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Research Article

Using a small, consumer-grade drone to identify and count marine megafauna in shallow habitats

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ABSTRACT. Large-bodied animals, megafauna, are disproportionately threatened and yet, remain relatively difficult to monitor, particularly true in the ocean. Consumer-grade drones have high definition imagery and offer a non-invasive way to monitor a subset of marine megafauna, especially those species that spend part of their life near the water's surface. However, a key question is the extent to which drone imagery data offer reliable abundance estimates due to potential detection restraints, and the ability to compare data from different locations. Here we tested the efficacy of a quadcopter drone to collect megafauna abundance data in multiple shallow-water habitats in the realistic background variation of shoreline development. On Great Abaco Island, The Bahamas we repeated drone surveys in nearshore habitats from June to August 2015 at three paired high and low human population sites. We tested the drone's detection probability using decoy organisms and found no effect of water quality or benthic characteristics on detectability. In short, the drones appear to work to monitor these species. We also noted patterns in the occupancy of the species on which we focused. We observed three shark, two ray, and two sea turtle species, finding higher abundances of all species in our low human population sites compared to high human population sites. Our results highlight the ability of consumer-grade drones to estimate the abundance and distribution of large-bodied elasmobranchs and sea turtles in shallow water habitats. Further, our study supports their capability to evaluate issues related to the conservation and management of nearshore ecosystems.

Keywords: Unmanned Aerial Vehicles (UAVs), non-invasive monitoring, human impacts.

INTRODUCTION

Large-bodied animals, megafauna, are some of the animals most vulnerable to and impacted by human activities (Lewison *et al.*, 2004; Dirzo *et al.*, 2014). Many megafauna species, particularly marine species, remain difficult to monitor due to their large home ranges and sensitivity to being captured and handled (Hueter & Manire, 1994). Aerial surveys are one methodology used to measure the size, density, and distribution of megafauna populations that spend part of their life near the ocean's surface (Loughlin *et al.*, 1992; Pollock *et al.*, 2006; Koski *et al.*, 2009). Aerial surveys allow researchers to monitor animals with low to no intrusion, thereby minimizing biases in observer presence and a detriment to animals (Jolly 1969; Hodgson *et al.*, 2013; Christie *et al.*, 2016). Traditionally conducted with observers on a small aircraft or a type of Unmanned Aerial Systems (UASs), such as military Unmanned Aerial Vehicles (UAVs), aerial surveys were limited to studies that could obtain proper aircraft permits and meet budgetary requirements (Pollock *et al.*, 2006). In the last decade, small, consumer-grade UAVs, herein drones, have become readily available, increasing the use of aerial imagery to study a wide range of fauna and flora, likely due to these drones being more affordable and easier to use than more traditional UASs (Koh & Wich, 2012). Also, technological advancements in camera imagery have increased detection probability from traditional aerial monitoring methods (Grier *et al.*, 1981; Hodgson *et al.*, 2013). Because of these improvements, small, consumer-grade drones may be a promising tool to assist conservation and management agencies in assessing how human activities affect sensitive marine megafauna.

Aerial surveys conducted in marine environments, either by manned aircraft or drones, have focused mainly

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on monitoring megafauna species that breach the surface; *e.g.*, mammals and sea turtles (Marsh & Sinclair, 1989; Loughlin *et al.*, 1992; Pollock *et al.*, 2006; Koski *et al.*, 2009). However, the high definition imagery produced by drones has led to a rise in investigations that use aerial surveys to study flora below the ocean's surface (Casella *et al.*, 2017; Chirayath & Earle, 2016; Kiszka *et al.*, 2016). For some fauna species, such surveys could also work well. Shark and ray species, for example, are large-bodied organisms that can be easily detected from an aerial image, especially in shallow habitats that are less than 3 m deep (Kessel *et al.*, 2013; Kiszka *et al.*, 2016). Despite this, little research has been conducted with drones to monitor the abundance and distribution of submersed megafauna in shallow water habitats (see Kiszka *et al.*, 2016).

In this study, we used a DJI Phantom Vision 2+® drone to test the accuracy of drones for identification and estimation of sharks, rays, and sea turtles abundance in shallow, clear water habitats along Great Abaco Island, The Bahamas. We selected our survey sites in the context of the realistic background variation of shoreline development to investigate how human activities alter the distribution of these populations. Our primary objectives for this study were to determine the efficacy of small, consumer-grade drones to collect reliable data in multiple shallow water habitats, provide baseline megafauna data for newly established protected parks, and test the capability of using such data for comparison studies.

MATERIALS AND METHODS

To assess the ability of drones to estimate the abundance and distribution of marine megafauna, we surveyed six tidal creek sites along the shoreline of Great Abaco Island, The Bahamas (26°25'N, 77°10'W) from June to August 2015 (Fig. 1).

These tidal creek habitats are shallow (<3 m deep), tidally-influenced estuaries that have narrow mouths, with creek width expanding inland (Fig. 2). Each site is bordered with red mangroves (*Rhizophora mangle*), and the benthic substrate is comprised of a mosaic of sand, dense and sparse seagrass meadows, macroalgae beds, hard bottom, and patch reefs. Island-wide, Abaco's tidal creek habitats are known foraging grounds for juvenile green sea turtles (*Chelonia mydas*) (Musick *et al.*, 1997) and have locally established shark and ray populations (Valdivia *et al.*, 2017). Any location on the island known or suspected to be a potential mating site for sharks, rays, and sea turtles was omitted from this study.

We also sought to determine if drone-based aerial surveys collect marine megafauna data appropriately to compare areas of conservation concern. To test this, we used sites selected in Stoner *et al.* (2011) which were assigned one of two categories: adjacent to high human impact (shoreline development) or adjacent to uninhabited, low human impact areas. The proxy for human impact level was the number of buildings within a 3 km radius from the midpoint of each site. We considered sites adjacent with a higher number of buildings to be more disturbed by nutrient loading, construction of artificial structures, and sedimentation (Stoner *et al.*, 2011 for details). We selected three high (84-1712 buildings; Treasure Cay, Cherokee, and Sandy Point) and three low human impact sites (0-10 buildings; Hills Creek, Snake Cay, and Cross Harbour; Figs. 1-2) and, using a paired design, we coupled a high and low human impact site within the same region of the island (Fig. 2). We selected site pairs within each region for similar creek mouth shape and average creek depth. Within each region, sites had a similar location on the island, benthic substrate, and distance to open ocean and currents, but we did not measure these variables for this study. Additionally, three of our sites are national parks (Snake Cay, Cherokee, and Cross Harbour), allowing us to provide baseline data of marine megafauna abundances to local and national management agencies.

To quantify the number of sharks, rays, and sea turtles at each site, we sampled the sites within each region on the same day and outgoing tide cycle, with a total of four sampling dates. For each site survey, we conducted two consecutive drone flights, in order to switch the drone's battery and maximize survey area. Each survey began closest to the tidal creek mouth and moved up the creek to avoid double counting; we assumed individuals were unlikely to swim against the tide within the time we replaced the drone's battery. We chose the initial starting position at each creek mouth from a stratified random sampling design (Marsh & Sinclair, 1989). Then we conducted parallel line transect surveys oriented perpendicular to the shoreline, covering the entire width of the creek. For paired sites, the order of site surveyed was chosen at random. We selected sampling time and conditions to ensure that water depth was between 1-1.5 m with good clarity. To maximize aerial-view detection, we completed all transect surveys in calm sea conditions (<1 Beaufort scale), allowing us to avoid potential view obstruction from surface waves.

Additionally, we conducted surveys during an outgoing diurnal tide to minimize individuals hidden within mangroves at high tide. The travel time between surveys of the high and low human impact sites within

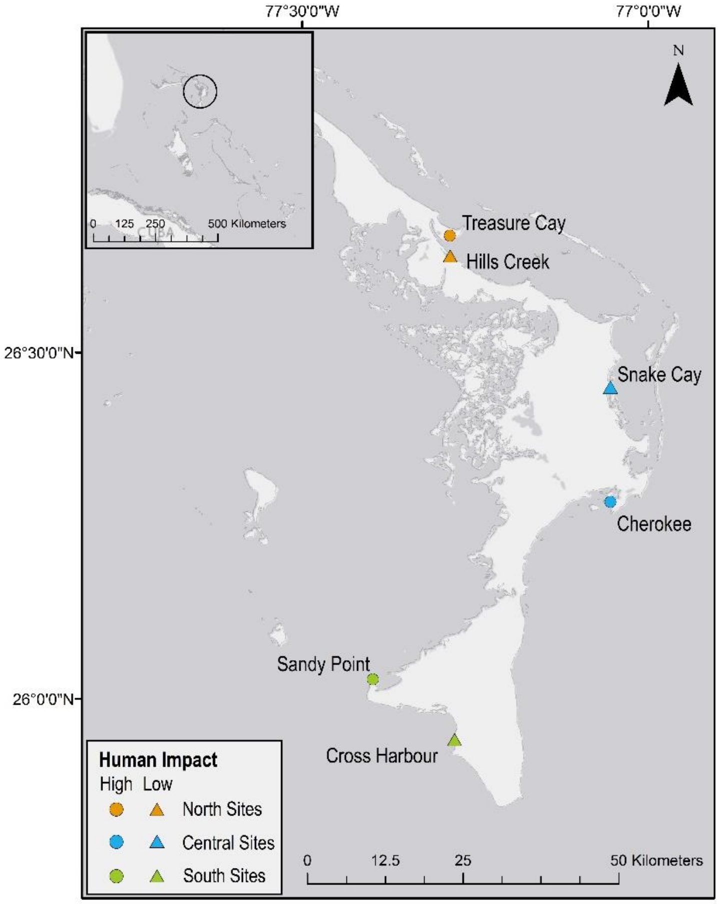

Figure 1. We conducted aerial surveys from June to August 2015 at six sites on Great Abaco Island, The Bahamas, quantifying the number of sightings of marine megafauna in nearshore habitats. Sites were classified as high or low human impact based on the number of buildings present within a 3-mile radius from the center of each human population center.

the central and north region was 20 min. For the south region, the time between site surveys was one hour, due to land access constraints.

For our aerial surveys, we used recorded video footage from a DJI Phantom Vision 2+® quadcopter drone (1.2 kg with camera, propellers, and battery) with a polarized lens attached to the camera to reduce glare. The camera had 14 megapixels with a resolution of 4384×3288 and high definition recording of 1080p30 & 720 p. Following the protocol of Kiszka *et al.* (2016), we flew the drone at a constant speed of 4.8 km h^{-1} at an altitude of 7.6 m. We tilted the camera 10° from parallel to the water's surface to reduce sun glare, increasing the frame size of usable recorded footage; *i.e.*, total viable survey area covered. The total distance of each site's transect survey was determined by drone flight time, range limit of its ground controller, the shape of the tidal creek to mouth, and then modified to match its paired site optimally. Each Phantom 1-3 DJI® drone battery offers up to 25 min of flight time; however, we found that the setup and total flight time for each battery gave us about 12 min of survey time. We manually conducted each drone flight path using premeasured visual landscape and seascape markings. Notably, we did not use any automated flight path software. There were compatibility issues with the DJI Phantom Vision 2+®, and we did not have access to cellular data or wireless internet at remote locations.

To determine the detection probability of submersed individuals from the deployed drone, we set up an experiment using mock-shark individuals at our central region sites (Fig. 3). Our mock-sharks mimicked juvenile lemon sharks, (*Negaprion brevirostris*) because they were the hardest to detect in the post-video process, due to their light color and slender shape.

Two snorkelers placed 10 mock-sharks, made of grey foam weighted down with twine and weights, randomly within the transect survey area at varying depths. The drone pilot was blind to the mock-shark locations. We conducted three surveys at each central

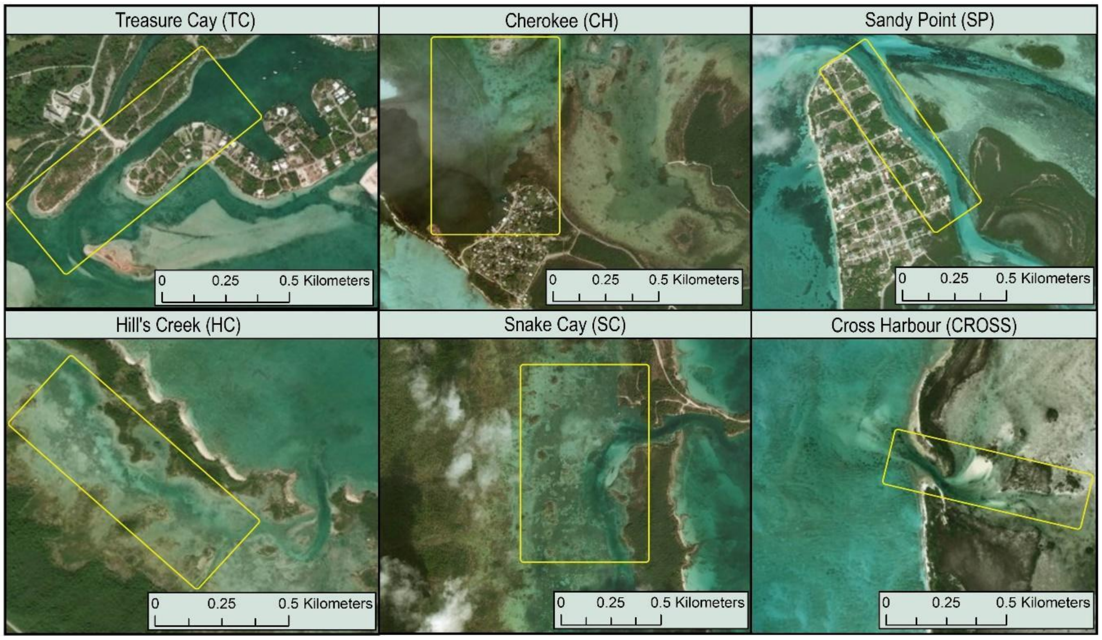

Figure 2. North, central, and south region, paired sites were: Treasure Cay (TC) & Hill's Creek (HC), Cherokee (CH) & Snake Cay (SC), and Sandy Point (SP) & Cross-Harbour (CROSS), high and low human impact respectively. The yellow rectangles indicate where we conducted drone surveys at each site.

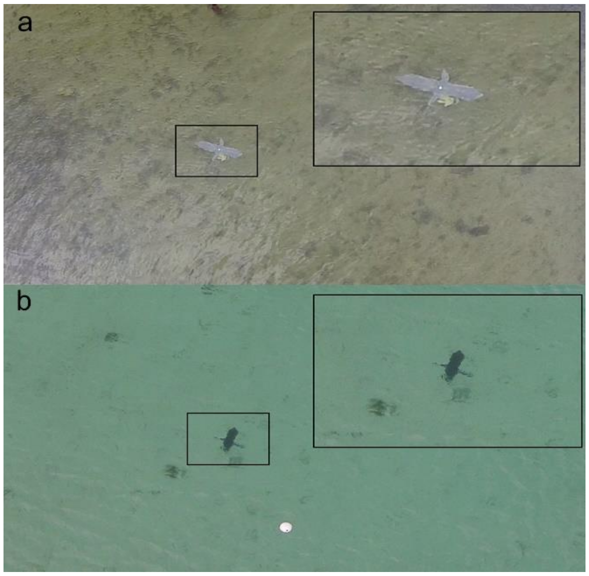

Figure 3. Images showing the mock-sharks used in our detection probability experiment at a) Cherokee (high human impact, and b) Snake Cay (low human impact). Both the drone pilot and the observer reviewing the video footage detected 100% of the mock-sharks in all six surveys.

region site, with the mock-sharks being relocated before each survey. The amount of individual mobility (*e.g.*, resting or swimming), was not a detection variable of concern because our aerial footage was recorded, allowing us to playback and review frames, and the movement of the drone eliminated the ability to detect whether an individual itself was moving. The central region's high human impact site had the most turbid water compared to all other sites and had the identical benthic substrate to the north region's high human impact site (*i.e.*, sand and macroalgae beds). The central region’s low human impact site contained all benthic substrates (*i.e.*, dense and sparse seagrass meadows, sand, hard bottom, and macroalgae beds) and had same water clarity to the other low human impact sites, as well as the southern high human impact site. We then reviewed the recorded video footage in the laboratory by the drone pilot and an additional observer, blind to the number and location of mock sharks, and recorded the number of individuals detected.

To quantify the species’ abundances for each site, we reviewed video recordings from both flights at each site, per sampling date, independently in the laboratory by two observers (Fig. 4). For all surveys, counts and species identification from observers were identical.

Since each drone flight recording had slightly different times (recordings were between 11-13 min), we determined the amount of reviewed footage by the region’s site which had the shortest recording for each sampling date. We recorded abundance estimates for each survey as the average number of individuals per minute, over the course of both flights, per sample date.

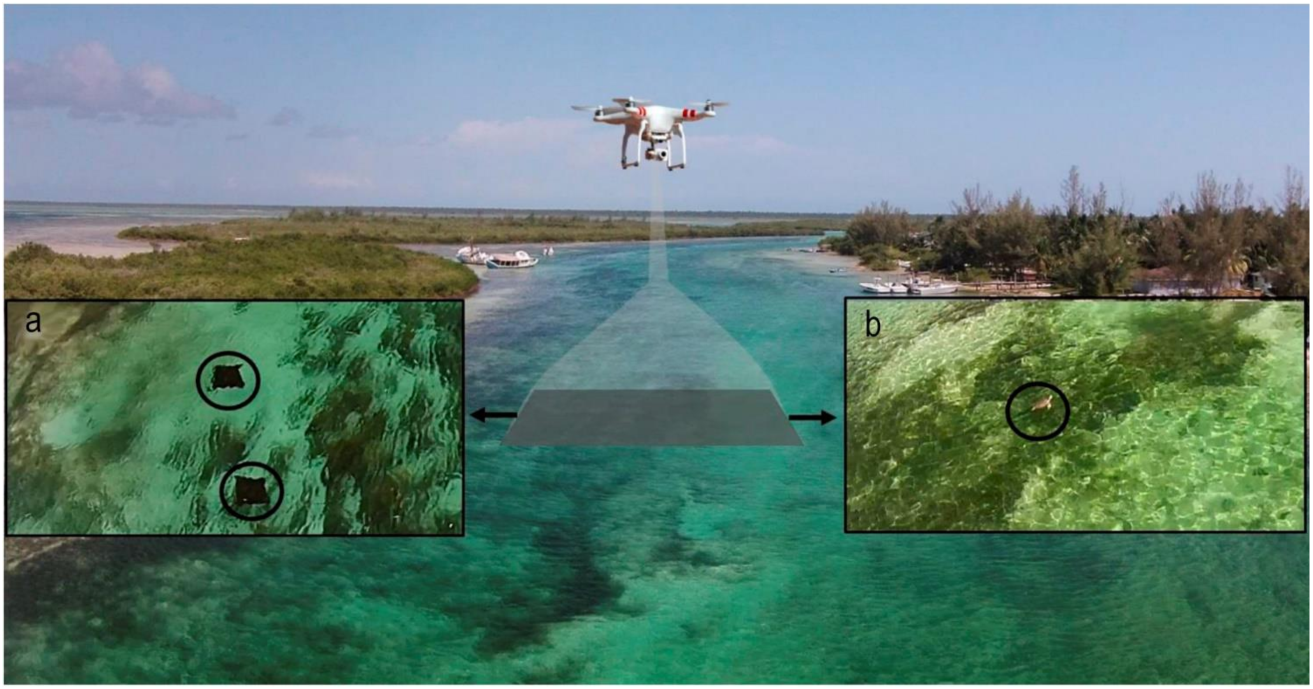

Figure 4. Example screenshots of recorded drone footage capturing. a) Spotted eagle ray (*Aerobatus narinari*) and b) either a Green (*Chelonia mydas*) or Hawksbill (*Eretmochelys imbricata*) sea turtle.

Using a two-way Analysis of Variance (ANOVA), we tested the differences in average total marine megafauna, elasmobranch, and sea turtle abundance per minute between high and low human impact sites within each region. Data were log-transformed to meet model assumptions and verified using the Shapiro-Wilk test as well as diagnostic plots including Q-Q and residuals vs. fitted. We performed all statistical analyses in R v3.3.1 (R Core Team 2016).

RESULTS

Across all of our sites, we recorded five species of elasmobranchs, including lemon sharks (*Negaprion brevirostris)*, nurse sharks (*Ginglymostoma cirratum)*, bonnethead sharks (*Sphyrna tiburo)*, southern stingrays (*Dasyatis americana)*, and spotted eagle rays (*Aetobatus narinari)*. We observed two species of turtles, hawksbill (*Eretmochelys imbricata)* or green turtles (*Chelonia mydas)*, but we were unable to distinguish between these species in aerial imagery. "Sea turtles" (pooling the two species) were the most frequently observed taxon in our videos; we observed 145 total turtles across all sites and sample dates. Elasmobranchs were less abundant across Abaco's creeks, observing 13 sharks and 28 rays total in all of our videos (Table 1).

For the detection probability experiment, all 10 mock-sharks were detected in all surveys (n = 6) in both central region sites. Our 100% detection mock-sharks gave us high confidence in the ability of our drone to detect live organisms in our survey sites. Abundances of live organisms were estimated as the average number of animals observed per minute from four replicate drone surveys per site. The south region sites had more elasmobranchs than did any other region (F = 4.6, df = 2, $P < 0.01$), estimating 0.1 ± 0.1 SE and 0.4 ± 0.1 SE elasmobranchs, for SP and CROSS respectively. Sites in our north region had the highest total abundance of megafauna, driven by a large number of sea turtles in these two sites (F = 6.4, df = 2, $P < 0.01$). For TC, we observed 0.3 ± 0.1 SE sea turtles and 0.8 ± 0.3 SE sea turtles at HC. For the central region sites, Cherokee and Snake Cay, we observed 0 and 0.3 ± 0.3 SE sea turtles and 0 and 0.1 elasmobranch, respectively.

For our comparison study testing, as a simple case example, the effects of shoreline development on marine megafauna abundance, development and region had a significant effect on the average total marine megafauna, elasmobranch, and sea turtle abundance per minute. For all response variables, there was no interaction effect between development and region: all fauna (F = 0.9, df = 2, $P = 0.88$), elasmo-branchs (F = 3.2, df = 2, $P = 0.06$), and sea turtles (F =

Table 1. Average individuals per survey from four surveys at each site. Paired sites were surveyed on the same diurnal, outgoing tide cycle. A high (H) and low (L) human impact site is paired by island region: south, central, and north and are shaded green, blue, and orange, respectively.

	Average number of observed individuals per survey			
Site	Sea turtles	Sharks	Rays	All fauna
Sandy Point (H)	0.8 ± 0.5 SE	0.3 ± 0.3 SE	1.5 ± 0.9 SE	2.5 ± 1.3 SE
Cross Harbour (L)	3.3 ± 0.6 SE	0.8 ± 0.5 SE	3.8 ± 1.0 SE	8.0 ± 0.6 SE
Cherokee (H)	0.5 ± 0.5 SE	0.3 ± 0.3 SE	0	1.0 ± 0.6 SE
Snake Cay (L)	6.0 ± 1.2 SE	0	1.3 ± 0.6 SE	8.3 ± 2.3 SE
Treasure Cay (H)	5.2 ± 1.2 SE	0.4 ± 0.4 SE	0.6 ± 0.4 SE	6.2 ±1.6 SE
Hills Creek (L)	13.0 ± 5.9 SE	1.0 ± 0.4 SE	0.2 ± 0.2 SE	14.8 ± 6.1 SE

0.1, df = 2, P = 0.92). For all marine megafauna (elasmobranchs and sea turtles combined), we observed twice as many animals in low human impact sites compared to high human impact sites (Fig. 5a; F = 14.7, df = 1, $P < 0.01$). Region had a slight effect on total marine megafauna (F = 3.5, df = 2, $P = 0.05$). The north region sites had more sea turtles whereas the south region sites had more elasmobranchs (Figs. 5b-5c, Table 1). Across all regions, we observed 2.5× more elasmobranchs and 7.5× more sea turtles in low human impact sites compared to high human impact sites (F = 4.6, df = 1, $P = 0.04$ and F = 10.7, df = 1, $P < 0.01$, elasmobranchs and sea turtles respectively; Figs. 5b-5c).

DISCUSSION

Our data suggest using small, consumer-grade drones may be an effective and non-invasive method for detecting and estimating the abundance of marine megafauna in shallow water habitats, particularly at relatively small spatial scales (*e.g.*, <3 km^2). Specifically, we provide evidence that these drones can detect elasmobranch species and sea turtles varying in size, shape, color, and mobility. With repeated surveys at six sites and directly testing our drone's detection probability with a mock-animal experiment, we show that drone's high definition imagery can detect elasmobranchs and sea turtles in shallow habitats within a range of water clarity residing over seagrass meadows, hard bottom, sand, and/or scattered patch reefs. Lastly, our study shows that consumer-grade drones are a useful tool to compare the abundance and distribution of marine megafauna in nearshore habitats exposed to varying intensity of human activities.

We consistently found fewer individuals of sharks, rays, and sea turtles in our high human impact sites compared to our low human impact sites (Fig. 5). However, we did not directly measure other environmental variables (*e.g.*, water temperature and ocean current) that may have been the ultimate drivers for differences among our selected sites (Speed *et al.*, 2010; Schlaff *et al.*, 2014). There are a few reasons why our observed pattern could be related to various human-driven causes. There may be a higher frequency of boats (which was observed during surveys), increasing the likelihood of collisions with animals and generating substantial underwater noise (Slabbekoorn *et al.*, 2010). The removal of habitat-forming species associated with shoreline development is also likely to affect the abundance of fauna (Davenport & Davenport, 2006; Jennings *et al.*, 2008). The loss of mangroves along shorelines, for example, can decrease shelter availability for both elasmobranchs and their prey, as well as increase sedimentation affecting nearby seagrass beds or patch reefs (Rogers, 1990). In general, our findings of fewer elasmobranchs in nearshore habitats, although preliminary, are consistent with previous research conducted in Bimini, The Bahamas. Researchers found that shoreline development and the associated loss of habitat, introduction of toxic pollutants, and decrease in prey populations led to decreases in lemon shark abundance, increased mortality rates and reduced body condition of individuals. Lemon sharks, like many megafaunas, are known to provide cross-ecosystem linkages due to their extensive ranges and ontogenetic habitat shifts (Jennings *et al.*, 2008), which is essential to consider for the potential cascading or other indirect effects shoreline development can have on neighboring ecosystems (McCauley *et al.*, 2012).

The region of the island also influenced abundance trends, with the north region sites having the highest sea turtle abundance estimates and south region sites having the highest elasmobranch abundance estimates. Although The Abacos are known foraging grounds for juvenile green sea turtles, particular locations on the island may have higher sea turtle densities because of a wide range of drivers within both life history

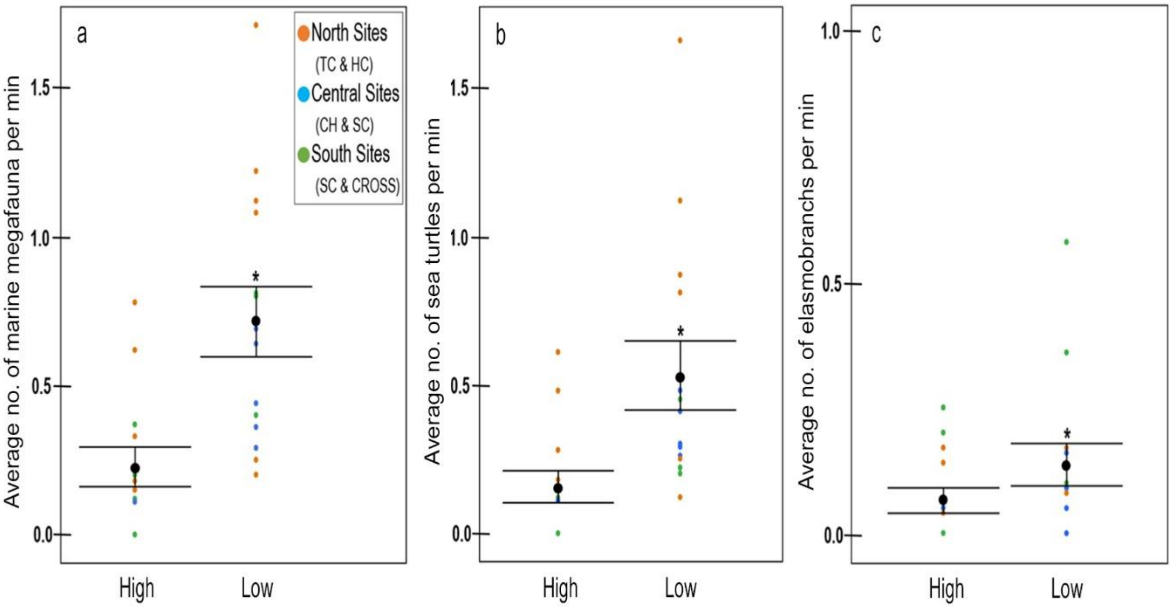

Figure 5. Sites with low shoreline development had, on the average, (a) higher abundance of total megafauna, (b) sea turtles, and (c) elasmobranchs, per minute of drone footage, than sites with high shoreline development. Between regions, the north sites had more overall sightings of sea turtles (C, $P < 0.01$*) but there were no other differences found among regions. Asterisks indicate statistical differences ($P < 0.05$) between these site classifications.

characteristics, *e.g.*, proximity to hatching location, and local habitat characteristics, *e.g.*, benthic substrate composition and seagrass productivity (Bjorndal & Bolten, 1988; Heithaus *et al.*, 2002). We did not directly measure variables to predict why the south region sites had higher abundance estimates of elasmobranchs. However, from personal communications with local research stations and fishers, the shorelines of southern Great Abaco Island are historically well-known for their shark and ray densities. Potential environmental variables include, but not limited to, proximity to deep-waters and high densities of prey species (Speed *et al.*, 2010; Clavelle & Jylkka, 2013).

Previous studies using consumer-grade drones to estimate the abundance and distribution of fauna have typically been short-term (*i.e.*, <1 month) and/or conducted within a single survey site. Our study is one of the first to show that these drones can repeatedly survey multiple sites and collect consistent abundance and distribution data. Confidence in abundance estimates was strengthened by testing the detection probability of marine megafauna in all ranges of the benthic substrate and water clarity of our sampled sites. Similar to Kiszka *et al.* (2016), we also limited our survey sites to locations where aerial imagery could only clearly see to the benthic substrate, thereby limiting water depth and turbidity to maximize detection. Although we did not use any software to program automated drone flights, newer drone models are compatible with most autopilot programs which can significantly expand survey area per drone flight and improve replicability of surveys. Noteworthy, for surveying remote locations, it is essential to review the calibration requirements as some drone models still require access to the wireless internet or cellular data before flying a pre-programmed flight.

We have shown that consumer-grade drones are a promising tool that is affordable, non-invasive, and easy to use for long-term monitoring of large-bodied species in subtropical and tropical nearshore habitats. Consumer-grade drones are becoming more technologically advanced, and new models typically have longer battery life and range extensions, potentially providing for increased survey length and time. Importantly, one should be aware of the potential limitations of drone models and be familiar with the local government regulations on the use of drones before using them. Monitoring how human activities affect marine megafauna is only one step in aiding in their protection and conservation-education, and public outreach is critical. The high definition footage recorded during monitoring can be used for engaging the public through social media, environmental presentations in schools, and the development of educational videos. There is still much to be considered regarding the use of drones in a conservation and management context, but our data suggest they can be a powerful tool.

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