Article

Determining Stingray Movement Patterns in a Wave-Swept Coastal Zone Using a Blimp for Continuous Aerial Video Surveillance

David Ruiz-García [1,2,*], Kye Adams [2,3], Heidi Brown [2] and Andrew R. Davis [2]

[1]   Marine Zoology Unit, Cavanilles Institute of Biodiversity and Evolutionary Biology, Universitat de València, 46980 València, Spain

[2]   School of Earth, Atmospheric and Life Sciences, University of Wollongong, Northfields Avenue, Wollongong NSW 2522, Australia; kye.adams@uwa.edu.au (K.A.); heidi@uow.edu.au (H.B.); adavis@uow.edu.au (A.R.D.)

[3]   Marine Ecology Group–Fisheries Research, University of Western Australia, Perth WA 6009, Australia

*   Correspondence: daruiz7@alumni.uv.es

check for updates

Abstract: Stingrays play a key role in the regulation of nearshore ecosystems. However, their movement ecology in high-energy surf areas remains largely unknown due to the notorious difficulties in conducting research in these environments. Using a blimp as an aerial platform for video surveillance, we overcame some of the limitations of other tracking methods, such as the use of tags and drones. This novel technology offered near-continuous coverage to characterise the fine-scale movements of stingrays in a surf area in Kiama, Australia, without any invasive procedures. A total of 98 stingray tracks were recorded, providing 6 h 27 min of movement paths. The tracking data suggest that stingrays may use a depth gradient located in the sandflat area of the bay for orientating their movements and transiting between locations within their home range. Our research also indicates that stingray behaviour was influenced by diel periods and tidal states. We observed a higher stingray occurrence during the afternoon, potentially related to foraging and anti-predatory strategies. We also saw a reduced route fidelity during low tide, when the bathymetric reference was less accessible due to stranding risk. Considering the increasing threat of anthropogenic development to nearshore coastal environments, the identification of these patterns can better inform the management and mitigation of threats.

Keywords: aerostat; UAV; blimp; spatial ecology; behaviour; batoid; high-energy coastal zone; *Bathytoshia brevicaudata*; *Bathytoshia lata*

1. Introduction

Stingrays (Dasyatidae) play a key role in the regulation of nearshore coastal ecosystems as bioturbators and mesopredators [1,2]. They create physical disturbances by digging holes in unconsolidated sediments to feed on infaunal invertebrates. In turn, they generate a mosaic of microhabitats with a distinct invertebrate diversity and abundance, acting as ecosystem engineers [3,4]. Such digging behaviour also enables the infiltration of oxygen and organic matter into sediments, supporting biogeochemical cycling [3]. These epibenthic mesopredators also play an important role by connecting trophic webs across habitats and controlling prey populations through predation [1,2,5]. However, stingrays represent one of the most threatened families of elasmobranchs [6]. They have low resilience against anthropogenic pressure because of their life-history traits, including slow growth, late maturity, and low fecundity [7]. Habitat destruction due to coastal development is an increasing threat affecting stingrays by compromising the viability of

coastal ecosystems [8]. Therefore, identifying important habitats and habitat use by stingrays is essential for their management and the mitigation of threats [9–11].

A common approach to identifying animal space usage and habitat requirements is to study their patterns of movement [12,13]. Understanding their spatial ecology sheds light on animals' life history, behaviour, and the influence of environmental conditions over their use of space [14,15]. Tracking animal movements in aquatic habitats can be challenging [16]. Recent improvements in acoustic and satellite telemetry have provided new insights into stingray behaviour and habitat use in coastal areas, including the identification of a variety of environmental factors such as tides and diel periods as drivers of their behaviour [9,17–19]. However, the fine-scale movement patterns of stingrays in nearshore surf zones are still poorly understood. This lack of information is partly due to technological difficulties when conducting research in these areas. Approaches such as acoustic telemetry are complicated by the high-energy dynamics that characterise surf zones, hampering acoustic signal detection [20,21]. In addition, the bottom-dwelling habits of stingrays hinder the use of GPS loggers, requiring a towed-float GPS tag which is only useful if the studied animals remain in shallow waters permanently [22]. Even when the use of tags is possible for studying fine-scale movement patterns, they can be prohibitively expensive and require invasive procedures to capture and tag the animals [23]. Furthermore, tagging technologies are unable to provide a complete understanding of animal behaviour, deducing it from position records which are often affected by the drift of dead reckoning data [24,25]. Thus, even though tracking marine animals via tags has been the norm in the last few years, new techniques are required to gain insight into animal habitat use in wave-swept coastal areas [26].

Aerial video surveillance is an emerging technique with great potential to provide behavioural information in high-energy coastal zones [23,27]. Unlike tagging methods, this non-invasive technique gathers continuous and direct information about animal locations and interactions [28,29]. Moreover, aerial video surveillance is relatively cost-effective given that, besides scientific staff, it only requires a platform to keep a camera suspended in the air [27]. Despite the potential environmental limitations related to light, wind, and water clarity conditions, this technique can provide access to areas where other tracking methods are unsuitable, even when they are remote or dangerous to access [27,28]. The use of this technique for gathering information on megafaunal habitat usage and spatial ecology in coastal zones promises to contribute significantly to improving the understanding and management of these ecosystems [29–31].

Recently, unmanned aerial vehicles (UAVs), also known as drones, have been used as a platform for suspending cameras. The application of drones in marine research constitutes a new approach for obtaining population estimates and study ecological interactions [23,28]. However, drones are noisy and may influence animal behaviour when in close proximity [32,33]. Another major limitation of drones is their battery life, which averages 30 min and constrains their observational capabilities, particularly if continuous surveillance is required [23,34]. Furthermore, researchers need to simultaneously operate the drone and monitor the field of view, which requires experience and can induce fatigue [34]. Aerostats (balloons or blimps) may constitute a more suitable aerial platform for particular cases by overcoming some of the limitations of drones [27]. Aerostats differ from drones by using helium for lift, offering a near-continuous coverage of study areas since they are only limited by the battery of the camera, which can exceed 8 h. In addition, they are silent, reducing potential impacts on wildlife [27]. Aerostats have been used for monitoring the occurrence of marine wildlife, including whales [35]; dugongs [36]; sharks [37]; and, complimentarily to the present study, seals, sharks, and stingrays [27], although no movement patterns have been analysed.

This case study aims to determine how stingrays use high-energy surf areas, while testing the capability of a blimp as an aerial platform for the continuous surveillance of wildlife movement ecology. Our focus was on determining the effect of diel periods and tidal stages on the occurrence of stingrays and their patterns of movement in the nearshore zone. We also sought to explore how stingrays behave when in close proximity to people.

2. Results

2.1. Stingray Occurence

In total, 16 aerial surveys were completed with a mean flight time of 4 h 16 min ± 15 min and a total elapsed time of 68 h 32 min. Stingrays, either smooth stingray, *Bathytoshia brevicaudata*, or black stingray, *Bathytoshia lata*, were observed on 98 occasions, from which 6 h 27 min of movement paths were retrieved (9.6% of the total recorded time). Low numbers of other marine megafauna were also recorded, including grey nurse sharks, *Carcharias taurus*, and Australian fur seals, *Arctocephalus pusillus doriferus*, and these have been reported by Adams et al. [27].

The occurrence of stingrays within the bay was significantly affected by the diel period (χ^2 = 10.78; df = 1; p = 0.001) but not by the tidal phase (χ^2 = 0.03; df = 1; p = 0.87). The number of stingray sightings was significantly higher than expected in the afternoon, whereas it was lower than expected during the midday time period (Figure 1).
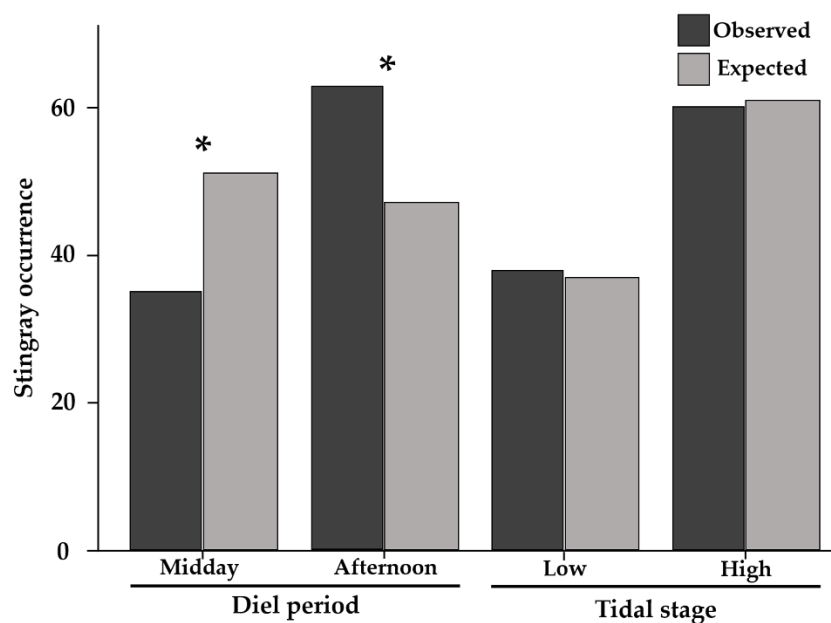

Figure 1. Comparison between the observed (black bars) and expected (grey bars) number of stingray sightings within the study area for each diel period and the tidal stage (n_t = 98). Significant differences (p < 0.05) in Chi-Square tests of independence are denoted by *.

2.2. Patterns of Movement

In 85 of the observations (87%), stingrays did not swim close to bathers (>5 m), but on 13 occasions stingrays swam in close proximity to them (<5 m). On five of these occasions (38%), stingrays showed behaviours that appeared to be influenced by the presence of humans. In order to classify such behaviour, the movement paths of these five sightings were analysed separately to the other 93 paths.

2.2.1. Movement Metrics

The mean duration of the tracking period for the 93 movements paths was 3 min 42 s ± 16 s (range 50 s–14 min 30 s), with an average distance of 144 ± 9 m (range 48–431 m) covered by each stingray and a mean swimming speed of 0.70 ± 0.02 m/s (range 0.33–1.42 m/s). The average path length and the duration of the tracking period for each stingray was significantly larger in the midday time period than in the afternoon (Z = −2.98; p = 0.003 and Z = −3.47; p = 0.001, respectively; Figure 2). In contrast, the tidal state did not have a significant effect on the path length (Z = −1.12; p = 0.264) or duration (Z = −1.86; p = 0.062), although we note a trend toward a longer path duration during high tide

(Figure 2). Stingrays also swam more rapidly in the afternoon and at low tide, although in neither case was this trend statistically significant (Z = −1.75, p = 0.081 and −1.71; p = 0.086 respectively; Figure 2).
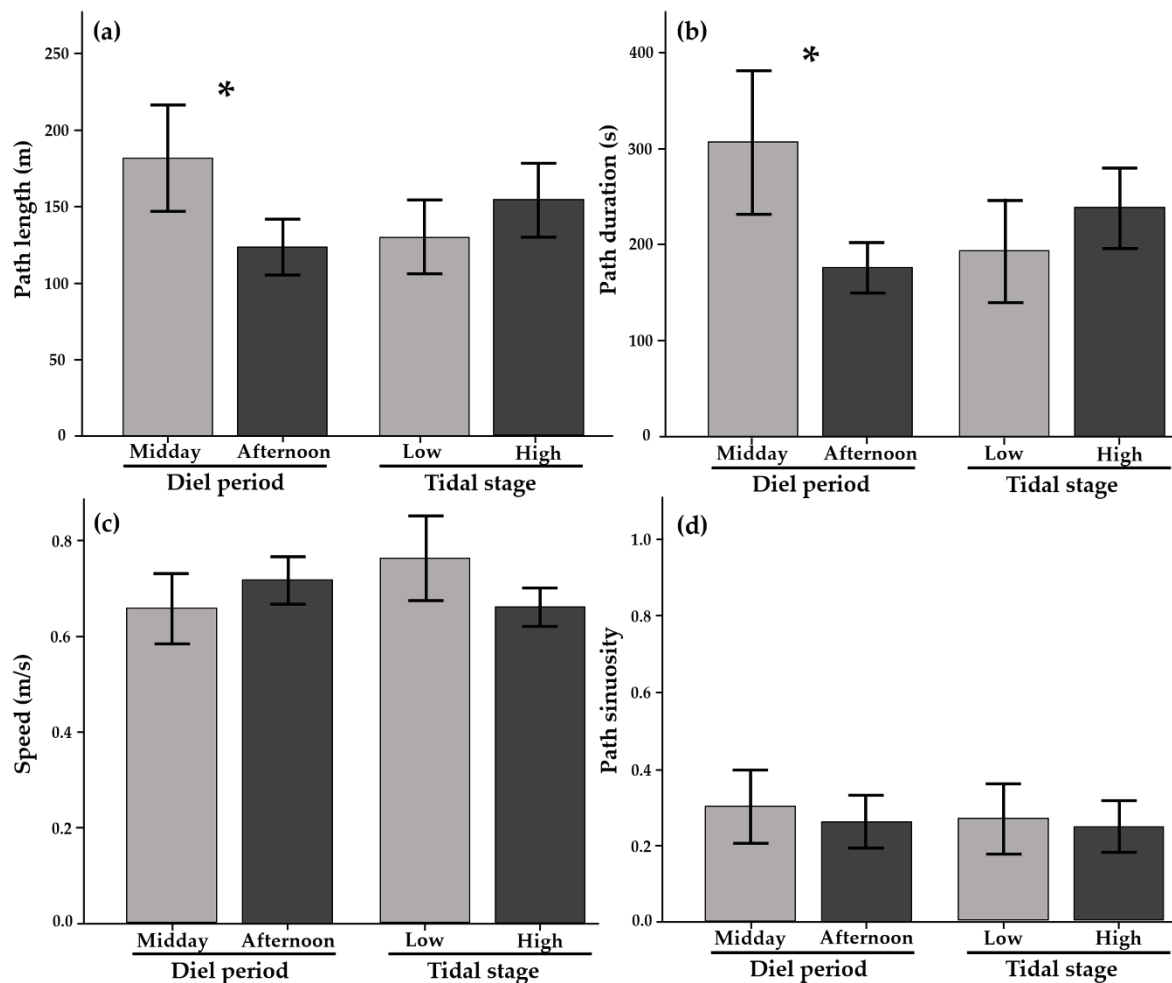

Figure 2. Comparison between the mean (±SE) (**a**) path length, (**b**) duration, (**c**) speed, and (**d**) sinuosity for each diel period and tidal state (n_t = 93). Significant differences ($p < 0.05$) in the Mann–Whitney–Wilcoxon tests are denoted by *.

On average, stingrays showed fairly low sinuosity movement paths across the bay (0.26 ± 0.03), which were consistent through diel periods (Z = −1.18; p = 0.238) and tidal states (Z = −0.247; p = 0.805) (Figure 2). However, there was variation in their path sinuosity with the structure of the habitat; animals showed a significantly more sinuous path at the northern headland than when they swam in the central area or southern headland (0.34 ± 0.04; 0.26 ± 0.03; 0.24 ± 0.04, respectively) (χ^2 = 6.53; df = 2; p = 0.038). Large quantities of drift algae were often associated with the northern headland.

2.2.2. Route Fidelity

Analysis of the 93 stingray movement paths revealed that these animals were using defined routes when navigating across the bay. This route, as shown by the maximum stingray density (Figure 3a), follows the edge of an abrupt change in bathymetry—a sandbar drop-off. A more detailed examination of each movement path revealed that in 87% of the sightings (81/93) the stingrays navigated unidirectionally either northwards or southwards following this defined route. Only in 13% of the occasions (12/93) the stingrays arrived at the bay through either of the rocky headlands, circled around, and left through this same area, without entering the central, sandflat area. The subdivision of path density by tidal state revealed that the stingray activity was more dispersed and the route fidelity was

lower at low tide relative to high tide (Figure 3b,c). In contrast, the route fidelity appeared unaffected by the time of day (Figure 3d,e).
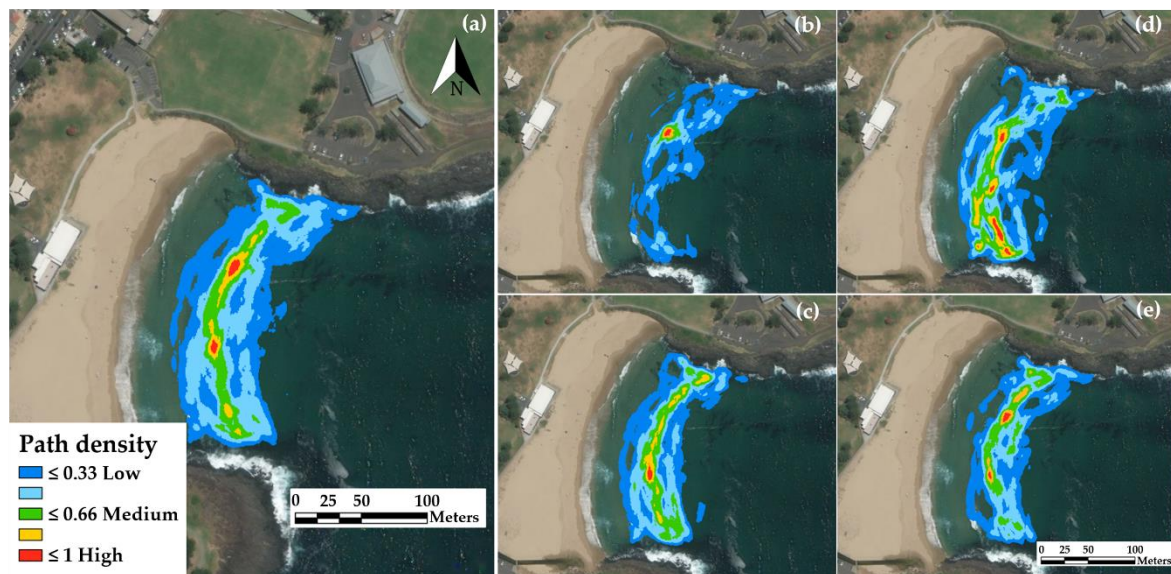

Figure 3. Density heat maps drawn from (**a**) the complete pool of stingray movement paths ($n = 93$); (**b**) from those paths occurring during low tide ($n = 34$), (**c**) high tide ($n = 59$), (**d**) midday ($n = 32$), and (**e**) afternoon ($n = 61$).

2.3. Human Influence on Stingray Movement Paths

The co-occurrence of stingrays and humans in close proximity (<5 m) was recorded a total of 13 times. On five of these occasions (38%), it occurred when stingrays swam into the shallower region of the central area—the designated "bather area", which is delineated by flags and patrolled by lifeguards. On each occasion, these stingrays conducted highly sinuous and long movement paths at a slow pace, a strikingly different pattern to their normal behaviour (Figure 4). On the remaining eight occasions (62%) in which stingrays were in close proximity, the swimmers were in deeper regions outside the bather area. Hence, the bathers were in lower abundance and the stingrays could swim below them. On these occasions, we did not observe the same behavioural responses as were observed in shallow water.
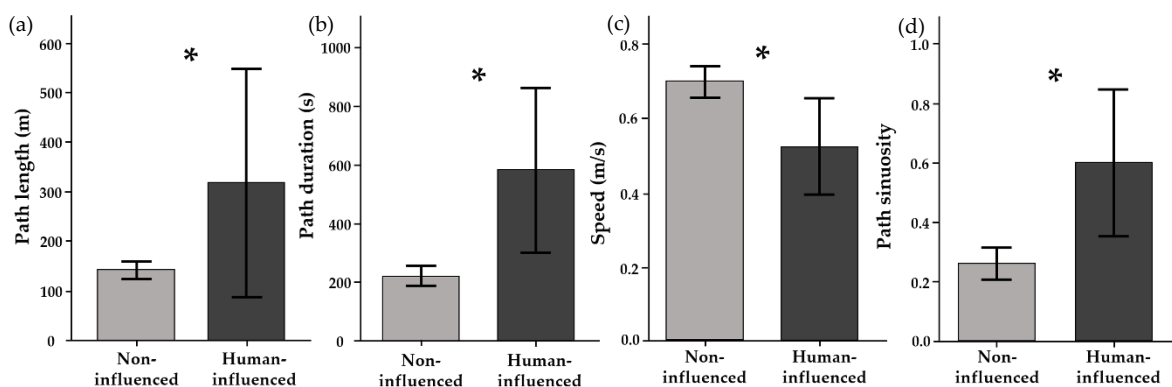

Figure 4. Comparison between the mean (±SE) (**a**) path length, (**b**) duration, (**c**) speed, and (**d**) sinuosity for stingray movement paths non-influenced ($n = 93$) and those influenced by humans ($n = 5$). Significant differences ($p < 0.05$) in Mann–Whitney–Wilcoxon tests are denoted by *.

3. Discussion

This is the first time that an aerostat, particularly a blimp, has been used as an aerial platform to study the fine-scale movement patterns of marine wildlife. Although there are some sampling limitations (e.g., dependency on light, weather, and water conditions), this novel approach enabled the continuous aerial video surveillance of a high-energy surf zone. The results of these prolonged surveys demonstrated that stingrays generally reached the studied bay through the lateral rocky headlands and exhibited an oriented pattern of displacement parallel to shore, but never exhibited stationary behaviours. Stingrays appeared to be following a 2 m depth contour when navigating across the bay from either of the rocky headlands. Acoustic telemetry studies of the southern stingray, *Hypanus americanus*, in the Mesoamerican Barrier Reef System suggested that these animals may also use depth contours for orientation [38]. Therefore, the use of spatially structured depth gradients may be a common strategy in stingrays to orientate their movements. Straight movement paths increase efficiency [39] and likely reflect directed movement towards certain locations, such as sheltering or feeding areas [38,40].

Oriented movements frequently involve experiential learning and memory, potentially increasing foraging efficiency [38,41] and reducing predation risk [42,43]. The stingrays in our study generally exhibited straight movements even at fine spatial scales, except when swimming in the northern headland, where the sinuosity increased significantly. Sinuous movement has been related to searching behaviours in other stingray species and demersal elasmobranchs—with animals seeking to locate resource patches, including foraging opportunities, shelter, or potential mates [19,44–46]. Our findings are consistent with stingrays using the central, sandflat area of the bay for transiting between locations in their home range and the northern headland for exploring resource patches.

Despite the general patterns we observed, some variation in habitat usage was detected during the diel periods and tidal states. The occurrence of stingrays within the bay was higher during the afternoon, when the light intensity began to decrease. In addition, the paths undertaken by stingrays during this period were faster and shorter, exhibiting a high route fidelity by following the edge of the depth contour. Increases in activity with reduced light intensity, especially at night, have been reported in other stingray species and have been attributed to the animals responding to local environmental factors, such as predation risk and prey availability [18,20,38,47,48]. Indeed, a higher use of shallower areas during the night has been observed for one of our target species, *Bathytoshia brevicaudata,* using pop-up satellite archival tags [17]. The authors suggested that this species may conduct diel vertical migrations from deep (>100 m deep) to shallow (<1 m deep) waters as a strategy to increase their feeding opportunities, remarking that it is unlikely that the predation risk had an influence on such movement patterns [17]. However, recent studies in southern Australia suggested that the presence of potential predators such as white sharks, *Carcharodon carcharias,* triggers a change in habitat use and the rate of movement of *B. brevicaudata* [49]. Clearly, the inability to determine nocturnal patterns of movement is a limitation of aerial video surveillance, but our results may indicate that the increased occurrence of stingrays and the shorter and faster movement paths that they undertook may be related to an increase in activity with decreasing light intensity, using the bathymetric gradient to quickly transit along their home range.

Variation in route fidelity was also observed in relation to tidal periods, with animals exhibiting lower route fidelity and slower rates of transit during low tide. We contend that, during low tide, the bathymetric reference was closer to shore and its use increased the risk of stranding for these large stingray species, likely triggering the observed behavioural change. Prior studies on other stingray species also documented that when water levels drop, individuals use deeper areas to transit and avoid stranding [9,18,19]. Previous research also suggested that some stingray species modulate their feeding and shelter behaviour in relation to tides, using the increased available area during high tide to forage while seeking refugia during low tide [18,20,50]. However, our results do not indicate that stingrays modulate their feeding or sheltering behaviour in the study area with tides.

A marked change in behaviour was observed when stingrays entered the bathing area and swam in close proximity to humans. This included long and highly sinuous paths in which the stingrays swam at a slow speed. The animals frequently made loops around humans; swimming next to them (≤1 m distance) for an extended period (≥1 min in all cases). This pattern was observed in five independent sightings and occurred on four separate days; it was noteworthy that on one occasion two stingrays interacted simultaneously with humans within the bather area. Prior research has reported that these interactions are frequent in areas nearby fish-cleaning facilities [51,52]. Such facilities are built at many Australian harbours and beaches to support recreational fishing, resulting in fish scraps being thrown into the water on a daily basis, providing food to stingrays and other scavengers, potentially altering their normal foraging behaviours [52,53]. There is evidence that both *Bathytoshia brevicaudata* and *Bathytoshia lata* frequent fish-cleaning stations, exhibiting grouping behaviours and altered patterns of movement, including a high dependence on fishers and human tolerance [51,52]. A boat ramp in the nearby Kiama Harbour includes a fish-cleaning station approximately 1 km away from our study location, and large stingrays have been observed scavenging on fish scraps there [54]. Considering that *Bathytoshia brevicaudata* have home ranges of approximately 25 km^2 [17], the stingrays that inhabit Kiama Harbour boat ramp may be the same stingrays that are seen in Kiama Surf Beach. It remains unclear whether human supplementation of food or animals being simply inquisitive accounts for the unusual behaviour of some animals in close proximity to humans.

The present study demonstrated that using a blimp as an aerial platform for continuous video surveillance constitutes a powerful approach for the study of fine-scale patterns of movement. Aerial surveillance is also an excellent platform to examine the behaviour of marine wildlife without requiring invasive procedures and minimising sampling disturbance. Moreover, this novel technology enabled easy access to high-energy environments where other techniques may be unsuitable, enhancing the value of this emerging tool for the research discipline of marine spatial ecology. We also provided new insights into stingray behaviour in surf areas, which likely apply broadly to other beaches. We provide support for previous research that has documented the influence of diel periods and tidal states in stingray behaviour [9,18,19,48]. Importantly, our research suggests that stingrays may use near-shore depth contours to orientate their movements when transiting through their home range. Given the increasing direct and indirect anthropogenic pressure upon coastal habitats [8], improving our understanding of habitat usage for these megafaunal ecosystem engineers is an important outcome. Looking to the future, the application of machine learning techniques to aerial surveillance promises to improve our understanding of megafauna in wave-swept environments even further [55].

4. Materials and Methods

4.1. Study Area

Aerial surveys were conducted during December 2017 and January 2018 at Surf Beach in Kiama, located in New South Wales, Australia (34° 40′ S; 150° 51′ E; Figure 5). This coastal embayment is enclosed by two rocky headlands. The morphology of this beach accords with a "low tide terrace" [56], characterised by a moderately steep drop-off joined to a shallow terrace composed of fine and coarse sand. At this site, the terrace stretches out, reaching a maximum depth of 1.5 m at approximately 30 m offshore during low tide and 50 m during high tide, where a 2 m-deep "drop-off" occurs. The depth continues to increase progressively until it reaches 7 m deep 300 m offshore. The study area experiences a semidiurnal tide, with a maximum tidal range of 2 m and a wave height ranging from 0.5 to 1.5 m during the surveys. Topographical rips occur adjacent to the lateral rocky headlands, fed by an inshore current whose direction varies with the wind and swell direction. Both topographic rips scour sand and generate a depressed channel approximately 2 m deep, extending offshore from the headlands. Since summer winds are primarily from the northeast, drift algae tend to accumulate in the north end of the bay. As a result of the hydrodynamic features of the embayment, it can be divided into three sub-habitats: (1) northern headland, characterised by a rocky substratum, low wave action, and high

rate of drift algal accumulation; (2) southern headland, also composed of rocky substratum, but with the highest wave action of the bay and no accumulation of drift algae; and (3) central area, composed of fine and coarse sediment (sandflat) and characterised by a high wave action and, as mentioned previously, a sharply demarcated depth contour. Wave breaking occurred once the waves hit the sandbar "drop-off". The foam generated by waves occasionally reduced the visibility in the shallowest areas (<1.5 m deep), especially near the southern headland, but rarely affected the visibility when tracking stingrays, which occurred in deeper areas beyond the sharp depth contour.
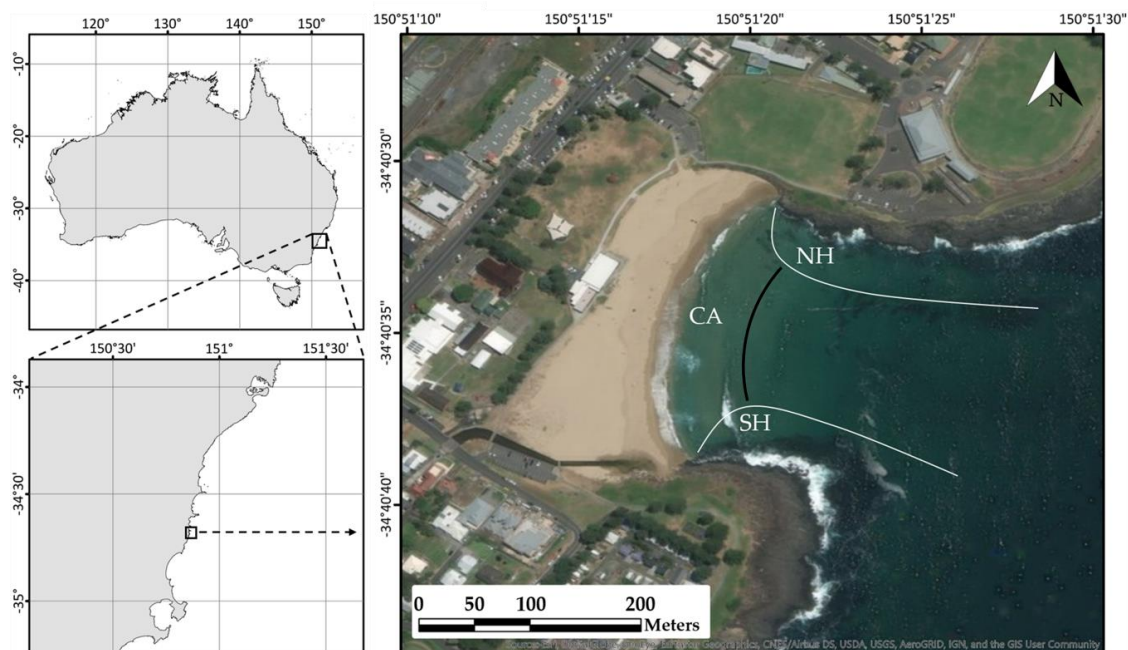
Figure 5. Geographical location of Kiama Surf Beach in Australia and map of the study area showing the three sub-habitats (NH: northern headland; CA: central area; SH: southern headland) and the sharp depth contour located approximately 30 m offshore during low tide and 50 m during high tide (black line).

4.2. Data Collection

Daily surveys were conducted between 11 am and 5 pm, except when winds exceeded 40 km/h. A helium-filled blimp of 5 m long and 1.8 m in diameter (Figure 6a), tethered onshore 70 m above sea-level, was used as an aerial platform for conducting aerial video surveillance. The camera attached beneath the blimp was a Tarot Peeper with a 10× optical zoom, capable of streaming and recording in 1080 p. The camera was equipped with a self-stabilising 3-axis gimbal with 360-degree rotation, which automatically sustained the field of view of interest and compensated the movement of the blimp driven by winds. However, the orientation and zoom could be manually controlled by an operator, who constantly monitored the streaming footage to spot marine megafauna, covering a total area of approximately 18,500 m² (see Supplementary Videos S1–S3 to observe the conditions and setup in action).
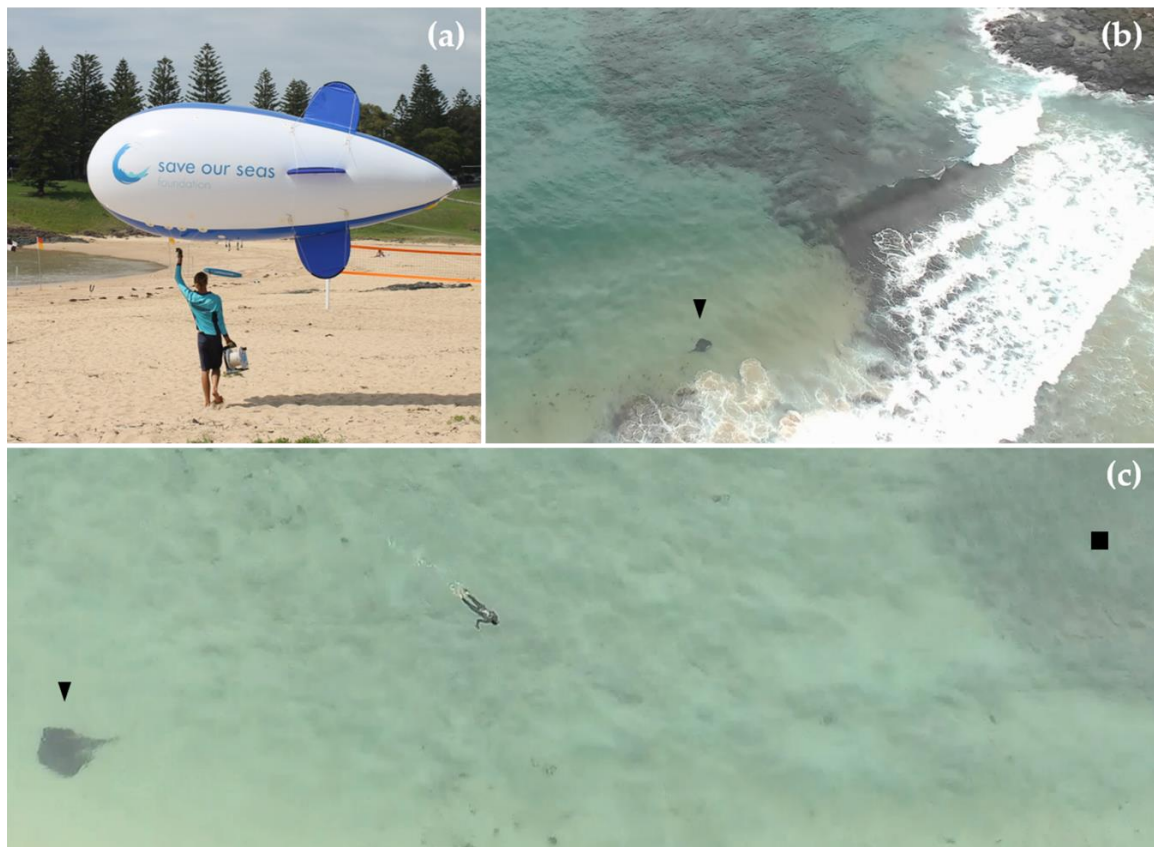
Figure 6. (**a**) Blimp used as aerial platform for conducting video surveillance; (**b**) Example of image taken from the blimp in which it is possible to determine the position of a stingray (▼) in reference to the broad view of the bay; (**c**) zoomed picture of a stingray (▼) swimming in close proximity to a swimmer and a school of Australian salmon (*Arripis trutta*) (■).

During the surveys, video footage from two large stingray species, each up to 2 m in disc width, was taken: *Bathytoshia brevicaudata* and *Bathytoshia lata* (Figure 6b,c) [57]. Although it was not possible to distinguish between these species from the video recordings, their large size and colour rendered them a good target for aerial video surveillance. Visual analysis of the stingray footage allowed the manual tracing of their movement paths. The oblique view from the camera was transformed into a perpendicular perspective by using 16 equidistant reference points to precisely determine the location of each stingray in the video frames of interest. The position of each stingray was recorded every 10 s using ArcGIS Pro 2.0. (ESRI, Redlands, California, USA). The selection of 10 s intervals aimed to optimise the resolution of the movement paths, while enabling the analysis of a large number of videos. The complete path of each animal was recorded in the metric X and Y coordinates using the WGS 1984 Web Mercator coordinate system in ArcGIS Pro.

4.3. Stingray Occurrence

The occurrence of stingrays was measured as the number of independent stingray sightings within the bay. The influence of the tidal state and diel period on stingray occurrence was assessed by conducting Chi-Square tests of independence. Analyses were performed in R 4.0.2 [58] using the chisq.test() specified by Mangiafico [59]. The tidal cycle was divided into two categories, given the maximum tidal range of 2 m: high tide (>1 m) and low tide (<1 m). Tidal information was obtained from the Australian Bureau of Meteorology [60] (see Supplementary Figure S1 for information about the tidal elevation over the entire study period).

The diel periods covered in this research were constrained between 11 a.m. and 5 p.m. due to the sharing of airspace with other stakeholders (daily flights of a shark patrol helicopter) and the work hours of lifeguards. Within this time frame, two diel periods were considered. We divided the survey period into two equal bouts of 3 h: (i) midday, from 11 a.m. to 2 p.m., producing a range of ~1.5 h from the meridian position of the sun, which occurred on average at 12.11 p.m.; and (ii) afternoon, from 2 p.m. to 5 p.m., ~1.5 h after the meridian position of the sun and 2 h before sunset, which occurred on average at 07.03 p.m. during the surveyed period. The diel periods were set based on the time of sun transit and the sunset times published by the Geoscience Department of the Australian Government [61].

The interaction between the tidal stages and diel periods could not be tested due to constraints in the surveying period. The number of sightings during the "low tide-afternoon" and "high tide-midday" categories were too low to conduct meaningful analyses.

4.4. Movement Metrics

The stingray trajectories were quantitively described using the total track duration, total distance covered, mean speed, and sinuosity. Sinuosity was calculated as the ratio of the Euclidian distance (length of a straight line between the end points of the curve) and the curvilinear length (actual path length) minus one, ranging from 0 (straight line) to 1 (closed loop). The effect of the tide, diel period, and presence of humans on these parameters was assessed by a non-parametric comparison of means. Analyses were performed in R using the wilcox.test() specified by Mangiafico [59]. In addition, each section of the movement paths was categorised according to the region of the beach (NH, SH, and CA) in which it occurred. The mean sinuosity of the stingray paths in each of the three regions was compared in order to examine differences in stingray behaviour relating to the characteristics of the subhabitat above which they are swimming. The comparison of means was conducted using the kruskal.test() following Mangiafico [59].

4.5. Route Fidelity

Route fidelity was assessed through the examination of density maps created with the tool Line Density from ArcGIS Pro. These maps differentiate between heavily used and less-frequented areas by calculating a density index. This index is calculated as the linear distance that stingrays cover within each square meter of the study area normalised to a range from 0 to 1. In order to examine differences in habitat usage between diel periods and tidal states, a density map for each of these categories was also created.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Navia, A.F.; Mejía-Falla, P.A.; López-García, J.; Giraldo, A.; Cruz-Escalona, V. How many trophic roles can elasmobranchs play in a marine tropical network? *Mar. Freshw. Res.* **2017**, *68*, 1342–1353. [CrossRef]
2. Martins, A.P.B.; Heupel, M.R.; Chin, A.; Simpfendorfer, C.A. Batoid nurseries: Definition, use and importance. *Mar. Ecol. Prog. Ser.* **2018**, *595*, 253–267. [CrossRef]
3. O'Shea, O.R.; Thums, M.; van Keulen, M.; Meekan, M. Bioturbation by stingrays at Ningaloo Reef, Western Australia. *Mar. Freshw. Res.* **2012**, *63*, 189–197. [CrossRef]
4. Hammerschlag, N.; Schmitz, O.J.; Flecker, A.S.; Lafferty, K.D.; Sih, A.; Atwood, T.B.; Gallagher, A.J.; Irschick, D.J.; Skubel, R.; Cooke, S.J. Ecosystem Function and Services of Aquatic Predators in the Anthropocene. *Trends Ecol. Evol.* **2019**, *34*, 369–383. [CrossRef] [PubMed]
5. Sheaves, M. Consequences of ecological connectivity: The coastal ecosystem mosaic. *Mar. Ecol. Prog. Ser.* **2009**, *391*, 107–115. [CrossRef]
6. Dulvy, N.K.; Fowler, S.L.; Musick, J.A.; Cavanagh, R.D.; Kyne, P.M.; Harrison, L.R.; Carlson, J.K.; Davidson, L.N.K.; Fordham, S.V.; White, W.T.; et al. Extinction risk and conservation of the world's sharks and rays. *eLife* **2014**, *3*, e00590. [CrossRef] [PubMed]
7. Cortés, E. Life History Patterns and Correlations in Sharks. *Rev. Fish Sci.* **2000**, *8*, 299–344. [CrossRef]
8. Knip, D.M.; Heupel, M.R.; Simpfendorfer, C.A. Sharks in nearshore environments: Models, importance, and consequences. *Mar. Ecol. Prog. Ser.* **2010**, *402*, 1–11. [CrossRef]
9. Davy, L.E.; Simpfendorfer, C.A.; Heupel, M.R. Movement patterns and habitat use of juvenile mangrove whiprays (*Himantura granulata*). *Mar. Freshw. Res.* **2015**, *66*, 481–492. [CrossRef]
10. Owoeye, K.; Musolesi, M.; Hailles, S. Characterizing animal movement patterns across different scales and habitats using information theory. *bioRxiv* **2018**, 311241. [CrossRef]
11. Sequeira, A.M.M.; Rodríguez, J.P.; Eguíluz, V.M.; Harcourt, R.; Hindell, M.; Sims, D.W.; Duarte, C.M.; Costa, D.P.; Fernández-Gracia, J.; Thums, M.; et al. Convergence of marine megafauna movement patterns in coastal and open oceans. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 3072–3077. [CrossRef] [PubMed]
12. Chapman, D.D.; Feldheim, K.A.; Papastamatiou, Y.P.; Hueter, R.E. There and Back Again: A Review of Residency and Return Migrations in Sharks, with Implications for Population Structure and Management. *Annu. Rev. Mar. Sci.* **2015**, *7*, 547–570. [CrossRef] [PubMed]
13. Legare, B.; Skomal, G.; DeAngelis, B. Diel movements of the blacktip shark (*Carcharhinus limbatus*) in a Caribbean nursery. *Environ. Biol. Fishes* **2018**, *101*, 1011–1023. [CrossRef]
14. Morales, J.M.; Moorcroft, P.R.; Matthiopoulos, J.; Frair, J.L.; Kie, J.G.; Powell, R.A.; Merrill, E.H.; Haydon, D.T. Building the bridge between animal movement and population dynamics. *Philos. Trans. R. Soc. B* **2010**, *365*, 2289–2301. [CrossRef]
15. Signer, J.; Ovaskainen, O. Detecting the influence of environmental covariates on animal movement: A semivariance approach. *Methods Ecol. Evol.* **2017**, *8*, 561–570. [CrossRef]
16. Hays, G.C.; Ferreira, L.C.; Sequeira, A.M.M.; Meekan, M.G.; Duarte, C.M.; Bailey, H.; Bailleul, F.; Bowen, W.D.; Caley, M.J.; Thums, M.; et al. Key Questions in Marine Megafauna Movement Ecology. *Trends Ecol. Evol.* **2016**, *31*, 463–475. [CrossRef]
17. Le Port, A.; Sippel, T.; Montgomery, J.C. Observations of mesoscale movements in the short-tailed stingray, *Dasyatis brevicaudata* from New Zealand using a novel PSAT tag attachment method. *J. Exp. Mar. Biol. Ecol.* **2008**, *359*, 110–117. [CrossRef]
18. Brinton, C.P.; Curran, M.C. Tidal and diel movement patterns of the Atlantic stingray (*Dasyatis sabina*) along a stream-order gradient. *Mar. Freshw. Res.* **2017**, *68*, 1716–1725. [CrossRef]
19. Martins, A.P.B.; Heupel, M.R.; Bierwagen, S.L.; Chin, A.; Simpfendorfer, C. Diurnal activity patterns and habitat use of juvenile *Pastinachus ater* in a coral reef flat environment. *PLoS ONE* **2020**, *15*, e0228280. [CrossRef]
20. Vaudo, J.J.; Heithaus, M.R. Diel and seasonal variation in the use of a nearshore sandflat by a ray community in a near pristine system. *Mar. Freshw. Res.* **2012**, *63*, 1077–1084. [CrossRef]

21. Huveneers, C.; Simpfendorfer, C.A.; Kim, S.; Semmens, J.M.; Hobday, A.J.; Pederson, H.; Stieglitz, T.; Vallee, R.; Webber, D.; Harcourt, R.G.; et al. The influence of environmental parameters on the performance and detection range of acoustic receivers. *Methods Ecol. Evol.* **2016**, *7*, 825–835. [CrossRef]

22. Martins, A.P.B.; Heupel, M.R.; Oakley-Cogan, A.; Chin, A.; Simpfendorfer, C.A. Towed-float GPS telemetry: A tool to assess movement patterns and habitat use of juvenile stingrays. *Mar. Freshw. Res.* **2020**, *71*, 89–98. [CrossRef]

23. Raoult, V.; Tosetto, L.; Williamson, J.E. Drone-based high-resolution tracking of aquatic vertebrates. *Drones* **2018**, *2*, 37. [CrossRef]

24. Wilson, R.P.; Liebsch, N.; Davies, I.M.; Quintana, F.; Weimerskirch, H.; Storch, S.; Lucke, K.; Siebert, U.; Zankl, S.; McMahon, C.R.; et al. All at sea with animal tracks; methodological and analytical solutions for the resolution of movement. *Deep Sea Res. Part II* **2007**, *54*, 193–210. [CrossRef]

25. Wilson, A.D.M.; Brownscombe, J.W.; Krause, J.; Krause, S.; Gutowsky, L.F.G.; Brooks, E.J.; Cooke, S.J. Integrating network analysis, sensor tags, and observation to understand shark ecology and behavior. *Behav. Ecol.* **2015**, *26*, 1577–1586. [CrossRef]

26. Bicknell, A.W.J.; Godley, B.J.; Sheehan, E.V.; Votier, S.C.; Witt, M.J. Camera technology for monitoring marine biodiversity and human impact. *Front. Ecol. Environ.* **2016**, *14*, 424–432. [CrossRef]

27. Adams, K.; Broad, A.; Ruiz-García, D.; Davis, A.R. Continuous wildlife monitoring using blimps as an aerial platform: A case study observing marine megafauna. *Aust. Zool.* **2020**, *40*, 407–415. [CrossRef]

28. Colefax, A.P.; Butcher, P.A.; Kelaher, B.P. The potential for unmanned aerial vehicles (UAVs) to conduct marine fauna surveys in place of manned aircraft. *ICES J. Mar. Sci.* **2017**, *75*, 1–8. [CrossRef]

29. Rieucau, G.; Kiszka, J.J.; Castillo, J.C.; Mourier, J.; Boswell, K.M.; Heithaus, M.R. Using unmanned aerial vehicle (UAV) surveys and image analysis in the study of large surface-associated marine species: A case study on reef sharks *Carcharhinus melanopterus* shoaling behaviour. *J. Fish Biol.* **2018**, *93*, 119–127. [CrossRef]

30. Bevan, E.; Whiting, S.; Tucker, T.; Guinea, M.; Raith, A.; Douglas, R. Measuring behavioral responses of sea turtles, saltwater crocodiles, and crested terns to drone disturbance to define ethical operating thresholds. *PLoS ONE* **2018**, *13*, e0194460. [CrossRef]

31. Kanno, S.; Schlaff, A.M.; Heupel, M.R.; Simpfendorfer, C.A. Stationary video monitoring reveals habitat use of stingrays in mangroves. *Mar. Ecol. Prog. Ser.* **2019**, *621*, 155–168. [CrossRef]

32. Mulero-Pázmány, M.; Jenni-Eiermann, S.; Strebel, N.; Sattler, T.; Negro, J.J.; Tablado, Z. Unmanned aircraft systems as a new source of disturbance for wildlife: A systematic review. *PLoS ONE* **2017**, *12*, e0178448. [CrossRef] [PubMed]

33. Erbe, C.; Williams, R.; Parsons, M.; Parsons, S.K.; Hendrawan, I.G.; Dewantama, I.M.I. Underwater noise from airplanes: An overlooked source of ocean noise. *Mar. Pollut. Bull.* **2018**, *137*, 656–661. [CrossRef] [PubMed]

34. Hassanalian, M.; Abdelkefi, A. Classifications, applications, and design challenges of drones: A review. *Prog. Aerosp. Sci.* **2017**, *91*, 99–131. [CrossRef]

35. Hain, J.H.; Harris, L.E. Aerostats for oceanographic and atmospheric research. *Sea Technol.* **2004**, *45*, 75–80.

36. Hodgson, A. "BLIMP-CAM": Aerial Video Observations of Marine Animals. *Mar. Technol. Soc. J.* **2007**, *41*, 39–43. [CrossRef]

37. Nosal, A.P.; Cartamil, D.C.; Long, J.W.; Lührmann, M.; Wegner, N.C.; Graham, J.B. Demography and movement patterns of leopard sharks (*Triakis semifasciata*) aggregating near the head of a submarine canyon along the open coast of southern California, USA. *Environ. Biol. Fishes* **2013**, *96*, 865–878. [CrossRef]

38. Tilley, A.; López-Angarita, J.; Turner, J.R. Effects of scale and habitat distribution on the movement of the southern stingray *Dasyatis americana* on a Caribbean atoll. *Mar. Ecol. Prog. Ser.* **2013**, *482*, 169–179. [CrossRef]

39. Zollner, P.A.; Lima, S.L. Search strategies for landscape-level interpatch movements. *Ecology* **1999**, *80*, 1019–1030. [CrossRef]

40. Benhamou, S. How to reliably estimate the tortuosity of an animal's path: Straightness, sinuosity, or fractal dimension? *J. Theor. Biol.* **2004**, *229*, 209–220. [CrossRef]

41. Van Moorter, B.; Visscher, D.; Benhamou, S.; Börger, L.; Boyce, M.S.; Gaillard, J. Memory keeps you at home: A mechanistic model for home range emergence. *Oikos* **2009**, *118*, 641–652. [CrossRef]

42. Papastamatiou, Y.P.; Cartamil, D.P.; Lowe, C.G.; Meyer, C.G.; Wetherbee, B.M.; Holland, K.N. Scales of orientation, directed walks and movement path structure in sharks. *J. Anim. Ecol.* **2011**, *80*, 864–874. [CrossRef] [PubMed]

43. Hollensead, L.D.; Grubbs, R.D.; Carlson, J.K.; Bethea, D.M. Analysis of fine-scale daily movement patterns of juvenile *Pristis pectinata* within a nursery habitat. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2016**, *26*, 492–505. [CrossRef]

44. Bartumeus, F.; da Luz, M.G.E.; Viswanathan, G.M.; Catalan, J. Animal search strategies: A quantitative random-walk analysis. *Ecology* **2005**, *86*, 3078–3087. [CrossRef]

45. Papastamatiou, Y.P.; De Salles, P.A.; McCauley, D.J. Area-restricted searching by manta rays and their response to spatial scale in lagoon habitats. *Mar. Ecol. Prog. Ser.* **2012**, *456*, 233–244. [CrossRef]

46. Meese, E.N.; Lowe, C.G. Active acoustic telemetry tracking and tri-axial accelerometers reveal fine-scale movement strategies of a non-obligate ram ventilator. *Mov. Ecol.* **2020**, *8*, 8. [CrossRef]

47. Cartamil, D.P.; Vaudo, J.J.; Lowe, C.G.; Wetherbee, B.M.; Holland, K.N. Diel movement patterns of the Hawaiian stingray, *Dasyatis lata*: Implications for ecological interactions between sympatric elasmobranch species. *Mar. Biol.* **2003**, *142*, 841–847. [CrossRef]

48. Ward, C.R.E.; Bouyoucos, I.A.; Brooks, E.J.; O'Shea, O.R. Novel attachment methods for assessing activity patterns using triaxial accelerometers on stingrays in the Bahamas. *Mar. Biol.* **2019**, *166*, 53. [CrossRef]

49. Rizzari, J.R.; Semmens, J.M.; Fox, A.; Huveneers, C. Observations of marine wildlife tourism effects on a non-focal species. *J. Fish Biol.* **2017**, *91*, 981–988. [CrossRef]

50. Gilliam, D.S.; Sullivan, K.M. Diet and feeding habits of the southern stingray *Dasyatis americana* in the central Bahamas. *Bull. Mar. Sci.* **1993**, *52*, 1007. Available online: https://nsuworks.nova.edu/occ_facarticles/560 (accessed on 25 September 2020).

51. Newsome, D.; Lewis, A.; Moncrieff, D. Impacts and risks associated with developing, but unsupervised, stingray tourism at Hamelin Bay, Western Australia. *Int. J. Tour. Res.* **2004**, *6*, 305–323. [CrossRef]

52. Pini-Fitzsimmons, J.; Knott, N.A.; Brown, C. Effects of food provisioning on site use in the short-tail stingray *Bathytoshia brevicaudata*. *Mar. Ecol. Prog. Ser.* **2018**, *600*, 99–110. [CrossRef]

53. NSW DPI. *NSW Recreational Saltwater Fishing Guide 2020–2021*; New South Wales Department of Primary Industries: Nowra, NSW, Australia, 2020. Available online: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0012/600222/16359-NSW-Recreational-Fishing-Guides-Saltwater-2020-07Winter.pdf (accessed on 22 July 2020).

54. Fist, R. *Stingray Show a Hit in Kiama*; Kiama Independent: Kiama, NSW, Australia, 2018. Available online: https://www.kiamaindependent.com.au/story/5165842/stingray-show-a-hit-in-kiama/ (accessed on 25 September 2020).

55. Gorkin, R.; Adams, K.; Berryman, M.J.; Aubin, S.; Li, W.; Davis, A.R.; Barthelemy, J. Sharkeye: Real-Time Autonomous Personal Shark Alerting via Aerial Surveillance. *Drones* **2020**, *4*, 18. [CrossRef]

56. Lemos, C.; Floc'h, F.; Yates, M.; Le Dantec, N.; Marieu, V.; Hamon, K.; Cuq, V.; Suanez, S.; Delacourt, C. Equilibrium modeling of the beach profile on a macrotidal embayed low tide terrace beach. *Ocean Dyn.* **2018**, *68*, 1207–1220. [CrossRef]

57. Last, P.R.; Naylor, G.J.P.; Manjaji-Matsumoto, B. A revised classification of the family Dasyatidae (Chondrichthyes: Myliobatiformes) based on new morphological and molecular insights. *Zootaxa* **2016**, *4139*, 368. [CrossRef]

58. R Development Core Team. *R: A Language and Environment for Statistical Computing*, R version 3.6.1; R Development Core Team: Vienna, Austria, 2019. Available online: https://www.r-project.org/ (accessed on 7 August 2019).

59. Mangiafico, S.S. *An R Companion for the Handbook of Biological Statistics*, version 1.3.3; Rutgers Cooperative Extension: New Brunswick, NJ, USA, 2015. Available online: https://rcompanion.org/rcompanion/ (accessed on 25 September 2020).

60. Australia's Official Weather Forecasts & Weather Radar: Bureau of Meteorology. Available online: www.bom.gov.au (accessed on 7 August 2019).

61. Compute Sunrise, Sunset & Twilight Times: Geoscience Australia. Available online: www.ga.gov.au/geodesy/astro/sunrise.jsp (accessed on 7 August 2019).