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A Pilot Study Into The Movement and Dispersal of Sawfishes

FINAL REPORT

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Cover images

Front: Green sawfish being tagged in Lagrange Bay, © Marie Windstein

Back: Prince Frederick Harbour, © Alastair Harry

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Executive summary

Sawfishes have experienced large reductions in their abundance and extent of occurrence globally, making them one of the most threatened groups of vertebrates. While in some parts of Australia populations are likely comparatively healthy, declines and range contractions have similarly been reported and, as such, their conservation remains a priority. A lack of data on many aspects of sawfish biology is a limiting factor in developing effective, evidence-based conservation strategies. Among the biggest knowledge gaps is the lack of data regarding the distribution and spatial ecology of larger juvenile and adult sawfish once they leave coastal nursery areas. Previous attempts to collect this information using satellite telemetry have had mixed success due to a combination of technological limitations and sawfish biological characteristics.

We revisited the use of satellite telemetry to track the movement and distribution of sawfish and assess the ability of this technology to provide data to address important knowledge gaps regarding their conservation. To do this, we deployed three different models of satellite tag to eight sawfish opportunistically captured during fish surveys in the Kimberley region of Western Australia between October 2021 and May 2022, and tracked their movements for up to 5 months. Except for two tags that failed to provide viable data, all other instruments transmitted high-quality locations daily, demonstrating the potential of satellite telemetry to study sawfishes in Australian waters. Our data revealed that all animals remained resident within shallow subtidal and intertidal habitats and occupied very small activity spaces over the duration of the tracking period. While dwarf sawfish, *Pristis clavata*, in Prince Frederick Harbour and Lagrange Bay appeared to only associate with mangrove-lined creeks, green sawfish, *Pristis zijsron*, in Lagrange Bay moved throughout the bay, primarily utilising open intertidal sandflat habitats.

We demonstrate that satellite telemetry can provide important data to address knowledge gaps surrounding sawfishes that will support the identification and abatement of threatening processes and support actions that may lead to the recovery of this taxon. We recommend further deployment of satellite tags in areas where sawfish remain abundant to identify the characteristics of critical habitats for larger sawfish to ultimately construct habitat suitability models able to discern the exposure of sawfish to threatening processes and the amount of habitat protected from such threats.

1 Introduction

Sawfishes are one of the most endangered group of vertebrates globally, with all five species listed by the International Union for the Conservation of Nature as Endangered or Critically Endangered. All five species have seen dramatic declines in their areas of occurrence, with sawfishes having disappeared from approximately 30 – 81% of their former known distribution (Dulvy et al. 2016). Despite being among the largest extant fishes, sawfish, for at least part of their life cycle, occur in shallow nearshore environments, where they are exposed to various anthropogenic pressures (Morgan et al. 2017, Scharer et al.

2017, Whitty et al. 2017). A recent global meta-analysis concluded interactions with fisheries and anthropogenic habitat modifications of coastal zones were the main factors for local extirpations of sawfishes (Yan et al. 2021). Australia represents an important outlier in the global decline of sawfish, with all four endemic species still encountered here (Dulvy et al.

2016, Yan et al. 2021). Northern Western Australia in particular, with its remoteness, low population density and low commercial fishing pressure is thought to harbour some of the last relatively healthy populations of the four Indo-Pacific species, the largetooth- (*Pristis pristis*), dwarf- (*Pristis clavata*), narrow- (*Anoxypristis cupsidata*) and green (*Pristis zijsron*) sawfish (Morgan et al. 2011). Quantitative data on sawfish populations in Australia are limited, although pristid species are suspected to have declined by > 50% and narrow sawfish by > 30% (Kyne et al. 2021). Currently, all species, with the exception of the narrow sawfish, are listed as Vulnerable in the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999*.

While considerable research has been undertaken on the biology of sawfishes in Australia over the last two decades, significant knowledge gaps remain to be addressed to support the recovery of this taxon, including comprehensive data regarding the distribution of sawfishes (Commonwealth of Australia 2015a, b). Indeed, distributional data is crucial to identify and mitigate impairments to recovery, including the exposure to several threats such as commercial and recreational fishing, habitat degradation, exposure to marine debris and understanding the degree of spatial protection sawfish receive from commonwealth and state marine parks (Commonwealth of Australia 2015b, Udyawer et al. 2021). At present, the movement of sawfishes in Australia is only well understood in a few selected locations, the Fitzroy River (largetooth and dwarf sawfish) and the mouth of the Ashburton River (green sawfish). Both areas are globally significant nurseries and the majority of distributional data stems from neonate and small juvenile animals (Morgan et al. 2017, Whitty et al. 2017, Morgan et al. 2021). Although the growing knowledge of sawfish nurseries is instrumental in delineating critical habitat, the lack of data on other stages of the sawfish life cycle provides an impediment to conservation and management.

Movement and distributional data on small juvenile sawfish have primarily been generated using acoustic telemetry, where passive receiving stations record the presence of nearby sawfish equipped with acoustic tags emitting a coded "ping" (Simpfendorfer et al. 2010).

While acoustic arrays are powerful tools to monitor large numbers of animals in a geographically restricted environment, they are less efficient when monitoring smaller numbers of individuals that disperse over larger geographic areas, since they rely on a tagged fish remaining within the acoustic array. In the case of nursery-bound sawfish, acoustic arrays have provided important insights into diel, seasonal and ontogenetic changes in habitat requirements for a number of sawfishes (Whitty et al. 2009, Simpfendorfer et al. 2010, Scharer et al. 2017, Morgan et al. 2021). While adults and larger sub-adults may frequent the same areas as smaller juveniles, their relative rarity and presumed greater dispersal makes acoustic telemetry less suitable for the study of their movements. Satellite telemetry via platform-terminal transmitters (PTTs, often referred to as SPOT tags) offers an alternative method to study the movement of individual animals and therefore removes inherent spatial biases in survey data and acoustic telemetry. However, for fully aquatic animals and especially benthic species such as sawfish, satellite telemetry provides a unique challenge, in that individuals must spend sufficient time at the surface for the ARGOS satellites to receive tag transmissions and estimate the location of the tag (and its carrier). To alleviate this problem, satellite-linked archival tags (PATs) use light-level geolocation to estimate a position, which in turn can be transmitted after the tag detaches from its carrier. While preliminary studies in the late 2000s on dwarf, narrow and freshwater sawfish in northern Australia did not yield useful insights into movement and habitat use (Stevens et al. 2008, Whitty 2008), both PAT and SPOT tags have since successfully been employed to study the congeneric smalltooth sawfish (*Pristis pectinate*) in the south-eastern United States. Novel tethered tag attachments for SPOT tags, as opposed to the direct fin- mounts typically used for pelagic sharks and sawfishes prior to the 2010s, were successfully used to quantify the movements of adult and sub-adult smalltooth sawfish, yielding important insights into critical habitats, seasonal migrations and by-catch risk (Carlson et al. 2014, Guttridge et al. 2015, Papastamatiou et al. 2015).

This project took advantage of opportunistic sawfish captures as part of fish surveys by the WA Department of Primary Industries and Regional Development (DPIRD) and the Karajarri Traditional Lands Association (KTLA) to test if technological improvements in satellite telemetry and the adoption of alternative attachment techniques can provide a viable solution to study the spatial ecology of sawfishes to support their recovery in Australian waters.

2 Methods

2.1 Capture and tagging

Sawfish were opportunistically tagged during two research surveys on nearshore fishes undertaken in Prince Frederick Harbour in October 2021 and in the Karajarri Indigenous Protected Area in May 2022. Sawfish were captured in shallow (< 2m depth) intertidal habitat using demersal gillnets set over mud or sand during the incoming tide. Gillnets were constructed from single-strand 1.10 to 1.30 mm diameter monofilament with a stretched mesh size between 165 and 203 mm. Sampling in Prince Frederick Harbour was undertaken from a 6 m aluminum dinghy that enabled nets to be checked continuously during deployment. Due to the presence of estuarine crocodiles, captured sawfish were brought into the dinghy to facilitate untangling of the rostrum and tag attachment. During this time, the rostrum was wrapped in a piece of marine carpet and the caudal fin was manually restrained while the animal was measured, DNA sampled and tagged.

We used three different tag types as part of this project, a towed ARGOS PTT (SPOT-253, Wildlife Computers Redmond, WA, USA), a satellite-linked pop-up tag (miniPAT, Wildlife Computers, Redmond, WA, USA) and a “hybrid” tag (SPLASH, Wildlife Computers, Redmond, WA, USA)(Fig. 1). SPLASH tags provide both FastLoc GPS locations and real-time location through ARGOS in a manner similar to SPOT tags. SPOT tags also provide light-level geolocations and depth data through ARGOS transmissions, both during deployment and after pop-up. SPLASH tags were set to transmit a maximum of 250 ARGOS messages per day for a total of 15 hours, synchronised with the times of daily satellite passes. One daily location was estimated via light-level geolocation and a maximum of six positions were calculated through FastLoc GPS. SPOT tags were set to transmit during every hour of the day, with a maximum of 500 messages in a 24-hour period. The SPLASH and PAT tags were programmed to detach from their carriers after 180 days to transmit their archived datasets.

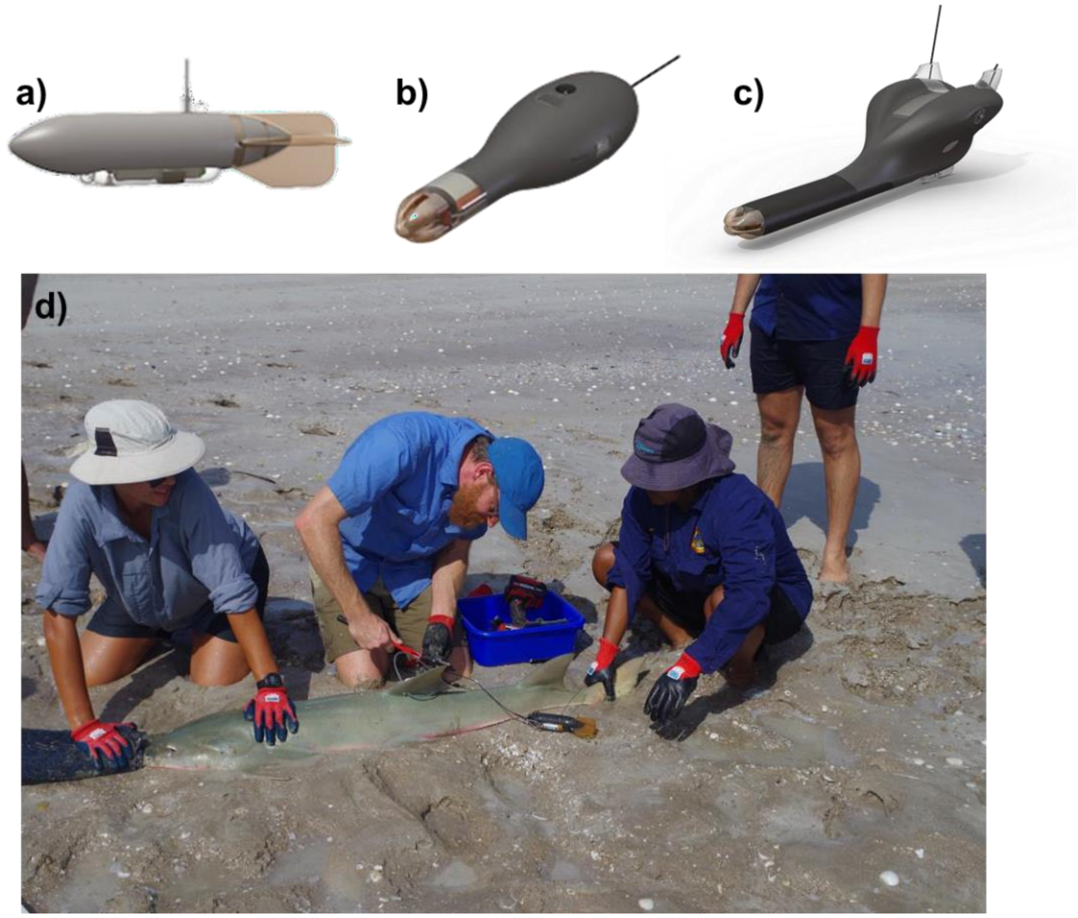

Figure 1. Three types of tags were utilised as part of this research: (a) SPOT-253, (b) miniPAT, and (c) SPLASH. The "harness loop" attachment technique (d) is shown on a 1750 mm dwarf sawfish equipped with a SPOT tag.

All tags were attached using a dorsal fin "harness" (see Papastamatiou et al. 2015). A single hole was drilled with a 4 mm drill bit in the base of the first dorsal fin, approximately 30–50 mm from the anterior margin. A loop of stainless-steel wire, first covered in heat-shrink-tubing and then in surgical tubing, was threaded through the hole and subsequently closed with two brass crimps to ensure the harness would detach from the animal following corrosion. The size of this loop was sufficient so that it would fold over the posterior margin over the dorsal fin, while allowing the tag to float freely above the fin when the animal was at rest. All tags were attached to the dorsal loop with a short tether covered in heat-shrink tubing. This tether was 300 mm long in both SPOT and SPLASH tags, and 100 mm in PAT tags. Tags were crimped to the tether using stainless steel crimps, which were then covered in heat-shrink tubing.

2.2 Data analysis

2.2.1 Spatial data

ARGOS data (SPLASH & SPOT)

The raw ARGOS transmission data were filtered using R package *SDLfilter* (version 2.2.0). First, any spatial-temporal duplicates were removed using the function *dupfilter* (Shimada et al. 2016), then any biologically unrealistic or high-error locations were removed using the function *ddfilter* (Shimada et al. 2012). Locations were considered biologically unrealistic if the speed from a previous and/or to a subsequent location exceeded a maximum speed threshold of 8.9 km/h (Shimada et al. 2012). Locations of class 3 are the most reliable location quality (LQ) and estimated to be within 150 m of the true location (see Table 1). The other LQ classes 2, 1, 0, A and B, decline in reliability and can be up to several kilometres from true locations; therefore, locations were retained only if LQ = 3. The filtered data were converted to a spatial points data frame using the package *sp* (Pebesma and Bivand 2005), in order to visualise both raw and filtered locations for each individual in QGIS version 3.18.

Table 1. Location quality (LQ) class and associated accuracies for ARGOS derived locations (www.argos-system.org).

Location quality class	Accuracy
3	< 150 m
2	150 – 350 m
1	350 – 1000 m
0	> 1000 m
A	None given
B	None given

Fastloc-GPS data (SPLASH)

GPS data were filtered for number of satellites (> 6) and altitude (< 100 m). 80% of all FastLoc-GPS data are accurate to within 40 m when > 6 satellites are used to calculate the location (Dujon et al. 2014).

GPE3 Light-level geolocation (PAT & SPLASH)

GPE3 is a statistical processing tool (state-space model) that estimates animal movement from tag observations of twilight, sea surface temperature and dive depth. The most likely location for any given time was estimated from the GPE3 processing tool using these observations and corresponding reference data (e.g., local sunrise and sunset time).

2.2.2 Vertical movements

Transmitted time-series depth data were visualised using Igor Pro (WaveMetrics, Lake Oswego, OR, USA). Data sets containing little or no gaps were analysed using a continuous wavelet transformation to investigate the temporal scales of diving behaviour (Sakamoto et al. 2009).

2.2.3 Environmental data

Tide

Neither Lagrange Bay nor Prince Frederick Harbour have tidal gauging stations; however, an analysis of the influence of tide on sawfish movement in Lagrange Bay was carried out using data from Tide Station # 1159 located in Roebuck Bay, Broome, WA (Australian Government Bureau of Meteorology). While minor differences in tidal height and timing are apparent based on modelled data, the difference is nominally small (< 20 minutes) between Broome and Lagrange high tide. For the purpose of this report, Lagrange tides have been assumed equal to those measured in Broome's port waters. Predicted high tides used for Lagrange, were obtained from http://www.bom.gov.au/australia/tides/#!/wa-lagrange-bay.

Bathymetry / Intertidal elevation

To visualise the effect of local bathymetric features, we compared sawfish tag locations with the National Intertidal Digital Elevation Model (NIDEM), a dataset for Australia's exposed intertidal zone (Bishop-Taylor et al. 2019). The model provides a three-dimensional representation of Australia's intertidal sandy beaches and shores, tidal flats and rocky shores and reefs at 25 m spatial resolution.

Rainfall

We visualised daily rainfall totals associated with sawfish movement at Prince Frederick Harbour. Rainfall data were taken from daily weather observations for Station 001019 in Kalumburu, Western Australia (Australian Government Bureau of Meteorology).

3 Results

In Prince Frederick Harbour five dwarf sawfish suitable in size for this project were captured between the 1st and 10th of October 2021. The total length (TL) of these individuals, which comprised three males and two females, ranged from 1760 to 2380 mm. Three individuals were tagged with SPOT tags and two were tagged with PAT tags (Table 1). At Lagrange Bay, a further three sawfish were caught on the 18th of May 2022. These included two green sawfish (TL 2200 and 2950 mm), one of which was tagged with a SPOT tag (PTT 233539) and the other with a SPLASH tag (PTT 226119). In addition, one sub-adult dwarf sawfish was captured (TL 1750 mm) and tagged with a SPOT tag (PTT 233540) (Table 2; Fig. 2).

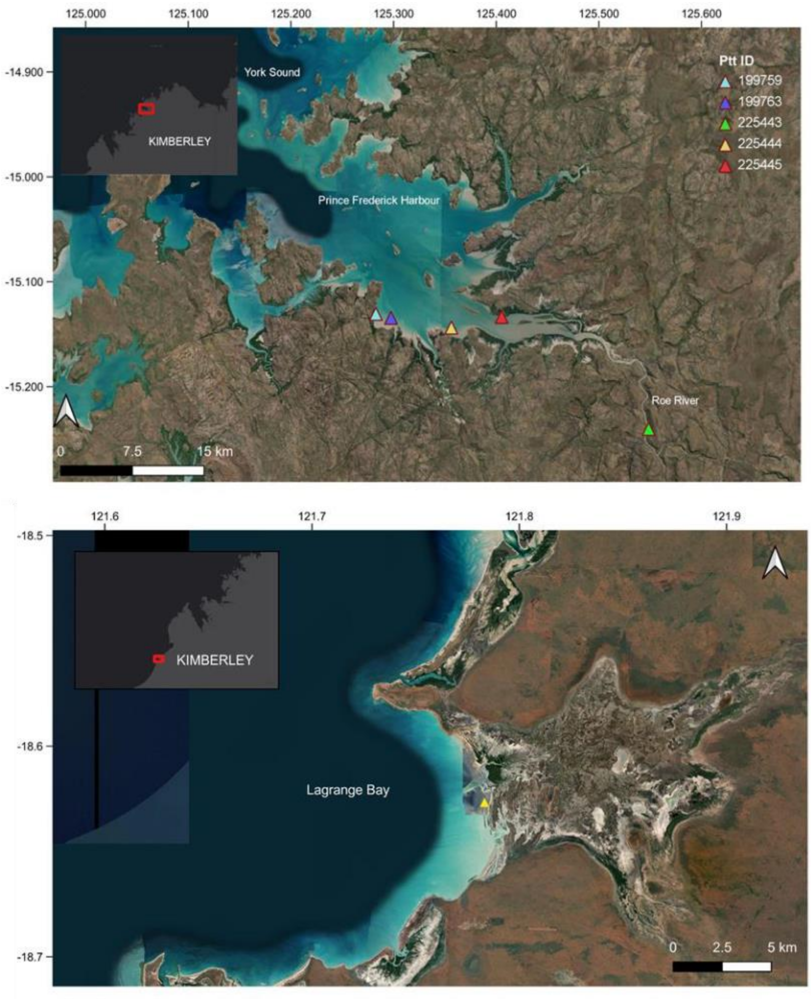

Figure 2. Tagging locations for sampled sawfish. Top Panel: Prince Frederick Harbour. Bottom Panel: Lagrange Bay. Please note that all three sawfish in Lagrange Bay were tagged in the same location.

Table 2. Sawfish captured and tagged in Prince Frederick Harbour and Lagrange Bay, Kimberley, Western Australia. Tag ID and type are included, as well as the capture date and location, and the sex and total length (TL) of each individual.

Species	Site*	PTT ID	Tag Type	Date	Location	Sex	TL (mm)	Tag longevity	Locations
P.clavata	PFH	225443	SPOT	01-Oct-2021	15.240349 °S, 125.548569 °E	M	1760	29.5 mins	3
P.clavata	PFH	225444	SPOT	06-Oct-2021	15.143769 °S, 125.356279 °E	M	2320	29.0 days	116
P.clavata	PFH	225445	SPOT	06-Oct-2021	15.133556 °S, 125.405306 °E	M	1900	135.0 days	315
P.clavata	PFH	199763	PAT	07-Oct-2021	15.134460 °S, 125.297447 °E	F	2230	123.0 days	NA
P.clavata	PFH	199759	PAT	10-Oct-2021	15.130625 °S, 125.282701 °E	F	2380	**	0
P.zijsron	LB	226119	SPLASH	18-May-2022	18.626615 °S, 121.785508 °E	F	2950	19.2 days***	90
P.zijsron	LB	233539	SPOT	18-May-2022	18.626615 °S, 121.785508 °E	F	2200	19.5 days***	195
P.clavata	LB	233540	SPOT	18-May-2022	18.626615 °S, 121.785508 °E	F	1750	19.7 days***	268

* Prince Frederick Harbour (PFH), Lagrange Bay (LB)

** tag failed to report

*** as of 15-Jun-2022, tag still transmitting

3.1 Data summary

For dwarf sawfish tagged with SPOT tags between 1 – 6 of October 2021 at Prince Frederick Harbour, overall durations of raw ARGOS transmissions varied (Table 2). PTT 225443 transmitted for < 30 minutes on the day of deployment. PTT 225444 transmitted for almost one month and PTT 225445 transmitted for > 4 months (135 days) before the tag detached from the individual on 18 February 2022. One of the PAT-tagged individuals also transmitted data for 4 months (PTT 199763). PTT 199759 did not transmit any data. All three individuals tagged at Lagrange Bay (PTTs 226119, 233539, 233540) on May 18, 2022 were still transmitting location data at the time of reporting (Table 2).

SPOT and SPLASH tags yielded a total of 942 locations, averaging 5.6 ± 4.9 raw daily locations. Proportionally, the quality of the raw ARGOS transmission data was high for all SPOT & SPLASH tag deployments. More than 50% raw ARGOS locations were LQ = 3 for individuals tagged at Prince Frederick Harbour (PTTs 225443, 225444, 225445) (Fig. 3). The majority of locations for individuals tagged at Lagrange Bay (PTTs 226119, 233539, 223540) were also high quality (LQ = 3); however, there were more LQ = 1 and 2 location classes at this site (Fig. 3, Table 3). There were also 14 Fastloc-GPS locations transmitted for the SPLASH-tagged green sawfish (PTT 226119). The message count per GPS location ranged from 1 to 14, the number of satellites ranged from 4 to 7 and altitude ranged from 12 to 13 m. All locations were considered high quality and retained.

After filtering the raw ARGOS transmission location data, 38.3% of raw ARGOS locations for all individuals combined were retained, although this varied per individual (Table 3). 453 locations with LQ < 3 were removed (48.1% of original combined raw data), two locations were removed as spatiotemporal duplicates (0.7%) and the speed filter removed 90 locations (19.9%). Figure 4 demonstrates the difference between raw and filtered location data for individuals tagged at Prince Frederick Harbour, where the total number of filtered locations for each individual was 2 (PTT 225443), 51 (PTT 225444) and 135 (PTT 225445) (Table 3).

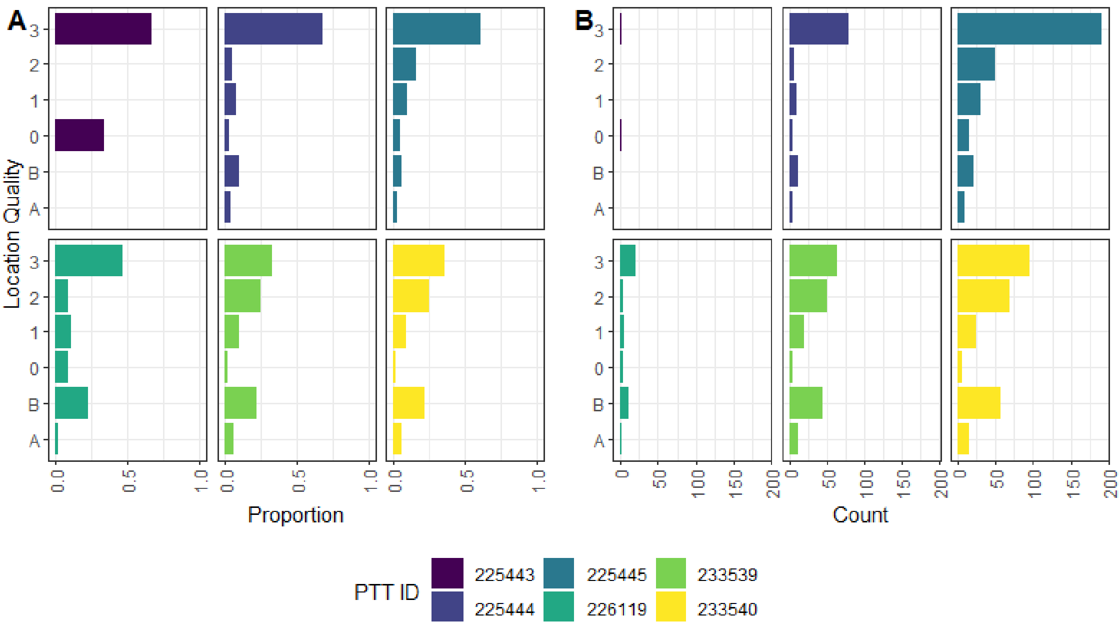

Figure 3. Location quality class proportion (A) and count (B) for raw ARGOS location from SPOT and SPLASH tags deployed on dwarf sawfish (P. clavata) and green sawfish (P. zijsron) at Prince Frederick Harbour and Lagrange Bay, Kimberley, Western Australia.

Table 3. Summary of ARGOS locations for dwarf sawfish (P. clavata) and green sawfish (P. zijsron) tagged at Prince Frederick Harbour and Lagrange Bay, Kimberley, Western Australia. Retained locations = proportion of locations after filtering raw data.

Species	**PTT ID**	**Raw (n)**	**Filtered (n)**	**Retained (%)**	**Daily** ($\bar{x}$ ± SD)	**Daily filtered** ($\bar{x}$ ± SD)
P. clavata	225443	3	2	66.7	3	2.0
P. clavata	225444	116	54	46.5	4 ± 1.8	2.0 ± 1.1
P. clavata	225445	315	143	45.4	2.6 ± 1.1	1.5 ± 0.6
P. zijsron	226119	45	19	42.2	3.6 ± 1.5	2.5 ± 1.1
P. zijsron	233539	195	61	31.3	9.3 ± 5.8	3.2 ± 3.1
P. clavata	233540	268	82	30.6	13.0 ± 6.3	4.3 ± 2.9
	TOTAL	**942**	**361**	**38.3**		

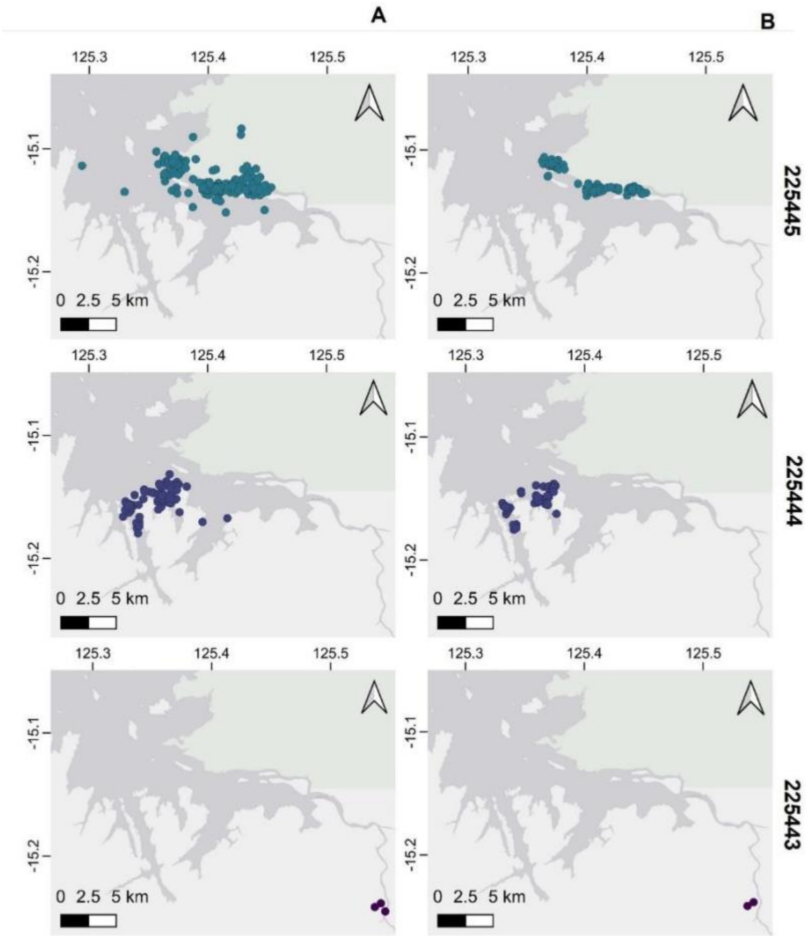

Figure 4. Raw ARGOS locations (A) compared to filtered ARGOS locations (B) for dwarf sawfish (P.clavata) tagged with SPOT tags at Prince Frederick Harbour, Kimberley, Western Australia.

3.2 Daily locations

The number of daily locations varied by individual and site (Table 3, Fig. 5). Raw daily locations ranged 0 – 26 per day across all tagged individuals (Table 3, Fig. 5). Once filtered, daily locations ranged from 0 – 12 per day across all tagged individuals (Table 3). At Prince Frederick Harbour, PTT 225443 only transmitted 2 locations on the first day of deployment. Daily locations were highest for PTT 225444 ($\bar{x}$ = 2.8 ± 1.2; Table 3). Daily locations for PTT 225445 were slightly lower ($\bar{x}$ = 1.8 ± 0.8; Table 4). For this individual, there was an extended period of zero consecutive daily locations (5 –14 December 2021, Fig. 5). At Lagrange Bay, the SPLASH tag (PTT 226119) transmitted GPS location data for the first 4 days, then ARGOS locations for the duration of the deployment, with occasional periods of 1 – 4 days without transmission (Fig. 5). Both PTTs 233539 and 233540 transmitted daily locations for the duration of the deployment (Fig. 5).

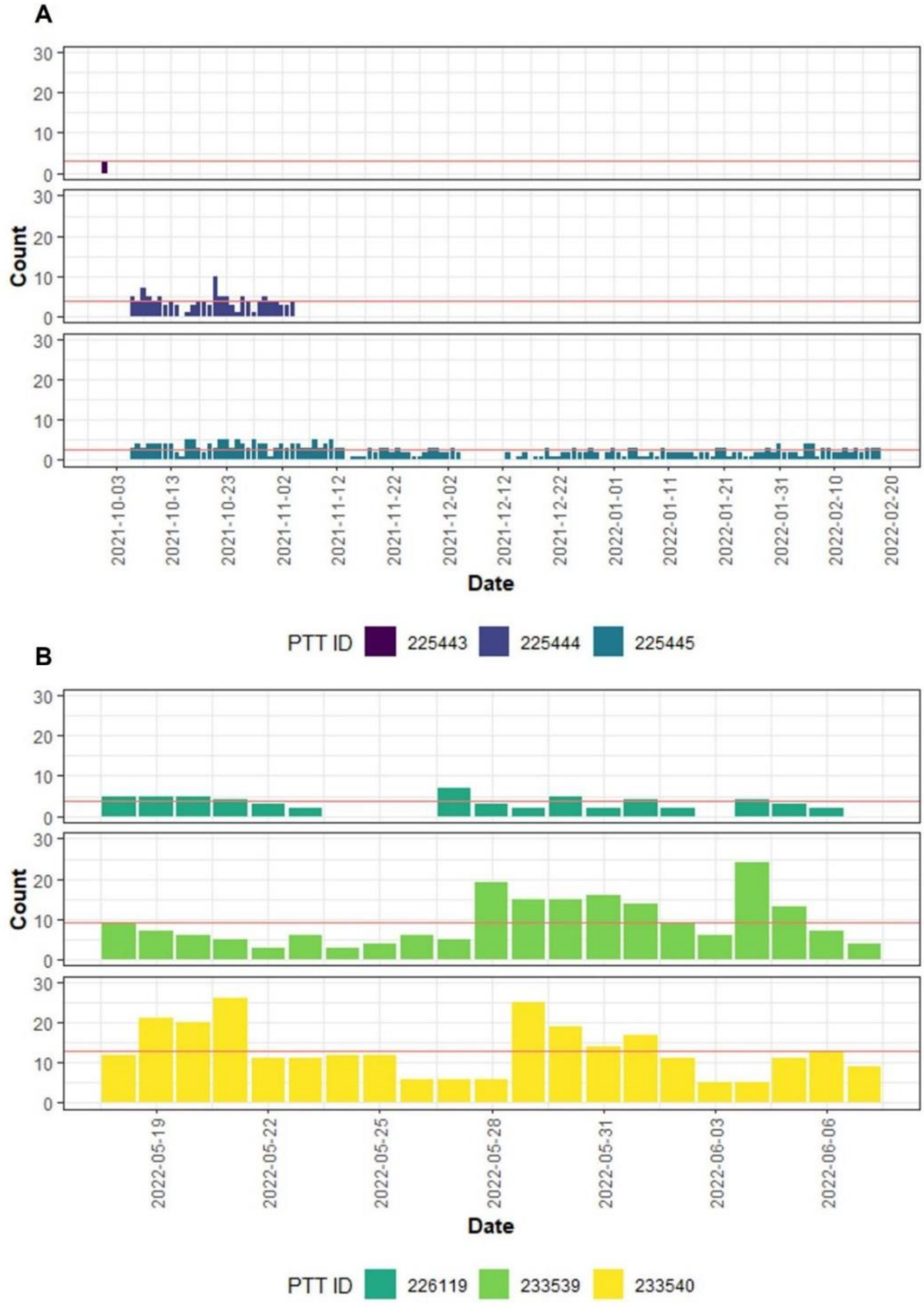

Figure 5. Raw daily ARGOS locations for dwarf sawfish (P.clavata) and green sawfish (P.zijsron) tagged with SPOT/ SPLASH tags at Prince Frederick Harbour (A) and Lagrange Bay (B), Kimberley, Western Australia. (red horizontal line represents individual mean).

3.3 Biological considerations

Prince Frederick Harbour

The first dwarf sawfish (PTT 225443) tagged on the Roe River only transmitted data on the day of tagging for a total duration of 29 minutes after deployment. This individual was discarded from any further analyses. PTT 225444 remained within approximately 5 km of the capture location (South Prince Frederick Harbour and the mouth of the Roe River), for the duration of the deployment (29 days) until location transmissions stopped on November 4th, 2021. Post capture, this individual initially moved westerly into a mangrove creek before returning to the area around the capture location (Fig. 6). PTT 225445 travelled eastwards from the capture location (mouth of the Roe River), where it remained resident for two months until December 4th, 2021 (Fig. 7). A 9-day period of no transmitted data for this individual (December 5th to 14th, 2021; Fig.5, A) appeared to coincide with the first prolonged rainfall event of the wet season (see Appendix A). Following this, the individual shifted westwards where it remained for another two months. The tag detached on February 18th, 2022, but was still transmitting locations, consistent with a floating tag. For the PAT-tagged dwarf sawfish (PTT 199763) at Prince Frederick Harbour, the capture/tag deployment location and tag pop-off location four months later were within 2.5 km of each other (Fig. 8). The other PAT-tagged dwarf sawfish (PTT 199759) did not transmit any location data.

Lagrange Bay

One green sawfish (PTT 226119) moved towards the southern end of Lagrange Bay from the capture location, then traversed the bay northerly before returning to the southern end of the Bay (Fig. 9). The other green sawfish (PTT 233539) used the middle and northern end of Lagrange Bay (Fig. 10). The dwarf sawfish (PTT 233540) remained in the middle of Lagrange Bay except for one short trip looping to the northern end of the Bay before returning to the area it was primarily residing in (Fig. 11). Clear tidal patterns were observed in the movements of all three sawfish tagged at Lagrange Bay, with locations further offshore coinciding with low tides and those closer to shore with high tides. The single dwarf sawfish (PTT 233540) appeared to heavily use the area adjacent to the tidal creek, with the deeper offshore channel being utilised on neap tides and deeper sub-tidal waters on spring tides (Fig. 12).

Vertical movements

Vertical movement data from the single recovered PAT tag from the dwarf sawfish in Prince Frederick Harbour (PTT 199763) and the transmitted depth data from the SPLASH tag deployed on the green sawfish in Lagrange Bay (PTT 226119) both showed that sawfish spent large proportions of their time in shallow water, with maximum depths of ~ 8 m in both cases (Fig. 13 and Fig. 14). Continuous wavelet transformation revealed that the green sawfish did not display a tidal pattern in its vertical movement when occupying shallow depths, but clear tidal patterns when occupying depths > 4 m (Fig. 13). Continuous wavelet transformations could not be applied to the PAT tag data from the dwarf sawfish in Prince Frederick Harbour due to many gaps in the transmitted time-series dataset; however, tidal signals were visible throughout the dataset.

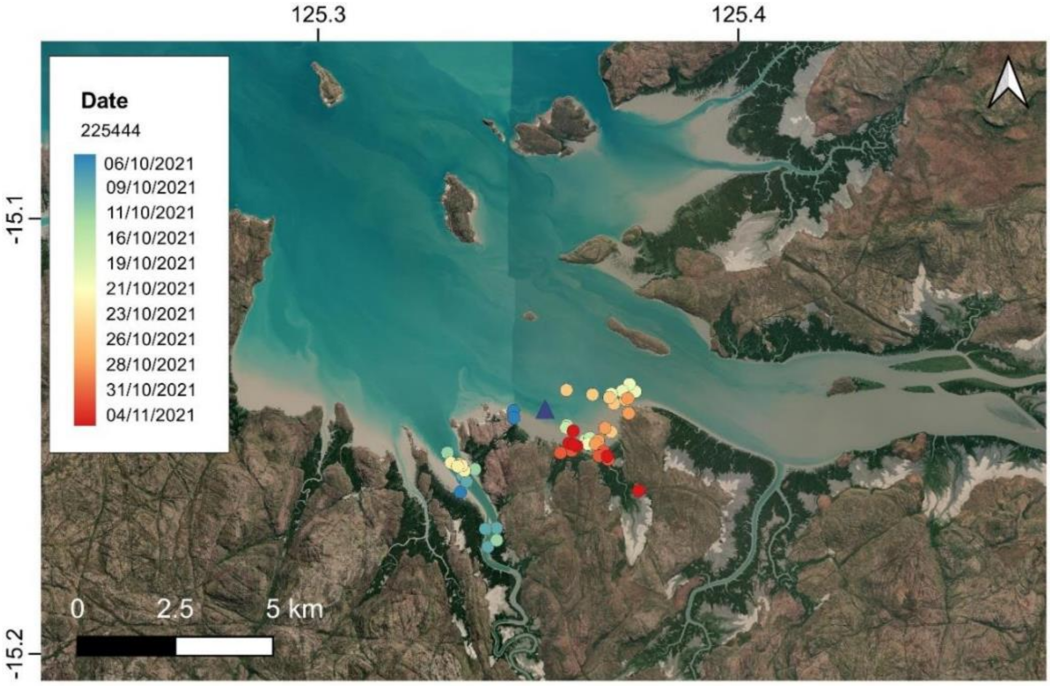

Figure 6. Dwarf sawfish (P. clavata) PTT 225444 movements. Locations coloured by elapsed time since capture/ tag deployment (see legend). Capture location = blue triangle. Note: only filtered high-quality locations shown.

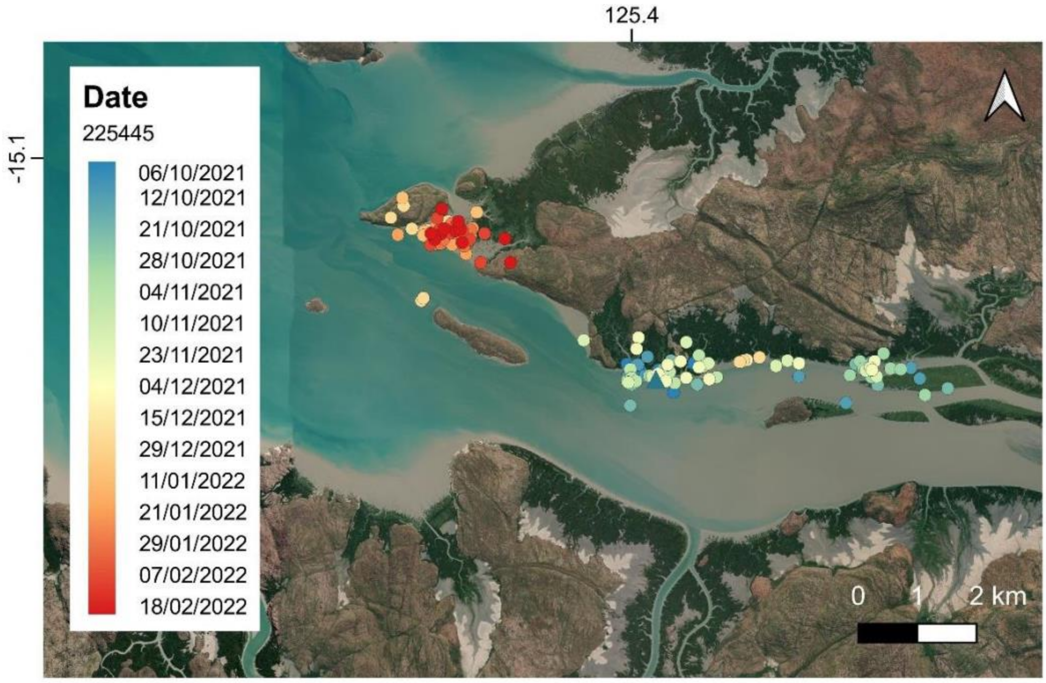

Figure 7. Dwarf sawfish (P. clavata) PTT 225445 movements. Locations coloured by time elapsed since capture/ tag deployment (see legend). Capture location = green triangle. Note: only filtered high-quality locations shown.

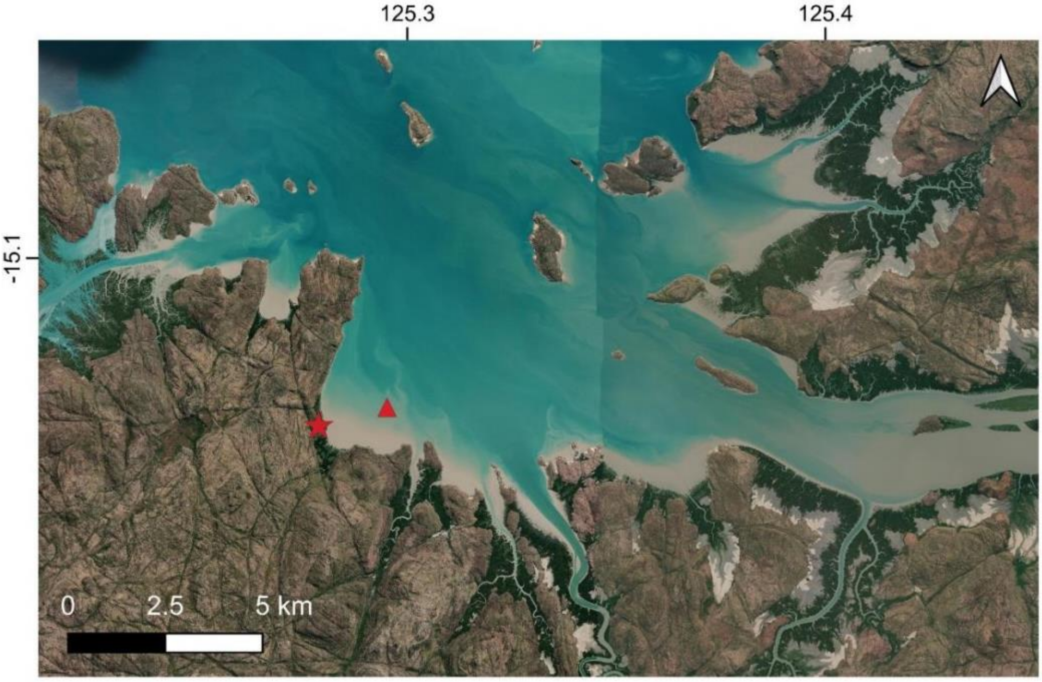

Figure 8. Dwarf sawfish (P. clavata) PTT 199763 capture/ tag deployment location (red triangle) and tag pop-off location (red star).

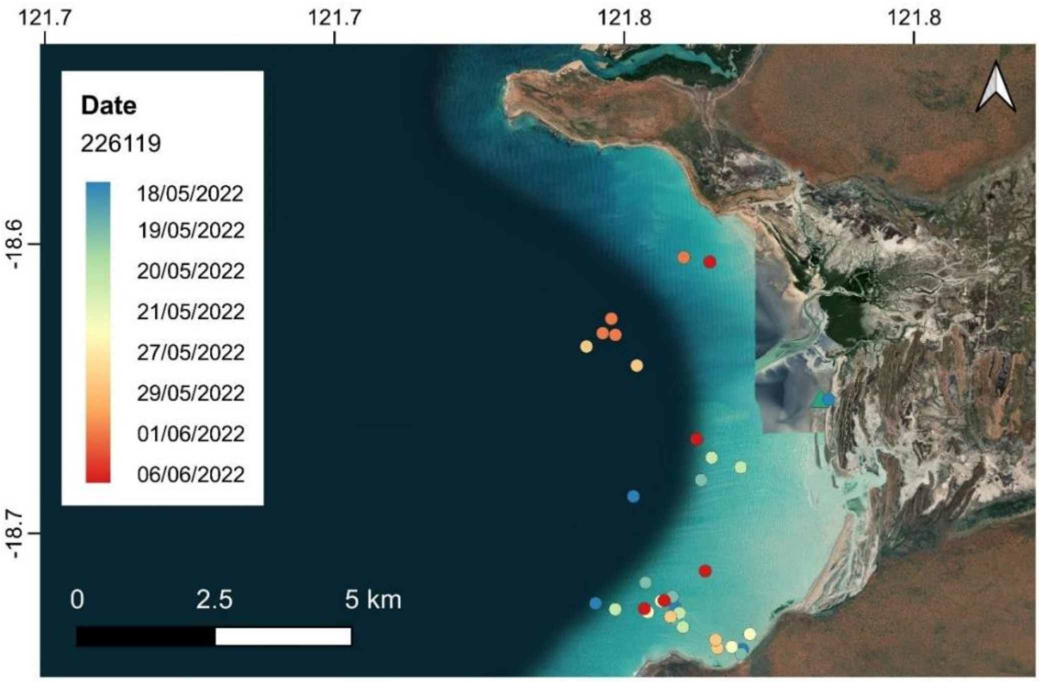

Figure 9. Green sawfish (P. zijsron) PTT 226119 movements. Locations coloured by time elapsed since capture/ tag deployment (see legend). Capture location = green triangle. Note: only filtered high-quality locations shown.

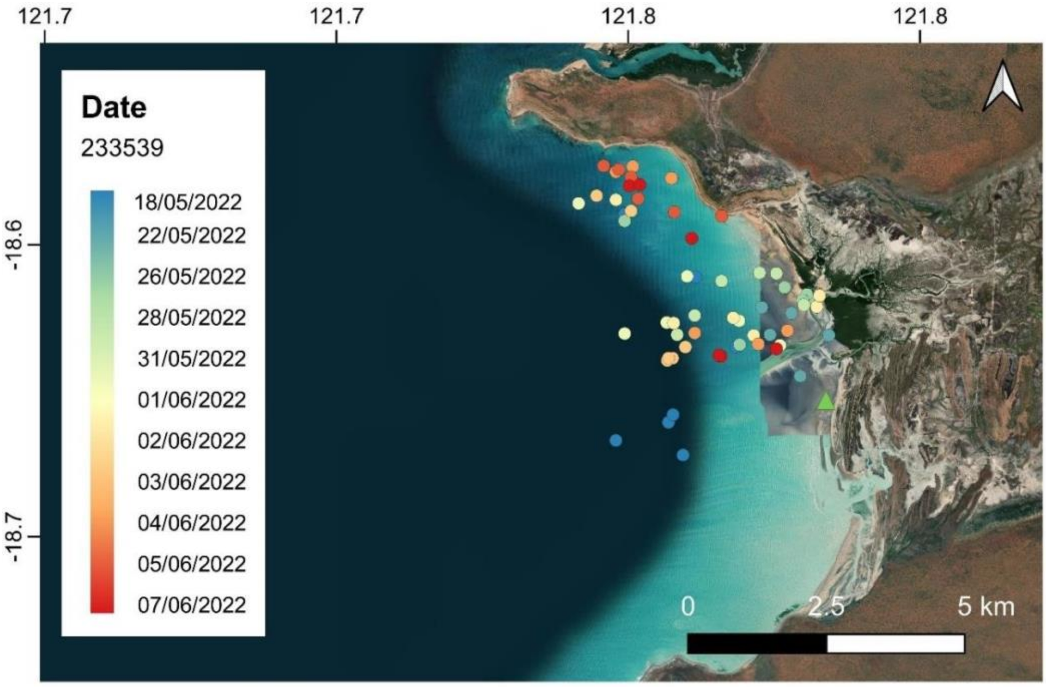

Figure 10. Green sawfish (P. zijsron) PTT 233539 movements. Locations coloured by time elapsed since capture/ tag deployment (see legend). Capture location = green triangle. Note: only filtered high-quality locations shown.

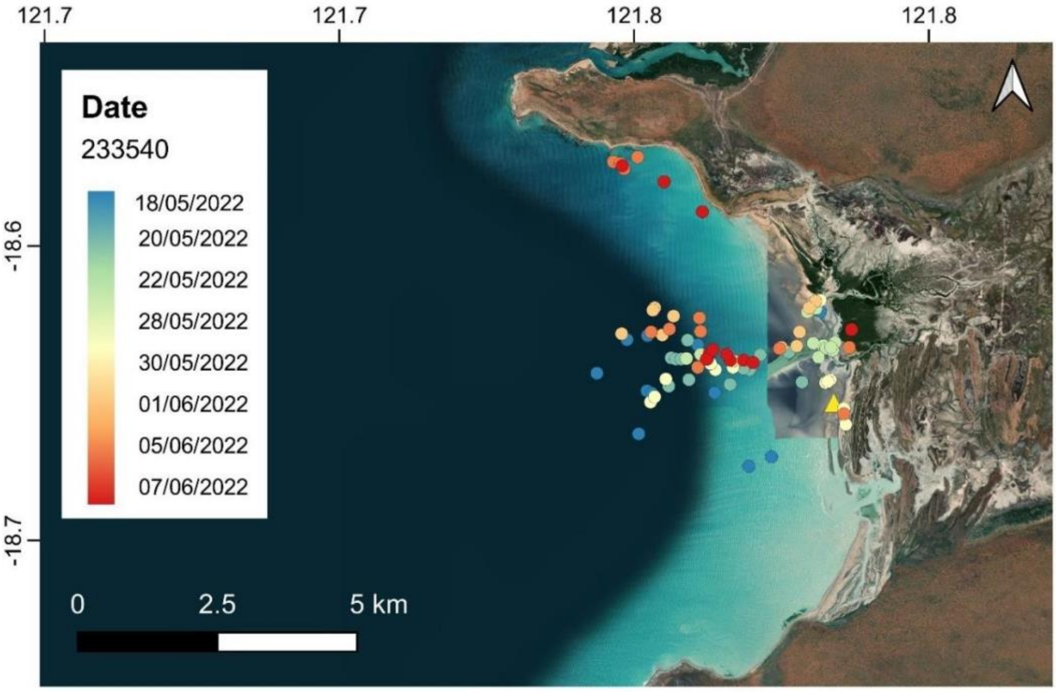

Figure 11. Dwarf sawfish (P. clavata) PTT 233540 movements. Locations coloured by time elapsed since capture/ tag deployment (see legend). Capture location = yellow triangle. Note: only filtered high-quality locations shown.

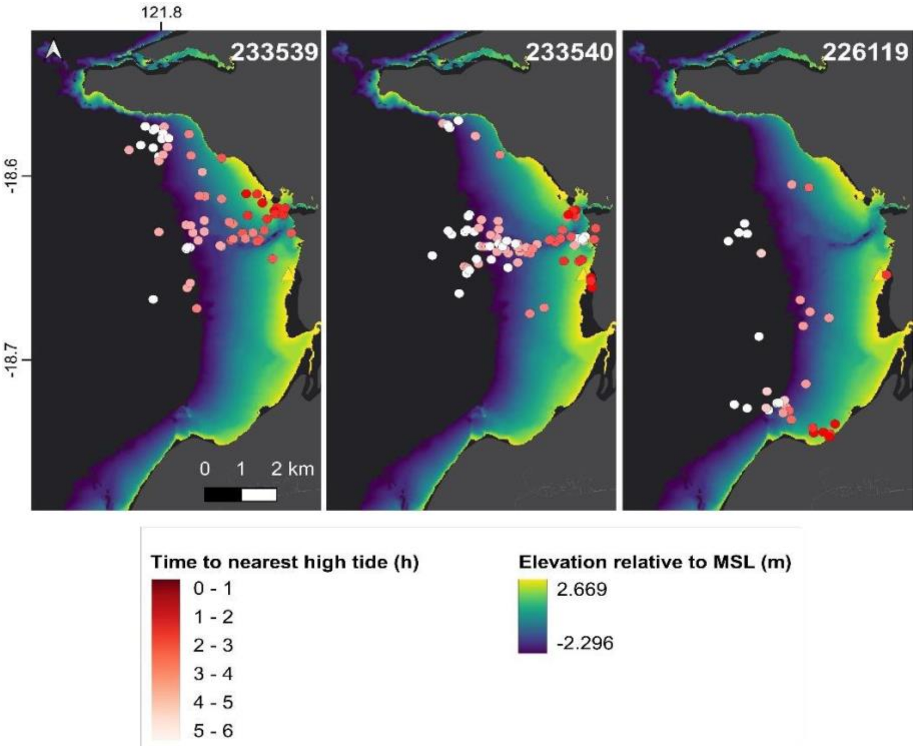

Figure 12. Tidal influences on the distribution of dwarf sawfish (P. clavata) PTT 233540 and green sawfish (P.zijsron) PTTs 233539 and 226119 movements in Lagrange Bay, Western Australia. Locations coloured by time to nearest high tide. Capture location = yellow triangle. Note: only filtered high-quality locations shown.

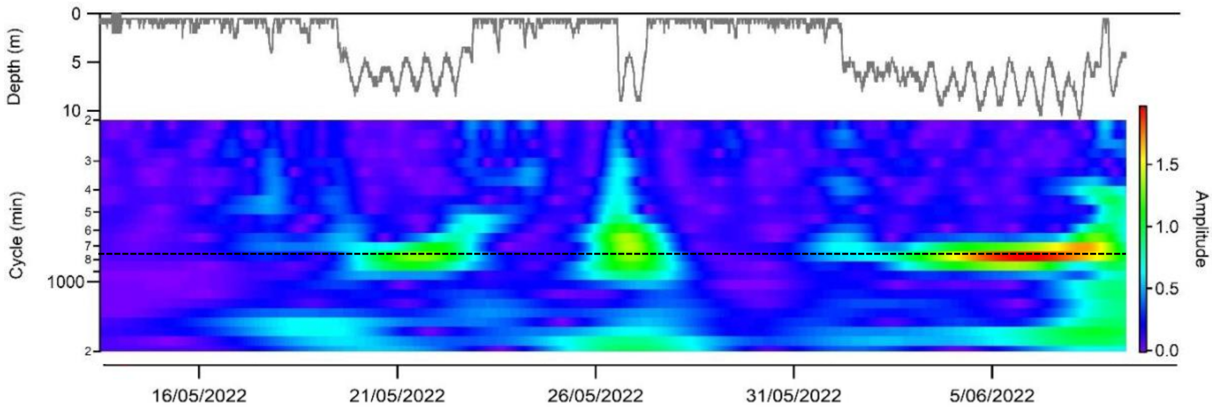

Figure 13. Green sawfish (P. zijsron) PTT 226119 vertical movements. The top panel displays the raw depth data, whereas the bottom panel displays the results of a continuous wavelet transformation. Warm colours display the cycle durations over which vertical movements were detected, with the black dashed line indicating tidal cycle duration. Note the absence of a tidal signal when the animal is in shallow waters compared to the strong tidal cycle when the animal occupies deeper water.

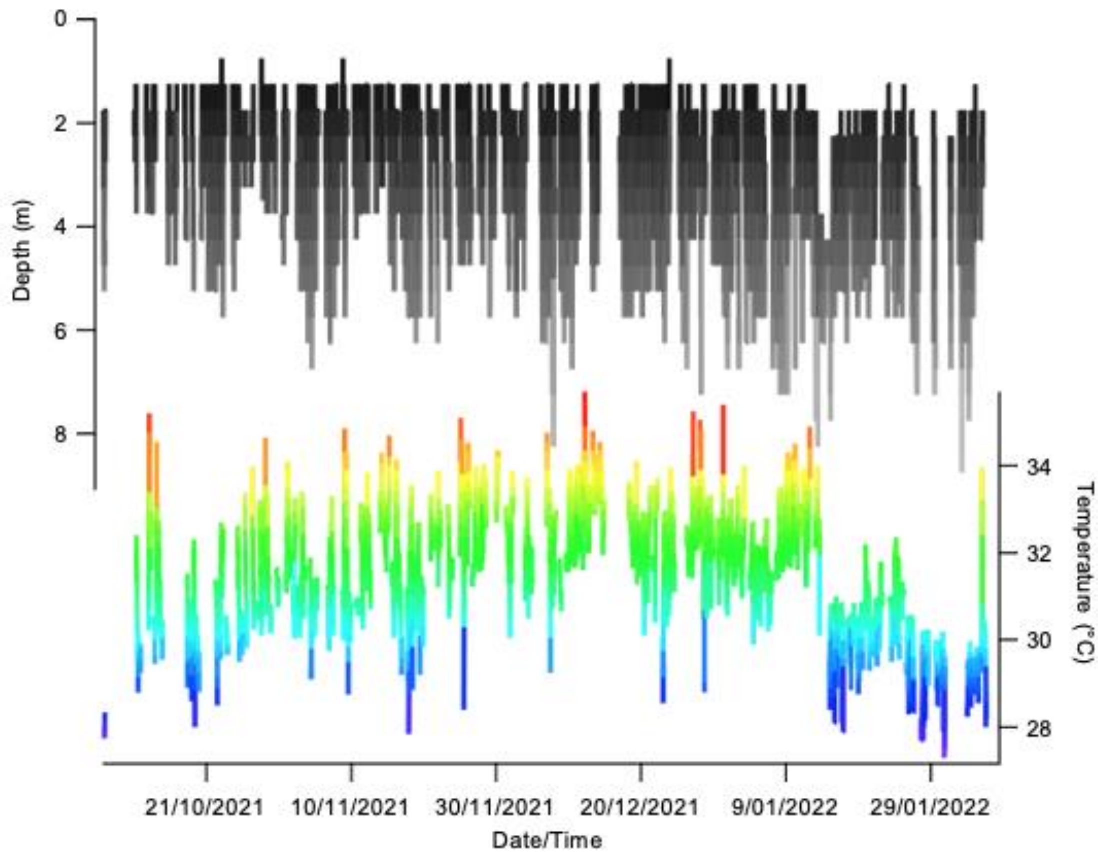

Figure 14. Dwarf sawfish (P. clavata) PTT 199763 vertical movements. The top panel displays the raw depth data, whereas the bottom panel displays the associated temperature. Note the sudden drop in temperature and periodic increase of depth in early January.

4 Discussion

4.1 Overview

Our work demonstrates that satellite telemetry, specifically towed ARGOS and FastLoc GPS tags, provide a viable means to study the movement, dispersal and habitat use of dwarf and green sawfish between 1.75 m and 3 m TL over intermediate (weeks – months) timescales. We were able to generate numerous daily positions for all successfully tracked animals, which is in stark contrast to previous attempts to track sawfish using SPOT tags in Australian waters, which yielded few to no locations for Pristis clavata and Pristis pristis. The major difference between the studies in the late 2000s and the present study is the mode of tag deployment; whereas both Stevens et al. (2008) and Whitty et al. (2008) used the direct attachment of the tag to the dorsal fin, we used a short, tethered attachment that was previously successfully used in Pristis pectinata in the south-eastern United States (Papastamatiou et al. 2015). While long tethers (up to several meters) have been used in whale sharks (Rhincodon typus) and mobulid rays to maximise tag transmissions (e.g. Gifford et al. 2007), potential entanglement risk in coastal species such as sawfish is considerable. Our results unequivocally demonstrate that long tethers are not necessary to allow for tag transmissions. This is a significant result since entanglement risk is expected to be significantly reduced and possibly eliminated when tethers are short (just 300 mm in our case). This should reassure both permitting bodies and animal ethics committees that towed tags can effectively be utilised in these near-shore species while limiting the risk of entanglement.

4.2 Methodological considerations

Of the three SPOT tags deployed in October 2021 on dwarf sawfish in Prince Frederick Harbour (PFH), a single tag transmitted close to the expected maximum deployment duration of 6 months before it started to drift with the tidal current, indicative of the brass crimps attaching the tether to the dorsal fin corroding and releasing the tag from the fish. This was an expected and desired outcome, since it may be ethically unacceptable for an animal to continue to tow a tag indefinitely once the battery runs out and the tag is no longer transmitting. While it is exceedingly difficult to ascertain why the other two tags in PFH ceased to transmit prematurely, there are several potential reasons (Hays et al. 2007). The single fish that only transmitted on the first day of deployment may have succumbed to post-release mortality because of depredation or physiological stress (Ellis et al. 2017). This individual was also tagged relatively far up the Roe River close to an area where the river forms a deep gorge. Had the individual moved further upstream into the Roe or Moran Rivers and remained resident in this area after tagging, it is possible the tag may not have been able to connect to the ARGOS satellite. For PTT 225444, which ceased transmitting after 6 weeks, tag malfunction is a possibility potentially because of the tag being bitten by a predatory animal, which is thought to be a common occurrence in towed tags (Tolentino et al. 2017). Estuarine crocodiles also occur in high abundance in PFH and its tributaries (Halford and Barrow 2017) and could also be responsible for malfunction of towed tags. All three tags deployed in May 2022 in Lagrange Bay are still transmitting to date, seven weeks following deployment.

The extensive use of very shallow intertidal habitat in all sawfish we have tracked is the likely reason for the frequent high-quality transmissions (~ 50% of all transmissions were LQ = 3), since tags can only transmit when the antenna is above the sea surface. Indeed, transmitted depth data from the SPLASH and PAT revealed that both green and dwarf sawfish routinely spent time in very shallow water. It is however imperative to point out that SPOT tags, or any tag relying on the transmission of radio waves for the purpose of generating locations, are likely to provide a partially biased representation of distribution. The benthic lifestyle of sawfish will result in the probability of successful tag transmission being determined by the depth of the seabed where the animal is located, since the tag's antenna is only able to break the surface when the sawfish occupies very shallow water. This is well illustrated in the larger green sawfish tracked in Lagrange Bay. While this fish was sending regular daily high-quality locations for the duration of the deployment period, it did not transmit for > 4 days on two separate occasions, which coincided with the animal moving into deeper waters (6 – 8 m), as determined by the SPLASH tags transmitted depth data. Subsequently, the habitat used by this fish for those four days is not represented in ARGOS data. Given that this is the only case where a fish displayed a protracted gap in transmission, this suggests that any systematic bias is relatively small. This may not necessarily always be the case. For example, very large green sawfish are found in depths of 70–100 m across the northwest shelf of Western Australia. These fish are unlikely to inhabit shallow areas for extended periods and therefore ARGOS derived locations are unlikely to be acquired. SPLASH tags are especially useful in such situations, given that locations can both be determined through ARGOS and GPS (both relying on antennae breaking the surface), but also light-level geolocation, which can yield estimates of location for as long as the animal is located within the photic zone.

4.3 Biological considerations

While preliminary in nature, our results are promising, yielding some novel biological insight into the movement and distribution of both green and dwarf sawfish in tidal nearshore environments. Firstly, the exceptionally high site fidelity over intermediate time scales by such large fish is potentially surprising. While high site fidelity has been recorded in neonates and young-of-the-year in many species of shark and ray, including sawfish, the restricted activity space of the larger individuals tagged in this study was somewhat unexpected (Speed et al. 2010). Indeed, both dwarf and largetooth sawfish subadults have been shown to occupy relatively small home ranges in the Fitzroy River during the dry season; however, this may have been an artefact of the heavy fragmentation of riverine/estuarine pools they inhabit (Whitty et al. 2017, Morgan et al. 2021). Here, we recorded very little dispersal and small activity spaces despite animals frequenting an open coastline in periods of weeks to months, the full duration of the tracking period. Moreover, the fish were almost exclusively associated with the intertidal and shallow sub-tidal areas. Indeed, while the behaviour of benthic sawfish may overrepresent the use of such habitats, the short time between successive locations in the intertidal indicates the animals are not straying far from those areas, which is also highlighted by the depth data from the single dwarf and green sawfish.

Not surprisingly, we found that tidal height appeared to be strongly associated with the distribution of sawfish in Lagrange Bay. This information mirrors the results by Stevens and colleagues (Stevens et al. 2008) who found inshore-offshore movement coinciding with tidal movements in sawfish acoustically tracked over short temporal scales. Tidal movements are most likely driven by abundant foraging opportunities that occur over productive intertidal mudflats and at the mouths of creeks (Heupel et al. 2018).

We found some commonalities in the habitat associations between the four dwarf sawfish tracked as part of this project, with fish in both PFH and Lagrange Bay being associated with the intertidal littoral zone adjacent to mangrove-lined creeks. Intertidal elevation data available for Lagrange Bay reveals that the single dwarf sawfish tagged here was almost exclusively associated with the creek and the area directly seaward of the mouth of the channel, which is flanked by intertidal mudflat. This is in stark contrast to the two green sawfish tagged in Lagrange Bay, which moved more broadly and utilised both the southern and northern parts of the Bay that are not fed by any significant tidal creeks and have sparse to no mangrove cover (as visually examined through satellite imagery). Dwarf sawfish have the most restricted distribution of all the sawfishes found across northern Australia. The findings of this study may suggest a greater dependency on habitats and features generated by high tidal flows compared to other sawfish species. Testing this hypothesis however will require additional high-resolution behavioural data of how dwarf and green sawfish utilise different habitat features which could be provided by modern biologging tags.

5 Conclusions and recommendations

Our results point to satellite telemetry being a valuable tool to study sawfish movement and habitat use. The large number of high-quality locations provided by ARGOS tags provide opportunities for detailed study of habitat selection, something that can be challenging with other techniques. While the longevity of tag deployments was promising, further refinement is warranted. While this will further increase the utility of such data, it should not be considered a prerequisite for further use of the technique.

In addition to demonstrating the utility of satellite tags to augment the sawfish research toolbox, our work also showed that the western Kimberley is a promising site for further studies. Because of the rarity of sawfish captures throughout most of Australia, attention should be paid to areas where populations are healthy, providing rare opportunities to understand sawfish habitat use that can be translated to management practices in places where populations are depleted. Indeed, much of the western Kimberley is relatively accessible, with logistical support from state government marine operations and skilled indigenous ranger groups in place, which is rare in places where sawfish remain abundant. These opportunities should be used to further our understanding of sawfishes.

Our results point to the challenges of conserving sawfishes not just in Australia, but also globally. The apparently high site fidelity for extended periods and close association with nearshore environments make sawfish highly vulnerable to human activities which are greatest in nearshore environments, including habitat modifications and fishing. Indeed, this may result in rapid, localised depletions of a population, since a large portion of the life-history of these species may be dependent on habitats most heavily impacted by human activities. While our data is currently not extensive enough to draw conclusions on the exposure of sawfish to various anthropogenic threats, or the efficacy of the Commonwealth and WA network of marine parks and sanctuaries to protect their habitat, it does provide a mechanism by which such data could be generated. An increased sample size of satellite-tracked sawfish through both strategic and opportunistic deployments in nearshore environments should be combined with environmental datasets, to create a habitat suitability model of the coastal zone for sawfish, as well as highlight seasonal patterns in habitat associations. Such a dataset would be crucial to quantify the exposure of sawfish habitat to human activity, as well as highlight potential areas that will benefit from threat abatement.

Such an approach should make use of the novel intertidal digital elevation model (Bishop-Taylor et al. 2019) to characterise the near-shore environment and develop a 2-dimensional model focused on the marine-terrestrial interface.

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7 Appendix A

Daily rainfall during the study period

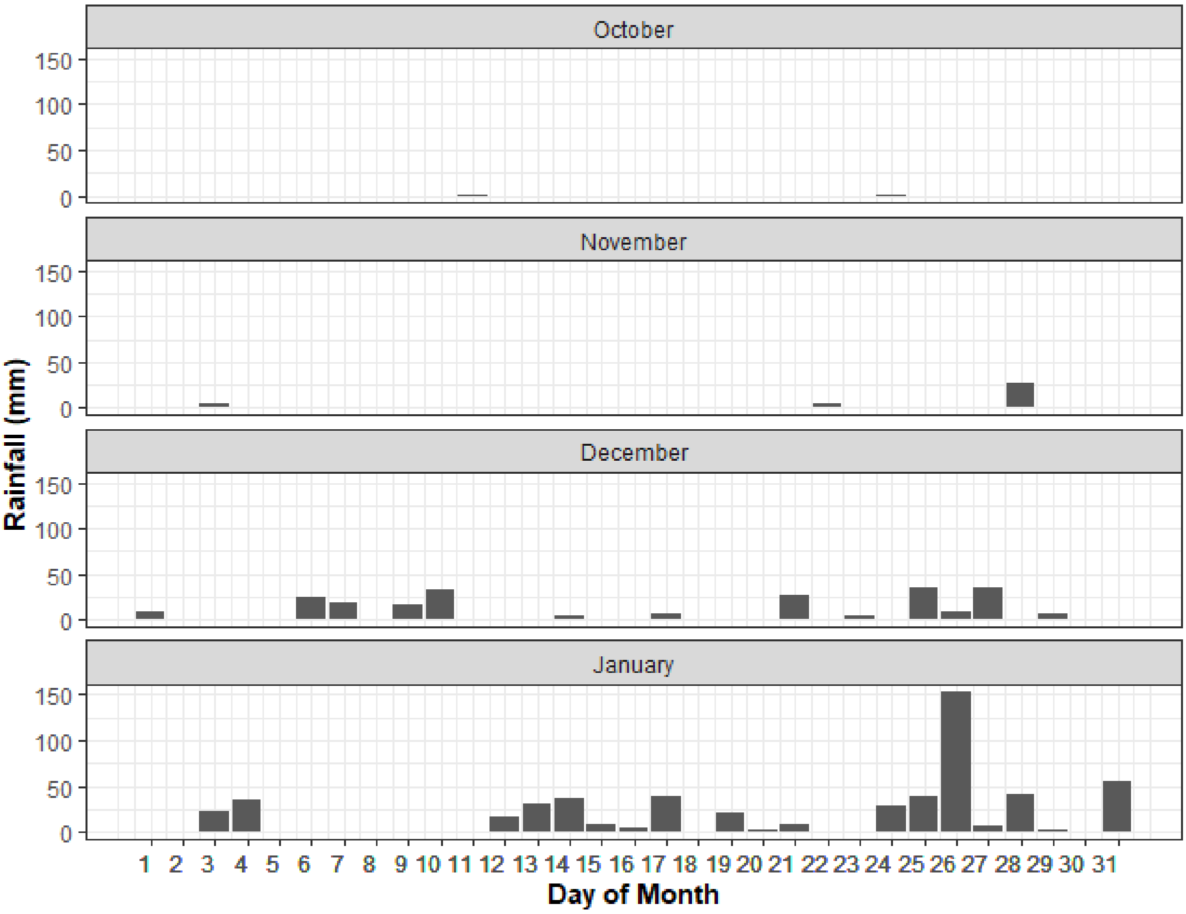

Figure 15. Daily rainfall (mm) for October 2021- January 2022. Rainfall data were taken from daily weather observations (station 001019), Kalumburu, Western Australia. ©Commonwealth Bureau of Meteorology 2003.

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