Behavioral Responses of Sea Turtles, Saltwater Crocodiles, and Crested Terns to Drone Disturbance

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I. Abstract

Drones have become a widespread tool for enhancing wildlife conservation studies, yet guidelines for the optimal use of these aircraft with respect to the visual and auditory disturbance they may introduce is often overlooked. In the present study the behaviors of three species of sea turtle (*Chelonia mydas, Natator depressus*, and *Eretmochelys imbricata*), saltwater crocodiles (*Crocodilus porosus)*, and crested terns (*Thalasseus bergii*) were observed in response to a commercially available drone flown at various altitudes (i.e. between 5 and 70 m). Drone flight trials were conducted at Bare Sand Island, Northern Territory (NT), and in Western Australia (WA) at Cape Domett and throughout Camden Sound. Adult sea turtles in nearshore waters off nesting beaches, or juveniles and adults in foraging habitats, exhibited no evasive behaviors (e.g. rapid diving) in response to a small drone at or above 20-30 m altitude. Juvenile *C. mydas* and *E. imbricata*, foraging on shallow, algal-covered rocky reefs also exhibited no changes in behavior to drones unless the aircraft was lowered to less than 10 m altitude. *N. depressus* adult females were not deterred by drones flying forward or stationary at 10 m altitude when crawling from the sea towards the dune, or digging a body pit or egg chamber, all critical stages of nesting. In contrast, *C. porosus* were significantly disturbed both in the water and when resting on the beach when a drone was present below 50 m altitude. Flyovers elicited a range of behaviors from minor, lateral head movements, to fleeing, or complete submergence. Similarly, a colony of *T. bergii* resting on a sand-bank displayed disturbance behaviors (e.g. flight response) when a drone was flown below 60 m altitude. The current study demonstrates a variety of disturbance thresholds for diverse species. Such thresholds should be considered when establishing optimal drone altitudes in behavioral and conservation studies.

II. Introduction

Unmanned aerial vehicles (i.e. UAVs or drones) have become widely-used as a cost-effective tool for enhancing wildlife conservation, management, and research. Among many benefits over traditional methods alone, drones provide a relatively cost-effective method for increasing collection efficiency, and evaluating animal behaviors, abundance and distribution of populations (Jones et al. 2006), enhancing animal photo ID and photogrammetry (Koski et al. 2009, Pomeroy et al. 2015), and increasing the accuracy of data collection (Hodgson et al. 2016). Additionally, a growing network of drone operators, hobbyists, and commercial users is broadening access to a wide array of openly-available online resources (e.g. image processing software and tablet-based operating apps). A key benefit of using drones in wildlife studies is minimizing or eliminating the potential influence of observer presence. Nonetheless, many applications require the operation of drones in the near vicinity of target species (e.g. <10 meters) to achieve sufficient resolution. However, studies focusing on the effects of drones near wildlife, are limited (Smith et al. 2016). Evaluating the impact of drones on target species, requires knowledge of 1) the physiological capabilities of each target species to detect the drone, 2) the level and nature of disturbance introduced by a specific model drone, and 3) background conditions of the habitat in which the study is conducted (e.g. ambient noise levels). Only then can an attempt be made to understand the broader implications of applying drone technology to behavioral and ecological studies that enhance wildlife conservation, research and management.

Previous studies have demonstrated the advantages of using drones in studies of a variety of marine taxa including sea turtles (Schofield et al. 2017a, 2017b), saltwater crocodiles (Evans et al. 2015, Elsey and Trosclair III 2016, Evans et al. 2016), shorebirds (Hodgson et al. 2016, Service 2017), and other marine megafauna (Hodgson 2007, Hodgson and Marsh 2007, Hodgson et al. 2013, Pomeroy et al. 2015, Christiansen et al. 2016, Kiszka et al. 2016, Hodgson et al. 2017). Many of these studies reported that the presence of a drone overhead during regular UAV operations elicited no observable behavioral response (Jones et al. 2006, Koski et al. 2009, Acevedo-Whitehouse et al. 2010, Hodgson et al. 2013, Evans et al. 2015, Christiansen et al. 2016). However, these were opportunistic observations as opposed to studies specifically focused on assessing the behavioral responses of taxa to drone disturbance. A critical component for evaluating the level of behavioral disturbance imposed by drones is understanding the spectrum of responses displayed by each species. Sea turtles in shallow habitats (i.e. <1 m water depth) can detect and respond to a threatening stimulus (e.g. humans walking towards them in shallow water) by swimming at high speed towards the perceived safety of deeper water, often generating a “bow wave” in front of the fleeing turtle (E. Bevan, *pers. obs*.). A range of behavioral responses to auditory disturbance have been reported in some birds, including *T. bergii*, ranging from minor head-scanning to flushing (Brown 1990, Dooling and Popper 2007). Pomeroy et al. (2016) examined two species of pinnipeds and detected behavioral responses to different types of drones flown at 30 m altitude or higher, were highly variable and depended on age, sex, and in some cases, reproductive status. Such studies suggest that future research using drones should consider variables such as season and reproductive status, age, and sex of target species, in addition to altitude when assessing threshold levels of behavioral responses to drones.

The physiological characteristics of a given species may contribute to the likelihood of drone detection and is key in assessing the impact of drones. Although limited, there is some data available on the auditory capabilities of sea turtles, crocodilians, and shorebirds that provide a basis for understanding whether such species can detect the sound emitted by drones and at what specific threshold. The auditory physiology of reptiles is adapted for detecting lower frequencies than that of birds (Ketten and Bartol 2005). In sea turtles (loggerhead (*Caretta caretta*) and *C. mydas*), peak auditory sensitivity in air occurs between 300 and 400 Hz, and in water between 50 and 400 Hz (Piniak et al. 2012). The American alligator (*Alligator mississipiensis*) exhibits optimal auditory capability between 800 and 1000 Hz (Higgs et al. 2002). Audiograms from 49 species of birds suggest that birds generally exhibit an optimal auditory frequency range of 2 to 3 kHz (Dooling and Popper 2007). Accordingly, the noise emitted by small, commercial drones (i.e. fundamental frequencies between 60 and 150 Hz, Christiansen et al. (2016), and harmonic frequency emissions at approximately 500 and 1000 Hz, Cabell et al. (2016)) is likely to be audible at low altitudes. How altitude and ambient noise levels influence the detectability of drone noise levels among different species in different habitats remains generally undetermined.

Evaluating drone detectability across altitudes is multifaceted and involves assessing a visual component (i.e. ability of target species to discern the drone or its shadow), and an auditory component related to the unique noise emission characteristics of each drone. Christiansen et al. (2016) measured noise levels emitted by two commercial multirotor drones and found them to have fundamental frequencies of 60 and 150 Hz. When the aircraft was at approximately 10 m altitude, these frequencies could not be measured above ambient noise levels beyond 1 m below the surface of the water. Coupling these findings with known auditory capabilities of several species of cetaceans and pinnipeds, Christiansen et al. (2016) concluded these marine mammals would likely be unable to detect the drones. Commercial multirotor drones have also been reported to emit harmonic frequencies at 500 to 1000 Hz (Cabell et al.

2016). Characterizing the noise emitted by multirotor drones is further complicated as sounds emitted by the aircraft change in response to wind gusts while hovering, and to operator controls during flight (Cabell et al. 2016). Each of these sound profiles presents a different auditory stimulus to target species and can elicit different types and intensities of animal disturbance behaviors.

In the current study, a small, commercial drone (DJI Phantom 4 Pro®) was used to conduct wildlife surveys at three primary study sites in tropical Australia: Bare Sand Island, Northern Territory (NT), Cape Domett, Western Australia (WA), and at multiple sites throughout Camden Sound, WA. Collectively, these locations provide prime nesting and/or foraging habitat for sea turtles (Whiting and Guinea 2006, Whiting et al. 2009), sea birds (Chatto 2001, Masini et al. 2009), and saltwater crocodiles (Kay 2005). Yet ecological studies in these habitats are often logistically challenging, and an overall paucity of data exists regarding species in remote tropical locations of WA and the NT compared to subtropical Queensland (Whiting et al. 2009). Drones offer a new and accessible methodology for enhanced monitoring capabilities in remote habitats. This study provides preliminary information that can guide the integration of drone-based studies into effective conservation resource management.

III. Methods

A DJI Phantom 4 Pro® (www.dji.com) drone was used to conduct all surveys in the current study. This drone can travel up to 5 km, and each high capacity battery (5870 mAh) provides a maximum of 30 min flight time. The drone was operated using the tablet-based Litchi™ app (VC Technology Ltd.) that displayed real-time drone telemetry information (e.g. drone altitude, speed, distance, etc.). Flight records were automatically uploaded to Airdata.com.

a. Sea Turtles

i. Nearshore Habitat

Drone-based surveys were conducted off Cape Domett (14°48.10S, 128°24.50E), a major *N. depressus* rookery in WA, as well as in the nearshore waters of Sampson Cove (15°32'26.57"S, 124°24'38.04"E), Camden Sound, WA. Cape Domett is a 1.9 km beach located in the Cambridge Gulf, WA. The focus of these surveys was to evaluate 1) the abundance of adult turtles, and 2) potential behavioral responses to the presence of a drone at various altitudes (i.e. 18 to 30 m altitude) while conducting straight-line transects parallel and perpendicular to shore.

Nine nearshore surveys were conducted off Cape Domett beach between 0730 and 1600 hrs from 5-11 August, 2017. Each drone survey consisted of two transects parallel to the nesting beach, one 500 m, the other 1 km offshore. Additionally, a straight-line transect was conducted perpendicular to the nesting beach out to 2 km offshore. All surveys were conducted from an initial altitude of

30 meters and a speed of approximately 6-8 m/s. If turtles were encountered, flight trials were conducted at 30 and 20 m if possible to evaluate potential behavioral responses at each altitude.

Nearshore surveys throughout Sampson Cove, Camden Sound, WA, were conducted on 15 August 2017. Surveys were conducted at approximately 1330 hr at an altitude of 50-60 m and paralleled the coastline at approximately 300-500 m offshore.

ii. Reef Habitat

An interconnected network of shallow, algal-covered rocky reefs extends between the islands of Fog Bay in the NT (Whiting 2002). Similar habitat comprises Yawajaba Island (i.e. Montgomery Reef) and Turtle Reef (16°16'2.45"S, 123°53'5.24"E) in Camden Sound, WA. All reefs become partially exposed during peak low tide. In the NT, two sites were surveyed between 26 June and 24 July, one south of Bare Sand Island (12°32'51.32"S, 130°25'4.14"E), and the second north of Bare Sand Island (12°30'46.26"S, 130°25'48.69"E). These sites are located in Fog Bay, approximately 50 km west of Darwin. Thirteen surveys were conducted at an altitude of 30 m and a speed of approximately 6-8 m/s between 1100 and 1500 hrs.

A total of 7 surveys were conducted on Montgomery and Turtle Reefs in Camden Sound, WA, on 16-17 August, and 18 August, respectively. These reefs were surveyed to evaluate the abundance and behavior of turtles (primarily green and hawksbill turtles) in foraging habitats. Six surveys were conducted at an altitude of 30 m, with one survey of Montgomery Reef conducted at 15 m altitude to compare behavioral responses of turtles to a drone at 15 and 30 m altitude. Surveys involved two types of transect paths, one that followed the edge of the reef between exposed shallow portions of the reef and the slope, and the second traversing the region from the slope of the reef in to its interior.

iii. Nesting Beaches

Bare Sand Island, NT and Cape Domett, WA, are important rookeries for the flatback sea turtle (Guinea et al. 1991, Whiting and Guinea 2006, Limpus and Fien 2009, Whiting et al. 2009). Drone flights over turtles that emerged to nest during daylight were conducted at various altitudes (i.e. between 10 and 30 m) during stages of the nesting process at which Witherington (1992) and Guinea (*unpub. data*) indicate sea turtles are particularly susceptible to being deterred from nesting: 1) initial emergence from the sea and progression towards the dune, 2) digging a body pit, and 3) constructing an egg chamber. The drone was flown perpendicular to the orientation of the turtle and out in front of its head to best achieve maximum visibility of the drone to each turtle. Any change in behavior or visual signs of disturbance (i.e. increased crawl speed, abrupt change in direction, abandonment of the excavated body pit or egg chamber, or return to the sea) were documented following each flyover. Drone flight trials were conducted for at least 2 consecutive stages of the nesting process for each turtle.

b. Saltwater Crocodiles

i. Nearshore Habitat

The abundance of saltwater crocodiles in nearshore waters was documented during eight drone-based surveys off Cape Domett, WA between 0730 and 1600 hrs from 5-11 August, 2017. Two straight-line transects parallel (one 500 m, the other 1 km offshore) and perpendicular (out to 2 km offshore) to shore were conducted to evaluate potential behavioral responses of crocodiles to drones. All surveys were conducted from an initial altitude of 30 meters and a speed of approximately 6-8 m/s. If crocodiles were encountered, flight trials were conducted at 40, 30, 20, and if possible, 10 meters, to evaluate potential behavioral responses at each altitude.

ii. Surf Zone

Drone flights were conducted on Bare Sand Island, NT, and on Cape Domett, WA, over *C. porosus* that were resting on the beach or in the surf zone. Surveys were conducted at an initial altitude of 30 m at a speed of 6-8 m/s. On Bare Sand Island, two drone flights over a 2.4-meter crocodile (length measured using imagery from the drone) were conducted on 26 and 28 June 2017 at 30 and 40 m altitude, as the crocodile was resting out of the water on a sand spit.

Eight surveys of the beach and surf zone for crocodiles at Cape Domett, WA, were conducted between 4 and 11 August 2017. Most drone surveys were conducted between 0530 and 0630 hrs when daylight was sufficient for optimal visibility of beach tracks. On 4 August 2017 a survey was conducted at 1330 hrs. The drone was flown at an altitude of 30 m parallel the primary nesting beach over the surf zone to document the presence of crocodiles and evaluate potential behavioral responses to the drone. If crocodiles were observed, flight trials were conducted at 40, 30, 20 m, and where possible, 10 m.

c. Nesting Birds

A sand bank approximately 1 km in length is located southwest of Bare Sand Island (12°33'3.37"S, 130°24'23.73"E). The sand bank provided a resting location for a colony of *T. bergii*. Eight drone surveys were conducted between 27 June and 24 July 2017, from 1200 to 1700 hrs, and at altitudes between 30 and 70 m. Flyovers were limited to two per day to avoid the possibility of habituation to the potential disturbance due to the drone. Flight trials began at the highest altitude being tested (e.g. 70 m) and progressed lower (e.g. 60 m) if no flushing response was elicited. If no flushing response was observed, then flight trials were conducted at progressively lower altitudes during subsequent surveys. If the colony took flight during flyovers, trials were stopped. The drone was launched from the southwestern tip of Bare Sand Island, approximately 1 km from the resting colony of crested terns. Once the drone was within 500 m of the sand island, the drone was flown at a speed of 3-5 m/s.

IV. Results

a. Sea Turtles

i. Nearshore Habitat

Two *N. depressus* (1 male and 1 female), 1 female *C. mydas*, and 1 sea turtle of unknown species and sex, were observed during drone flights over coastal waters off Cape Domett beach, WA (Figure 1). Although the turtles encountered during flights spent relatively little time at the surface of the water (i.e. 3-60 sec), the turtles did not exhibit avoidance behaviors (i.e. rapid diving or change in direction) indicative of a threatening stimulus when the drone was at or above 20 m altitude (Table 1 and Figures 2 through 6).

Near Sampson Cove in Camden Sound, WA, two *N. depressus* were observed by drone in nearshore waters from an altitude of 50-60 m (Figure 7). In both instances the turtles did not display any avoidance behaviors indicative of disturbance due to the presence of the drone, however, both turtles spent relatively little time at the surface of the water (i.e. 10-30 seconds) and submerged before drone flight trials could be conducted for each turtle (Figure 8).

ii. Reef Habitat

Juvenile *C. mydas* and *E. imbricata* were observed foraging on algal-covered rocky reef habitat near Bare Sand Island, NT, and Montgomery and Turtle Reefs, WA (Figure 9 a-c). Each survey sampled the behavioral responses of multiple turtles (i.e. >10 turtles/survey) to the drone when turtles were completely submerged, at the surface of the water, or partially exposed while feeding on algae in extremely shallow reef habitat. The submerged turtles were either stationary, potentially foraging on the reef, or slowly swimming along the bottom at approximately 2 m depth or less. Turtles at the surface were encountered floating over the reef slope, or over deeper channels along the reef. Analysis of survey videos indicated no discernable behavioral responses of turtles to the presence of the drone at either 15 or 30 m.

On 17 and 18 August 2017 at Montgomery Reef and Turtle Reef, respectively, drone flight altitudes were reduced from 30 m to 5 and 9 m, respectively. These flights passed over sea turtles foraging in less than 2 m of water. On Montgomery Reef, the *C. mydas* was at less than 0.5 m depth of water. This turtle displayed no response to the presence of the drone, despite a shadow cast in front of the turtle (Figure 10a). On Turtle Reef, a *E. imbricata* was observed slowly swimming over the reef at 1-2 m depth of water. In the presence of the drone, it appeared to increase the force of flipper strokes, potentially to accelerate to slightly deeper water before slowing and turning around as the altitude of the drone decreased (Figure 10b). This behavior could be classified as a minor behavioral response to a drone flying at low altitude. However, rapid avoidance or major evasive responses were not observed during this trial.

iii. Nesting Beach

On Bare Sand Island, NT, an adult female *N. depressus* emerged from the sea to nest on 25 July at 1900 hr. The drone was flown ahead of and perpendicular to the orientation of the head of the turtle while ascending the beach and during the initial stages of body pitting (Figure 11). On Cape Domett, WA, five female *N. depressus* emerged from the sea to nest from 5 to 9 August between 1600 and 1700 hrs. Collectively, the stages of nesting during which a female turtle is likely to be disturbed, (i.e. emerging from the sea, and digging a body pit and egg chamber) were examined for signs of drone disturbance at various altitudes (i.e. between 10 and 40 m) (Figure 12). No disruption or abandonment of the nesting attempt was observed for any of the turtles encountered at any altitude.

b. Saltwater Crocodiles

A total of 11 drone surveys were conducted at Bare Sand Island, NT and Cape Domett, WA, resulting in 31 crocodile sightings. It is possible that the same individuals were observed on multiple surveys over the study period, given the tendency of crocodiles to return to established core activity areas (Kay 2005). However, individual identity could not be verified in the present study and each crocodile observed was treated as a new sighting.

i. Nearshore Habitat

Eighteen of the 31 crocodile sightings in the present study were observed swimming in nearshore waters off Cape Domett. Signs of crocodile disturbance in nearshore waters typically included minor to substantial lateral movements of the head and/or submergence (Supplementary File 1).

ii. Surf Zone

At Bare Sand Island, one crocodile was observed basking on the sand during each survey. One to four crocodiles were observed during each drone survey at Cape Domett. However, in contrast to Bare Sand Island, crocodiles at Cape Domett were only observed basking on the sand on the initial sampling day (4 Aug), after which all crocodiles were observed resting in the surf or swimming in nearshore waters. Signs of crocodile disturbance when basking on the sand included minor to substantial lateral head movements and/or retreat to deeper water.

Collectively, drone surveys of crocodiles at Bare Sand Island and Cape Domett suggest that adult and sub-adult crocodiles basking on the sand or swimming in nearshore waters are disturbed by drones when flying below approximately 50 m in altitude (Figure 13). All trials conducted at 10 m altitude caused rapid head movements, after which crocodiles either submerged or retreated to deeper water (Supplementary File 2).

c. Nesting Birds

The mean size of the *T. bergii* colony on the sand-bank over the eight drone surveys was 153 birds (range = 19 - 334 birds) (Table 2). Flight trials indicated that the *T. bergii* colony was generally disturbed by a drone flying below 60 m altitude (Figure 14). Observed disturbance behaviors consisted of increased vigilance and flushing.

V. Discussion

Collectively, the current study demonstrates that the threshold altitude for disturbance when using a drone varies by species. A key advantage of the current study was the consistent use of the same drone coupled with consistent protocols to evaluate behavioral responses of multiple species to drones throughout a range of habitats across northwestern, tropical Australia. It is likely that different drones and flight patterns may elicit different behavioral responses for the species evaluated. However, with drone type and flight pattern held relatively constant, the differences in threshold altitude eliciting disturbance behaviors are indicative of fundamental differences in behavioral responses between the species.

An important consideration of the current study is that observed differences in behavioral responses to drones may be founded in the basic ecology of each species. A drone more closely resembles the appearance of a typical shorebird predator (e.g. a raptor), than a familiar predator of a turtle or a crocodile (e.g. a shark). Each species is likely to vary in how quickly or whether it associates a drone with a threatening stimulus. Regardless, the findings in the current study characterize important threshold altitudes above which the behaviors of target species do not change. Future drone-based behavioral studies should incorporate these measures in to their experimental design.

a. Sea Turtles

i. Nearshore Habitat

The current study provides further support for the use of drone technology in studies of sea turtles in a variety of habitats, including nesting beaches (Bevan et al. 2015, Bevan et al. 2016), and turtle cleaning stations (Schofield et al. 2017b). Our findings indicate that operating a drone at or above 20 m altitude is a non-invasive protocol for studying behaviors of adult sea turtles in nearshore waters off nesting beaches.

One cautionary element of our study is that four of the six sea turtles encountered in nearshore waters exhibited relatively short surface intervals (i.e. 3-60 seconds), which could be interpreted as a potential behavioral response to disturbance due to the drone. However, based on Piniak et al. (2012), *C. mydas* and *C. caretta* exhibit optimal in-air sensitivity to auditory stimuli between 300 and 400 Hz and while in water between 50 and 400 Hz. Although the range of auditory sensitivity has been found to vary with taxa and age class, the maximum range of auditory responses to stimuli for *C. mydas* and *C. caretta* turtles ranges from 200 to 1000 Hz in water, and other species of sea turtle are likely to exhibit similar capabilities (Ketten and Bartol 2005). Thus, it's possible sea turtles detect the noise emitted by small, commercial drones when at the water's surface or while on the nesting beach (i.e. when auditory capabilities fall between 300-400 Hz). However, drone sound levels reported in previous studies (i.e. 60 – 200 Hz fundamental frequencies) have been measured with the drone at a lower altitude (i.e. 5-10 m) than the altitude used in surveys in the current study (Cabell et al. 2016, Christiansen et al. 2016). The degree to which noise levels diminish at higher altitudes, such as at 15 m or higher, has yet to be measured. The noise emitted from small drones (e.g. <2kg weight), though potentially audible at an altitude less than 10 m might not be distinguishable above background noise at higher altitudes (Christiansen et al. 2016). For the two sea turtles we encountered in Camden Sound, the drone was flying at an altitude of 50-60 m, nearly twice the altitude at which flights over the sea turtles observed off Cape Domett were conducted. The noise emitted by a drone at this higher altitude would likely have been beyond the audible limits of detectability. It is also possible that the short duration of surface intervals observed in the current study represent natural variation in sea turtle behavior when at the surface. *N. depressus, C. caretta, C. mydas*, leatherback (*Dermochelys coriacea*) and Kemp's ridley (*Lepidochelys kempii*) sea turtles, have been reported to spend less than 10% of their time at the surface of the water (Sato et al. 1995, Eckert et al. 1996, Gitschlag 1996, Hays et al. 2000, Hays et al. 2001, Sperling et al. 2010).

An additional concern when evaluating the potential for drone disturbance in sea turtles, is whether individuals are startled by the drone's shadow. However, in only one of our encounters was the shadow visible within the drone's field of view and therefore potentially visible to the turtle. This turtle rested at the surface for 40 seconds before slowly submerging. However, given that this is only a single observation, further investigation is needed to assess the potential impact of a drone's shadow on sea turtle disturbance. The drone used in the current study was white, making it difficult to distinguish against a bright sky. If sea turtles could visually detect the drone at 30 m altitude, we would have expected to see rapid submergence behavior. However, despite a relatively short surface interval, none of the sea turtles in the current study exhibited rapid diving or avoidance behavior (e.g. rapid change in direction of movement). Our drone approached 4 of the 6 sea turtles from either the front or within the peripheral field of view of the individual, yet sea turtles did not immediately dive after being sighted from the drone. Furthermore, two sea turtles continued to rest at the surface for 40 seconds to over a minute after being encountered with the drone.

Although sound levels emitted by the DJI Phantom 4 Pro® used in the current study have not been studied, the noise emitted is likely to be similar to that reported for other drones in previous studies (Cabell et al. 2016, Christiansen et al. 2016). This suggests that a drone of this model operated above 20 m altitude is a suitable protocol for conducting nearshore surveys that avoid disturbing sea turtles.

ii. Reef

Our drone surveys of *C. mydas* and *E. imbricata* observed foraging in reef habitat demonstrates the utility of drone technology for enhancing studies of sea turtle abundance, distribution, and behaviors in shallow reef habitats. Foraging sea turtles did not behaviorally respond to the drone at 15 or 30 m altitude, suggesting that altitudes above 15 m are adequate for providing high resolution imagery of shallow reef habitat and documenting natural sea turtle foraging behaviors.

Seawater cascading off reefs at low tide and/or flowing over elevated pieces of rock/coral were clearly observed from the drone at the 15 and 30 m altitudes. If foraging sea turtles had been disturbed by the drone, it is likely that a fleeing sea turtle and a bow wave generated by the rapid flight response would also have been obvious from the drone. Yet this response was not observed during any of the surveys.

The drone cast a shadow ahead of its path in most of our flight transects, yet even with a shadow moving along the reef and bisecting the paths of several sea turtles from 15 and 30 m altitudes, no significant disturbance was observed in sea turtles. Our finding supports the previously discussed observation at Cape Domett, WA, where adult sea turtles in nearshore waters similarly did not perceive the shadow as a threat. Thus, it is possible that drone shadows are not impacting the behavior of sea turtles.

On Montgomery reef, a sea turtle we observed partially exposed and foraging in water at less than 1 m depth, was not disturbed by a drone flown over at 5 m altitude. The background turbulence of the water cascading off the reef at low tide may have masked the sound of the drone and obscured the turtle's ability to detect the drone. In contrast, a sea turtle observed foraging in 1-2 m water depth at

Turtle Reef exhibited a potential disturbance response (i.e. the sea turtle moved towards deeper water) with the drone less than 10 m above the water. The survey was conducted at a falling mid-tide, when the seawater had not yet started rushing off the exposed reef flat. It is possible that, without the background noise of water rushing off the reef flat, the turtle could detect the drone at 10 m altitude. Additional observations are needed to characterize foraging behaviors of different sea turtle species when drones are present at low altitudes.

Collectively, our findings suggest that drones could be used to study sea turtles at low altitudes (i.e. from 15-30 m), without disturbing individuals foraging on a reef when background noise is sufficient to mask potential disturbance due to the drone. Such studies could provide fine-scale assessments of sea turtle foraging activities in shallow, clear reef habitats.

iii. Nesting Beach

The results from the current study were consistent across multiple locations and sea turtle populations and suggest that the nesting processes of *N. depressus* are not disrupted by drones at or above 10 m in altitude. Based on the auditory range of *C. mydas* and *C. caretta* above the water (i.e. 300 – 400 Hz), it is possible that sea turtles detect noise emitted from small drones at low altitude. Nonetheless, if nesting sea turtles can detect the drone, it did not appear that the drone provided a perceived threatening stimulus sufficient to change nesting behavior or cause abandonment of a nesting attempt. Drone technology may therefore be an optimal tool for eliminating human observer presence, a known factor in sea turtle disturbance (Witherington 1992), while studying nesting processes or monitoring nesting activity on beaches.

b. Saltwater Crocodiles

Drone surveys of saltwater crocodiles resting on sea turtle nesting beaches and resting or swimming in nearshore waters suggests that crocodiles may require higher altitudes than sea turtles when operating a small drone to study their behaviors.

Crocodiles have a relatively diverse array of vocalizations when compared to other reptiles. These vocalizations aid in group coordination, mating, territorial defense, and maternal care (Bierman et al 2015). Auditory capabilities are concentrated at low frequencies and there is behavioral evidence that crocodilians respond to directional auditory stimuli (Grap et al 2015, Bierman et al 2015, Higgs et al 2002). Preliminary results from the current study suggest that specific activities (i.e. basking on the beach, in the surf, or actively swimming in nearshore waters) may influence the threshold altitude above which a drone can be used without eliciting behavioral responses from crocodiles (Figure 12).

Previous studies evaluated a variety of drones (both multirotor and fixed-wing designs) to locate crocodiles and alligators and their nests from altitudes of 100 to 300 m with no indication that drones disturb individuals (Elsey and Trosclair III

2016, Evans et al. 2016). However, mapping or behavioral studies require imagery in greater detail and higher resolution and necessitate lower altitude surveys.

Regardless, video imagery from the current study suggests crocodiles can detect and potentially localize the sound emitted from a small drone. Thus, studies comparing the auditory and directional capabilities of crocodilians, and the noise disturbance caused by commonly-used drones represents an area of need in conservation management research.

c. Nesting Birds

The auditory capabilities reported for birds (i.e. optimal frequencies between 2-3 kHz), coupled with the range of sound emission reported for small commercial drones (i.e. 60 – 200 Hz), suggests that noise emitted by drones at low altitudes were audible to the colony of *T. bergii.* Our preliminary results suggest that studying colonies of *T. bergii* requires a higher altitude approach than the other species investigated in the current study to avoid disturbance (i.e. > 60 m altitude). Similar measures of disturbance for *T. bergii* using a different model drone at an altitude of 75 m support our conclusion that this species is not disturbed by the presence of a drone above 60 m altitude (Hodgson et al 2016).

At Raine Island National Park (RINP), Queensland, preliminary data suggests that other avian species are even more sensitive to drone disturbance (Queensland

Parks and Wildlife Service, 2017). Guidance for drone use within RINP indicates that drone altitudes of 80 and 120 m, respectively, are required to avoid disturbing the brown booby (*Sula leucogaster*) and the common noddy (*Anous stolidus*). Such findings suggest that drone disturbance may be species-specific and different avian species will exhibit different threshold altitudes below which disturbance behaviors will be elicited. Thus, the drone disturbance threshold of a target species should be determined prior to initiating drone-based studies.

Future studies of *T. bergii* should incorporate other factors, such as environmental conditions, time of day, and reproductive status, to determine how these factors may influence behavioral reactions of *T. bergii* to drones. The flight trials in the current study were conducted between June and July 2017, which falls within the known breeding season for *T. bergii* in the NT (Chatto 2001). However, breeding colonies in this region have been reported to number in the thousands to hundreds of thousands, and the average colony size reported in the current study was only a few hundred individuals. It is possible that the group of *T. bergii* observed by drone on the sand bank represents a relatively small portion of individuals from a nearby larger breeding colony. A comparison of the behavioral responses to drones of non-breeding with breeding colonies, could provide insights on whether reproductive status influences behavioral responses to drones.

VI. Summary/Conclusions

Drones are rapidly revolutionizing the observational and monitoring capabilities of scientists working in remote habitats where survey locations are often logistically challenging or dangerous to access. However, without first quantifying the impact of drones on wildlife, the benefit of minimizing observer presence may be diminished. The current study demonstrates that a variety of disturbance thresholds exist for the suite of species that may occur within a single habitat. In establishing optimal drone-use protocols, resource managers are challenged with balancing the quality and type of data needed, with the level of disturbance inflicted upon a variety of species. The current study provides preliminary information to address these concerns and highlights promising directions for future research in this advancing field.

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