

Ontogenetic depth partitioning by juvenile freshwater sawfish (*Pristis microdon*: Pristidae) in a riverine environment

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Abstract. The freshwater sawfish (*Pristis microdon*) is a critically endangered elasmobranch. Ontogenetic changes in the habitat use of juvenile *P. microdon* were studied using acoustic tracking in the Fitzroy River, Western Australia. Habitat partitioning was significant between 0+ (2007 year class) and larger 1+ (2006 year class) *P. microdon*. Smaller 0+ fish generally occupied shallower water (<0.6 m) compared with 1+ individuals, which mainly occurred in depths >0.6 m. Significant differences in hourly depth use were also revealed. The depth that 1+ *P. microdon* occupied was significantly influenced by lunar phase with these animals utilising a shallower and narrower depth range during the full moon compared with the new moon. This was not observed in 0+ individuals. Habitat partitioning was likely to be related to predator avoidance, foraging behaviours, and temperature and/or light regimes. The occurrence of 1+ *P. microdon* in deeper water may also result from a need for greater depths in which to manoeuvre. The present study demonstrates the utility of acoustic telemetry in monitoring *P. microdon* in a riverine environment. These results demonstrate the need to consider the habitat requirements of different *P. microdon* cohorts in the strategic planning of natural resources and will aid in the development of management strategies for this species.

Additional keywords: external tagging, ontogeny, telemetry.

Introduction

The freshwater sawfish (*Pristis microdon*), listed as critically endangered on the IUCN Red List of Threatened Species (Compagno *et al.* 2006), is a euryhaline elasmobranch that inhabits several tropical river systems in eastern Africa, India, south-eastern Asia, New Guinea and northern Australia (Last and Stevens 1994; Compagno and Last 1998; Thorburn *et al.* 2007). Of these areas, the Fitzroy River in the Kimberley region of northern Western Australia is arguably one of the most important remaining nursery grounds for this species (Morgan *et al.* 2004; Thorburn 2006; Thorburn *et al.* 2007). The Fitzroy River is largely unregulated and remains relatively undisturbed, with no commercial fishing occurring. However, owing to the high discharge of potable water, the river's water resources are being considered for future water extraction programs that may impact the aquatic fauna in the river.

Pristis microdon is a benthic ray noted for its rostrum or 'saw'. The rostrum, which has between 17 and 24 'teeth' (Thorburn *et al.* 2007; Whitty *et al.* 2008) protruding from both lateral sides, aids in prey detection and capture (Breder 1952; Simpfendorfer 2005) (Fig. 1a). In the Fitzroy River, known prey include the lesser-salmon catfish (*Neoarius graeffei*), other small teleosts and cherabin (*Macrobrachium rosenbergii*) (Thorburn

et al. 2007). Predators of juvenile *P. microdon* include estuarine crocodiles (*Crocodylus porosus*), bull sharks (*Carcharhinus leucas*) and humans (Thorburn 2006; Thorburn and Rowland 2008; S. C. Peverell, unpubl. data). In Western Australia, pupping occurs during the wet season near river mouths (Thorburn *et al.* 2007; Whitty *et al.* 2008). Following pupping, juveniles move upstream where fewer large predators are found; some individuals have been found upstream at least 400 km from the river mouth (Morgan *et al.* 2004). Juveniles have been found to emigrate into marine waters just before maturation at approximately 2.4 m total length (TL) for males and 2.8 m TL for females (Thorburn *et al.* 2007; Whitty *et al.* 2008). Although aspects of the morphology, trophic ecology and general distribution have been investigated (Morgan *et al.* 2004; Thorburn 2006; Thorburn *et al.* 2007), the small-scale movements and habitat use of *P. microdon* remain largely unstudied.

The present study tested the hypothesis that juvenile *P. microdon* are able to move through relatively shallow runs (characteristic of this system during the dry season), which would enable their upstream migration. It was further hypothesised that owing to morphological differences between size/age classes and the likely utilisation of different food resources, there would be ontogenetic differences in habitat use. Lastly, as tracking of *P. microdon* has not been previously conducted, the present



Fig. 1. Attachment methods for (a) Vemco V13 acoustic tags on 0+ *Pristis microdon* and (b) Vemco V16 acoustic tags on 1+ *P. microdon*.

study also aimed to test the efficacy of passive acoustic tracking on this species in a riverine environment.

Materials and methods

Study area

The Fitzroy River is a tropical river that flows through the western Kimberley and discharges into the King Sound in northern Western Australia (17°33'12''S, 123°35'20''E) (Fig. 2). Discharge in the river is highly seasonal with water levels peaking in the

wet season (January–April), often >10 m above their dry season level when the river becomes an extensive series of pools connected by shallow runs. Large tides (>9 m) periodically influence the lower 16 km of the river, which is highly turbid compared with the non-tidal regions of the catchment (in the dry season).

Six pools in the lower 150 km of the Fitzroy River were selected for the passive tracking of *Pristis microdon* between June and November 2007 (2007 dry season) (Fig. 2). The pools ranged between 2.5 and 4.2 m in maximum depth, between 0.5

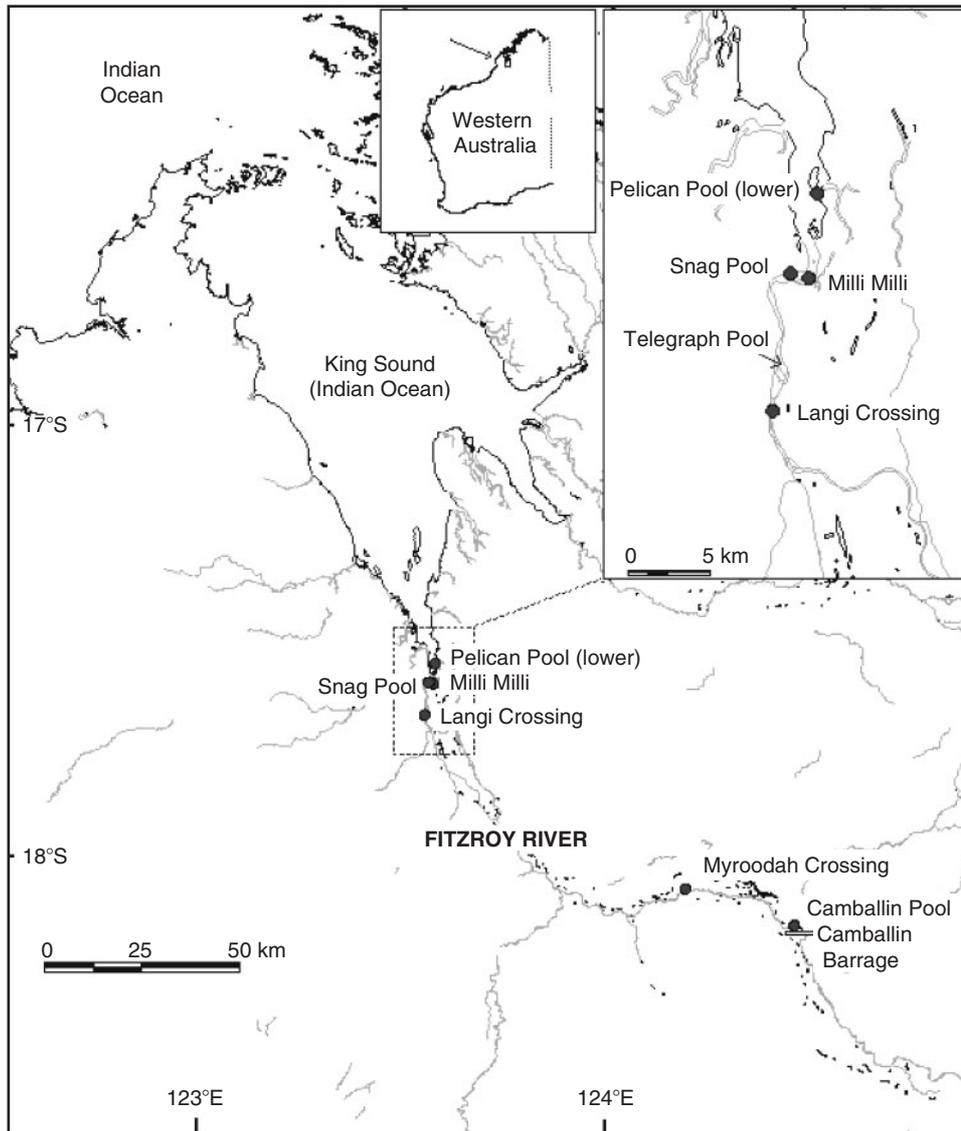


Fig. 2. Study sites in the Fitzroy River showing the locations of the Vemco VR2W acoustic receivers.

and 2.75 km in length, and were <100 m in width. The bottom topography was generally uniform with the deepest holes on the outer bends and sand bars on the inner bends, and with depths gradually decreasing approaching the shallow runs that separated the pools (generally <0.5 m in depth). Run depth increased up to several metres (depending on the distance from the river mouth and the tidal height) when tidal waters were present as well as during high flow periods. Four pools monitored in the present study were located in the lower 16 km of the river (Lower Pelican Pool (river mouth; 17°33'12''S, 123°35'20''E), Milli Milli (5.8 km from the mouth; 17°35'59''S, 123°35'03''E), Snag Pool (7 km from the mouth; 17°35'50''S, 123°34'25''E) and Langi Crossing (16 km from the mouth; 17°40'22''S, 123°33'48''E)). Two other monitoring stations, Myroodah Crossing (115 km from the mouth; 18°04'51''S, 124°11'54''E) and Camballin Pool (name given by the authors as no formal name could be

found) (148 km from the mouth; 18°10'01''S, 124°27'48''E), were located in the strictly freshwater upper regions of the river (Fig. 2).

Acoustic array and range testing

In June 2007, an acoustic array was installed consisting of six Vemco (Nova Scotia, Canada) VR2W acoustic receivers (see Fig. 2 for locations). Receivers were set-up as 'gates' (see Heupel *et al.* 2006) to record the passing of sawfish in and out of pools or deeper waters. All receivers were secured to moorings that enabled surface retrieval, as diving was not feasible owing to the presence of estuarine crocodiles (*Crocodylus porosus*). The moorings were also designed to have minimal movement during peak river flows in the wet season. The design of each mooring consisted of a ~65-kg concrete block (or when possible a

piling or a stable snag/tree) attached to a secondary smaller sand anchor (7–20 kg) via a 4-m galvanised chain. The smaller anchor was used to reduce movement and entanglement of the chain and rope (described below) and allow a person to use the total 6–7 m (chain + rope) to retrieve the receiver. A 3-m length of rope (25 mm diameter) joined the sand anchor (via a galvanised thimble and D-link attached to the anchor arm) to two aluminium floats (one surface and one subsurface) set ~1 m apart (the floats were used to compensate for rising and falling river levels). Aluminium floats were used to prevent damage and/or sinking of the floats by crocodiles. Following the design of Clements *et al.* (2005), an extra 1-m piece of rope (25 mm diameter) (with thimbles spliced at both ends) was connected 1 m above the anchor and 0.5 m below the subsurface float creating an extra piece to hang down in a loop. Receivers were attached upright to the loop using five large cable ties. The purpose of the loop was to maximise the detection range at all times by keeping the receivers upright during strong river flows. Temperature loggers were attached to the mooring and set to record at 3-h intervals. All receivers and temperature loggers, with the exception of Lower Pelican Pool (unobtainable because it was buried at the time of download), were downloaded in October/November 2007. The GPS coordinates were recorded for each receiver's location.

Range testing was conducted to determine the detection limit of each VR2W using both Vemco V16 and V13 test tags. The test tags were factory set and identical to the deployed tags, but with a shorter (3–6 s) non-random transmission interval and battery life. The test tags were attached to a portable mooring 1 m above the substrate and placed at 50-m intervals upstream and downstream of the receiver for between 250 and 1200 m, depending on the size and shape of the pool. At each interval, the tag was submerged for a minimum of 4 min. During each test interval, the research vessel was moved out of the area and the engine stopped to prevent interference with the acoustic signal. The V16 test tags were tested in all monitored pools in June 2007. Range testing of V13 test tags was conducted in Snag Pool, Langi Crossing and Camballin Pool in October 2007. A second V13 range test trial was conducted at Langi Crossing. This test included the addition of a thin silicone coating on the tag to determine the influence of the V13 attachment method on the strength of the acoustic transmission (see attachment method below).

Sampling and tagging

In June/July 2007, a total of 35 *P. microdon* were captured in Snag Pool (33 individuals) and in Camballin Pool (two individuals) using 4', 6' and 8' (approximately 10 cm, 15 cm and 20 cm, respectively) stretched monofilament gillnets and hook and line methods. The nets were set throughout the day and night and checked regularly (1–2 h depending on the level of bycatch). Of the 33 individuals captured in Snag Pool, four were fitted with a Vemco V13TP-1 L (120 s interval \pm 15 s; depth sensitivity 0.22 m) and three with a Vemco V16TP-5H (60 s interval \pm 15 s; depth sensitivity 0.15 m) coded acoustic tag. Shark casings (protective coverings with attachment holes on both the anterior and posterior ends) encapsulated the V16 tags to prevent damage to the tag, but these casings were not available for the V13 tags during the study. V13 and V16 tag life was estimated to be 1028 and 480 days respectively. The tags were externally attached to the dorsal fins of juvenile *P. microdon* by the following methods.

The V13 tags were attached to flexible Jumbo Rototags (Dalton Supplies, Woolgoolga, New South Wales, Australia) using three small plastic cable ties, which were then coated in marine silicone to prevent damage to the sawfish and slipping of the plastic cable ties (Fig. 1a). The altered Rototags were then attached in a similar fashion to that described by Heupel *et al.* (1998) (Fig. 1a). The V16 tags were attached just above the base of the first dorsal fin via two (diameter = 4 mm) nylon bolts passed through holes in the shark casing and holes in the fin created using a 5-mm implant-grade drill bit (Fig. 1b). A prefabricated template was used to accurately place the holes in the fin and to give support to the fin while using the drill bits. Stainless steel nuts and washers were used to secure the bolts in place. The animals were not chemically sedated during tagging, but were turned on to their backs causing them to enter a tonic immobility-like state found to occur in other elasmobranch species (Watsky and Gruber 1990; Henningsen 1994). *Pristis microdon* tagged with V13 tags ranged between 842 and 990 mm TL and represented the 2007 (0+) cohort (see Thorburn *et al.* 2007). The V16 tagged individuals ranged in size between 1555 and 1611 mm TL and represented the 2007 (1+) cohort (see Thorburn *et al.* 2007). In the case of all tagged specimens, the tag weight was less than 1% of the tagged animals calculated bodyweight, which is less than that recommended by Blaylock (1990).

Environmental conditions

Tidal data were supplied by the Western Australian Department of Planning and Infrastructure. *In situ* observations of tides at Snag Pool and Langi Crossing were used to determine the timing and level of influence that different tides had on each area. This information was used to determine the influence of tides on the movements of animals between pools.

Lunar and solar data were downloaded from the United States Naval Observatory Astronomical Application Department (<http://aa.usno.navy.mil/data>). Lunar data were used to determine if individuals displayed different movement patterns in association with changing lunar illumination levels. Times of sunrise, zenith and sunset were used to determine the relationship between depths occupied by individuals and light intensities/positions of the sun.

Temperature and salinity were manually recorded at each site in June and October 2007. Salinity values were based on the Practical Salinity Scale of 1978. Temperature loggers on the moorings also recorded pool temperatures at 1 m from the substrate in 3-h intervals and were downloaded in October 2007. Secchi disc readings were taken at the beginning of the dry season (June) and turbidity readings were taken in the late dry season (October). These variables were recorded to determine if they had any association with the movements of *P. microdon*.

Data analysis

Statistical analyses were conducted using SPSS version 15 (SPSS, Chicago, IL, USA) and JMP version 4 (SAS Institute, Cary, NC, USA). The significance of differences in depth between cohorts, time (h) and individuals was determined. Measurements of depth utilisation by each individual at different times were not independent, so a repeated-measures ANOVA (Girden 1992) was undertaken with cohorts as the between-subject (individual) effect and hours as the within-subject effect.

The recorded range test transmissions were divided by the expected number of transmissions (expected = 240 s/time between test tag transmissions (3–6 s)) for each interval to determine the maximum range in which 95% of transmissions were received. A Student's paired *t*-test was used to test for differences in transmission strength between silicone and non-silicone coated V13 tags.

Lunar phases were grouped into two categories: new moon (0–32% illumination); and full moon (66–100%). A Kruskal–Wallis test (Conover 1971) was used with the depths occupied during night hours (21:00–04:00 hours) and daylight hours (06:00–19:00 hours) by *P. microdon* in accordance with these two lunar phases. Depth data gathered during half-moon phases were omitted from the statistical tests to ensure that depths between subsequent moon phases were not correlated.

A χ^2 test (Greenwood and Nikulin 1996) was used to determine whether significant differences occurred between the amounts of time spent at different depths during the different temperature periods of the day (recorded eight times over a 24-h period). For the χ^2 test, temperatures in each day were scaled one through to eight, with one being the coldest temperature of the day and eight being the warmest, which compensated for changing pool temperatures over time/months.

Results

Environmental conditions

Environmental measurements in the river were variable and dependent on pool location, the time of year and tidal presence. Salinity in the tidally influenced pools rose to between 10 and 25 between June and October 2007, whereas Myroodah Crossing and Camballin Pool remained fresh (Fig. 3a, b). The temperature range was similar in each pool (18.6–31.6°C) (Fig. 4). The recorded temperature differences between the surface and bottom waters ranged between 0°C (when tidal waters were present) and 4.3°C. When tidal flows were not present, turbidity decreased the further upstream the pool was located (e.g. Secchi depth of 0.27 m at Pelican Pool and Secchi depth of 1.59 m at Camballin Pool) (Table 1). Turbidity increased substantially when flows increased (i.e. with incoming and outgoing tides) (Table 1).

Acoustic array and range testing

At the time of the VR2W receiver downloads, all moorings remained in their original position, but only five of the six were retrievable from the surface. The irretrievable mooring was the most downstream (Lower Pelican) and it had become buried by sand to just beneath the subsurface float. Two surface floats had been shot at and had sunk, but subsurface floats allowed the mooring to remain upright.

Range testing demonstrated the detection radius (95% accuracy) by the VR2W receivers for the V16 test tag to be between 50 and 450 m (Table 2). The V13 test tag detection range was between 50 and 350 m (Table 2). The detection range and range testing distance were dependent on the length and shape of the individual pools. The detection radius for the receivers was found to be greater than the width of the pools (<100 m) within which the receivers were installed, suggesting a high chance of detection when tagged animals moved past the receivers. There

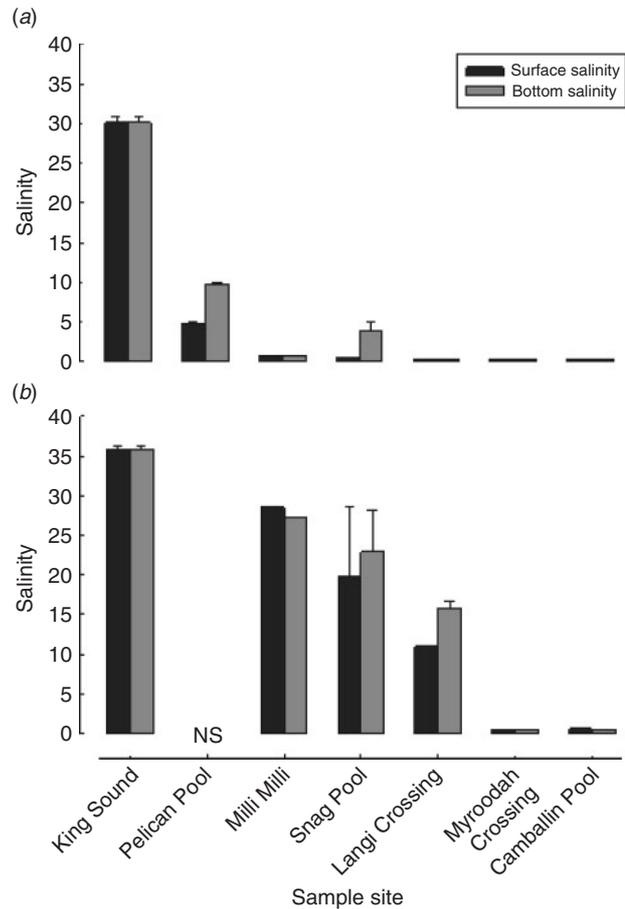


Fig. 3. Mean salinity profiles of the monitored stations/pools for (a) June 2007 and (b) October 2007.

was no evidence of a significant difference between V13 tags with and without a silicone layer at Langi Crossing (Student's paired *t*-test, d.f. = 14, $P = 0.383$).

Transmission details

Between June and October 2007, all tagged individuals were primarily detected in the pool of initial capture (Snag Pool) and the neighbouring downstream pool (Milli Milli) for between 25 and 75 days (40 ± 8.5 (mean \pm s.e.) from V16 tags and 51.8 ± 13.24 from V13 tags). A total of 28 346 and 8181 transmissions were recorded from these two receivers for the V16 and V13 tags, respectively; V16 transmission intervals were half that of V13 tags (Table 3). One animal was recorded briefly (six transmissions in a 3-h period) at Langi Crossing (Fig. 5; Table 3). Excluding this animal, all final transmissions occurred at Snag Pool with four of the six final transmissions occurring in mid August 2007, and the remaining two occurring in late July and early October 2007 (Fig. 5). No transmissions were recorded on the other receivers.

Movements and influential factors

The tag depth sensor data demonstrated that new recruits (0+ sawfish) largely remained in shallower water compared with

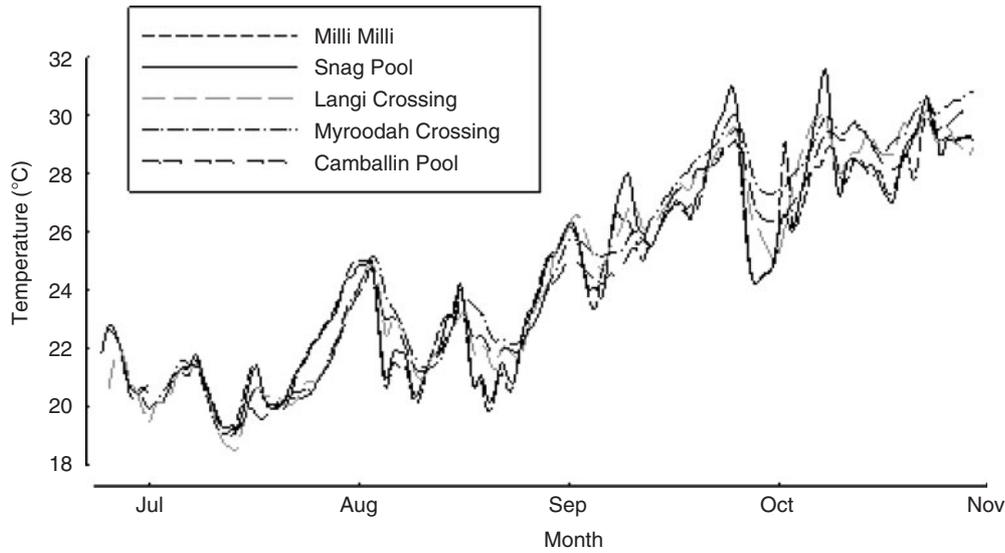


Fig. 4. Temperature profiles of the monitored stations/pools in the Fitzroy River during the 2007 dry season.

Table 1. Summary of the environmental records from pools in June and October

Z_{max}, maximum depth of the pool; t, temperature range in the pool between June and October 2007; S, surface/bottom salinity range in the pool between June and October 2007 reported in practical salinity units; turbidity, mean turbidity (± s.e.) in the pool (taken at slack tide). Secchi depth was taken in June 2007. NA, not applicable

Receiver station	Z _{max} (m)	t (range) (°C)	S (range)	Secchi depth (m)	Turbidity (ntu)
Pelican Pool	2	NA	4.0–NA/7.9–NA	0.27	NA
Milli Milli	2.2	19–30.3	0.6–0.7/0.6–1.1	0.57	NA
Snag Pool	2.9	19.3–31.6	0.3–0.5/0.3–12.8	0.75	22.7 ± 0.94 ^A
Langi Crossing	3.4	18.6–30.1	0.2–11.2/0.2–20.1	1.31	13.3 ± 1.06
Myroodah Crossing	4.2	19–30.8	0.3–0.5/0.3–0.5	1.42	5.3 ± 0.90
Camballin Pool	4	19.2–30.3	0.3–0.6/0.3–0.6	1.59	2.8 ± 0.11

^ADuring incoming/outgoing tides the turbidity reached 734.3 ntu (s.e. = 18.8).

the larger (1+ sawfish) individuals (depth of transmissions was 0.49 ± 0.01 (mean ± s.e.) and 0.83 ± 0.01 for 0+ and 1+ sawfish respectively) (Fig. 6a, b). The repeated-measures ANOVA with individuals nested within age cohorts revealed that, despite significant differences in depth utilisation between individual sawfish within a cohort ($F = 118.231$, d.f. = 5, 10 968, $P < 0.001$), there were also significant differences between cohorts ($F = 13.328$, d.f. = 1, 5, $P = 0.014$). This analysis also revealed that there was an overall significant difference in the depth utilisation between hours of the day ($F = 43.296$, d.f. = 23, 10 968, $P < 0.001$) and a significant interaction between hours of the day and age cohort ($F = 27.063$, d.f. = 23, 10 968, $P < 0.001$). The 0+ sawfish generally occupied shallower habitats between 12:00 and 17:00 hours (i.e. afternoon) compared with times throughout the remainder of the day; in contrast, 1+ sawfish generally occupied deeper habitats (~0.5 m deeper) between 06:00 and 12:00 hours (i.e. morning) (Fig. 7).

The acoustic data also demonstrated that the smaller 0+ individuals (<1 m TL) readily moved between Snag Pool and Milli Milli Pool, even though at low tide these pools were separated

Table 2. Mean detection range (± s.e.) of the V16 and V13 test tags at the corresponding stations

Receiver station	V16 (m)	V13 (m)
Pelican Pool	100 ± 50	–
Milli Milli	175 ± 25	–
Snag Pool	375 ± 75	–
Langi Crossing	225 ± 75	350 ± 38 (downstream)
Myroodah Crossing	325 ± 75	–
Camballin Pool	275 ± 25	100 ± 38

by a 0.7-km stretch of shallow water (generally <0.5 m). Larger 1+ individuals were only recorded moving between these pools at times when tidal waters were present. At these times, movements of 0+ individuals were almost exclusively (~98%) with the flow of the tide. In contrast, the 1+ individuals moved both

Table 3. Transmissions of each tagged *Pristis microdon* at each receiver/station
V16 tags, 1038503, 1038505, 1038506; V13 tags, 1042224, 1042226, 1042227, 1042229

Receiver station	1038503	1038505	1038506	1042224	1042226	1042227	1042229
Pelican Pool	–	–	–	–	–	–	–
Milli Milli	–	12 002	1	331	3306	149	244
Snag Pool	8498	2364	5481	744	988	809	1610
Langi Crossing	–	–	–	6	–	–	–
Myroodah Crossing	–	–	–	–	–	–	–
Camballin Pool	–	–	–	–	–	–	–
Total	8498	14 366	5482	1081	4294	958	1854

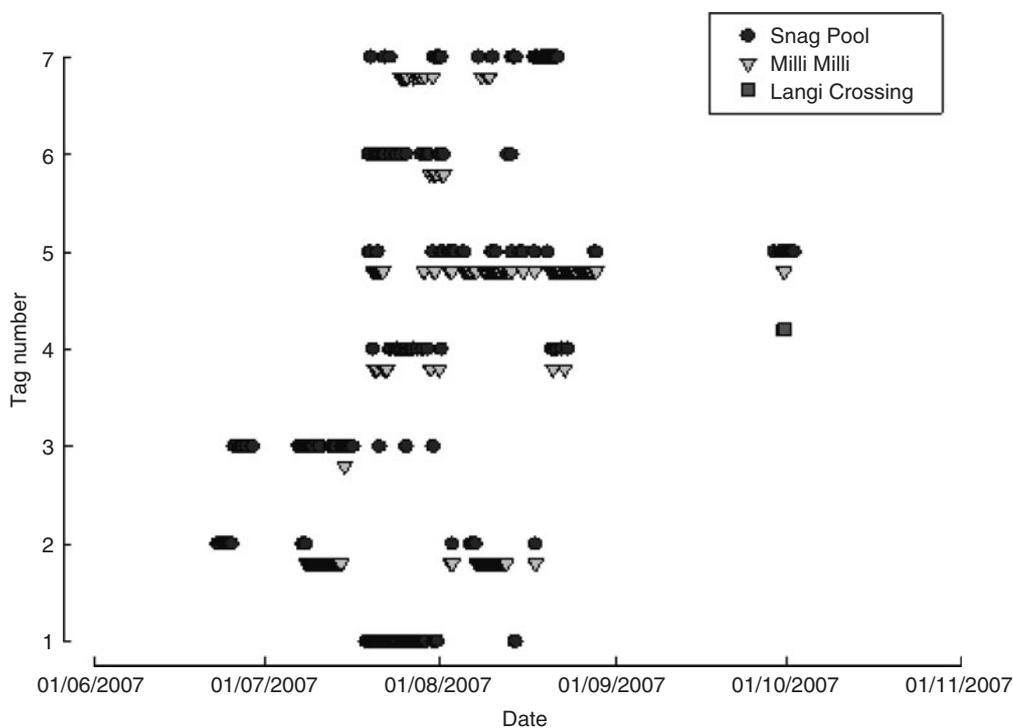


Fig. 5. Movement of *Pristis microdon* tagged with Vemco V16 (1, tag 1038503; 2, tag 1038505; 3, tag 1038506) and V13 (4, tag 1042224; 5, tag 1042226; 6, tag 1042227; 7, tag 1042229) acoustic transmitters in the Fitzroy River between the different receivers/pools over time. Dates are listed as dd/mm/yyyy.

with (50% of recorded 1+ individual movements) and against (50% of recorded 1+ individual movements) tidal flow between these sites. Movement by one 0+ individual into Langi Crossing only occurred after a >11-m tide.

No changes in the movement of 0+ *Pristis microdon* were observed in relation to changes in moon phase. However, 1+ *P. microdon* were observed to utilise very shallow waters (<0.2 m) during the full moon and water depths greater than 1.5 m during the new or half moon (Fig. 8a, b). The mean depth of the 1+ sawfish during the full moon was 0.51 m (± 0.017 s.e.) compared with 0.87 m (± 0.014 s.e.) during the new moon. A Kruskal–Wallis test demonstrated that the depths occupied by *P. microdon* between the new and full moon were significantly different ($\chi^2 = 254.3$, $P < 0.001$) for the 1+ year class.

A χ^2 test showed a significant difference (d.f. = 7, $P < 0.001$) between water temperatures throughout the day and the depth used by the sawfish, with animals occupying shallower waters more often when daily temperatures were peaking and deeper depths when temperatures were at their lowest.

Discussion

Passive acoustic telemetry was found to be a useful method for the short-term (months) tracking of critically endangered juvenile *Pristis microdon* in a dynamic riverine environment during the northern Australian dry season. The present study demonstrated that there are differences between the movements and habitat use of 0+ and 1+ age cohorts. These differences

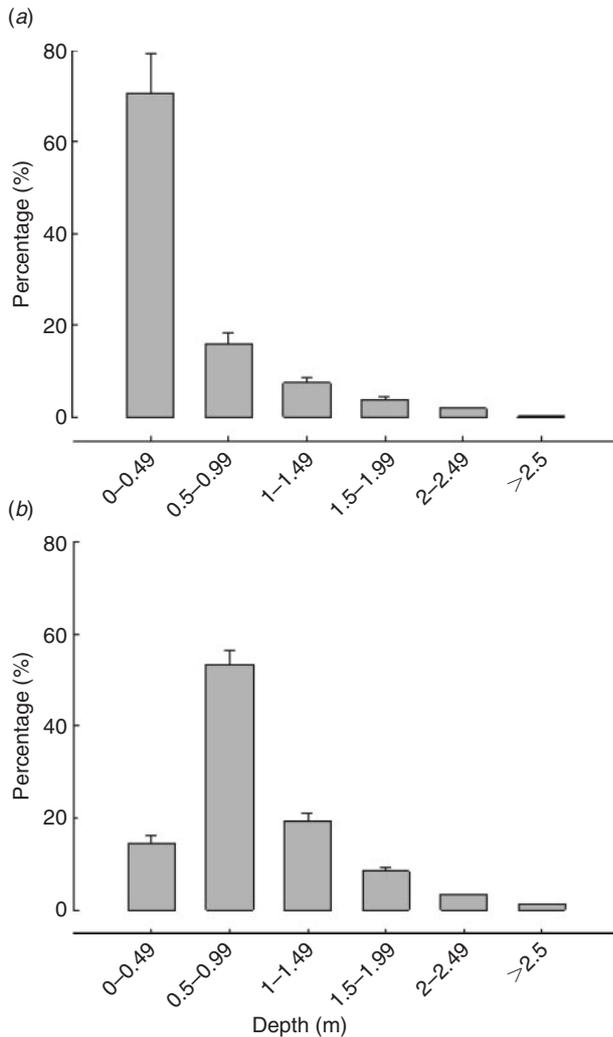


Fig. 6. Mean percentage (± 1 s.e.) (at each corresponding hour) depth occupied by (a) 0+ (V13) and (b) 1+ (V16) *Pristis microdon* in the Fitzroy River.

were found to be influenced by various environmental factors, including flow (tides), water temperature, moon phase and light intensity.

The movement data spanned 2–3 months and suggested a high degree of short-term tag retention and survivorship of animals. Cessation of recorded transmissions after ~90 days may have resulted from the movement of individuals into an unmonitored pool (e.g. Telegraph Pool, see Fig. 2) or non-detection of tags by receivers. However, the latter possible cause appears unlikely based on the range testing data. In previous years, Telegraph Pool has been shown to host a large number of sawfish (Thorburn *et al.* 2007) and is the only major pool between Snag Pool and Langi Crossing. In addition, premature tag shedding, tag removal by anglers or tag malfunction may have also played a role in the termination of the recorded transmissions (Eklund and Schull 2001; Hays *et al.* 2007).

External tag retention can be highly variable and is dependent on the method used to secure the tag (Stevens *et al.* 2000;

Domeier *et al.* 2003). A tag retention study on captive sawfish would aid in determining the longevity of the attachment methods used in the present study. However, because of the paucity of captive animals, sample sizes may be limited, making it difficult to accurately examine retention rates. It is also difficult to mimic the natural environment in the dynamic system these animals are found in, which may be a cause for premature tag shedding. Double-tagging studies have been shown to be a useful method in investigating tag retention with other species, including raggedtooth sharks (*Carcharias taurus*) (Dicken *et al.* 2006), school sharks (*Galeorhinus galeus*) (Hurst *et al.* 1999) and skipjack tuna (*Katsuwonus pelamis*) (Adam and Kirkwood 2001) and may be useful in determining the retention rates of tags in *P. microdon*. The current study has demonstrated successful methods of acoustic tag attachment and means of investigating habitat use in juvenile *P. microdon* over a short period of time, but further research is required to determine the long-term efficacy of this monitoring methodology.

Acoustic tracking demonstrated that habitat partitioning (by depth) occurred between 0+ and 1+ *P. microdon*. Following Simpfendorfer (2006), who observed similar behaviour in smalltooth sawfish (*Pristis pectinata*), possible reasons for 0+ individuals inhabiting the extreme shallows may be for predator avoidance, optimising growth or as a consequence of foraging behaviour (Sims 2003; Matern *et al.* 2004; Wetherbee *et al.* 2007). The occurrence of larger 1+ individuals in deeper water may simply be attributed to a requirement for more space to manoeuvre, while also maintaining close proximity to potential prey. Varying prey size, type and location has been observed to result in different foraging behaviours between different age groups of elasmobranchs (Ebert 2002; McElroy *et al.* 2006) and may have contributed to the habitat partitioning observed in 0+ and 1+ *P. microdon* in the present study. Vertical movements of both age classes also varied. Although the vertical movement of 1+ individuals was <2 m, it consisted of 25–50% of the pools' vertical profile. As a result of high turbidity levels, even a 0.5-m change in depth results in a large change in light intensity (Anthony *et al.* 2004). Such a change in light intensity is important to note as the vertical movements of 1+ *P. microdon* may also be at least partly influenced, directly or indirectly, by temperature and/or light levels. The occurrence of these animals in shallow depths when water temperatures were the warmest and deeper depths when water temperatures were the coldest supports this hypothesis. Other elasmobranchs, including bat rays (*Myliobatus californica*) (Matern *et al.* 2004), leopard sharks (*Triakis semifasciata*) (Hight and Lowe 2007) and small-spotted catsharks (*Scyliorhinus canicula*) (Sims *et al.* 2006), have also been shown to display a similar diel movement pattern correlated with temperature/thermoregulation. Light intensity has also been shown to influence movements in several elasmobranch species, including manta rays (*Manta birostris*) (Dewar *et al.* 2008) and megamouth sharks (*Megachasma pelagios*) (Nelson *et al.* 1997). Increase lunar illumination has been noted to make prey more vulnerable to large predators leading to a change in predator and prey movements (Fraser and Metcalfe 1997). Movement of 1+ *P. microdon* into shallower water during a full moon may be a sign of predator avoidance, or perhaps that *P. microdon* individuals are following prey into shallower water. Although light levels may influence this pattern, these animals exhibited similar behaviour

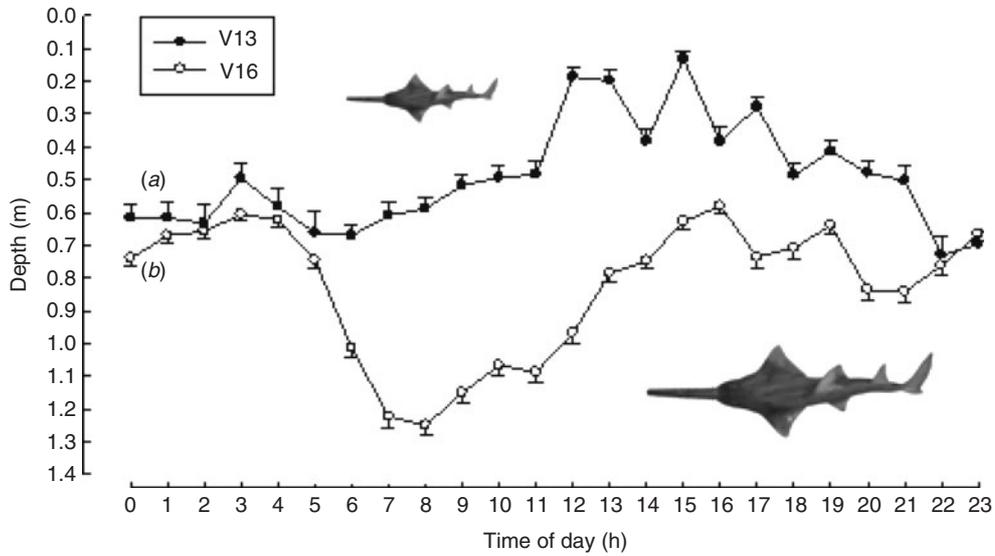


Fig. 7. Mean depths at different hours of the day for (a) 0+ (V13) and (b) 1+ (V16) *Pristis microdon* in the Fitzroy River.

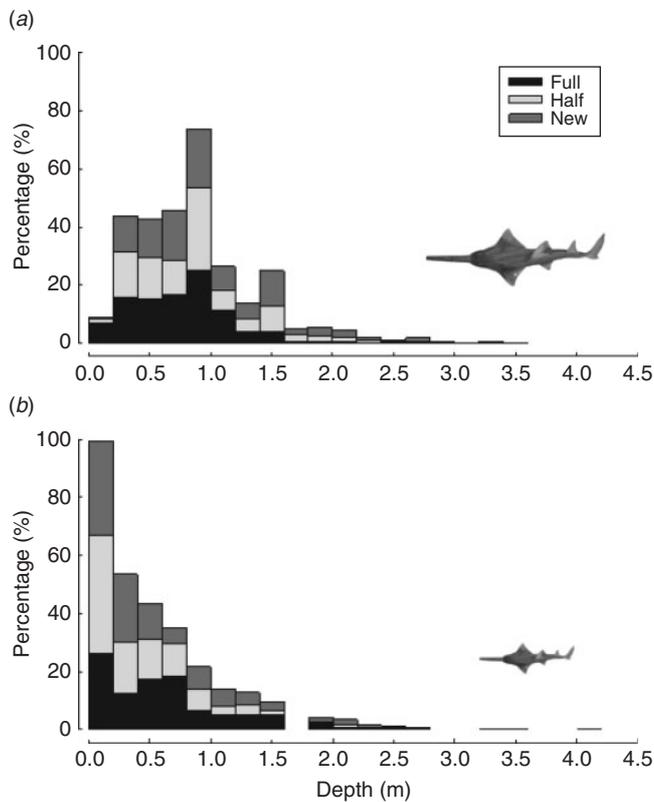


Fig. 8. Proportion of time spent by (a) 1+ (V13) and (b) 0+ (V16) *Pristis microdon* at corresponding depths during different lunar phases in the Fitzroy River.

in the daylight hours, suggesting that there may be other factors involved that are correlated with the different lunar phases. However, the coincidence of the vertical movements of *P. microdon* with the sun's position suggests that light is still an important

factor associated with their movements. Unfortunately, as temperature and light levels are highly correlated with one another, along with time of day, it is difficult to discern the exact cue for these movements. Further research under controlled conditions would be useful in separating the effects of temperature and light on *P. microdon*.

The ability of 0+ *P. microdon* to navigate through shallow runs and riffle zones gives these young-of-the-year an advantage over larger individuals. Having the ability to manoeuvre through shallow water gives them access to an area occupied by numerous prey species (Morgan et al. 2004), while limiting interspecific and intraspecific competition with larger-bodied animals. This would also reduce the predation on 0+ *P. microdon* from deeper-bodied predators such as *C. leucas* (Thorburn and Rowland 2008). However, in the presence of tidal waters, 0+ individuals demonstrated more restricted movements (moving with the direction of the tidal flow) than 1+ *P. microdon* (moving with and against the direction of tidal flow). This behaviour has been considered to be a means of energy conservation in sandbar sharks (*Carcharhinus plumbeus*) (Medved and Marshall 1983) and leopard sharks (*T. semifasciata*) (Ackerman et al. 2000). It is especially important for young animals, such as the smaller 0+ individuals, to reduce energy expenditure so that growth is maximised and the risk of predation is reduced (Parker 1971; Sogard 1997). Although the ability to manoeuvre through shallow runs should have allowed 0+ *P. microdon* to move far upstream, as previous years' capture data have suggested (Thorburn 2006), the results of the present study showed that this had not occurred. The lack of recorded transmissions at Langi Crossing from most of the animals could have been a result of tag problems. However, this may also suggest that animals displayed some level of site fidelity for an unmonitored area between Snag Pool and Langi Crossing, or that water levels were too low to allow movement between Telegraph Pool and Langi Crossing without the assistance of tides. This latter argument is further supported as the one animal that made it to Langi Crossing did so only after a >11-m tide (noting that only tides of >11-m reach Langi

Crossing). Further monitoring of animals in this area and a double-tagging study would help answer this question.

The moorings used in the present study proved to be a successful method of anchoring and retrieving receivers from a boat, despite a few minor issues. As explained by Heupel *et al.* (2006), selecting the appropriate mooring design is crucial for the recovery of VR2W receivers and depends on the habitat. The fine sediment and small gravel found in many riverine environments make sand anchors a useful tool to prevent mooring movement. This was demonstrated by the success of the two-stage anchor system used in the current study, as it was able to handle tidal forces and allowed for surface retrieval (excluding Pelican Pool, which receives the greatest tidal influence). Similarly, subsurface floats proved useful in keeping the moorings vertical as the water levels dropped and after the surface floats were sunk. As the moorings were only exposed to dry season conditions, further research is needed to investigate the effects of wet season flows on installed moorings.

The results of the present study demonstrate that 0+ *P. microdon* are able to move through relatively shallow (<0.5 m) runs between pools during the dry season, aiding their movement upstream. However, during the mid to late dry season some runs, such as that between Telegraph Pool and Langi Crossing, would likely be too shallow for the passing of even 0+ individuals (without the assistance of tidal waters). This information highlights the importance in the timing of pupping/movement upstream to allow the young-of-the-year access to safer nursery grounds. It also demonstrates that a decrease in water levels, an inevitable effect of water extraction and/or damming projects, may result in decreased movement upstream by *P. microdon*. The present study also provides strong evidence of habitat partitioning by 0+ and 1+ *P. microdon*. Selection pressure for 0+ *P. microdon* to generally remain in the extreme shallows (0–0.6 m) may be related to several factors, including predator avoidance, foraging behaviour, higher light levels and higher water temperatures. In contrast, the 1+ fish, which are less susceptible to predation and/or have reduced manoeuvrability in the shallows, use deeper waters and seldom enter the shallow waters inhabited by the 0+ *P. microdon*. Lastly, the present study demonstrates that passive acoustic tracking is a useful method to study the habitat utilisation of *P. microdon* and that the tag attachment methods used are effective for at least several months in a riverine environment.

Future work should explore seasonal trends in the habitat use of older age classes in marine, estuarine and freshwater habitats. This information is important for the conservation of this species by helping to define critical nursery habitats and examining the effects of anthropogenic influences on the sustainability of *P. microdon* populations.

Acknowledgements

We would like to thank the Department of the Environment, Water, Heritage and the Arts (DEWHA) for financially supporting the project. Thanks in particular to Narelle Montgomery (DEWHA) for project support. We would also like to thank the Jarlmadang Rangers (Travis Fazeldean, Kimberley Watson, Nyaburu Watson, Kenny Watson, Angus Butt, Josh Albert and William Lennard), the Yiriman Project (Hugh Wallace-Smith, Michelle Coles, Darryl Combs, Mick Apanah and Simon Keenan), Mark Allen, Simon Visser, Nicole Phillips, Ferdy Bergmann and Ryan Bell for their assistance

in the field. Thanks to Alan Lymbery and James Tweedley for statistical assistance. Thanks to Yeeda Station and Liveringa Station for access on their land and Mitre 10 Derby for donating consumables to the project. We would like to thank Jim and Gerry Kelly for allowing us to store equipment and ourselves at their residence. Finally, we would like to thank the reviewers of this document, including Colin Simpfendorfer, for their aid in increasing the value of this work. This research was made possible by an exemption from the *Fish Resources Management Act 1994* that was provided by the Western Australia Department of Fisheries (Permit no. 190-2008-40). Ethics approval for this work was provided by Murdoch University's Ethics Board.

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Manuscript received 30 May 2008, accepted 29 December 2008