Towed-float GPS telemetry: a tool to assess movement patterns and habitat use of juvenile stingrays

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Abstract. GPS telemetry provides high-accuracy spatial data on animal movement; however, it has rarely been used with benthic organisms, such as stingrays, because of their irregular surfacing behaviour or bottom-dwelling habits. This study evaluated the use of towed-float GPS tags to assess movements of juvenile stingrays, with active tracking performed simultaneously for comparison. Four juvenile \textit{Urogymnus granulatus} individuals (2 females and 2 males; average 32.2-cm disc width) were tracked in April 2016. Individuals travelled 1332.15 ± 269.58 m south-east across Pioneer Bay at an average speed of 6.87 m min\textsuperscript{-1} in 3.7 h. Stationary tests demonstrated that the quality of the data obtained by towed-float GPS tags could not be matched by active, acoustic or ARGOS telemetry, reaching, on average, 99% of successful fixes and <15-m accuracy. Location error varied significantly based on the number of satellites detected, with error decreasing as the satellite number increased. This study demonstrated the potential of towed-float GPS telemetry for high-resolution assessment of movement patterns and habitat use of juvenile stingrays in shallow coastal water. If well applied, this technique can increase our knowledge of juvenile stingray ecology and their essential habitats.

Additional keywords: biotelemetry, elasmobranch, \textit{Urogymnus granulatus}.

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Introduction

Biotelemetry devices have become increasingly useful in assessing behaviour, energetics, physiology and ecological aspects of free-swimming marine animals (Cerutti-Pereyra \textit{et al.} 2014; Ogburn \textit{et al.} 2017). Recent improvements to tracking devices and systems have supported studies over broader spatial and temporal scales (Braun \textit{et al.} 2014; Bullock \textit{et al.} 2015; Heupel \textit{et al.} 2015). Modern devices have also been developed to go beyond simple animal movement, collecting data such as acceleration, magnetic fields, pH, water depth, temperature and salinity (Cooke \textit{et al.} 2004; Hart and Hyrenbach 2009; Browning \textit{et al.} 2018). The telemetry capabilities are rapidly improving, and size and price of this technology are reducing, hence, diversifying ecological research. Advances in telemetry not only improve our understanding of the biology of species, but can also help improve management (Hussey \textit{et al.} 2015).

A variety of biotelemetry methods have been used to track marine animals (Ajemian and Powers 2014). These include acoustic telemetry, where information is transmitted to moored or mobile receivers (Heupel \textit{et al.} 2006), satellite telemetry where locations of tags are estimated by satellite-based systems, and logger-based telemetry where data are stored for post-recapture processing (Hussey \textit{et al.} 2015). Some telemetry approaches combine more than one of these methods, especially to overcome the need to recapture animals to obtain stored data (Cooke \textit{et al.} 2016). The choice of telemetry approach for a particular study requires consideration of the aims, species, location and budget (Riding \textit{et al.} 2009). Species that occur in environments that challenge conventional telemetry equipment make study more difficult and may require innovative approaches. For example, species that occur in shallow structurally complex habitats make acoustic approaches difficult because of limited signal-transmission distances (Royer and Lutcavage 2008; Costa \textit{et al.} 2015), or those that live in the deep sea where tagging animals is difficult and the extreme pressures can damage equipment (Cooke \textit{et al.} 2013).

GPS telemetry is a biotelemetry approach that has been broadly and successfully employed to assess movement patterns of terrestrial and aerial animals (Sims \textit{et al.} 2009). This technology has reduced many of the bias and precision issues often reported in other telemetry methods, such as acoustic and ARGOS-based satellite telemetry (Hebblewhite and Hayden 2010). However, GPS-telemetry devices for marine animals have historically been large and heavy, drastically reducing their use. In addition, tracking marine animals with GPS loggers has proved challenging, because of irregular-surfacing behaviour or bottom-dwelling habits that limit data acquisition.
(Schofield et al. 2007). Recently, terrestrial ecologists developed very small data-logging GPS tags for use on birds and small mammals (Ryan et al. 2004). This advancement also supported the use of GPS telemetry for smaller marine species because of sophisticated systems that allow prompt recording of GPS locations when individuals surface or move close to the surface (Sims et al. 2009). Despite significant improvements in size, weight, accuracy and precision, the need to recover GPS loggers to obtain data remains an issue. The need to recover loggers has meant that this technology has not been widely adopted to assess movements of organisms with low recapture rates, such as stingrays.

Recent global analysis identified stingrays (superorder Batoidea, order Myliobatiformes) as one of the most endangered families of elasmobranch (Dulvy et al. 2014). Unsustainable by-catch, habitat destruction and changes in climate are rising threats for stingrays around the world (Chin et al. 2010). Worrisomly, stingrays are highly susceptible to these human pressures mainly because of their life-history features, such as low fecundity, late sexual maturity and slow growth (Stevens 2000). Therefore, a better understanding of stingrays’ activity patterns through the use of non-lethal biotelemetry techniques is essential for effective management and conservation of the group (Papastamatiou and Lowe 2012).

Stingray anatomy and behaviour are a consideration in decisions about which telemetry techniques to use. This is particularly true for juveniles. In some species, their small size and dorso-ventrally flattened body (Last et al. 2016) hamper the attachment of large loggers or telemetry devices (Grusha and Patterson 2005). In addition, juvenile stingrays often inhabit shallow and muddy waters, which hinders the use of acoustic telemetry (Heupel et al. 2015). Blaylock (1990), Le Port et al. (2008), Riding et al. (2009), Ajemian and Powers (2014) and Branco Nunes et al. (2016), for example, used satellite telemetry to assess movement patterns of batoids. However, these studies used large stingray (short-tailed stingray, *Dasyatis breviceps*; southern stingray, *Dasyatis americana*) and pelagic myliobatid ray (cownose ray, *Rhinoptera bonasus*; New Zealand eagle ray, *Myliobatis tenuicaudatus*; spotted eagle ray, *Aetobatus narinari*) species that were capable of carrying large telemetry packages. Such an approach is not appropriate for juvenile stingrays. Nevertheless, the occurrence of juvenile stingrays in shallow water, and the shrinking size of GPS logger tags, means that they may be able to tow a small tag in a float to provide position estimates, much like eagle rays did in the study of Riding et al. (2009).

No study has attempted to use GPS logger telemetry for juvenile stingrays. If suitable, this methodology would enable longer tracks, collect greater amounts of high-accuracy location data, reduce labour costs and reduce observer-induced behaviour biases. In some situations, it may also allow data collection beyond the ability of human observers, such as, in difficult-to-access areas, limiting weather conditions, and over long distances. Thus, the present study aimed to evaluate the performance of GPS loggers attached to floats (towed-float GPS tags) as an effective, accurate, minimally invasive and less labour-intensive tool to assess fine-scale movement patterns and habitat use of juvenile mangrove whiprays, *Urogymnus granulatus*.

**Materials and methods**

**Study area**

Orpheus Island is located in the central region of the Great Barrier Reef, within the Palm Island Group. The island stretches for 12 km and comprises 1368 ha. Pioneer Bay is one of several bays on the western side of Orpheus Island. This bay has an open water area strongly influenced by tidal variation. Tides in Pioneer Bay are semi-diurnal (Parnell 1986) and meso-tidal, reaching a maximum of 3.5 m at high tides. The 400-m-wide Pioneer Bay (0.8 km² of open water area) is composed of a reef flat (Parnell 1986) and living corals along the seaward edge (Hopley et al. 1983). The inner reef flat consists of sand, coral rubble and abundant dead micro atolls. Living corals can be observed on the outer reef, ~100 m from cemented beach deposits. A small area of mangrove (red mangrove, *Rhizophora mangle*; white mangrove, *Avicennia marina*; and myrtle mangrove, *Osbornia octodonta*) is located in the southern inner reef flat.

**Study species and catching methods**

The mangrove whipray, *Urogymnus granulatus* (family Dasyatidae), is a large-bodied stingray (up to 141-cm disc width) widely distributed in the tropical waters of the Indo-West Pacific region. Juveniles are found in shallow, turbid coastal waters, especially in mangroves and estuaries. Unfortunately, there is little information in the scientific literature pertaining its life history, spatial ecology and population dynamics.

Juvenile mangrove whiprays are common benthic inhabitants of sandy and mangrove habitats of Pioneer Bay (Davy et al. 2015). Individuals were captured under mangrove roots or on shallow sandy and reef flat areas of Pioneer Bay by using seine or dip nets, between the 25 and 27 April 2016. Once captured, stingrays were measured (disc width, DW), sexed and tagged with a uniquely numbered spiracle tag (Fig. 1a). Date, location, and time of capture and release were recorded. None of the procedures took longer than 5 min.

**GPS device**

GPS logger tags (Lotek, Wireless PinPoint Beacon 120) were used for this research. Loggers were customised to suit the project goals, i.e. they were waterproofed, weighed 20 g (5% of estimated juvenile stingray of 400 g) and measured 40 × 16 × 10 mm (L × W × H). A lightweight and flexible antenna was attached to each tag to allow detection of GPS satellite signals (Fig. 1b). Tags could record up to 1500 location attempts and their rechargeable nature allows their long-term re-use when recaptured. Each tag had a programmable schedule that defined the interval of location recording. An embedded Lotek radio beacon enabled tag relocation after a programmed period. Recorded data were downloaded from recovered tags by using Lotek Wireless PinPoint Host software.

**Accuracy and precision of the GPS device**

Stationary trials were performed to test the accuracy and precision of tags in determining locations across Pioneer Bay. Several locations were chosen as test areas and divided into the following three categories: (1) fixed points above water with a
clear view of the sky (Uncovered), (2) fixed points in mangrove trees to simulate when stingrays moved into or adjacent to mangrove habitats (Covered) and (3) on tethered float-mounted GPS device to simulate animal tracks (Float). It is important to point out that, during Float tests, the accuracy was expected to be less certain than for fixed-station tests, because tethered floats could move 1–2 m from a central point of attachment, depending on the tide and wind. Devices were set to record one location every 5 min and left in place for 12 h, i.e. one full GPS satellite constellation cycle. The true location of each fixed station was taken with a hand-held GPS Garmin GPSMAP 78sc (accuracy to 10 m from the true location).

To determine the performance of each device at each location, the following factors of positional accuracy and precision were measured: (1) the fix success rate (FSR), i.e. attempts that successfully acquired a location (proportion of the total amount of fixes, \( n = 145 \)); and (2) location error (LE), i.e. the linear distance between fix position recorded by the loggers and the true location. Each of these metrics depends on the number of satellites and their geometric configuration at the time of computing a GPS point. A minimum of four satellites was needed to record a three-dimensional (3-D) fix and the adoption of dilution of precision (DOP) filters, which is a metric that expresses the precision of a successful location fix, was necessary for an indication of good satellite geometry. In this study, locations were validated if they were based on at least four satellites (Sea Mammal Research Unit SMRU, http://smub.st-and.ac.uk, accessed 25 November 2018; Schofield et al. 2007) and had a DOP values of <10 (Adrados et al. 2002). To assess the impact of these factors on the FSR and LE, data were assessed in both raw and filtered form (detailed below). By quantifying the FSR and LE in stationary trials, a baseline reference was established to determine the relative accuracy of the towed-float GPS tags.

**Accuracy of float-mounted GPS devices**

Stability, buoyancy, relative hydrodynamic drag and ability to avoid entanglement of different-shaped floats were tested in a salt-water tank before design finalisation. Small cone-shaped foam floats with a short lead keel showed the best results in these trials. The size and weight of the float were also considered to achieve minimum drag levels (~10 cm long and 40 g, 10% of the average body mass in air). The towed-float GPS device was attached to the spiracle tag of mangrove whiprays with 2-kg test monofilament fishing line, ~1.5 m in length. Once attached, each device was towed by the stingray throughout shallow reef-flat habitats (Fig. 2). Previous research by Davy et al. (2015) demonstrated that juvenile mangrove whiprays rarely entered water >0.5 m deep; so, they were not expected to pull the float below the surface. Tags were set to record locations once every 5 min. Tags were fitted during the falling tide and retrieved at high tide. Devices were recovered by cutting the fishing line when tracks were terminated. The ability of mangrove whiprays to remove the tag by themselves in the case of entanglement was tested during the second track, by letting the individual move into mangrove roots where they take refuge at high tides (A. P. B. Martins, unpubl. data). Active acoustic telemetry was performed simultaneously to the towed-float GPS telemetry for comparison purposes. Vemco V9 acoustic transmitters, measuring 21 mm in length, weighing 1.6 g in water and emitting signals every second at the frequency of 81KHz, were also attached to the spiracle tags of each individual. A Vemco VR100 acoustic receiver connected to a directional hydrophone was placed in a recreational kayak and towed by foot by an observer.
The movements of each tagged individual were recorded by the observer every 5 min by using a hand-held GPS. The distance between the observer and the tagged animal was only a few metres and, so, smaller than was the error associated with the hand-held GPS.

Data processing, screening and analysis

Date, time, latitude and longitude were recorded every 5 min with the GPS logger. Raw data from the GPS tags provided a time-series of successful and unsuccessful fix attempts, while additionally reporting the number of satellites used in computation and the corresponding DOP values. Only fixes taken at the same time by active and GPS tracking tags were included in the analysis, reducing uncertainty in the distance between the real and estimated points. So as to estimate the LE, latitude and longitude values were projected onto UTM coordinates (Zone 55). Data points were screened to remove significant outliers (i.e. LE > 250 m, n = 1). Furthermore, positional fixes were analysed in both a raw (unfiltered) and filtered (number of satellites of ≥4 and DOP of <10) form to explore the effects of satellite number and constellation geometry on the performance of the tags.

Stationary tests

The effects of applying filters to the data were tested by calculating differences in the mean LE for each treatment by using a Welch’s t-test to account for the unevenness of sample sizes. A one-way ANOVA was performed to look at the differences in LE among treatments. Values of LE were log-transformed to meet assumptions of normality. To evaluate differences in the number of satellites among treatments and how LE varied with the number of satellites, Kruskal–Wallis non-parametric tests were utilised because of violations in the assumptions of normality. A Tukey’s honest significant difference (HSD) test was also utilised to provide multiple pairwise comparisons among the means of the treatments.

Tracks

The distance and speed of each individual were calculated by, first, estimating the linear distance between each positional fix and then dividing by the time interval between each fix (5 min). Location errors between hand-held GPS units and GPS tags were estimated to assess the accuracy and precision of float-mounted GPS devices. Each successful position fix was also categorised into two different habitat types (mangrove and reef flat) by overlaying each GPS track with a satellite image of Pioneer Bay; successful fixes were considered to be in mangroves only if they were contained within mangrove areas. Welch’s t-tests for unequal variances were performed to evaluate differences in the mean LE among habitat types.

This study was conducted under Great Barrier Reef Marine Park Authority Permit G15/37987.1 and James Cook University Animal Ethics Permit A2310.

Results

Accuracy and precision of the GPS loggers

Unfiltered v. filtered datasets

In total, 24 stationary tests were performed between 25 and 27 April 2016 (Uncovered = 10, Covered = 11, Float = 3). Accuracy and precision of GPS loggers varied significantly between unfiltered and filtered datasets (Table 1). For example, LE and DOP values decreased by 22 and 125% respectively, from unfiltered to filtered datasets. The FSR also decreased from unfiltered to filtered datasets. The average number of connected satellites increased by 16% when filters were applied. However, when the different treatments were considered, only Covered tests showed significant differences between unfiltered and filtered datasets. This result suggests an advantage of applying filters when tracking animals through covered habitats, such as mangroves. Thus, all further analysis was completed using the filtered dataset.

Stationary GPS logger tests

The FSR of GPS loggers followed expected trends across all treatment locations. Open areas, such as Uncovered and Float treatments, had a 13% increase in successful fix rates when compared with the Covered treatment (Float v. Covered and Covered v. Uncovered, Tukey’s HSD, P < 0.001) (Table 1). The number of satellites used ranged from four, the minimum necessary for computation, to 11, which is the maximum acquired throughout this study. The average number of satellites varied significantly among treatment locations (Kruskal–Wallis: χ² = 86.94, d.f. = 2, P < 0.001; Fig. 3a). Both Uncovered and Float tests had significantly higher FSRs than did the Covered treatment.

Values of DOP ranged from 0.6 to 9.4 (with 10 being the allowed maximum value) and, similar to previous trends, both Uncovered and Float tests recorded lower average DOP values (Float v. Covered and Covered v. Uncovered, Tukey’s HSD, P < 0.001; Fig. 3b). Although LE varied significantly among Covered, Uncovered and Float tests (ANOVA: F = 35.49, d.f. = 2, P < 0.001), the Float treatment recorded the lowest average LEs (7.75 ± 0.4 m) when compared with both Uncovered (12.2 ± 0.4 m) and Covered (13.4 ± 0.5 m) treatments.

Table 1. Summary of fix success rate (FSR), mean location error (LE) both with and without dilution of precision (DOP) filter for each treatment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Tests (n)</th>
<th>FSR ± s.e. (%)</th>
<th>LE (m; mean ± s.e.)</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filtered</td>
<td>Unfiltered</td>
<td>Filtered</td>
<td>Unfiltered</td>
</tr>
<tr>
<td>Uncovered</td>
<td>10</td>
<td>90.4 ± 0.03</td>
<td>99.5 ± 0.002</td>
<td>12.23 ± 14.66</td>
</tr>
<tr>
<td>Covered</td>
<td>11</td>
<td>66.2 ± 0.04</td>
<td>86.5 ± 0.02</td>
<td>13.43 ± 16.70</td>
</tr>
<tr>
<td>Float</td>
<td>3</td>
<td>81.5 ± 0.06</td>
<td>99.5 ± 0.001</td>
<td>7.75 ± 8.28</td>
</tr>
</tbody>
</table>

Note: * indicates significance at P < 0.001. s.e., standard error.
(Float v. Covered and Float v. Uncovered, Tukey’s HSD, $P < 0.001$; Fig. 3c). Thus, both open locations (Uncovered and Float) had the highest accuracy and precision from the GPS tags.

The LE also varied significantly on the basis of the number of satellites, generally decreasing as the satellite number increased, except at the highest numbers of satellites (Kruskal–Wallis, $\chi^2 = 206.87$, d.f. $= 7$, $P < 0.001$, Fig. 4). Location error decreased by 78% when fix locations decreased from nine to four satellites. In contrast, LE tended to increase when fix locations were acquired from more than nine satellites, most likely owing to the low number of recorded values (10–11 satellites; $n = 2$).

**Accuracy of float-mounted GPS device during stingray tracks**

Four juvenile mangrove whiprays (2 female and 2 males; average 32.2 cm DW) were equipped with towed-float GPS devices and tracked between 25 and 27 April 2016. All tracks were performed during the day. On average, each individual travelled 1332.15 ± 269.58 m (mean ± s.e.) across reef flat and mangrove habitats at an average speed of 6.87 m min$^{-1}$. The average duration of each track was 223.9 ± 36.4 min (mean ± s.e.; Table 2).

During tracks, the number of recorded satellites ranged from three to eight, with mean values for each track just over four satellites (Fig. 5a). As seen in stationary testing, LE tended to decrease with an increasing number of satellites. Mean DOP values differed among tracks, but were always low (Fig. 5b). Location error was significantly different
among tracks (Fig. 5c), possibly being related to differences in DOP values. Overall, the LE of individual locations ranged from <1 to 87 m during tracks (Fig. 6), yet, on average, remained consistent and did not vary significantly between mangrove and reef-flat habitats \( (t = 0.416, P = 0.678; \text{Fig. 7}) \).

### Discussion

The results of the study have demonstrated that towed-float GPS tagging is a useful tool in studying the movements of juvenile stingrays, such as mangrove whiprays, that live in shallow water. Float-mounted devices allowed GPS tags to maintain the connection to satellites during the entire period of

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**Table 2. General information of each track**

<table>
<thead>
<tr>
<th>Track</th>
<th>Sex</th>
<th>DW</th>
<th>Date of track</th>
<th>Duration of track (h)</th>
<th>Distance of track (m)</th>
<th>Speed (m min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>F</td>
<td>32</td>
<td>25 Apr. 2016</td>
<td>5:41</td>
<td>1817.7</td>
<td>6.99</td>
</tr>
<tr>
<td>B</td>
<td>M</td>
<td>35</td>
<td>26 Apr. 2016</td>
<td>4:03</td>
<td>1783.9</td>
<td>8.49</td>
</tr>
<tr>
<td>C</td>
<td>F</td>
<td>30</td>
<td>26 Apr. 2016</td>
<td>2:50</td>
<td>486.88</td>
<td>3.04</td>
</tr>
<tr>
<td>D</td>
<td>M</td>
<td>32</td>
<td>27 Apr. 2016</td>
<td>2:30</td>
<td>1240.1</td>
<td>8.85</td>
</tr>
</tbody>
</table>

**Fig. 5.** Performance of GPS tags during tracking of juvenile mangrove whiprays (Tracks A, B, C, D). Mean (a) number of connected satellites, (b) dilution of precision (DOP) values and (c) location error (m). Error bars show ± standard error.
tracking and reached 99% of successful fixes, which is higher than the 90.5% recorded by Riding et al. (2009) for tracks of eagle rays. When compared with active acoustic telemetry, GPS tags provided very similar location estimates. The average difference in location per fix was $\leq 15$ m, fitting well within the average of modern GPS loggers (10–28 m; Hansen and Riggs 2008).

Stationary tests helped evaluate the performance of GPS tags before attachment to the study species (Frair et al. 2010). Tests showed that reef-flat areas generally acquired a higher number of satellites and more successful fixes, and were, therefore, the areas that were likely to produce the highest accuracy and precision for the GPS tags in Pioneer Bay. Negative effects of mangrove canopy cover on the GPS-logger performances, such as reduced location precision and fix rates, were observed. Frair et al. (2010), Webb et al. (2013) and Forin-Wiart et al. (2015) found similar decreases in location data quality because of the interference of thick canopy cover over GPS devices. To minimise this aspect during tracks, mangrove whiprays were tagged during the falling tide, when they move out of mangrove habitats, and retrieved at high tide, when they return to mangrove patches and tags tangled on mangrove roots. In addition, results showed that the application of filters had no significant influence on data recording for loggers located in the reef flat; however, these filters were essential to ensure accurate results for areas with canopy cover. Thus, filters were demonstrated to be effective tools to improve location accuracy and essential

Fig. 6. Towed-float GPS-logger tracks from four individual juvenile mangrove whiprays across the reef flat and mangrove habitats in Pioneer Bay, Orpheus Island. Circles indicate size of location error at each positional fix taken every 5 min and are sized relative to map scale.

Fig. 7. Mean location errors of towed-float GPS loggers between different habitats: mangrove (covered) and reef flat (uncovered). Error bars show ± standard error.
when assessing movement patterns of species such as mangrove whiprays that use covered habitats.

During tracks with filters applied, LE values were consistent and did not vary significantly between reef-flat and mangrove habitats. Although canopy cover influenced accuracy and precision of data recorded during the stationary tests, during tracks, the largest LEs were surprisingly found in open areas. The number of satellites per recorded fix turned out to be the major negative factor in data recording. Additional research is required to fully understand this aspect.

The developed float device showed adequate stability, buoyancy and retention of the GPS logger. The chosen length of the monofilament, first adopted by Sims et al. (2009), facilitated continuous communication between GPS loggers and satellites, and reduced the drag forces on the attachment point that could possibly have affected mangrove whipray movements. Thus, the attachment of a towed-float device proved effective for slow-moving mangrove whiprays in Pioneer Bay, corroborating results found by Riding et al. (2009) and Sims et al. (2009), who also obtained high-quality results for low-speed rays. Our results reinforced those of previous studies because data showed that juvenile mangrove whiprays usually swim at a low speed unless disturbed.

The use of towed-float GPS tags on mangrove whiprays has three potential disadvantages. The first disadvantage is the stress in response to the attachment of tags (Weimerskirch et al. 2002). The towed-float GPS device was developed to cause minimal damage and stress. Individuals showed a short-term reaction to capture and tagging procedures, with some moving away from the capture point and others resting immobile at the site of release (A. P. B. Martins, unpubl. data). However, all tagged individuals maintained speeds (mean 6.7 m min\(^{-1}\)) similar to those observed by Davy et al. (2015; mean 5–6 m min\(^{-1}\), depending on tide), suggesting that the towed float had little effect on their regular movement. So, it appears that tagging stress was minimal and did not have lasting effects. The second disadvantage is the possibility of entanglement on mangrove roots, rocks and coral reefs (Gifford et al. 2007). This problem was solved through the use of a 2-kg monofilament as the tether connecting the towed-float device to the stingrays. In case of entanglement, the line broke easily, causing minimal damage to the animal and reducing the stress of recapture for tag removal. However, this also meant that movements could not be fully investigated by this methodology at high tide (e.g. how far do they move on high tides). A combination of methodologies is needed to address this issue. Finally, the method may not provide sufficiently accurate results to answer research questions. Estimation of LEs is essential for evaluation of any telemetry method (Royer and Lutcavage 2008). In the present study, the average distance between the true and predicted locations was 12.1 ± 0.28 m, which is within the average precision of modern GPS loggers (10–28 m) established by Hansen and Riggs (2008). This result provided a sufficient level of precision to estimate fine-scale habitat-use patterns and swimming speeds of tagged juvenile mangrove whiprays.

Despite the above-cited potential issues, the quality of the spatial data obtained with GPS tags in Pioneer Bay could not have been replicated with such accuracy by other conventional telemetry methods. Human resources and bias, tidal cycles and night periods, for example, limit active tracking. Meso-scale tides and the shallow and sandy characteristics of Pioneer Bay hamper the use of passive acoustic telemetry. This was confirmed by Davy et al. (2015), who used passive acoustic telemetry to track mangrove whiprays at Orpheus Island and obtained low spatial accuracy because of environmental conditions, and Welsh et al. (2012), who identified the detection range for 9-mm transmitters as being low within Pioneer Bay, namely, ~60 m, which is only a fraction of the reported range in deeper, less complex habitats. Mangrove whipray benthic habits could negatively affect the capability of ARGOS-based systems in recording high-accuracy data (tens of metres) and could never achieve similar temporal resolution because of the limited number of satellite overpasses in the tropics (Riding et al. 2009). Archival geolocation tags and pop-up satellite archival tags (PSAT) would not be useful to assess movement of stingrays in small areas because of the large size of loggers and positional errors up to hundreds of metres for light-based geolocation (Svedäng et al. 2007; Hazel 2009; Elston et al. 2015). Thus, towed-float GPS tags provide an excellent option for tracking the movements of small, limited-range animals in very shallow water for short periods.

Despite the small number of tracked animals, towed-float GPS tags showed potential to provide insight into juvenile mangrove whipray movements, which could be applied to similar species in other locations. In addition to the quality of the data obtained, this method was advantageous by allowing deployment of multiple towed-float GPS tags simultaneously, because no further monitoring is required after tag deployment (Riding et al. 2009). When well employed, the use of GPS loggers will enable the description of poorly known movement patterns, ontogenetic shifts, habitat preferences and essential habitats. As a result, the finer-scale data that GPS loggers provide in open habitats could have important application in studies that inform fisheries management and conservation, helping address interdisciplinary ecological issues and aid management decisions for essential habitats and threatened species (Schofield et al. 2007; Hart and Hyrenbach 2009).

**Conclusions**

This study has demonstrated the potential of towed-float GPS telemetry for assessing geographical extent, movement patterns, site fidelity, spatial dynamics, habitat preferences and behaviour data of juvenile stingrays over short periods. Use of this methodology must be carefully designed according to the study species, its life stages and study areas. If well applied, GPS loggers can provide more accurate data on juvenile stingray locations and movements than do other telemetry methods, especially when used in inter-tidal habitats. Our study was the first to use of towed-float GPS telemetry to document fine-scale movements of mangrove whiprays. Broad-scale use of this technique could enhance our understanding of habitat use and conservation, movement patterns and ecology of juvenile stingray populations and their essential habitats.

**Conflicts of interest**

C. A. Simpfendorfer is an Associate Editor for *Marine and Freshwater Research*. Despite this relationship, he did not at any
stage have Associate Editor-level access to this manuscript while in peer review, as is the standard practice when handling manuscripts submitted by an editor to this journal. Marine and Freshwater Research encourages its editors to publish in the journal and they are kept totally separate from the decision-making process for their manuscripts. The authors have no further conflicts of interest to declare.

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Himantura bremi


Handling Editor: Bradley Wetherbee

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