-fold when the sun was at the observer's back (Strobel and Butler 2014). Whereas photographic counts may mitigate the effects of survey azimuth and sun glint, shadows may obscure nests at canopied sites, or even increase nest detection of species with low contrast to their environment. Whereas sun glint and survey azimuth were not evaluated during this study, a better understanding of how sun glint and survey azimuth affect nest detection will help investigators maximize detection accuracy. Finally, future studies of the effect of Contrast Stretching, Histogram Equalization and Adaptive Equalization processes on waterbird nest detection would be beneficial. Contrast stretching is used to improve dark images through expanding the range of intensity values of an image (Al-amri 2011, Allayear et al. 2018), histogram equalization enhances contrast by adjusting the image intensity (Zohaib et al. 2018), and adaptive Histogram Equalization adjusts the intensity of images to improve the contrast of images (Zhu 2012). The use of Contrast Stretching, Histogram Equalization and Adaptive Equalization techniques has been used to increase the detection of human faces in dark images (Allayear et al. 2018), and it’s possible the methodology could be employed to increase the detection of dark-colored waterbirds obscured by shadows under the canopy.

As the use of drones becomes more widespread so too will the likely applications in ecological and wildlife science (Crutsinger et al. 2016). Drones have accurately estimated nest abundances of several avian species (Bevan et al. 2018, Vermeulen et al. 2013, Elraham et al. 2005, Jones et al. 2006, Chabot et al. 2015), but the quality of drone-derived data is dependent on limitations regarding current drone technology, the specific model of drone and camera used, the GSD requirements of a particular study, and the experience of the drone pilot. During this study, we purchased and became proficient in operating a drone, obtained the necessary authorization to fly it, and processed and later analyzed the data ourselves. This was an accomplishment that required a highly specialized skillset and took two years to develop. Prospective drone operators should anticipate a learning curve associated with flying a drone and processing and analyzing data. Although we have identified a number of limitations and considerations for the use of drones for surveying waterbirds, we believe the net benefits of using drones over traditional methods will continue to improve.

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