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REGULAR ARTICLE

Performance and detection range of acoustic receivers in mangrove habitats

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Abstract

Acoustic telemetry has been used to monitor the movement of aquatic animals in a broad range of aquatic environments. Despite their importance, mangrove habitats are understudied for the spatial ecology of elasmobranchs, with acoustic telemetry rarely used inside mangrove habitats. One reason for this may be a general assumption that acoustic signals would not be able to be detected by receivers in such shallow, structurally complex, environments. This study tested whether acoustic receivers can be used inside mangrove habitats to track the movement of sharks and rays. Thirty-eight receivers were deployed in a mangrove system in Pioneer Bay, Orpheus Island, Great Barrier Reef, including inside mangroves, mangrove edges, and adjacent reef flat areas. The detection range and receiver performance metrics, such as code detection efficiency, rejection coefficient, and noise quotient, were examined and tested among habitats. The results highlighted that the signal from transmitters was successfully detected inside mangrove habitats as well as on the adjacent reef flat. The range to detect at least 50% of transmissions was up to 20 m inside mangroves and up to 120 m outside mangroves. The performance metrics of acoustic receivers inside the mangrove habitat were characterized by low background noise, low rejection rates, and reasonably high code detection efficiency. Furthermore, this study tested the application of this method on juvenile blacktip reef shark *Carcharhinus melanopterus* and mangrove whipray *Urogymnus granulatus*, and demonstrated that it can be used to successfully track animals inside mangrove habitat. This novel method could reveal further information on how sharks and rays use mangrove habitats.

KEYWORDS
acoustic telemetry, blacktip reef shark, IMOS ATF, mangrove whipray, range testing, vegetated coastal wetlands

1 | INTRODUCTION

Acoustic telemetry is a useful tool to study the spatial ecology of aquatic animals (Hussey et al., 2015). Passive acoustic monitoring, in particular, can be used to provide detailed insights into the habitat use and movement patterns of animals by remotely monitoring their presence in a given area over relatively long time frames (months to years) with a reasonably low labour cost (Heupel et al., 2006). Advances in telemetry technology have not only lowered the financial cost of acoustic receivers and transmitters but also offered more variety in equipment in terms of size, battery life, additional sensors (e.g., pressure, temperature and acceleration), and communication ability between equipment and users (Donaldson et al., 2014; Hussey et al., 2015). Along with improvements in equipment, improvements in spatial analysis methods (Whoriskey et al., 2019) have enabled new insights into the relationship between aquatic animals and their habitats (Espinoza et al., 2021; Papastamatiou et al., 2013).

As acoustic monitoring uses acoustic signals, this method can only be used where the acoustic signal from the transmitter can reasonably travel through the environment and be detected by a receiver. Transmissions from acoustic transmitters are subject to a range of effects that can impact on the ability to detect a transmission. These include attenuation (e.g., signal is absorbed by particles or organisms in the water), reflection (e.g., signal hits hard objects in the water), and refraction (e.g., signal hits a boundary, such as thermocline and changes travel direction) (Heupel et al., 2006). In addition, other environmental noise at a similar frequency can interfere with detection and as such the code from the transmitter can be misunderstood or missed by the receiver (Simpfendorfer et al., 2015). Thus, the detection performance of receivers is known to be affected by physical (e.g., wave action, rain, wind, topography), biological (e.g., biological noise, animal movement, algal blooms), and anthropogenic (boat and other human activity noise) factors (Cooke et al., 2013; Heupel et al., 2006). Hence, the effectiveness of telemetry research depends on the system in which the experiment is conducted and the equipment configuration. As a result, understanding the detection range and receiver performance before conducting animal monitoring is essential to accurately interpret the collected data (Kessel et al., 2014).

Acoustic monitoring has been most commonly deployed to investigate movement patterns of animals that have relatively high fidelity to a study site in relatively deep, physically open habitats, such as large rivers, lakes, and offshore, open water marine systems (e.g., Hanson et al., 2007; Heupel & Simpfendorfer, 2008, 2015) because these systems often have few impediments to detecting transmitter signals and this makes interpretation of results straightforward. Environments in which signal transmission is regularly impeded, such as in nearshore, shallow, vegetated or coral reef systems, have sampling difficulty for an acoustic telemetry study because of the challenges in designing methods that allow the collection of useful data. For example, the detection range of acoustic receivers in shallow coral reef environments that have complex topography was smaller than that in open water habitats due to the complex topography and

inherently noisy environment of the reef (e.g., Cagua et al., 2013; Welsh et al., 2012). The presence of vegetation also negatively affects receiver performance by blocking and attenuating signals, resulting in low detection probability and small detection range. For example, Swadling et al. (2020) compared the detection efficiency of acoustic receivers between transmitters positioned above and among a seagrass canopy and found a significant reduction in detection range when the transmitter sat among the canopy (from 90 to 45 m). Similarly, Weinz et al. (2021) conducted range testing of acoustic receivers in seasonally submerged vegetated habitats in a freshwater system and reported substantial differences in detection range (from nearly 200 m when vegetation coverage was low to less than 10 m when the coverage was high). Thus, environmental conditions, such as biological noise, shallow water, and vegetation density, can be a challenge for acoustic telemetry. If these factors are not incorporated into the animal tracking studies, the data can be misinterpreted and lead to misunderstanding movement.

Nearshore vegetated habitats are important to aquatic animals due to their productivity and the ecological services they provide (i.e., food, nursery and shelter) (Sievers et al., 2019). Mangroves are one of the most productive systems in tropical and subtropical areas, and a variety of animals, including invertebrates, teleosts, elasmobranchs, amphibians, reptiles, birds, and mammals, are dependent on mangrove habitats, which support coastal ecosystems as a whole (Nagelkerken et al., 2008; Rog et al., 2017). Despite their significance to coastal ecosystems, mangroves are currently under pressure of deforestation globally (FAO, 2023; Goldberg et al., 2020). Knowledge of the relationship between mangrove systems and the animals that use them is critical to predict how coastal communities may respond to the loss of mangrove systems. For acoustic telemetry, however, mangrove systems are challenging environments to operate in mainly due to the shallow water depth, which changes rapidly with tidal movements, physical complexity from submerged trunks and roots (e.g., Swadling et al., 2020), and turbidity (e.g., Cooke et al., 2013). As a result, there have been no long-term acoustic telemetry studies conducted within mangrove habitats (i.e., inside mangrove forests) (Kanno et al., 2023).

In other nearshore vegetated ecosystems, there are some studies that may provide insights to guide studies in mangroves. Recently, several studies tested the detection performance of active and passive acoustic telemetry in wetland environments with submerged aquatic vegetation in lakes and found that acoustic transmitters can be used in vegetated shallow water environments (Swadling et al., 2020; Thiemer et al., 2022; Weinz et al., 2021). Matley et al. (2022) conducted passive acoustic monitoring for yellow perch *Perca flavescens* in vegetated lake habitats with the consideration of range test results. They collected range test data prior to animal movement monitoring and interpreted the spatial ecology of perch accurately by incorporating the temporal variability in detection range due to submerged vegetation. Their study highlighted that results are possible within acoustically challenging environments with appropriate testing.

The aim of this study was to determine if acoustic monitoring in dense mangrove habitats could yield useful ecological data on how

elasmobranchs, and potentially other taxa, use this habitat. The objectives for this study were (1) to test the detectability of acoustic transmitters in structurally complex mangrove habitats by examining the detection range and how it varies with diel period, tidal height, and habitats, (2) to examine receiver performance in mangrove habitat and compare it to non-mangrove habitats, and (3) to demonstrate whether acoustic monitoring can be used to track the movements of animals in mangrove habitats by examining the movement of sharks and stingrays known to enter mangrove habitats (e.g., George et al., 2019; Martins et al., 2020).

2 | METHODS

2.1 | Study area

The study was conducted in Pioneer Bay, Orpheus Island, 17 km offshore of the coast of northeast Queensland, Australia (Figure 1). The bay has both fringing (i.e., mangroves growing along the coast) and patchy (i.e., mangroves growing sparsely with a space between each other, rather than densely) mangrove areas with a reef flat which extends ~400 m from the shoreline to the reef crest with patchy coral rubble areas. There are four distinct mangrove stands in the bay, which vary in their width and shape: two small mangrove stands forming isolated patches at the sandy beach and two fringing mangroves occur along the north and south shorelines. The south fringing mangroves are longer and wider than the north fringing mangroves,

reaching a width of ~85 m from the shoreline. Mangrove stands are predominantly composed of red mangroves *Rhizophora stylosa*, mixed with gray *Avicennia marina* and myrtle mangroves *Osbornia octodonta*. The mangroves in the study area are evergreen year-round and the extensive arching prop roots make structurally complex habitats in mangrove stands.

The main substrate in the mangrove areas is a soft sand-mud mixture and some sections have rocky substrate, especially at the seaward end of both the south and north fringing mangroves. The reef flat and two small mangrove stands in the middle of the bay are covered throughout with soft mud and sand. In the reef flat away from the shoreline mangroves, there are patchy corals and algal-dominated coral rubble in the proximity to the reef crest. The tidal range is ~4 m and semidiurnal, and mangrove areas are normally flooded at high tide and completely exposed at low tide. The reef crest is exposed occasionally at very low tide (when predicted tidal height is roughly <70–80 cm).

2.2 | Ethical statement

The care and use of experimental animals complied with James Cook University (JCU) Animal Ethics Committee animal welfare laws, guidelines and policies as approved by the JCU Animal Ethics Committee A2672. Research permits were issued by GBRMPA G15/37987.1 and the Department of Agriculture and Fisheries, Queensland Government 208733.

FIGURE 1 Maps of the study site and receiver deployment. Circles indicate receivers (different zones in different colors: pink = zone 1, reef flat; green = zone 2, mangrove edge; blue = zone 3, mangrove middle; purple = zone 4, mangrove rear); ▲ and x indicate the 1-month and 2-day transmitter positions, respectively.

2.3 | Field methods

2.3.1 | Receiver deployment

An array of 38 acoustic receivers (VR2W; Vemco Ltd.) was installed in Pioneer Bay in October 2020 and removed in December 2021. Four receivers were located at the landward edge of the reef crest, three on the reef flat midway between the reef crest and the shoreline, and 31 either along the mangrove edge or inside mangrove stands (Figure 1). The array was designed to examine the performance of receivers deployed inside mangroves to track the movements of sharks and rays. For this purpose, the habitat type of each receiver location was categorized into four zones (hereafter the zones): (1) reef flat, (2) mangrove edge, within 2 m of the seaward edge of the mangrove root system, (3) mangrove middle, midway between mangrove edge and mangrove rear receivers where there was sufficient space, and (4) mangrove rear, within 10 m of the landward edge of the mangrove stand and at least 25 m away from the shore line. Within mangrove stands distances was less than 20 m between receivers.

Prior to deployment, the approximate locations of receivers were planned, but final locations were determined in the field, with deployment occurring in more open areas within the mangrove root complex whenever possible. Receivers were deployed at each designated location by driving a 45-cm star picket into the substrate and digging a hole for placing the receiver body in next to the picket (the hole size was ~10 cm diameter, ~25 cm deep). A receiver was placed in the hole and cable tied to the picket. The hole was refilled, with at least the top 5 cm of the receiver above the substrate (Figure 2). Receivers were deployed in this way to enable transmitter detection at the lowest possible water levels and thus maximize detection times during each tidal cycle.

Data were downloaded from all receivers in December 2020, May 2021, and December 2021 (on removal). During downloads, six receivers were found to be not working properly and were replaced with new receivers. Those six receivers were on the mangrove edge zone and more than 50 m away from the transmitters, and the receiver removal was conducted prior to both inside and outside

range testing, therefore, receiver replacement did not significantly affect the range-testing data.

2.3.2 | Deployment of transmitters for range testing

One transmitter (V13AP, Vemco) was attached to a solitary mangrove tree just seaward of the southern mangrove stand for 1 month. This test was designed to simulate how transmissions from transmitters on animals swimming seaward of the mangrove edge would be detected by the different types of receivers (edge, middle, rear). This testing is hereafter called outside mangrove testing as the test transmitter was placed outside of mangrove habitats. In addition, two transmitters (V13AP, Vemco) were attached to prop roots within the southern mangrove stand for 2 days, one between the edge and middle receivers and one between the middle and rear receivers. Each transmitter was placed in a small net bag and the bag was tied to the root or trunk of a tree about 25 cm above the substrate. The 2-day test transmitters were used to test receiver performance inside mangrove habitats, i.e. among the mangrove trees. This testing is hereafter called inside mangrove testing. All transmitters were recovered after the study. All test transmitters had pressure and acceleration sensors (hence, there were two consecutive ID numbers for each transmitter, one for each sensor). The deployed test transmitters were submerged in water at high tide and completely exposed at low tide.

2.4 | Data analysis

2.4.1 | Detection range

To test the detection range of acoustic receivers in the mangrove system, the detection probability (%D) was calculated as the number of detections recorded by each receiver divided by the total possible codes sent from the transmitter during the test period. The total possible pings coded by one transmitter (with two independent sensors)

FIGURE 2 Receivers deployed among mangrove roots.

was calculated based on (i) the interval of signal made by one transmitter and (ii) the time period when the transmitter was able to send a signal underwater and the receiver was able to detect that signal. This latter requirement occurred because of the cyclical inundation of the mangroves. The mean ping rate of transmitters was 120 s, with pings alternating between the different sensors (pressure or acceleration). Thus, if only data from one sensor was used in analysis, then the ping frequency was 240 s. Next, the study time period was calculated based on tidal cycle data. The time period for the range test was the total time when the two following conditions were met: (1) a transmitter could send a valid signal and (2) the signal was able to be detected by underwater receivers. The signal could be detected by receivers in the study area when the transmitter was submerged. The tidal height at which these conditions were met was determined by comparing the timing of detections with depth indicated as 0 m by the transmitter depth sensor and local tide charts. Based on 186 data points with 0 m depth the average minimum tidal height at which detections were first made was ∼2.0 m. Finally, the total number of possible pings was calculated. For the 1-month test transmitter, for example, the ping interval for one transmitter (includes two sensors) was 120 s and the total time of the local tidal height >2 m was 375 h (125 h for day and 250 h for night), therefore the total number of possible pings was 11,250 (375 × 60/2).

To determine the detection range of at least 50% of detections, distances between the transmitters and each receiver were calculated and plotted against %D. The data from outside and inside mangrove tests were plotted separately to examine if the detection range was different when the transmitter was inside mangrove habitats or outside mangroves. The relationship between %D and distance was plotted separately for each receiver zone (i.e., reef flat, edge, middle, and rear). A binomial curve was fitted to distance-detection probability data using a general linear model. Additionally, a generalized linear mixed model (GLMM) was used to examine if %D was affected by (1) distance between receiver and transmitter, (2) the zone, and (3) day or night shift. An individual receiver was incorporated into the model as a random factor. The model selection was conducted outside and inside mangrove tests separately. Day and night were determined based on local sunset/sunrise times. The full model (%D ∼ Distance + Zone + Day or Night + [1|Receiver]) was fitted using the "lme4" package (Bates et al., 2015) in the R program environment (R Core Team, 2022). The "MuMIn" package (Bartoń, 2023) was used to evaluate all combinations of parameters to determine the best-fit model that best explained the data. The best-fit model was selected based on Akaike Information Criterion (AIC) model evaluation and the analysis of deviance test (type II Wald chi-square tests) was used to test which factor or factors were statistically significant.

To examine if water depth affected the number of detections made, detection per depth was analyzed using a chi-square test. To do this, first, the total number of hours when tidal height was >2 m during the outside mangrove test was calculated based on hourly tide charts. Second, the estimated water depth was calculated for each detection using the pressure sensor data. Third, both tidal height and estimated water depth data were categorized into the depth bins (15 cm) separately. This step enabled the calculation of the

frequencies of tidal height occurrence and frequency of detections at the given depth. Finally, the frequency data of tidal height occurrence at the study site and detections at the estimated depth were tested for independence using a chi-square test to examine if detection was made equally throughout the water depth of >2 m or more (or less) detection was made at a particular water depth.

2.4.2 | Event data

Event data were collected from December 2020 to December 2021 and included 41 tags deployed during the animal tracking study. The system used in this study had a coding scheme where each code sent eight (V13) or 10 pulses (V13AP) to transmit data (the number of pulses is different in different transmitter types). The transmitter information sent using this eight- or 10-pulse code is composed of three sections. The first section, called the synchronization interval, is the time between the first two pulses. This value is so tightly defined that it is rarely replicated by environmental noise, allowing the receiver to identify it as transmission from a transmitter among other similar noises in the environment. The second section is the unique identification number of the transmitter. The third section is a checksum that is used to validate the code. The code detection is discarded if the checksum is invalid. The numbers of valid codes, pulses detected, and codes rejected are stored in the receiver, along with the number of pulses detected. These data can be used to calculate the code detection efficiency (CDE) and the rejection coefficient (RC), as demonstrated by Simpfendorfer et al. (2008). CDE and RC were calculated by the following formula:

$$CDE = D/S$$

$$RC = C/S$$

where D is the number of valid detections, S is the number of valid synchronization intervals (as an estimate of the number of codes transmitted), and C is the number of codes rejected because of an invalid checksum. CDE is the proportion of detection and transmitted codes, and if CDE = 1, the receiver detects 100% of codes transmitted. RC is the proportion of codes rejected and the number of codes transmitted, and a low RC value (close to 0) indicates a low frequency of an invalid checksum and that the receiver detects transmission well.

The stored data were also used to estimate the noise quotient (NQ) as described by Simpfendorfer et al. (2008) as follows:

$$NQ = P - (S \times cl)$$

where P is the number of pulses detected and cl is the number of pulses used for one valid code; since some transmitters used an eight-pulse code and others used a 10-pulse code, here we used the midpoint of $cl = 9$. Essentially, if there is a significant amount of environmental noise that can be detected by the receivers as a pulse, the data would show more pulses than could possibly be transmitted by a

transmitter. Positive NQ values indicate more environmental noise because this means that there are more pulse-like noises in the environment that are detected by the receiver.

CDE and RC data were stored daily while NQ was stored both hourly and daily. Daily CDE, RC, and NQ were compared between the four receiver zones using a linear mixed-effect model with an individual receiver as a random factor with analysis of deviance test and a post hoc Tukey's HSD was conducted to assess if receiver performance was different among the zones. In addition, hourly NQ was compared between the zones and time of the day using a linear mixed-effect model with individual receiver as a random factor. An analysis of deviance chi-square test was then conducted to examine if NQ values had a different trend throughout the day between the zones. For these analyses, CDE, RC, and NQ values were log-transformed prior further analysis.

2.5 | Animal tracking test

To examine if the acoustic receivers in mangroves could be used for animal tracking, tagged sharks and rays were released into the study area. Two animals, one blacktip reef shark *Carcharhinus melanopterus* (Quoy & Gaimard, 1824) and one mangrove whipray *Urogymnus granulatus* (Macleay, 1883), were caught and tagged for the trial. Animals were caught by a seine-netting or rod-and-reel fishing, their size measured, and their sex and maturity state (juvenile or subadult) recorded. A transmitter (V13 or V13AP; Vemco Ltd.) was surgically implanted in the abdominal cavity. The animal was placed in a container filled with water taken directly from the study site to ensure ambient conditions were maintained. Once the individual was immobilized, an ∼2-cm incision was made in the abdomen with a sterile scalpel, and the transmitter was inserted and pushed cranially until it was completely within the abdominal cavity. Finally, the incision was closed using surgical sutures. After checking the health condition of the animal and safety of the environment, the animal was released. The whole procedure took less than 5 min. All animal capture and surgery techniques were consistent with Animal Ethics approval from James Cook University A2672.

Detection data downloaded from the receiver array were used to estimate animal positions using the mean-position algorithm described by Simpfendorfer et al. (2002) in the R environment (R Core Team, 2022). The time step for position averaging was 15 min. The positions of the two selected individuals were mapped to display locations and examined if they were detected within mangrove stands.

3 | RESULTS

3.1 | Range test

3.1.1 | Outside mangrove range test

Detection probability (%D) increased as the distance between the transmitter and receiver decreased (Figure 3). The receiver located
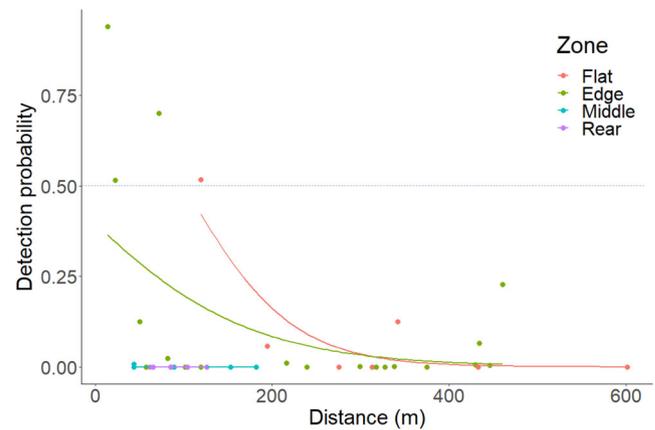

FIGURE 3 Detection probability of the four zones for the outside mangrove test. The dotted line indicates 50% of detection probability.

TABLE 1 Analysis of deviance table for outside range test.

Best model: %D ∼ day or night + (1|receiver)

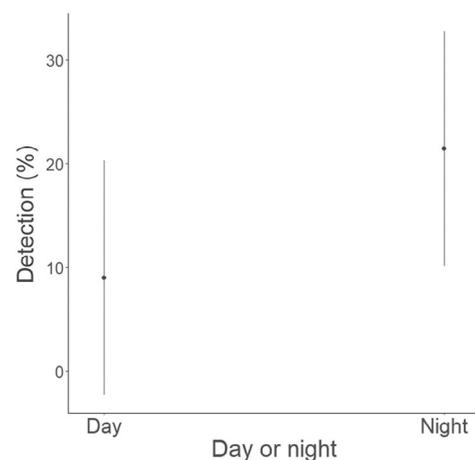|	Chi-square	df	p value
Day or night	11.801	1	<0.001
Distance	0.274	1	0.6007
Zone	1.3576	2	0.5072

FIGURE 4 Predicted detection probability between day and night for the outside mangrove test.

closest to the test transmitter (distance of 18.9 m) had the highest value of %D (94.0%). The detection range of at least 50% of detections was up to 120 m (Figure 3). This is the flat receiver located 120 m away from the transmitter that recorded more than 50% of detection. Four receivers located in the edge and flat zones had %D greater than 50%, which means there was no major physical obstruction between the transmitter and the receiver. The other receivers, especially located in the middle and rear zones, had few or no detections even when the range was less than 50 m. These results were supported by the GLMM demonstrating that distance and zone had
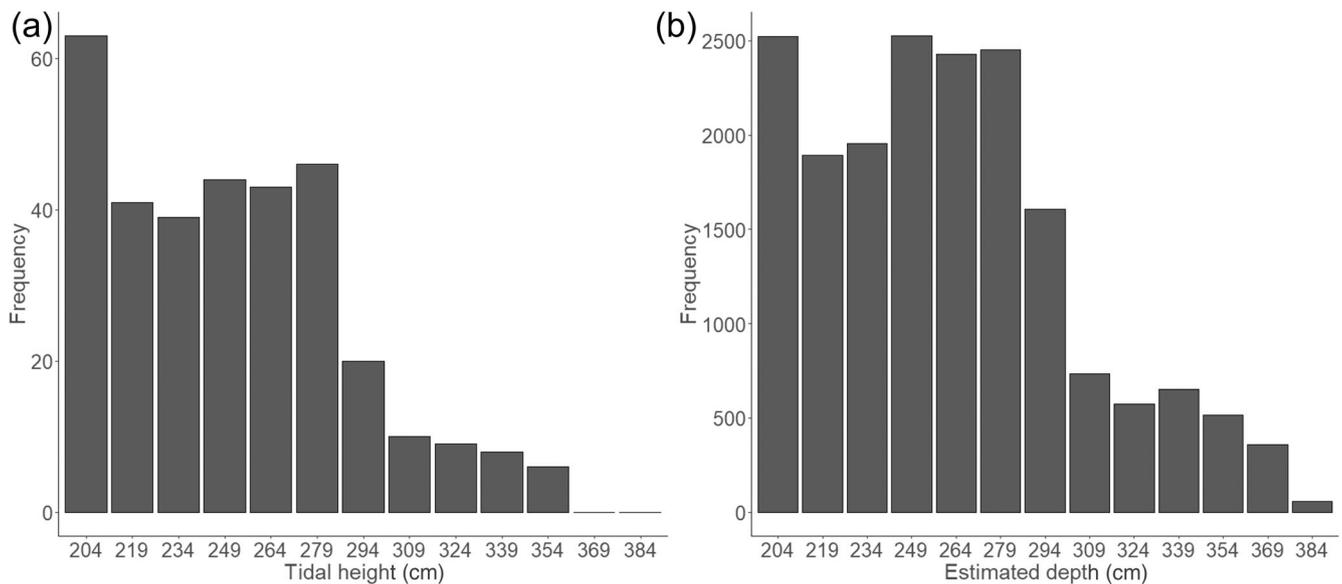
FIGURE 5   Frequencies of (a) tidal height at Lucinda and (b) detections at estimated depth.
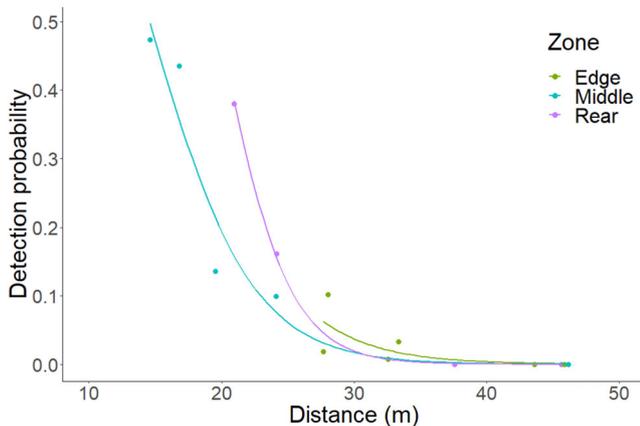

FIGURE 6   Detection probability of the different zones for the inside mangrove test. The dotted line indicates 50% of detection probability. No detection was made by the flat receivers.

no significant effect on %D (Table 1). However, day or night significantly affected %D, with %D being higher at night than during the day (Table 1 and Figure 4).

The frequency of the tidal height at the study area and the frequency of detection at estimated water depth were not independent (chi-square test: $X^2 = 143$, $df = 132$, p value $= 0.242$) (Figure 5). Between 200 and 320 cm depth, detection was made equally throughout water depths >2 m.

3.1.2 | Inside mangrove range test

Detections were recorded by the six receivers located closest to the transmitters, while all other receivers had no detections (Figure 6). The receivers adjacent to the transmitters (<20 m) had 40%–45%

TABLE 2   Analysis of deviance table for the inside range test.

Best model: %D ∼ day or night + distance + zone + (1|receiver)

	Chi-square	df	p value
Day or night	13.9686	1	<0.001
Distance	14.0604	1	<0.001
Zone	2.4405	2	0.2952

detection probability (%D) and the detection range was ∼15 m (Figure 6). Receivers located >20 m from the transmitters had very few or no detections. Detection probability was significantly affected by distance and day or night but not by zone (Table 2 and Figure 7). %D was higher when the distance was smaller and during the day than at night inside mangroves (Figure 7).

3.1.3 | Receiver event data

The event data results differed between inside (middle and rear) and outside (reef flat and edge) mangrove receivers (Figure 8a–c). Overall, inside mangrove zones showed low rejection rates and reasonably high code detection efficiency, while the outside mangrove zones showed greater noise, low rejection rates, and lower code detection efficiency.

Daily code detection efficiency (CDE) was significantly different between the mangrove rear and the other three zones, where overall CDE was lower in the rear mangrove zones than the other three zones (analysis of deviance type II Wald chi-square test: $X^2 = 18.727$, $df = 3$, $p < 0.001$) (Figures 8a and 9a). Daily rejection coefficient (RC) was low in all four zones and less than 2.5% of codes were rejected due to invalid checksums (Figure 8a). This indicates that there were very few transmitter collisions throughout the study. RC was
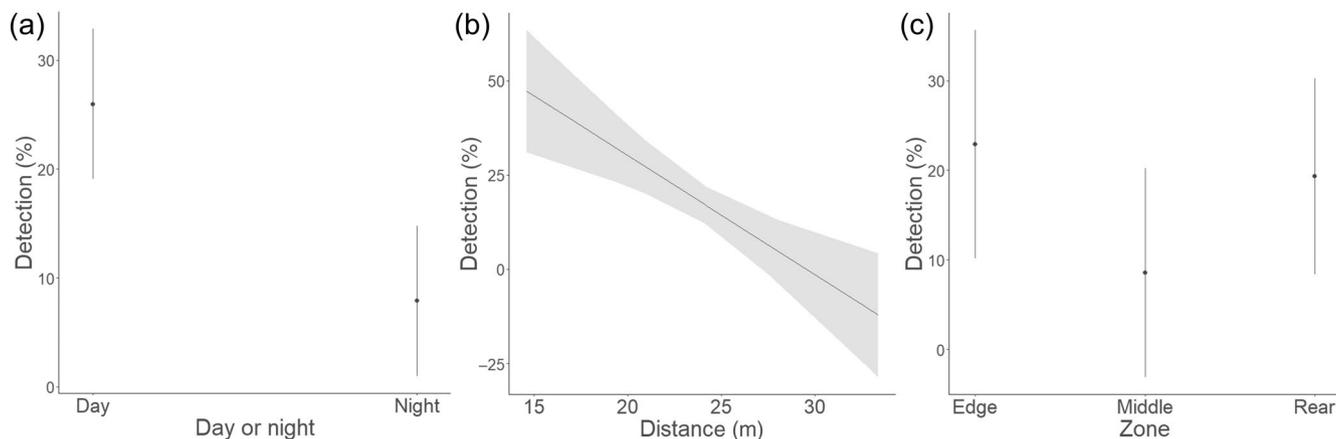
FIGURE 7 Predicted detection probability (a) between day and night, (b) distance, and (c) zones for the inside mangrove test.
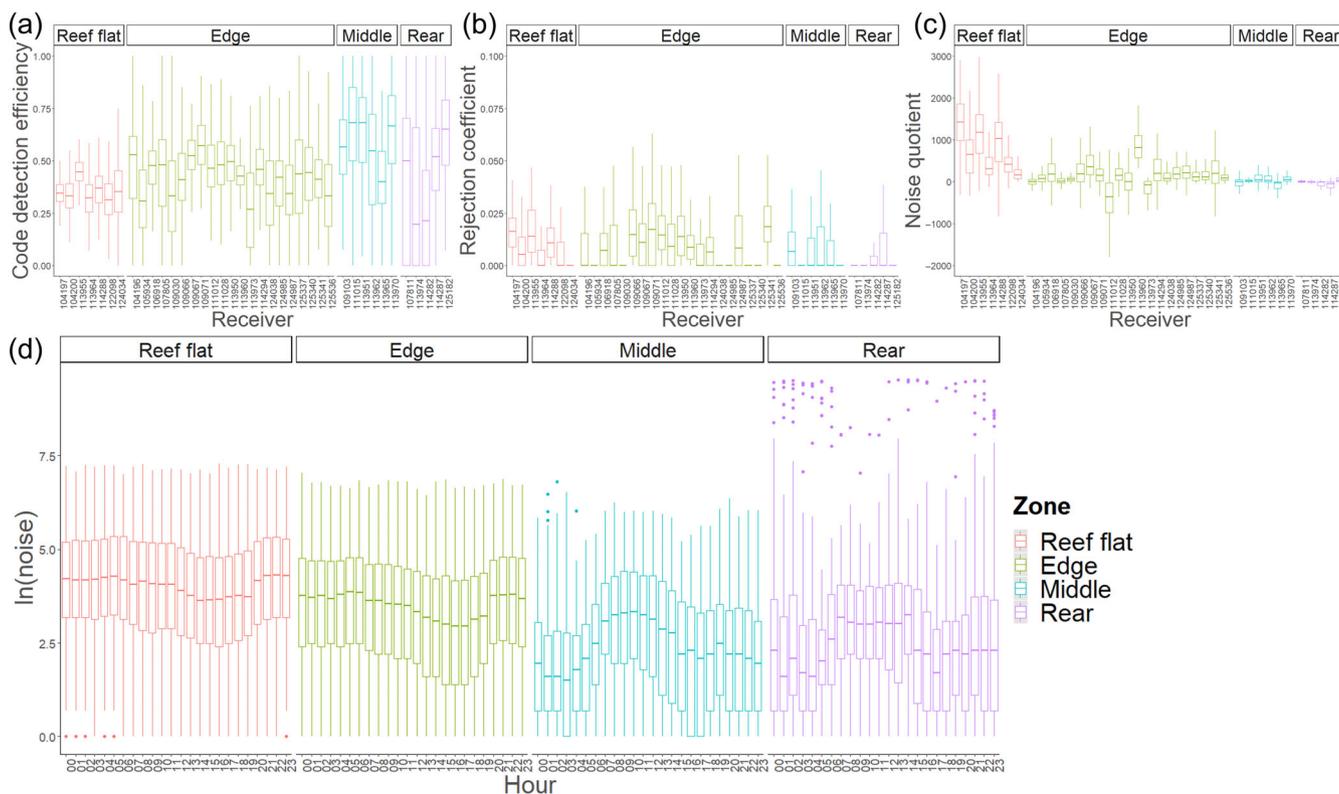

FIGURE 8 Results of receiver performance. (a) Daily rejection coefficient, (b) daily code detection efficiency, (c) daily noise quotient by receivers, and (d) hourly noise quotient (log-transformed). (a–c) are presented by different receivers. (d) demonstrates noise quotient by time of the day.

significantly different among the zones, but the effect was small (analysis of deviance test: $X^2 = 8.4106$, $df = 3$, $p = 0.038$) (Figure 9b). RC was lower in the mangrove rear than the other three zones (Figure 9b). Daily noise quotient (NQ) values were significantly different among the four zones (Table 3 and Figure 8c). Daily NQ was the highest in the reef flat zone, followed by the edge and the middle, and was lowest in the mangrove rear zone (analysis of deviance test: $X^2 = 98.835$, $df = 3$, $p < 0.001$) (Figure 9c).

Hourly NQ data showed two distinct patterns (Figure 8d, log transformed), where the noise at the reef flat and edge mangrove zone declined from 12 to 5 pm before gradually increasing again, while the inside mangrove zone increased around 5 am and declined around midday. There was a significant interaction effect between hour and zone on hourly NQ (Table 3) and hourly NQ was overall highest at the reef flat, low in the middle and rear zones, both fluctuating similarly throughout the day (Figure 9c). Hourly NQ values in the
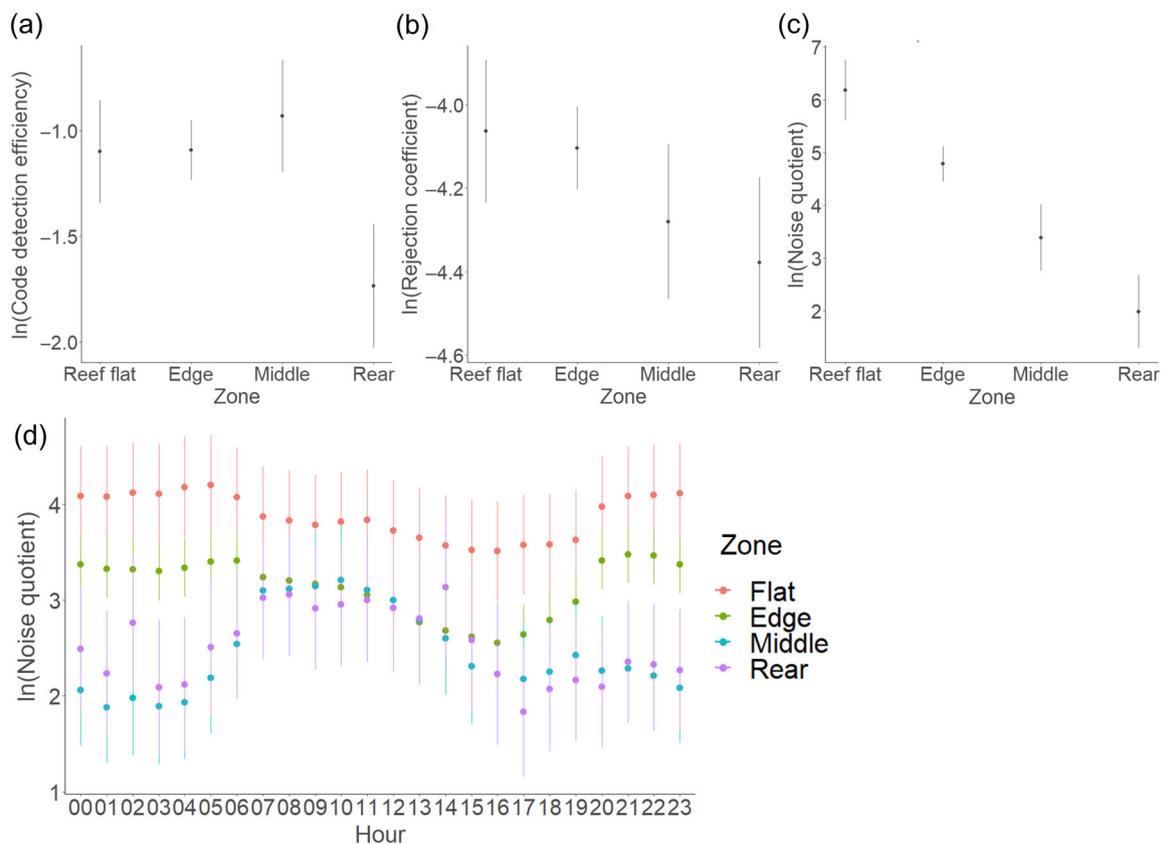
FIGURE 9   Predicted values of (a) daily rejection coefficient, (b) daily code detection efficiency, (c) daily noise quotient by receivers, and (d) hourly noise quotient based on linear mixed-effect models. Values are log-transformed for analysis.

TABLE 3   Analysis of deviance test results for hourly noise quotient.

	Chi-square	df	p value
Zone	17.046	3	<0.001
Hour	3429.848	23	<0.001
Zone × hour	2021.06	69	**<0.001**

Note: Bold value indicates statistical significance.

mangrove edge moved between the reef flat and the middle and rear mangrove zones (Figure 9c). The data inside mangroves (middle and rear) need to be treated with caution as the sample size was small and few detections were made by close receivers, as stated above.

3.1.4 | Animal application

A blacktip reef shark and a mangrove whipray were successfully tagged and tracked between December 7, 2020 and May 24, 2021, and December 8, 2020 and December 7, 2021, respectively. The acoustic receivers at the reef flat, edge, middle, and rear mangrove zones successfully detected tagged animals. The trajectories of a juvenile shark (blacktip reef shark, 671 mm total length, female) and juvenile stingray (mangrove whipray, 325 mm disc width, male) were mapped for 1 day for the shark and four consecutive days for the stingray due to the difference in activity levels of these animals. The trajectories demonstrated that both were detected by the middle and rear receivers at the south mangrove stand (Figure 10a,b). The shark roamed over the reef flat, repeatedly swimming near the south mangrove edge and occasionally visiting middle and rear mangrove areas (Figure 10a,b). Examination of the timing of these events showed that the use of the middle and rear mangrove areas occurred during the high-tide periods of the presented days. The trajectory of a juvenile stingray demonstrated frequent use of rear mangrove zones (Figure 10c,d).

4 | DISCUSSION

This study demonstrated that acoustic receivers can be used for tracking animals where dense mangrove roots are present. As expected, dense mangrove roots and trunks blocked signal transmission (e.g., Claisse et al., 2011; Thiemer et al., 2022), resulting in only very short detection ranges for receivers deployed within the mangrove habitat. Receivers only logged at least 50% of detections from a transmitter when it was located within 20 m. When the distance between the transmitter and the receiver was more than 20 m in mangrove habitat, detections were rare. While detection ranges in the
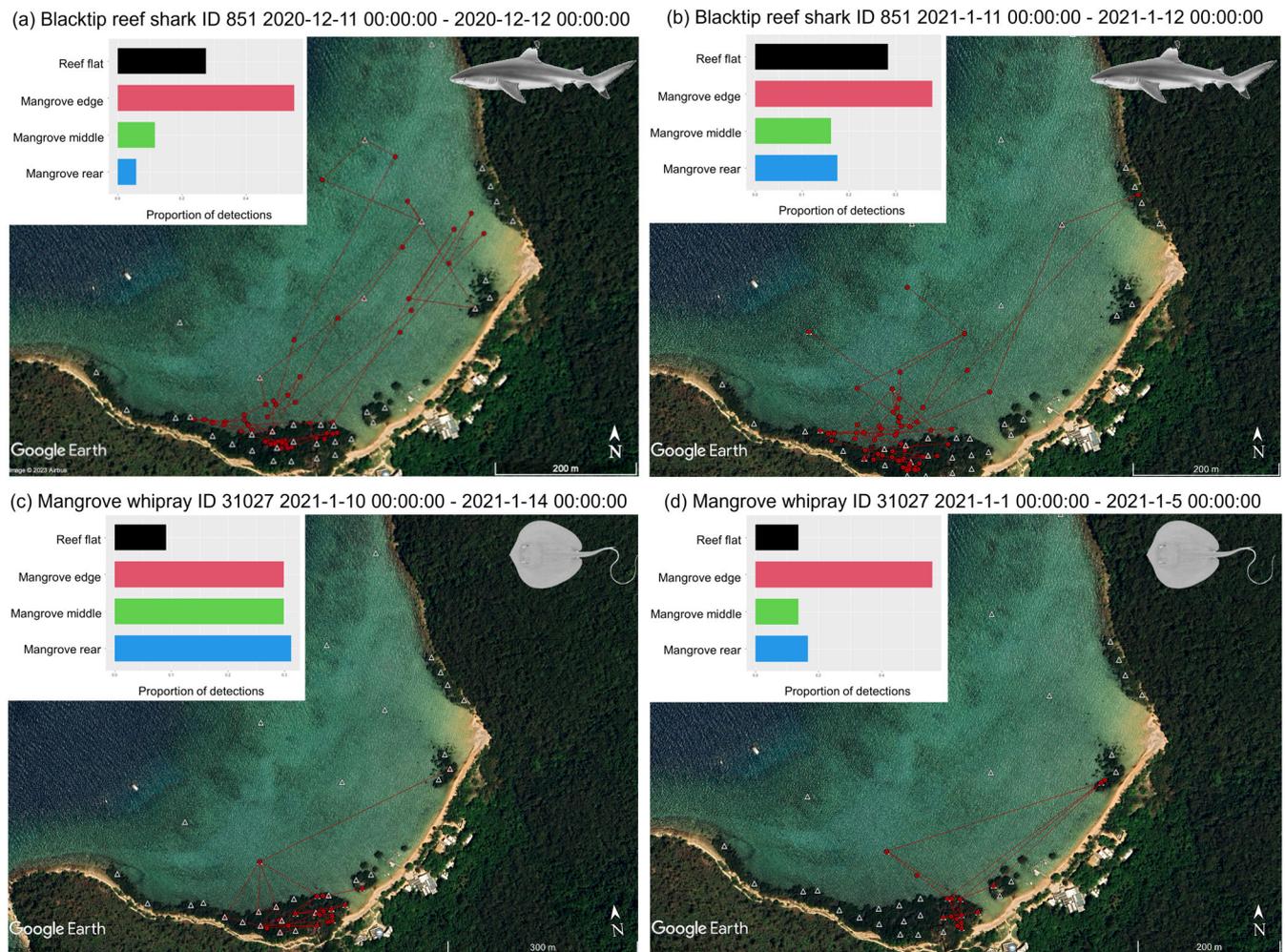
FIGURE 10 Trajectories of tagged animal movement and bar graphs of the proportion of detections in the four different zones. Blacktip reef shark (ID 851) (a) from December 11, 2020 to December 12, 2020 and (b) from January 11, 2021 to January 12, 2021. Mangrove whipray (ID 31027) (c) from January 10, 2021 to January 14, 2021 and (d) from January 1, 2021 to January 5, 2021. △ represents acoustic receivers.

mangrove habitat were small, placement of receivers in a dense array (mean distance between adjacent receivers = 19.1 m) enabled the reception of many signals from transmitters and thus facilitated the tracking of animals inside the mangrove habitat. Very local detection, as in this situation, is an advantage for animal tracking because if the transmission from the tagged animal was detected there is a high probability it was present within a small area, and hence its location is known with a relatively high level of accuracy.

The detection range of acoustic receivers is expected to be small in topographically complex environments, such as vegetated and coral reef habitat. As expected, the detection range inside mangrove habitats in this study (i.e., ∼20 m) is comparable to those reported from shallow seagrass, macrophytes, and coral reef environments (Table 4). For example, Swadling et al. (2020) tested the detection probability and detection range among the seagrass canopy and found that the detection range was up to 40 m. Similarly, Weinz et al. (2021) and Thiemer et al. (2022) conducted range testing in two macrophyte habitats and the detection range was less than 8 and 20 m, respectively. Welsh et al. (2012) conducted acoustic receiver performance tests in

a shallow (∼5 m deep) coral reef at the same bay at Orpheus Island (a little farther offshore) and reported the detection range was as low as 60 m. Such small detection ranges are caused by low detection probability, and there are several possible factors that could lead to poor detection probability in mangrove habitats. First, signal blockage by physical structure was likely a major factor affecting detection probability as there were many obstacles (i.e., mangrove trees) between the transmitter and most receivers (Selby et al., 2016; Weinz et al., 2021). Second, water depth is an important factor for conducting acoustic telemetry; in very shallow water, acoustic signals do not travel far, resulting in low performance (Claisse et al., 2011; Cooke et al., 2013). Threshold water depth that acoustic signals can travel and be detected properly varies in the study site, and this study demonstrated that when tidal height was greater than 2 m and mangrove habitats were flooded, the detection probability was not affected by tidal height. Finally, reef environments are known to be quite noisy and environmental noise can interfere with the detection ability of acoustic receivers (e.g., Welsh et al., 2012), hence the proximity to the reef environments in this study may have affected acoustic receiver

TABLE 4 Comparison of the detection range between shallow structurally complex habitats.

Reference	Habitat type	Transmitter placement condition	Detection range (m)
Swadling et al. (2020)	Seagrasses	Above seagrass canopy	85
		Within seagrass canopy	40
Weinz et al. (2021)	Macrophytes	Highest SAV density	7.85 ± 1.98
		Lowest SAV density	196.08 ± 51.89
Thiemer et al. (2022)	Macrophytes	Not applicable	17.26 ± 0.74
This study	Mangroves	Inside mangroves	20
	Reef flat	Outside of mangroves	100
Claisse et al. (2011)	Coral reefs	5–10 m deep	30
		10–15 m deep	40
		15–20 m deep	50
Welsh et al. (2012)	Coral reefs	<5 m deep	60

Abbreviations: NA;SAV, submerged aquatic vegetation.

performance in the adjacent mangrove systems. It may also be possible that the mangrove habitat is noisy, but this has rarely been tested. The results of the NQ analysis suggest that the mangrove habitat was less noisy than the reef flat habitat, but further research is needed to understand the noise environment within mangrove habitats.

In mangrove edge and reef flat (i.e., outside mangroves) habitats, the detection range was up to 120 m when there were no obstacles between the transmitter and the receivers. One receiver located 120 m away from the transmitter in the reef flat zone had a detection probability greater than 50% during the 1-month test where the transmitter was located on the edge of the mangrove habitat. There were no major obstacles between this receiver and the transmitter, resulting in an exceptionally high detection probability in the reef flat zone. Other than this receiver, detections were not received even when the distance was less than 100 m because thick mangroves were present between the receiver and the transmitter, and the transmission was blocked as such. In dense mangrove habitats, the distribution of vegetation (or any kinds of obstacles in the study area) influences the detection range more than the distance between transmitter and receiver does. In some contexts, the density of vegetation and the structural complexity of habitat may matter more than distance. In addition, shallow water depth and the topography of the reef flat might affect detection efficiency (e.g., Cagua et al., 2013). The detection range in this study for both inside and outside mangrove habitats was much smaller than that in open water or estuarine river systems, for example ∼450 m in an estuarine river system in Simpfendorfer et al. (2008), ∼650 m in open water in Huveneers et al. (2016), and ∼950 m at an offshore reef atoll in Meyer et al. (2010). These findings suggest that detection range is fundamentally different depending on environmental factors such as topography, habitat type, and water depth, and therefore the range test prior to the animal tracking is essential to interpret the tracking and monitoring data (e.g., Matley et al., 2022).

Detection probability during testing was different between day and night. In the present study, outside and inside mangrove tests showed the opposite pattern between day and night. In the outside experiment, detection probability was higher at night than in the day, whilst in the inside experiment it was higher during the day. Diel patterns in detection probability have been observed by several studies. For example, some studies have reported that detection frequency drops with the onset of sunset and stays low at night until increasing at sunrise (e.g., Payne et al., 2010; Stocks et al., 2014), and attributed this pattern to an increase in biological noise at night that interfered with signal transmission and detection. In contrast, Welsh et al. (2012) found no diel pattern in detection probability in the coral reef environment in Pioneer Bay. Although this field study could not identify the potential causes of this diel pattern in detection, one possible explanation is the difference in daily fluctuation in environmental and biological noise (background noise) between reef flat and mangrove habitats due to physical context (e.g., open vs. sheltered) and biological differences (e.g., faunal composition). Importantly, the comparison between the inside and outside tests should be treated with caution because of the difference in study durations (2 days vs. 1 month) and the number of detections (much fewer detections inside mangroves than outside).

The performance metrics of acoustic receivers were tested for the first time in a mangrove habitat and were characterized by low background noise and low rejection rates (i.e., middle and rear mangrove zones). In this study, less than 2.5% of codes were rejected due to an invalid checksum, indicating that there were very few transmitter collisions (e.g., Simpfendorfer et al., 2008). Noise analysis results suggest that inside mangroves (i.e., the back and middle zones) was a less noisy habitat than outside mangroves (i.e., the reef flat and mangrove edge zones). Noise in the reef flat zone was especially high compared to the other zones, which is not surprising as the coral reef environment is very noisy (Welsh et al., 2012), and as such the total number of detections was most likely to be lower than the synch codes transmitted by the transmitter due to noise, resulting in low code detection efficiency. Inside mangrove zones, in contrast, was less noisy and showed higher code detection efficiency than that from the reef flat and mangrove edge receivers. Lack of noise in mangrove zones possibly occurs because mangrove trees block noise from the outside, such as wind, rain (Gjelland et al., 2013), and waves (Stocks et al., 2014), and therefore the water surface was calmer inside mangroves. In addition, the mangrove habitats were located away from

the noisy reef. Thus, the results of receiver performance metrics support the use of acoustic receivers in mangrove habitats. As this experiment demonstrates, codes sent from the transmitters were detected with high code detection efficiency, low rejection rates, less noise, and virtually no signal collision inside mangrove habitats as long as the transmitter was nearby.

Diel variation in the degree of noise was found to be different in the inside and outside mangrove habitats. In the outside mangrove zone, noise was relatively higher throughout the day except in the late afternoon and evening (between 2 and 8 pm), when the level of noise dropped. This is somewhat contradictory with the findings by Payne et al. (2010) and Radford et al. (2008) that biological noise increased at night in reef environments. Inside mangroves, the level of noise increased in the morning after sunrise until midday and then dropped and stayed low outside of those hours. It is difficult to explain why we observed this pattern in noise inside and outside mangroves in the current study, but there was likely to be unknown factor(s) causing the daily noise pattern. Patterns in diel noise difference are likely to vary significantly between systems (reef vs. non-reef) and possible causes of this diel pattern in noise could be animal activity and surface water movement (Gjelland et al., 2013; Payne et al., 2010). Future research should examine the source of background noise inside mangroves to examine what possible effect it may play in acoustic receiver performance.

The range-testing data from the inside mangrove test need to be treated with caution because of the short duration of range testing (2 days). Although the data demonstrated a general pattern of short detection range inside mangroves, future research with longer duration (at least 2 weeks) would be beneficial to assess more detailed information. In addition, the receiver deployment method is known to affect receiver performance (Heupel et al., 2006; Huveneers et al., 2016). Although this needs future research in mangrove habitats, this study demonstrated the effectiveness of the deployment method we used because some receivers recorded more than 90% of signals that arrived at the receiver and previous research has been successfully conducted using the same deployment method (Schlaff, 2020). Biofouling on the receiver, which is another major factor that negatively affects the receiver performance (Heupel et al., 2008), had negligible effects in this study because biofouling was minimal. Lack of biofouling may have been in part because of the regular drying of receivers at low tide, which would have reduced the ability of fouling organisms to survive.

The results of animal tracking demonstrated that the receiver array was able to track tagged sharks and rays when they were present in areas well inside mangrove habitat, including in very shallow areas located in dense mangroves. Based on range test results, the detections by middle and rear mangrove receivers indicated the presence of individuals nearby (likely within 20 m), confirming that tagged sharks and rays were regularly roaming near the rear and middle receivers. Although the use of mangrove root habitat by stingrays and blacktip reef sharks in the study area was previously observed by active acoustic tracking (George et al., 2019; Martins et al., 2020), passive monitoring (Davy et al., 2015), and video observation (Kanno

et al., 2019), the present study revealed these species move farther into the dense mangrove areas and away from the edge habitat than previously thought. For the shark, the proportion of detections was generally higher at the reef flat and edge zones than the middle and rear mangrove habitats, presumably due to limited accessibility of mangrove habitats during low tide. The stingray was, in contrast, detected less in the reef flat zone likely because their flattened body shape allows mangrove whiprays to remain in very shallow water (less than 20 cm) at lower tidal levels and move much less than blacktip reef sharks (Davy et al., 2015; George et al., 2019; Martins et al., 2020), therefore they are rarely detected by reef flat receivers. Thus, acoustic receivers deployed in the different zones in mangrove habitats were able to reveal differences in the use of mangrove habitats between juvenile sharks and stingrays.

Importantly, acoustic receivers and transmitters were successfully used for monitoring the movements of sharks and rays within mangrove habitats in this study. Conducting the range test prior to the animal application allowed us to examine if the design of a receiver array in the mangrove system was appropriate and demonstrated a very localized detection range inside mangrove habitats. The receiver performance metrics identified low rejection rates and environmental noise, meaning that the acoustic receivers and transmitters functioned appropriately within a mangrove habitat as long as the short detection range was taken into account in the array design. Those test results gave strong support for how to interpret the data obtained from the animal tracking in mangrove habitats, and therefore the animal application test revealed the holistic movement of individuals within mangrove habitats. Future research using acoustic telemetry should reveal more detailed habitat use and movement patterns of aquatic animals, such as elasmobranchs, in mangrove habitats and help us better understand the role mangrove habitats play for nearshore species.

AUTHOR CONTRIBUTIONS

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