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Using biotelemetry to assess drone effects on whale sharks

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Abstract

The use of unoccupied aerial vehicles or drones for wildlife research has proliferated in recent years and they have proven to be a valuable tool for collecting data for population surveys, morphometric and body condition measurements, and for observing behavior. The need to assess the impacts of drones themselves on wildlife is increasingly being recognized, not only for ethical considerations but also before attempting to record "natural behavior." While effects of drones have been seen in some marine species, such as whales, dolphins, and seabirds, these are highly variable across and within taxa and are typically assessed through observations of behavior. Effects on water-breathing animals are understudied. Drones have already been used in studies of the world's largest fish, the whale shark (*Rhincodon typus*), but their effects on the species are yet to be quantified. This study is the first to use biotelemetric data to assess the effects of drones on the natural behavior of a water-breathing marine species. Rather than relying on observations of behavior that can be impacted by observer bias, we employed behavioral data-logging tags, incorporating tri-axial accelerometers and magnetometers, to record fine-scale whale shark activity and diving behavior in the presence and absence of a drone. Activity was measured by the vector sum of the dynamic body acceleration (VeDBA), calculated as the vector sum of the dynamic components of tri-axial acceleration, and tail beat frequency (TBF) as an indicator of swimming effort. Generalized linear mixed modeling found no evidence that drone presence (10–60 m altitude) or its vertical movement (ascent/descent) increased whale sharks' diving or activity compared to when the drone was absent. Our study provides confidence to researchers and managers that drones are a minimally invasive research tool for whale sharks, although we advocate a precautionary approach to their use and consideration of their potential effects on non-target species. Furthermore, our method of objectively assessing the effects of drones using biotelemetry could be effectively applied to a wide range of species inhabiting the aquatic, terrestrial, and aerial environments, facilitating comparisons within and among species, and allowing multispecies or ecosystem assessments.

KEYWORDS
animal behavior, biotelemetry, human disturbance, noninvasive monitoring, remote sensing, unoccupied aerial vehicle (UAV)

INTRODUCTION

Unoccupied aerial vehicles (UAVs), hereafter "drones," have decreased in both size and cost, resulting in greater accessibility and a proliferation of use for many applications, including recreational, commercial, and scientific (Johnston, 2019). Drones are a valuable tool for wildlife research and studies employing them are increasingly common. A review of scientific literature published between 2000 and 2020 found 223 publications involving drones and wildlife, with more than 85% published after 2015 (Mo & Bonatakis, 2022). A further review, up to 15 December 2024, identified 1572 peer-reviewed publications on the use of drones with wildlife (Afridi et al., 2025). Drones were first used to detect animals and conduct population surveys in 2005 and 2010 respectively (Mo & Bonatakis, 2022). More recently, other uses have been developed, such as collecting aerial photographs for estimating body condition and measuring morphology (e.g., Allan et al., 2019; Christiansen et al., 2019; Durban et al., 2015; Krause et al., 2017), recording vocalizations (e.g., Fu et al., 2018; Kloepper & Kinniry, 2018), and collecting blow samples from cetaceans (e.g., Centelleghe et al., 2020; Nelson et al., 2019). However, drones can negatively impact wildlife (Afridi et al., 2025), for example, causing birds to abandon breeding sites (Pires Mesquita et al., 2020), inducing stress responses (Ditmer et al., 2015; Weimerskirch et al., 2018), and fleeing or increased vigilance, which reduce activities such as foraging or parental care (Schroeder et al., 2020). Awareness of the potentially negative effects on animal welfare and the increasing use of drones to study the natural behavior of animals has brought greater attention to the importance of assessing their effects on both target and non-target species (Afridi et al., 2025; Mo & Bonatakis, 2021).

The effects of drones vary considerably by taxa and are also influenced by factors such as approach distance, flight speed and altitude, noise emissions, airframe and changes in noise intensity, as well as the biological state (e.g., breeding), and behavioral state (e.g., resting or foraging) of the study species (Afridi et al., 2025; Mo & Bonatakis, 2021). For example, flight-initiation distance in response to drone approaches varies between 22 species of terrestrial and aquatic birds (Weston et al., 2020), behavioral disturbance thresholds vary for different species of sea turtles, saltwater crocodiles (*Crocodylus porosus*), and crested terns (*Thalasseus bergii*) (Bevan et al., 2018), and the behavior of bottlenose dolphins (*Tursiops* spp.) is more likely to change with decreasing drone altitude (Giles et al., 2021). However, although drones are increasingly being used as a tool for research on surface-associated elasmobranchs (Butcher et al., 2021), knowledge of their effects is limited to stingrays that showed no observable reaction to drones (Bourke et al., 2023). Drones have been used to observe the fine-scale movement patterns (Raoult et al., 2018) and behavior of elasmobranchs (e.g., sharks feeding on whale carcasses; Lea et al., 2019; Tucker et al., 2019 or attacking live whales; Dines & Gennari, 2020), collect images for morphometric measurements (Setyawan et al., 2022), conduct species surveys (Ayres et al., 2021), and measure swimming kinematics (Porter et al., 2020). However, if drones are to be employed to observe "natural" behavior or the effects of other stimuli (e.g., tourism, human disturbance) on elasmobranchs, the effects of the drones themselves must first be established.

Drones are already being used to research the world's largest elasmobranch, the whale shark (*Rhincodon typus*), including to observe whale shark feeding behavior and co-occurrence with golden cownose rays (*Rhinoptera steindachneri*) in the Sea of Cortez (Frixione et al., 2020); for the collection of aerial images for estimating body measurements in the Gulf of California (Whitehead et al., 2022); to document a rare occurrence off a river mouth in Brazil (Nascimento et al., 2021) and unusual interspecific interactions with other elasmobranchs in Revillagigedo National Park, Mexico (Pancaldi et al., 2022); and to monitor compliance with whale shark tourism regulations off the Yucatan Peninsula, Mexico (Ninh, 2024). They also have potential for use in aerial surveys, assessing impacts of tourism (Gayford et al., 2023), and observing other behaviors.

Given the increasing use of drones in whale shark research, it is important to assess whether they cause disturbance, especially for behavioral studies, where unquantified drone effects could confound the findings. Most studies of disturbance of wildlife by drones rely on visual observations of the animals' behavior (Mo & Bonatakis, 2021). However, observational studies may fail to detect fine-scale changes in behavior and activity levels and cannot detect any physiological effects (Bateman & Fleming, 2017; Gallagher & Huveneers, 2018). Rather than relying on observations to assess the impacts of drones on whale sharks, we measured their activity and diving behavior using biotelemetry, that is, "Daily Diary" tags (DDs; www.wildbytetechnologies.com). The DDs collect fine-scale movement data on multiple sensors (including tri-axial accelerometers and magnetometers) at up to 40 Hz, allowing animal movements and behavior to be quantified and defined (Shepard et al., 2008; Wilson et al., 2008). These tags have proven to be a valuable research tool for whale sharks and have provided a wealth of data on diving and movement strategies (Gleiss et al., 2011), locomotory activity and feeding (Gleiss et al., 2013), energy use (Wilson et al., 2022) and the effects of tourism (Reynolds et al., 2025).

Whale sharks can display a number of avoidance behaviors when disturbed or threatened, such as banking (i.e., turning their dorsal surface towards the threat), changing direction, increasing acceleration and diving (Norman, 1999). If the presence of a drone was perceived as a threat, we expected that avoidance behaviors would increase. However, although knowledge of whale shark sight and hearing capabilities is limited (Yopak & Peele, 2022), because whale sharks do not often break the water surface (unlike marine mammals or reptiles), and the noise of drones penetrates poorly into the water at depths below 1 m (Christiansen et al., 2016), we expect there would be little to no effect of drones on the species. Making such an assumption, however, could result in ethical and experimental concerns. Therefore, we tested the hypothesis that there would be no change to the activity levels and/or diving behavior of whale sharks in the presence or absence of drones using objective data collected from biotelemetry, allowing insights into the effects of drones on whale sharks that would not otherwise have been possible.

METHODS

Study area

At Ningaloo Reef in Western Australia (WA), 21°59′57″S, 113°54′33″E, a predictable constellation of whale sharks occurs (Norman, Holmberg, et al., 2017) and supports a lucrative tourism industry (Huveneers et al., 2017) during the austral autumn/winter, although whale sharks are present year-round (Norman, Whitty, et al., 2017; Reynolds et al., 2017). Ningaloo Reef lies within Ningaloo Marine Park (NMP) managed by the WA state government Department of Biodiversity, Conservation and Attractions (DBCA) which is also responsible for regulation and management of the commercial whale shark tourism industry.

Permits and drone regulations

This research was conducted under a Fauna Taking (Scientific or Other Purposes) Licence issued by DBCA (FO25000033-20b) and an Animal Ethics Permit issued by Murdoch University Research and Integrity Office (RW3327/21).

At the time of writing, a permit is required for commercial drone use in WA national parks (including NMP) but not for recreational use. Drone flights must adhere to the safety rules of the Civil Aviation Safety Authority (CASA), which include staying further than 30 m from people and not flying over or above them at any height. The DBCA rules also state that drones "must not disturb wildlife" and must maintain a separation distance of 60 m from whale sharks and marine mammals (Government of Western Australia, 2025); however, there is nothing in the CASA regulations that restricts recreational drone use around wildlife (Civil Aviation Safety Authority, 2025). Permission for our drone flights to approach whale sharks closer than stipulated in these rules was given as part of our permit from DBCA.

Data collection

In May and August 2024 at Ningaloo Reef, 13 whale sharks were tagged with a package that was attached to the first dorsal fin of free-swimming sharks by a researcher snorkeling alongside (Table 1; Figure 1A). The package consisted of a custom-made, spring clamp with a DD and a continuous acoustic transmitter with depth sensor (V16-5H; www.innovasea.com) attached to opposite arms (Figure 1B). Because the DDs archive data and must be retrieved in order to access these, the tagged sharks were actively tracked from a research vessel (at distances >50 m) using a directional hydrophone and an acoustic receiver (VR110 and VH100; www.innovasea.com) that detected transmissions from the acoustic tag on the shark. This allowed constant observation of the tagged sharks so that the timings and heights of drone flights (and other activities that could affect their behavior such as tourism interactions) could be recorded, and the tag package retrieved at the end of each tracking period. Researchers estimated the total length (TL) of tagged sharks to the nearest 0.5 m using boats or swimmers as scale (Sequeira et al., 2016) and checked for the presence or absence of claspers to determine sex. Photographs of tagged sharks were taken and entered in Sharkbook: Wildbook for Whale Sharks (www.sharkbook.ai) to identify individuals (Arzoumanian et al., 2005).

TABLE 1 Information on whale sharks (*Rhincodon typus*) tagged with a Daily Diary behavioral data-logging tag and a continuous acoustic transmitter at Ningaloo Reef, Western Australia, used in this study to assess the effects of drones on whale shark activity and diving behavior.

Date	Shark ID	Estimated TL (m)	Duration of deployment (hours:minutes)	Drone flown with shark	Total no. dives during tag deployment[a]
11/05/2024	A-1927	5.5	2:15	Y	1
23/05/2024	A-380	8	2:18[b]	Y[b]	0[b]
24/05/2024	A-485	9	2:14	Y	6
26/05/2024	A-1929	5	1:59	Y	1
27/05/2024	A-833	5.5	2:01	Y	7
28/05/2024	A-1930	5.5	1:49	Y	NA[c]
14/08/2024	A-718	6	1:11	N	3
16/08/2024	A-1244	6	0:36	Y	0
16/08/2024	A-1964	6.5	1:18	Y	3
17/08/2024	A-1956	7	0:37	Y	0
17/08/2024	A-644	9	1:03	Y	3
19/08/2024	A-666	7.5	1:06	N	2
21/08/2024	A-1963	5	1:04	Y	0

Note: Shark ID established from photographs entered in Sharkbook: Wildbook for Whale Sharks (sharkbook.ai).

Abbreviations: N, no; NA, not applicable; Y, yes.

[a] Excluding first 15 min after tagging.

[b] Tag flooded 30 min after deployment and data when the drone was present were not recorded.

[c] Depth sensor on Daily Diary tag failed; therefore, depth could not be calculated and data were excluded from all analyses.

While sharks were being tracked, a waterproof drone (Swellpro Splashdrone 4, www.swellpro.com; 2.18 kg, 450 mm diameter) was flown directly above the tagged sharks (Figure 1C,D) and their responses were recorded by the DD. Sharks are only visible from the air when they are swimming within ~5 m of the surface, depending on water turbidity, wind, and weather conditions (T. Klein, Ningaloo Aviation, personal communication). Shark tagging and tracking and drone flights were conducted only under favorable weather and sea conditions (Beaufort sea state ≤3), allowing good visibility of whale sharks near the waters' surface. When the tracked shark was near the surface (<5 m depth as confirmed by the depth sensor of the acoustic tag), the drone was launched from a stable platform onboard the research vessel, ascending to a height of 60 m, and flown towards the shark (indicated by the directional hydrophone) until visual contact was made. We hypothesized that the height of the drone above the shark, or the movement of the drone (either ascending or descending) may influence any effect the drone may have on the shark. Therefore, we flew the drone at three different heights above the shark, starting at 60 m, descending to 30 m and then 10 m, and then ascending to 30 m and 60 m again. These altitude changes were repeated until the shark dove or the drone battery ran low and we recorded the time spent at each height and the timing of the drone's descent or ascent between these heights. If the shark dove at any time while the drone was overhead and visual contact was lost, the drone would ascend to 60 m and continue to fly in the direction of travel of the shark (as indicated by the directional hydrophone) until the shark resurfaced and visual contact was re-established. If the shark did not resurface within 5 min or the drone battery ran low, the drone was retrieved, the battery replaced, and the drone relaunched when the depth sensor of the acoustic tag indicated that the shark had returned to the surface.

DD data and metrics

Initial visualization and analyses of the DD data were performed using the customized software Daily Diary Multiple Trace (DDMT) (www.wildbytetechnologies.com) (Wilson et al., 2018). The timings and heights of the drone flights and ascents or descents and periods when the drone was not present were collated from the field observations, imported into DDMT and time-synchronized with the DD data. This allowed data to be labeled as *drone absent* or one of five categories when the drone was present: *drone at 10 m*; *drone at 30 m*; *drone at 60 m*; *drone ascending*; and *drone descending*. Metrics derived from the DD data for each

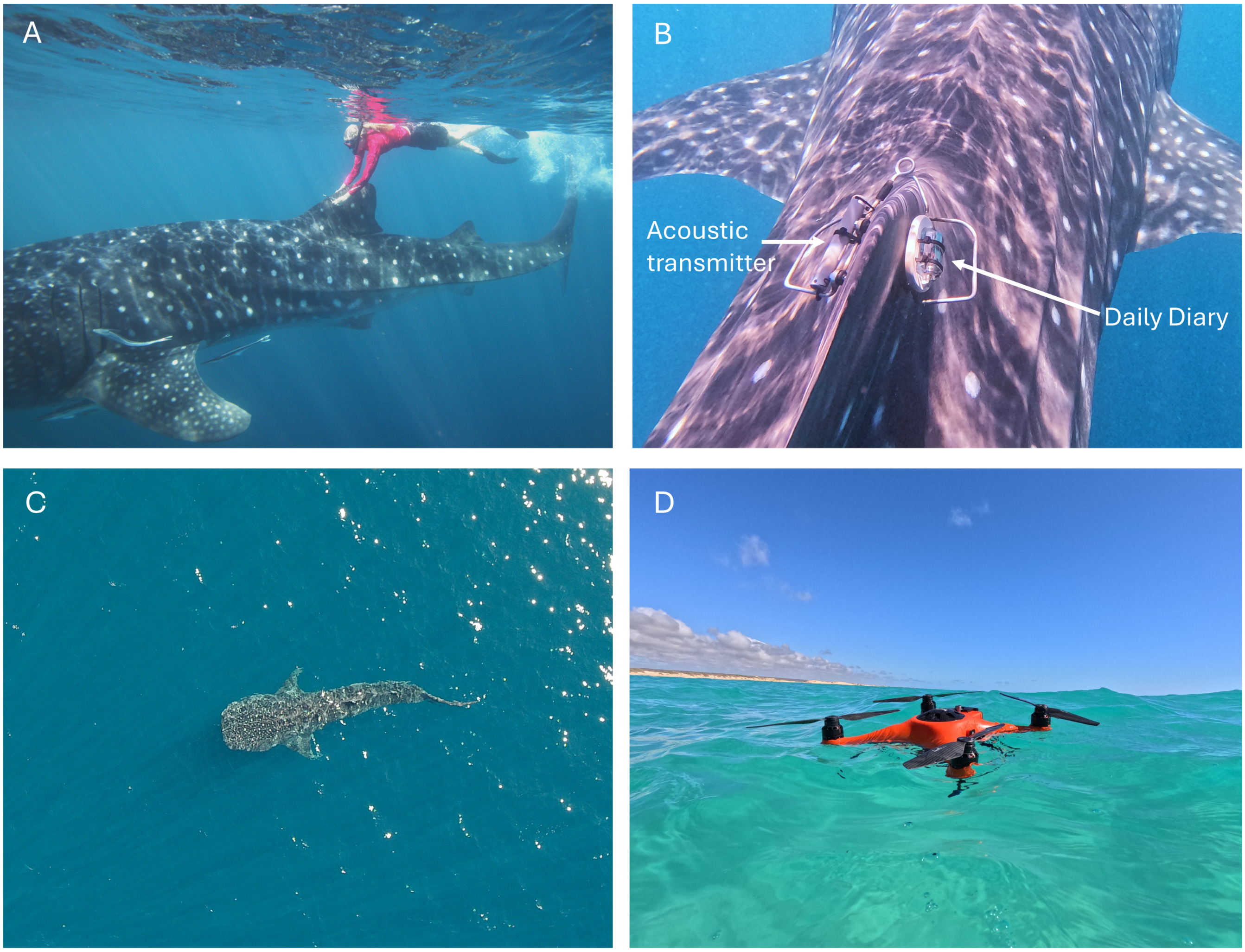

FIGURE 1 (A) Researcher deploying a tag package on the first dorsal fin of a whale shark (*Rhincodon typus*) at Ningaloo Reef, Western Australia. (B) The tag package consists of a Daily Diary behavioral data-logger and a continuous acoustic transmitter. (C) Image of a tagged whale shark taken from (D) the Swellpro Splashdrone 4 that was used as the stimulus to assess the impacts of drones on whale shark activity levels and diving behavior in this study. Photo credits: Valerie Cornet (A, C); Samantha Reynolds (B, D).

deployment were downloaded from DDMT with these labels marked. Periods of time when other activities that could have affected the shark's behavior or activity levels were occurring (e.g., tourism activities (Reynolds et al., 2025), researchers in the water with the shark) were excluded from all analyses. We also excluded the first 15 min of each deployment to minimize the possibility of any effect of deploying the tag on the sharks being reflected in the results (Reynolds et al., 2025). All data with the drone present were necessarily collected when the shark was at the surface. In addition, the metrics recorded by the DD vary depending on whether the shark is swimming at the surface, at depth, ascending or descending (Gleiss et al., 2011; Wilson et al., 2022), and water depth attenuates sounds produced in air by the drone (Christiansen et al., 2016). We therefore only used data from when sharks were shallower than 5 m depth.

Among other data, the DDs recorded magnetometry and accelerometry data at 6 and 20 Hz, respectively, and pressure (used to calculate depth) at 2 Hz on a micro Secure Digital card. We used vectorial dynamic body acceleration (VeDBA) (Qasem et al., 2012) and tail beat frequency (TBF) derived from the DD data as quantitative measures of whale shark activity. VeDBA, calculated as the vector sum of the dynamic components of tri-axial acceleration, is a well-established measure of activity and can be used as a proxy for energy expenditure (Qasem et al., 2012). TBF is also an indicator of activity, with increased frequency and amplitude of tail beats resulting in increased acceleration in sharks.

The number of dives (defined as a descent from the surface to at least 10 m with a subsequent return to the surface) made by each shark while the drone was present or absent was counted in DDMT and the amount of time the drone was present and/or absent with each shark was calculated. We hypothesized that all three metrics would increase in the presence of the drone if whale sharks were disturbed by it because these metrics quantify some of the avoidance behaviors that whale sharks are known to employ when evading disturbance, that is, increasing acceleration and diving (Norman, 1999). These metrics have previously been used to examine the effects of tourism on whale sharks at Ningaloo Reef (Reynolds et al., 2025). VeDBA was calculated in DDMT using the raw, tri-axial accelerometry data (see Shepard et al., 2008). TBF (i.e., the number of oscillations of the tail from side to side per minute) was derived from the tri-axial magnetometry data following the method described by Reynolds et al. (2025).

Data analyses

Data were collated, sub-sampled to 1 Hz and further analyzed in R version 4.4.2 (R Core Team, 2024). To test the effects of drones on whale shark activity, we fitted generalized linear mixed models (GLMMs) using the lme4 package (Bates et al., 2015). Our response variables were VeDBA and TBF, as measures of whale shark activity. Fixed predictor variables were "drone state" (categorical: drone absent; drone at 10 m; drone at 30 m; drone at 60 m; drone ascending; drone descending) and shark TL (in meters), with individual identity (Shark ID) included as a random predictor variable to account for non-independence of repeated measures from each shark. We tested for residual temporal autocorrelation in model residuals using the DHARMa package (Hartig, 2024) and found that median lag-1 autocorrelation values were low and not significant (VeDBA: autocorrelation function [ACF] $= 0.07$; $p = 0.19$; TBF: ACF $= 0.05$; $p = 0.23$), indicating that temporal autocorrelation was minimal after accounting for individual effects.

To test whether whale sharks dove to avoid the drone, we fitted GLMMs using the lme4 package with the number of dives as the response variable. Because data on the number of dives was paired (i.e., a count of how many dives each shark had made with and without the drone present) and the amount of time each shark spent with or without the drone present varied, we used a repeated-measures mixed model with an offset for the duration of time the drone was present or absent for each shark. Again, we fitted models with fixed predictor variables "drone state" (categorical: drone present; drone absent) and shark TL in meters, with individual identity (Shark ID) included as a random predictor variable.

For all three response variables, VeDBA, TBF and number of dives, models that included all predictor variables (and the interaction of drone state and shark TL) as described above were run, followed by models excluding the interaction, and separate models for each fixed predictor variable. Models for VeDBA and number of dives both had a Poisson distribution, TBF models had a gamma distribution, all with a log link, and were chosen based on the type of response data and the normality of residuals in diagnostic plots. Comparisons of Akaike information criterion (AIC) scores (and ΔAIC scores) were made and the model with the lowest AIC score for each response variable was selected as the most parsimonious (Table 2). Means and 95% CI derived from these models are reported, used for plotting and for assessing any differences between factors of the predictor variables.

RESULTS

All 13 DD tags deployed on whale sharks were retrieved on the same day as deployment. Tagged sharks ranged in estimated TL from 5 to 9 m (mean 6.6 m) and deployments lasted between 36 min and 2 h 18 min (mean 1 h 30 min) (Table 1). Deployment times varied because of drone battery life and technical issues, tourism industry operations, weather and other logistical constraints on boating operations. Although all tags were retrieved and data were recovered, because of technical issues with the drone or tags, we had data on sharks' activity levels and diving behavior while the drone was present from 9 deployments and data while the drone was absent from 12 deployments (Table 1).

During drone flights, whale sharks were observed swimming slowly at the surface in relatively straight paths. This is typical behavior of whale sharks at Ningaloo Reef during daylight hours, when the tourism industry operates (Reynolds et al., 2025) and when our tracking took place. Other behaviors, such as active feeding, were not observed.

Model results

For all three response variables, VeDBA, TBF and number of dives, the most parsimonious models were those that included drone state only (drone absent; drone at 10 m; drone at 30 m; drone at 60 m; drone ascending; drone descending) (Table 2). Shark TL and the interaction of TL and drone state were not significant in any models (all p values ≥ 0.29) and were removed from the final models.

Mean VeDBA for each drone state when the drone was present ranged from $0.051g$ (CI $= 0.048$–$0.054g$) for drone descending to $0.053g$ (CI $= 0.050$–$0.056g$) for drone at 10 m. The mean VeDBA when the drone was absent

TABLE 2 Model selection for three response variables derived from Daily Diary behavioral data-logging tags deployed on whale sharks (*Rhincodon typus*) at Ningaloo Reef, Western Australia, and used in this study to assess the effects of drones on whale shark activity (vector sum of the dynamic body acceleration [VeDBA] and tail beat frequency [TBF]) and diving behavior.

Response variable	Model type	Model terms	AIC	ΔAIC
VeDBA	GLMM (Poisson distribution, log link)	VeDBA ~ drone state × TL + (1|Shark ID)	−95,376.0	194.0
		VeDBA ~ drone state + TL + (1|Shark ID)	−95,430.3	139.7
		VeDBA ~ drone state + (1|Shark ID)	**−95,570.0**	**0.0**
TBF	GLMM (Gamma distribution, log link)	TBF ~ drone state × TL + (1|Shark ID)	2182.6	18.4
		TBF ~ drone state + TL + (1|Shark ID)	2196.1	31.9
		TBF ~ drone state + (1|Shark ID)	**2164.2**	**0.0**
Dive frequency	GLMM (Poisson distribution, log link)	Dives ~ drone state × TL + (1|Shark ID)	100.6	39.9
		Dives ~ drone state + TL + (1|Shark ID)	89.0	28.3
		Dives ~ drone state + (1|Shark ID)	**60.7**	**0.0**

Note: Models were compared using Akaike information criterion (AIC). Rows with boldface text indicate the most parsimonious models using a criterion of lowest AIC score (with delta AICs [ΔAIC] of ≥2). Models included drone state (categorical: drone absent; drone at 10 m; drone at 30 m; drone at 60 m; drone ascending; drone descending for VeDBA and TBF; and drone present vs. drone absent for Dive frequency) and shark total length (TL in meters) as fixed predictor variables. The identity of each shark (Shark ID) was included as a random effect in all models. Models for Dive frequency included an offset for the duration of time the drone was present with or absent from the sharks.
Abbreviation: GLMM, generalized linear mixed model.

was 0.051*g* (CI = 0.049–0.054*g*), and all *p* values were ≥0.11, providing no evidence that the presence or movement of the drone significantly increased sharks' VeDBA (Figure 2A).

Similarly, there was no evidence that the presence of the drone (at any height or its ascent or descent) significantly increased sharks' TBF compared to when the drone was absent (all *p* values ≥0.31). Mean TBF for sharks when the drone was absent was 6.23 (CI = 4.62–8.41), and for drone states when the drone was present, ranged from 6.51 (CI = 5.18–8.71) for drone descending to 7.32 (CI = 5.29–10.12) for drone at 10 m (Figure 2B).

Data from the DDs showed variable diving patterns of the 12 tagged sharks for which we had depth data. The numbers of dives sharks made over the total duration of their tracking (excluding the 15 min post tagging period) ranged from 0 to 7 (mean 2.2) or from 0 to 3.47 dives h^{-1} (mean 1.39 h^{-1}) (Table 1). On average, the rate at which sharks dove when the drone was present (0.75 dives h^{-1}; CI = 0.31–1.80) did not vary significantly compared to when it was absent (1.25 dives h^{-1}; CI = 0.63–2.49) ($p = 0.15$) (Figure 2C).

DISCUSSION

This study was the first to use biotelemetric data to assess the effects of drones on the natural behavior of a water-breathing marine species. Biotelemetry tags allow high-resolution data to be gathered remotely, removing the potential subjectivity of observers and/or the unintended influence on animal behavior that can occur in observational studies, and provide objective data with which to assess disturbance in animals (Grainger et al., 2022). As we hypothesized, there was no significant increase in the activity levels (measured as VeDBA and TBF) or diving frequency of whale sharks when the drone was present compared to when the drone was absent. The effects of drones vary considerably between species and taxa, although the effects on water-breathing animals are understudied (Mo & Bonatakis, 2021). Our work provides insights into the responses of whale sharks and joins growing evidence that drones have negligible impacts on water-breathing animals relative to marine mammals (or terrestrial animals and birds) because of their differing visual and auditory capabilities and lack of surfacing (Mo & Bonatakis, 2021; Raoult et al., 2020).

Drone altitude, approach distance, and noise levels can have significant impacts on the responses of animals to drones (Afridi et al., 2025; Mo & Bonatakis, 2022). Our findings that the proximity of the drone (height above the whale shark) and/or its movement (ascending or descending above the shark) did not influence the sharks' activity levels (Figure 2A,B) may indicate that sharks could not perceive the drone. Even when the drone was at only 10 m above the water's surface, or ascending or descending, sharks' mean VeDBA and TBF did not increase significantly compared to when the drone was absent. The noise produced by a Splashdrone was previously tested at Ningaloo Reef and showed a ~40 dB

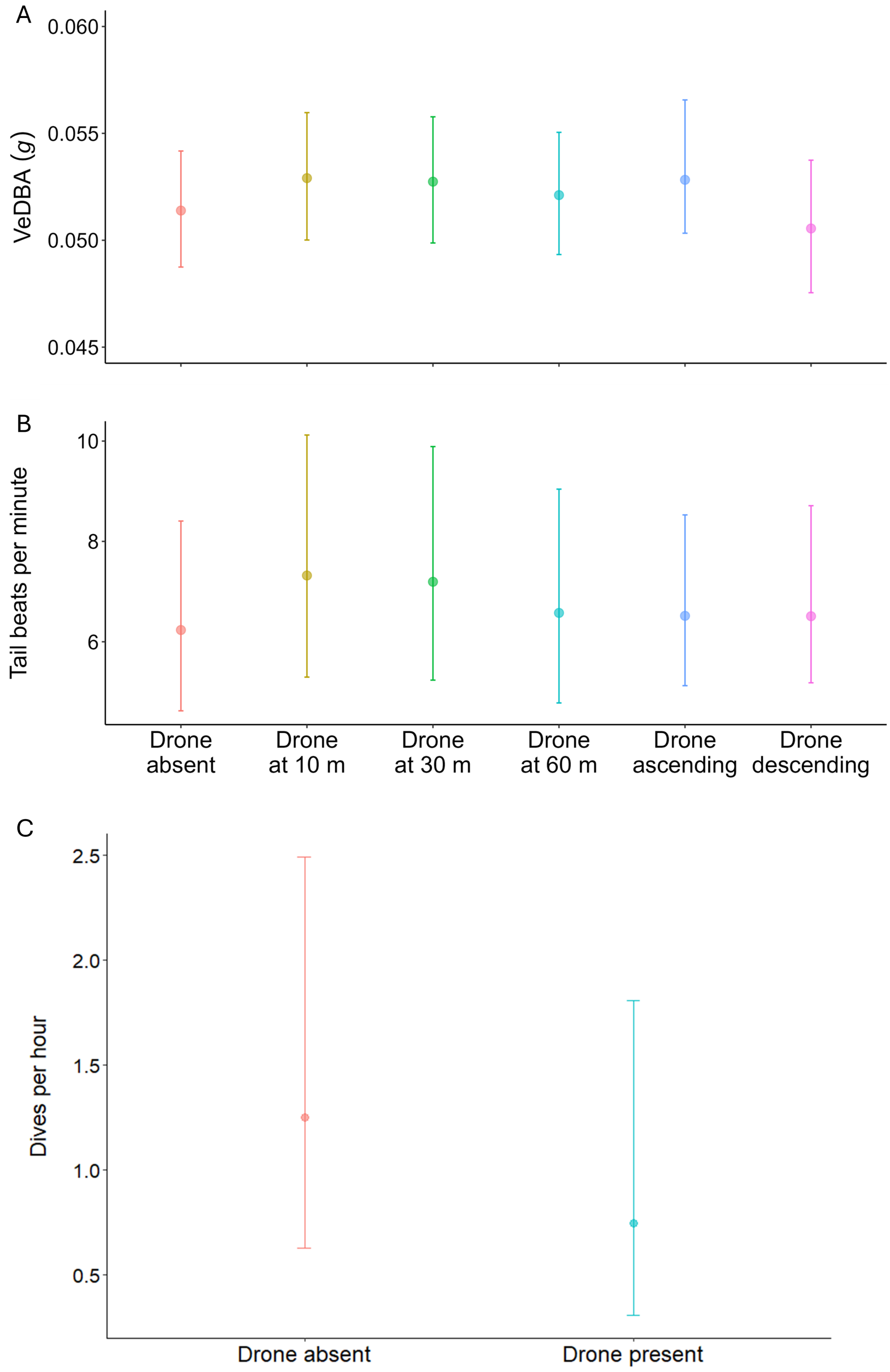

FIGURE 2 Results from generalized linear mixed models (GLMMs) investigating the effects of drones on whale shark (*Rhincodon typus*) activity, as measured by (A) the vector sum of the dynamic body acceleration (VeDBA [*g*]) and (B) tail beat frequency, and (C) diving behavior. Circles and error bars represent the means and 95% CIs derived from the GLMMs.

reduction across the air–water interface, which could not be distinguished above ambient noise at 1 m depth when the drone was flown at ≥10 m altitude (Christiansen et al., 2016). Day-time reef noise at a shallow coral reef in French Polynesia was measured at ~127 ± 0.9 dB re 1 μPa (Raick et al., 2021), likely comparable to

Ningaloo Reef. The Splashdrone tested by Christiansen et al. (2016) produced noise levels less than this: ~95 dB re 1 μPa at a depth of 1 m. The model of the Splashdrone tested in that study was not specified, but weight and diameter were reported as 2.3 kg and 500 mm, respectively, slightly larger and heavier than the Splashdrone 4 used in our study (2.18 kg, 450 mm diameter), but likely comparable in terms of noise emissions. Given that the noise of the drone attenuates with depth (Christiansen et al., 2016; Laute et al., 2023) and falls below ambient levels at depths >1 m (Christiansen et al., 2016), and whale sharks usually swim at least the depth of their first dorsal fin below the surface (which in captive whale sharks of ~6–8 m TL have been measured at ~0.45–0.60 m [R. Matsumoto, Okinawa Churaumi Aquarium, personal communication]), the noise heard by whale sharks is likely minimal. However, although whale sharks possess the largest ear canal of all animals, suggesting possible enhanced hearing sensitivity (Muller, 1999; Myrberg, 2001), little is known about the auditory capabilities of the species (Yopak & Peele, 2022), and it is unclear whether they could perceive the drone via auditory cues.

An alternative way the drone may be perceived by whale sharks is through sight, which is thought to be poor (Yopak & Peele, 2022). Although the drone was bright orange in color, whale sharks may not be able to distinguish colors (Hart et al., 2011), and the drone's size and height above the sharks (≥10 m) may have precluded it being seen. Because of their size, whale sharks have no natural aerial predators, so they may not have evolved senses for detecting and reacting to such threats. Comparable aerial stimulus in nature could come from seabirds that may feed on the same aggregating prey as whale sharks but pose no threat to them. Even if the sharks could detect the drone through acoustic, visual, or other means, it is unlikely that it would be perceived as a threat.

Diving is a recognized avoidance behavior in whale sharks and has been used to assess disturbance, particularly due to tourism interactions (Haskell et al., 2014; Norman, 1999; Quiros, 2007; Reynolds et al., 2025). If whale sharks were disturbed by the presence of the drone, we would have expected them to display their typical reaction to a disturbance at the surface and dive away from the source. That there was no statistically significant change in the diving rate of whale sharks when the drone was present or absent (Figure 2C) indicates a lack of detectable reaction to the drone. Interestingly, whale sharks make fewer dives on days when they are subject to tourism operations than on days when they are not, although their diving behavior appears highly variable with some sharks remaining at depth for at least 4 h and others spending high proportions of their time at the surface (Reynolds et al., 2025). Sharks in our study also showed variation in their diving behavior with four of them never diving during our tracking and two sharks making six and seven dives, respectively. Whale sharks are negatively buoyant and therefore must actively swim to stay at the surface. They use their negative buoyancy to glide during diving, helping them to save energy (Gleiss et al., 2011) and diving may also be used to search for prey (Gleiss et al., 2013) or to thermoregulate (Thums et al., 2013). It appears that whale sharks move up and down the water column for a variety of reasons and were not influenced by the presence or movement of the drone.

The whale shark tourism industry at Ningaloo Reef consists of 15 commercial vessels that are licenced by the WA government to operate whale shark tours. They use piloted light aircraft to locate sharks for their customers to swim with. Drones are increasingly being used recreationally in the area and offer an alternative way for individuals to locate whale sharks without having to join a commercial tour (personal observation) which, as of 2025, costs more than AUD 500 per adult (A. Moir, Three Islands Whale Shark Dive, personal communication). It is currently impractical for tour operators to use drones to locate sharks; however, with advances in drone technology, such as improved battery life, visualization, and communications range, this may become a viable, cost-effective option in the future. This has implications for the operations of the tourism industry and the management of it and NMP by the WA government.

NMP is also home to many other species, including marine mammals, reptiles, and seabirds, which are prone to disturbance by drones (Bevan et al., 2018; Giles et al., 2021; Mo & Bonatakis, 2021; Raoult et al., 2020; Weimerskirch et al., 2018). Although whale sharks may not be significantly affected by drones, management regulations and research involving drones should consider the potential impacts on other species. Regulations governing drone use in NMP state that drones "must not disturb wildlife"; however, they also acknowledge that disturbance "might not be immediately obvious" (Government of Western Australia, 2025). In the absence of targeted research that clarifies species-specific responses to drone activity, it remains challenging for users to comply with these regulations and for managers to enforce them effectively. Biotelemetry tools, such as the DDs, offer a promising means to detect disturbance responses that are not visible through conventional observation. These tools could be used across marine, terrestrial, and aerial taxa, facilitating multispecies comparisons and contributing valuable insights to inform management and conservation strategies (Afridi et al., 2025). Further research on species inhabiting NMP is warranted.

The fact that we found no effect of drones on whale shark activity and diving behavior during their typical surface swimming provides confidence to researchers wishing to use drones as a minimally invasive research tool for whale sharks, and potentially other water-breathing species. However, we were unable to test the effects of drones on other whale shark behaviors such as foraging and indeed, a lack of behavioral disturbance does not preclude physiological effects. Stress responses to drones have been found to occur in some species even though no visible changes in behavior indicating disturbance were observed (e.g., American black bears, *Ursus americanus* (Ditmer et al., 2015), and king penguins, *Aptenodytes patagonicus* (Weimerskirch et al., 2018)). Wildlife research is typically conducted with the intention of benefiting the study species and therefore should strive to use minimally invasive methods. There may be effects on whale sharks that we were unable to record with the DDs or that cannot be discerned from observations, and it is possible that drones may have effects on whale shark behaviors in which sharks in our study were not engaged. We therefore advocate further research to increase sample size and test the effects of drones on different behaviors. We encourage a precautionary approach to drone use, and suggest that flights should be conducted at the highest altitude and greatest horizontal distance possible (depending on the research aims) (Laute et al., 2023) to minimize the potential for currently undetectable impacts on animal physiology and welfare (Duporge et al., 2021).

CONCLUSIONS

Before using drones for wildlife research, especially if the aim is to assess or quantify “natural behavior,” it is imperative that the effect of the drones themselves is quantified in order to understand any confounding effects they may have. Our study found no evidence of an effect of drones on whale sharks’ activity levels or diving behavior when the drone was flown at or above 10 m altitude. When used appropriately and considering the potential effects on non-target species, drones are an effective, minimally invasive platform to use in whale shark research and could provide a wealth of information on morphometrics, local-scale movements, and behavior.

With the proliferation of drone use around wildlife for research, commercial and recreational purposes, and the development and implementation of laws and regulations not keeping pace, our study highlights the utility of biotelemetry for objectively assessing the effects of drones and provides a method that could be applied to a wide range of species. This would facilitate comparisons both within and among species and assist with the management and regulation of drone use with wildlife.

AUTHOR CONTRIBUTIONS

Samantha D. Reynolds, Bradley M. Norman, and Rory P. Wilson conceived the ideas. Samantha D. Reynolds, Bradley M. Norman, Rory P. Wilson, Valerie J. Cornet, and Vincent Raoult designed the methodology. Samantha D. Reynolds, Bradley M. Norman, and Valerie J. Cornet collected the data. Samantha D. Reynolds, James Redcliffe, and Mark Holton analyzed the data. Rory P. Wilson and Mark Holton provided hardware and software. Samantha D. Reynolds led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Reynolds et al., 2026) are available from Figshare: https://doi.org/10.6084/m9.figshare.31025743.

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