



Residency, home range and tidal habitat use of Green Turtles (*Chelonia mydas*) in Port Curtis, Australia

Richard D. Pillans¹ · Gary C. Fry¹ · Michael D. E. Haywood¹ · Wayne Rochester¹ · Colin J. Limpus³ · Toby Patterson² · Russel C. Babcock¹

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Abstract

To understand habitat requirements of green turtles in an important foraging area subject to both anthropogenic and natural perturbations, we examined residency, home range and habitat use of juvenile, sub-adult and adult green turtles (*Chelonia mydas*) in Port Curtis, Australia, using passive acoustic telemetry. Acoustic tags were attached to turtles at Pelican Banks ($n=33$) and Wiggins Island ($n=16$). Between May 2013 and September 2014, tagged turtles were detected > 1.3 million times by 46 acoustic receivers. Data demonstrated variability in residence index and home range size between Pelican Banks and Wiggins Island that was largely attributed to larger body size at Pelican Banks and habitat differences. Tide had a significant influence of movement and habitat use. At Pelican Banks turtles moved into intertidal seagrass beds at high tide and retreated to the channel at low tide. At Wiggins Island, high tide 50% KUD area was more than double low tide area and turtles moved into the mangroves at high tide and retreated to channels at low tide. Diet reflected availability of food resources; seagrass dominated diet at Pelican Banks whereas epiphytic red algae dominated diet at Wiggins Island. There was no evidence of a diurnal shift in home range or habitat use. The use of intertidal areas by both turtles and small recreational craft during high tide at Pelican Banks resulted in increased risk of vessel strike. Unusually short residency at Pelican Banks suggested that animals had either relocated to another foraging area or a combination of recent flooding, port development and reduced seagrass coverage during the period of monitoring resulted in higher emigration rates than previously demonstrated for this species. Acoustic telemetry is a valuable tool for obtaining fine-scale, long-term data on movement and residency of green turtles.

Introduction

How individuals within a population utilize available space and habitat has important implications for managing important habitat such as key foraging areas (Hazen et al. 2012; Gredzens et al. 2014; Pillans et al. 2014; Zeh et al. 2014;

Griffin et al. 2020). While our understanding of broad scale migratory patterns of marine turtles has improved (Hays and Scott 2013; Shimida et al. 2020), our understanding of movement and habitat use within foraging areas has been identified as a key knowledge gap for management of these threatened species (Hamann et al. 2010). In green turtles (*Chelonia mydas*), individual adult male and female turtles faithfully migrate between breeding areas (courtship and nesting) and resident feeding areas (Limpus et al. 1992; Balazs 1994; Troeng et al. 2005; Shimida et al. 2020). However, on any resident feeding area there is a large degree of variation in the extent of dispersal between feeding and breeding grounds with individuals at a breeding ground coming from feeding grounds as close as 8 km away to > 4000 km away (Limpus et al. 1992; 2005; Shimida et al. 2020). Immature and adult green turtles forage in tidal and sub-tidal coral and rocky reefs, seagrass meadows, and sand and mudflats primarily for seagrass, algae, mangrove leaves and fruit, and

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✉ Richard D. Pillans
Richard.Pillans@csiro.au

¹ CSIRO Oceans and Atmosphere, St Lucia, Brisbane 4067, Australia

² CSIRO Oceans and Atmosphere, Castray Esplanade, Hobart 7004, Australia

³ Department of Environment and Science, Dutton Park 4152, Australia

occasionally on jellyfish, invertebrate egg masses, dead fish and small crustaceans (Limpus 2008).

Given that turtles spend the majority of their lives at foraging grounds (Musick and Limpus 1997; Plotkin 2003), there is a surprising paucity of data on movement patterns and habitat use of animals within foraging grounds. For many regions, habitat use and residency at foraging areas has long been identified as a key knowledge gap (Hamann et al. 2010). However, within Queensland there is abundant evidence of very high fidelity to small foraging areas that persist for decades between long-distance reproductive migrations (Chaloupka and Limpus 2001; Chaloupka et al. 2004; Shimida et al. 2020). Marine turtles are threatened by a range of anthropogenic factors at their foraging grounds. These include habitat loss, increased mortality associated with boat strike, entanglement in fishing gear, disease and pathogens (Lutcavage et al. 1997; Lutcavage and Lutz 1997; Hazel and Gyuris 2006). As a result of this site fidelity interspersed with long distance nesting movements, anthropogenic mortality on a single feeding ground has the potential to impact multiple populations (Dethmers et al. 2006, 2010).

Recaptures of thousands of flipper tagged turtles along the Queensland coast since the 1970s have shown long-term fidelity of juvenile and adult green turtles as well extensive breeding movements, followed by return to foraging areas (Limpus and Read 1985; Hirth et al. 1992; Limpus et al. 1992, 2005; Shimida et al. 2020), but they do not provide data on the extent of habitat use or localised movements between recaptures. While acoustic telemetry is increasingly being used to examine movement in marine turtles (Renaud et al. 1995; Makowski et al. 2006; MacDonald et al. 2012; Fujisaki et al. 2016; Selby et al. 2019; Smith et al. 2019; Matley et al. 2020), within Australia, studies conducted to date are limited to a few individuals monitored for short time periods that do not encompass seasonal or annual variability (Whiting and Miller 1998; Hazel et al. 2013). Satellite telemetry has also successfully been used to investigate both breeding migration (Spring and Pike 1998; Shimida et al. 2020) and habitat use in green turtles (Gredzens et al. 2014; Christiansen et al. 2017; Chambault et al. 2020). While satellite telemetry provides data on space use and movement, the requirement for the tag to be at the surface when satellites are in orbit above the animals results in a few detections per day compared to hundreds of detections per day in acoustic tags when tags are in range of a receivers. Within Australia, there are few published papers on studies using telemetry conducted within coastal waters, particularly with respect to long-term fine scale use of foraging areas.

This study was initiated following increased rates of strandings and reduced health of turtles within Port Curtis region that were at least partly attributed to the cumulative impact of natural and anthropogenic disturbances during 2011 (Flint et al. 2014). Port Curtis is the largest industrial

port in Queensland and has received considerable attention with respect to water quality, habitat modification and reduced health of fish, crabs and turtles (Limpus et al. 2012; Meager and Limpus 2012; Gaus et al. 2012; McCormack et al. 2013; Flint et al. 2014; Dennis et al. 2016). Green turtles from the southern Great Barrier Reef genetic stock (FitzSimmons and Limpus 2014) dominate the populations foraging in coastal waters of eastern Australia south of Cooktown (latitude 15° S) with Port Curtis region recognised as an important feeding ground supporting the southern Great Barrier Reef genetic stock of green turtles (Limpus 2008; Limpus et al. 2013). There is increasing concern over the viability of seagrass beds and coral reefs along the Great Barrier Reef (Duarte 2002; Erftemeijer and Lewis 2006) due to intensification of Extreme Climate Events and coastal development (Babcock et al. 2019) occurring along the east coast of Australia. The green turtle (*Chelonia mydas*) is classified as vulnerable under the Australian Environment Protection and Biodiversity Conservation Act (1999) and the Queensland Nature Conservation Act 1992. There is a legislative requirement to better understand how populations may be impacted by reduced food resources, increased risk of vessel strike and coastal development. In contrast to previous short-term acoustic studies, we present results from a long-term study of fine-scale habitat usage and residency from passive acoustic telemetry. We investigated residence, movement and habitat use of juvenile, sub-adult and adult green turtles in Port Curtis by capturing animals in their foraging grounds and tagging them with acoustic tags and monitoring movement with arrays of acoustic receivers over annual time scales.

Materials and methods

Study areas and acoustic receiver array

Acoustic receivers (Vemco VR2Ws) were deployed in Port Curtis to monitor the movement of tagged turtles around Pelican Banks and Wiggins Island (Fig. 1). The array of receivers consisted of 21 receivers at Pelican Banks and 25 at Wiggins Island. Receivers were attached to subsurface moorings and held 1–3 m above the substrate by floats. Receivers were spaced 600–800 m apart. Pelican Banks was selected as an example of comparatively optimal habitat for turtles as it has relatively high seagrass cover and extensive, intertidal and subtidal sand flats with subtidal channels up to 6 m deep.

Percentage seagrass cover at Pelican Banks and on sand flats to the west of Facing Island was estimated from images taken of a 0.25 m² quadrat at 346 sites throughout the area. A GoPro Hero 3 was mounted 57 cm off the bottom on a custom-built stainless steel frame which allowed

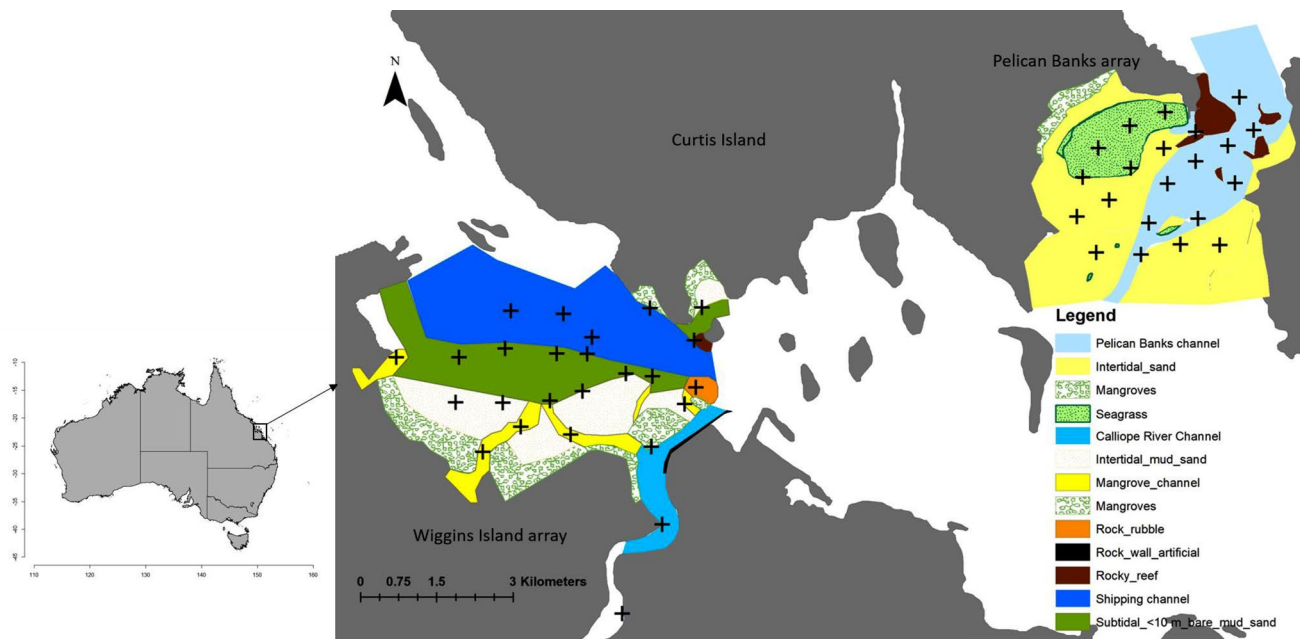


Fig. 1 Map showing the location of acoustic receivers at Pelican Banks and Wiggins Island. The habitat types used in electivity analysis are shown in each array

the whole 0.25 m² quadrat to be photographed remotely by a smartphone. A connection between a smartphone and the GoPro was achieved by gluing WiFi antennae to the back of a smartphone housing and the exterior of the GoPro housing and connecting the two antennae with a 10-m long coaxial cable. Percentage cover of seagrass, algae, soft coral, hard coral, mud, sand, gravel and rock was visually estimated by observers that had been trained to estimate percentage cover by studying standard percentage cover images generated in R.

The presence/absence and percentage cover of seagrasses were mapped and a predicted surface of seagrass percentage cover was generated using the kriging routine of the geostatistical analyst extension in ArcMap 10.0 (ESRI 2011).

The Wiggins Island area provided an example of a location more heavily influenced by port activities as it is adjacent to Liquid Natural Gas (LNG) loading facilities on Curtis Island as well as the Wiggins Island coal loading terminal (Fig. 1). Dredging and high traffic adjacent to the LNG processing wharf on Curtis Island prevented us from placing receivers on the northern side of the shipping channel adjacent to this area. While this area has historically had seagrass (Davies et al. 2015), we found very little seagrass at the time of our study with habitat comprising predominantly of bare sand/mud with some rocky reef/rubble areas adjacent to Wiggins Island and access to intertidal mangroves via narrow channels.

Turtle capture and handling

Green turtles were captured around Wiggins Island and Pelican Banks in May and November 2013. Turtles adjacent to Pelican Banks were captured by jumping on them from moving vessels over intertidal and subtidal flats (rodeo method; as described in Limpus and Walter 1980). Around Wiggins Island, the low visibility precluded this standard method. Instead, turtles were captured in gillnets with a mesh size of 22 cm set across mangrove drains on the ebb tide. Nets were monitored continuously and as soon as a turtle became entangled in the net, the animal was removed. One additional turtle was captured in a 300-m seine net adjacent to Wiggins Island at high tide. Captured turtles were taken back to shore and processed. All captured turtles were double tagged with titanium flipper tags, measured for midline curved carapace length (CCL, ± 0.1 cm) and weighed on a spring balance (± 0.5 kg, if over 30 kg) or on an electric balance (± 0.01 kg, if under 30 kg). Turtles captured in May 2013 were examined by laparoscopy to determine the sex, maturity and breeding status. Changes to regulations precluded the use of laparoscopy on the turtles captured in November 2013, resulting in immature turtles not being sexed and breeding condition not evaluated for these turtles. Turtles were assigned to age-class based on internal examination or carapace length using the following criteria: A = adult (known sexually mature from laparoscopy), AT = adult sized (defined from carapace (CCL > 90 cm) and for males,

tail measurements ($TCL > 25$ cm), SP = Pubescent immature (gonads and ducts differentiating from that of a young immature), SA = Prepubescent immature (defined from carapace measurements— $CCL > 65$ and < 90 cm), J = Juvenile (defined from carapace measurements $CCL > 35$ and < 65 cm). Adults (A, AT), sub-adults (SP, SA) and juvenile were pooled to examine differences between age-classes.

Acoustic tagging

All tagging was conducted as part of a collaborative project with Queensland Department of Environment and Heritage Protection and was conducted animal ethics permit number: SA-2012-11-395 (DAFF Animal Ethics, Queensland Turtle Conservation Project (QTCP): Telemetry and data logging). Once turtles were restrained, the post marginal scutes above the back flipper were cleaned with cloth soaked in Hexawash surgical wash. Following cleaning, an acoustic tag was attached to the post marginal scutes by drilling either one or two 3 mm-diameter holes through the carapace (Fig. 2). Acoustic tags were secured by 3 mm stainless steel bolts soaked in Hexacon surgical wash. A large stainless steel washer was placed over the bolts on the dorsal surface and secured with Nyloc bolts. The protruding ends of the bolts were cut off and a two-part epoxy resin (Sika Anchor-Fix®-3+, Sika Australia Pty Ltd.) placed over the bolts to smooth their profile. All acoustic tags were coated with high-strength hard antifouling paint before being attached. The post-marginal scutes were chosen as the attachment site to minimize the instrument's hydrodynamic impact on the turtle and to ensure eventual detachment by natural out-growth (van Dam and Diez 1996). Attachment methods were adapted from other studies (see Mendonca 1983; van Dam and Diez 1996; Seminoff et al. 2002; Doody et al. 2009) with tag location been shown not to interfere with flipper movements of turtles (Seminoff et al. 2002; Doody et al. 2009). Depending on turtle size, individuals were tagged with a V13-1L, V16-4H or V16-6H Vemco coded transmitter (tag). Transmitters ranged in length from 36 to 98 mm and weighed between less than 1137 g in air. The pulse rate of transmitters varied from 30 to 180 s and battery life varied from 1090 to 3650 days depending on the frequency of each ping and the power output of the tag. Receivers were downloaded every 6 months throughout the study.

Analysis of acoustic tag detection data

For acoustic tags, the detection span of each individual was calculated as the date from first detection to last detection whereas days detected was the total number of days on which each individual was detected. Residence Index (RI) was calculated by dividing detection span by days detected. The number of receivers each tag was detected by is represented

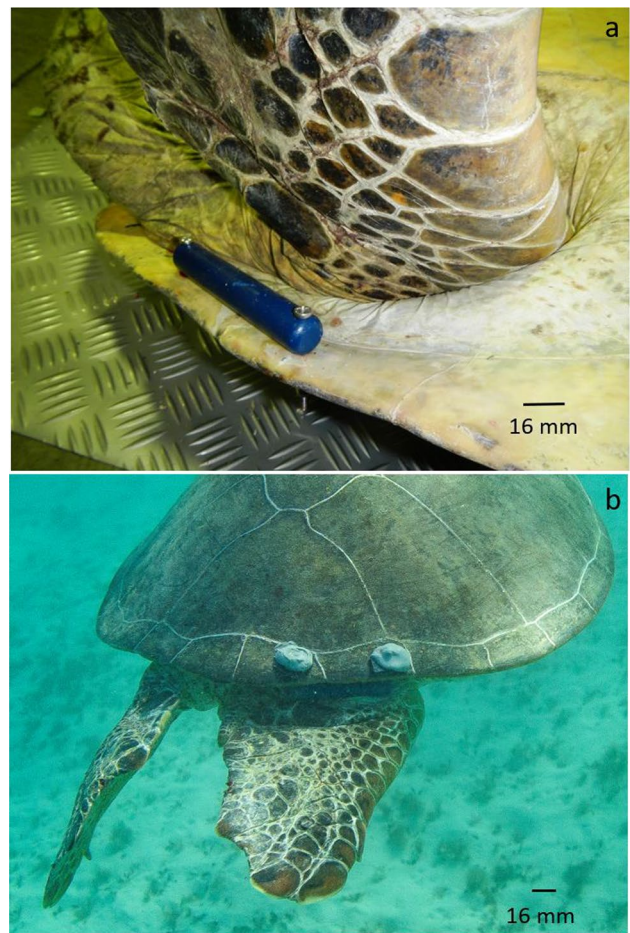


Fig. 2 **a** Position of Vecmo V16 tag on the LHS ventral surface of post marginal skutes. **b** Dorsal surface of a green turtle tagged with a V16 showing epoxy covering cut off bolts (note this tag on RHS side)

as “number of receivers detected on”. The number of daily detections over time for each individual was plotted to provide an overview of detection span and detection frequency for animals tagged at Pelican Banks and Wiggins Island.

Home range measures

Kernel distribution was calculated for those animals that were detected for more than 30 days and on at least one receiver. Area utilisation was estimated using the utilisation distribution and its estimates with kernel techniques (Worton 1989). Utilisation distribution is a probability density function that quantifies an individual's relative use of space (Kernohan et al. 2001). It depicts the probability of an animal occurring at a location within its home range as a function of relocation points (data obtained from receiver detections) (White and Garrott 1990). Kernel utilisation distribution has been widely used to investigate animal movement from acoustic telemetry of a range

of species ranging from marine turtles (Makowski et al. 2006; MacDonald et al. 2012), dugongs (Zeh et al. 2014), fish (Pillans et al. 2014) and elasmobranchs (Pillans et al. 2020). We tested the two most commonly used methods: the reference smoothing parameter function (h_{ref} ; Wor-ton 1989) and the least squares cross validation function ($h_{\text{ls cv}}$; Silverman 1986) and found the reference smoothing parameter (h_{ref}) provided the most realistic representation of space use, with $h_{\text{ls cv}}$ tending to produce unrealistic multiple kernels that were fragmented and clustered around receivers, excluding important areas occupied by turtles. Kernel utilisation distribution (KUD; 50 and 95%) was calculated using the adehabitatHR package in R (Calenge 2006). Passive acoustic detections resulted in thousands to hundreds of thousands of detections of individuals on each receiver with identical X and Y coordinates. To alleviate this issue, we randomly assigned acoustic detections within a 200-m radius of each receiver. This radius was chosen based on range test data from turtles tagged with both satellite and acoustic tags (Pillans unpubl. data) as well the detection range of stationary test tags within the array.

Kernel utilisation distribution (KUD) for the entire detection span of each individual was calculated for turtles that were detected on two or more receivers and for more than 30 days. Kernel utilisation distribution (KUD) can only be calculated when animals are within range of receivers. For animals that departed the array and then returned, KUD was calculated using detections before and after departure when there was at least one period of residence greater than 30 days. Total KUD area was used to examine any sex, size- (age-class), diurnal- and tide-related differences as well as habitat use within the Wiggins Island and Pelican Banks array. The mean monthly 50 and 95% KUD area of all individuals was calculated in each year to examine seasonal patterns in movement. Paired t-tests were used to investigate differences in detection and home range measures between sexes, age-class and sites (Wiggins Island and Pelican Banks). Unless otherwise stated, all values are presented as mean \pm standard deviation (SD) of the mean.

To determine the influence of tide on movement and habitat use, 50 and 95% KUDs of individual turtles were calculated during the period 1 h each side of high and low tide for each month/year and for the entire monitoring period. Tide times were obtained from Australian Bureau of Meteorology (<http://www.bom.gov.au>). Diel differences were examined by calculating 50 and 95% KUD's for day and night using local time of sunrise and sunset. The utilisation distribution overlap index (UDOI; Fieberg and Kochanny 2005) was used to measure the degree of overlap between individual turtles (as per Hazel et al. 2013) and also to compare the degree of overlap for individuals

1 h either side of high and low tide and for day and night. UDOI calculations were done in R using the adehabitatHR package (Calenge 2006).

Habitat use

To determine habitat use of green turtles at Wiggins Island and Pelican Banks, habitat types within the two arrays were classified based on aerial imagery and a spatial habitat database collected while deploying receivers in May 2013. Habitat types at Pelican Banks and Wiggins Island are shown in Fig. 1. The degree of overlap between the utilisation distribution of each individual and each habitat type was calculated as the proportion of the utilisation distribution within the habitat (i.e. probability density integrated over the space occupied by the habitat). Electivity for turtles tagged at Pelican Banks and Wiggins Island was calculated using habitat types at the location they were tagged in (i.e. if an individual was tagged at Pelican Banks, electivity was calculated using only detections from Pelican Banks). Ivlev's electivity (E ; Ivlev 1961) was calculated as follows: $E = (r_i - p_i)/(r_i + p_i)$ where r_i is the relative use of habitat i in the study area (i.e. the proportion of the utilisation distribution overlapping the habitat) and p_i is the proportion of the entire study area corresponding to that habitat. To provide a p_i that better represented the coverage of the acoustic array, we substituted the area (proportion) of each habitat with the proportion of the utilization distribution of a hypothetical reference animal that was detected an equal number of times by all receivers. For this reference animal, electivity calculated as above is zero for all habitats.

To examine differences in habitat use between day and night and between high and low tide, the KUDs and KUD areas (50 and 95%) of each individual were calculated for daytime and night-time and for high and low tide. Daytime was from sunrise to sunset. Night-time was from civil twilight following sunset to civil twilight preceding sunrise. Periods of high and low tide were defined as periods within 2 h of high and low tide, respectively. Habitat utilization and electivity for day/night and high/low tide were calculated as above. To examine habitat use of animals that moved between Pelican Banks and Wiggins Island, electivity was calculated for periods when they were either at Pelican Banks or Wiggins Island. The significance of differences in habitat utilization between day and night and between high and low tide was tested with multivariate analysis of variance (2-way: day/night by tag and high/low tide by tag). Because the response variable was a vector of proportions (the proportion of an individual's KUD in each habitat), it was transformed with the log-ratio transform (Aitchison 1986). For Pelican Banks, mangrove was excluded because it was out of the detection range of the array. For Wiggins Island,

the smallest habitats were merged with adjacent habitats (rock wall artificial with Calliope River channel; rocky reef and rock rubble with subtidal bare mud/sand). Post-hoc tests for individual habitats were made with Wilcoxon signed rank tests.

Results

Turtle size and acoustic detections

A total of 49 green turtles were tagged in Port Curtis between May and November 2013. Animals tagged at Pelican Banks

Table 1 Turtles tagged at Pelican Banks: acoustic tag number, satellite tag number, date tagged, sex, age class, curved carapace length (CCL) and mass of turtles tagged with acoustic tags

Tag ID	Date tagged	Sex	Age class	CCL (cm)	Mass (kg)	Detection span	Days detected	RI	50% KUD (km ²)	95% KUD (km ²)
27928	01-May-13	F	A	101.1	126.0	500	273	0.55	0.74	3.56
27949	01-May-13	F	A	106.2	130.0	499	495	0.99	0.96	4.12
27948	02-May-13	F	A	113.8	158.0	98	4	0.04		
27935	03-May-13	F	A	98.3	115.5	256	246	0.96	0.53	3.90
27944	03-May-13	F	A	110.0	134.0	63	63	1.00	1.25	6.12
26572	05-Nov-13	F	A	107.4	141.0	291	185	0.64	0.91	4.02
26575 ^a	05-Nov-13	F	A	111.0	153.0	306	217	0.71	1.99	13.84
16229	07-Nov-13	F	A	96.2	106.0	77	4	0.05		
26571	07-Nov-13	F	A	105.6	140.0	7	7	1.00		
26573	07-Nov-13	F	A	105.8	142.0	146	137	0.94	1.76	6.89
26576	07-Nov-13	F	A	99.5	120.0	224	212	0.95	0.96	4.42
27924 ^a	02-May-13	M	AT	96.7	88.0	236	172	0.73	4.17	25.40
27952 ^a	02-May-13	M	AT	98.8	103.0	149	136	0.91	0.97	8.02
27934	03-May-13	M	AT	93.5	77.5	5	5	1.00		
27936	03-May-13	M	A	100.2	102.5	437	321	0.73	0.84	4.47
27942	03-May-13	M	AT	94.8	97.5	400	186	0.47	1.24	5.11
27945	03-May-13	M	AT	95.7	96.5	4	4	1.00		
27980 ^a	05-Nov-13	M	A	96.5	97.0	314	258	0.82	1.05	9.17
28352 ^a	07-Nov-13	M	A	93.6	93.0	137	131	0.96	1.50	6.14
26568 ^a	06-Nov-13	M	A	97.7		229	191	0.83	4.59	25.19
27926	02-May-13	F	SP	101.6	119.5	15	15	1.00	2.20	9.25
27923	03-May-13	F	SA	70.7	39.0	495	417	0.84	1.97	8.48
27925	03-May-13	F	SA	74.5	36.5	498	411	0.83	0.92	4.98
27929	03-May-13	F	SA	69.7	34.0	414	371	0.90	0.61	3.73
27930	03-May-13	F	SA	71.0	39.0	483	272	0.56	0.95	5.45
27938	03-May-13	F	SA	67.8	32.5	146	52	0.36	0.96	5.04
27939	03-May-13	F	SA	65.2	28.4	498	425	0.85	0.96	3.71
27940	03-May-13	F	SA	67.9	28.8	189	189	1.00	0.54	6.33
27927 ^a	03-May-13	F	J	61.1	25.4	497	344	0.69	1.73	6.80
27657	08-Nov-13	I	J	59.8	24.0	306	205	0.67	1.64	6.01
27663	08-Nov-13	I	J	56.0	21.0	51	15	0.29		
27661	09-Nov-13	I	J	43.6	9.4	1	1	1.00		
27933	03-May-13	M	J	57.9	19.5	21	15	0.71		

The detection span, number of days each individual was detected and the Residence Index (detection span/days detected) as well as 50 and 95% KUD area (km²) are shown. Age class abbreviations: A=adult (known sexually mature), AT=Adult (defined from carapace and tail measurements), SP=Pubescent immature (gonads and ducts differentiating from that of a young immature), SA=Prepubescent immature (defined from carapace measurements), J=Juvenile

^aShows individuals that were tagged at Pelican Banks but also detected at the Wiggins Island array. KUD estimates were only calculated for individuals detected for more than 30 days

Table 2 Turtles tagged at Wiggins Island: acoustic tag number, satellite tag number, date tagged, sex, age class, curved carapace length (CCL) and mass of turtles tagged with acoustic tags

Tag ID	Date tagged	Sex	Age class	CCL (cm)	Mass (kg)	Detection span	Days detected	RI	50% KUD (km ²)	95% KUD (km ²)
27951	02-May-13	F	J	51.8	13.2	502	458	0.91	1.28	6.73
27931	03-May-13	F	J	51.5	14.5	248	248	1.00	0.83	4.10
27932	03-May-13	F	J	50.6	14.4	211	199	0.94	1.02	4.77
27941	03-May-13	F	J	48.2	12.1	256	237	0.93	1.14	6.32
27943	05-Nov-13	F	J	47.9	10.2	500	485	0.97	0.32	1.96
27947	02-May-13	M	J	58.8	22.3	502	413	0.82	0.55	2.68
27950	02-May-13	M	J	54.6	17.9	500	448	0.90	1.13	5.77
27937	03-May-13	M	J	56.1	18.0	500	475	0.95	0.80	5.14
27946	03-May-13	M	J	46.4	11.1	500	490	0.98	0.46	1.97
27622	05-Nov-13	I	J	46.0	11.8	199	156	0.78	0.36	2.34
27629	05-Nov-13	I	J	60.0	22.8	313	308	0.98	0.61	3.05
31598	05-Nov-13	I	J	52.1	17.0	313	219	0.70	1.32	4.79
27662	06-Nov-13	I	J	49.1	14.7	180	180	1.00	0.34	2.11
29771	07-Nov-13	I	J	52.7	17.8	222	118	0.53	0.57	3.63
27656	08-Nov-13	I	J	48.2	13.2	200	107	0.54	0.37	2.03
27658	08-Nov-13	I	J	52.7	16.9	258	186	0.72	0.48	2.74

The detection span, days detected, Residence Index (RI) as well as well as 50 and 95% KUD area (km²) of individuals are shown

($n=33$) were primarily adults and sub-adults with a size range of 43–114 cm CCL, whereas those at Wiggins Island ($n=16$) were all juveniles with a size range of 46–60 cm CCL. Details of size, sex and detection history of turtles tagged at Pelican Banks and Wiggins Island are shown in Tables 1 and 2, respectively. Between 1 May 2013 and 16 September 2014 (when receivers were removed), there were 1,385,100 detections of tagged turtles by the 46 acoustic receivers. There were 706,362 detections of the 33 turtles tagged at Pelican Banks, with individuals detected between 2 and 62,751 times on 1–36 receivers for 1–495 days after tagging. Of the 16 turtles tagged at Wiggins Island, there were 678,738 detections with individuals detected between 425 and 127,137 times on 5–18 receivers for 181–502 days after tagging. The number of daily detections throughout the monitoring period for each individual turtle at Pelican Banks and Wiggins Island is shown in Fig. 3a, b, respectively.

Residence and home range

For turtles tagged at Pelican banks, RI was similar for adult males (0.82 ± 0.15 SD), females (0.71 ± 0.35), sub-adult females (0.79 ± 0.22) and juveniles of unknown sex (0.67 ± 0.25) (Fig. 4a). The 50% and 95% KUD area in adult males was $2.20 (\pm 1.71)$ and $12.57 (\pm 9.63$ SD) km², respectively, and higher than all other age-class and sex combinations; however, the difference was not significant (Student's t -test, $p > 0.12$). For adult females, sub-adult females and juveniles of unknown sex, mean 50% and 95% KUD

area were very similar (1.14 ± 0.61 to 1.68 ± 0.06 km² and 5.87 ± 2.05 to 6.74 ± 4.1 km²), respectively (Fig. 4b). The cumulative 50% and 95% KUD contours of all turtles tagged at Pelican Banks are shown in Fig. 5a.

For turtles at Wiggins Island, there was no significant difference in RI, 50% and 95% KUD area between juvenile male and females (Fig. 4b) The cumulative 50 and 95% KUD contours of turtles tagged at Wiggins Island are shown in Fig. 5b. Mean residence index in juvenile females was $0.95 (\pm 0.03$ SD) compared to $0.91 (\pm 0.07$ SD) in juvenile males. For juveniles at Wiggins Island where sex was not determined (those animals tagged in November 2013), residence index was $0.75 (\pm 0.19$ SD) and significantly lower than both males and females (Fig. 4b). The mean 50% KUD area in females, males and unknown sex was $0.82 (\pm 0.41$ SD), $0.73 (\pm 0.30$ SD) and $0.58 (\pm 0.34$ SD) km², respectively, with no significant difference the three groups (Student's t -test, $p > 0.28$). Similarly, for 95% KUD area, there was no significant difference (Student's t -test, $p > 0.15$) between the groups with mean values of $4.3 (\pm 2.06$ SD), $3.8 (\pm 1.84$ SD) and $2.9 (\pm 0.99$ SD) km², respectively, in males, females and individuals of unknown sex (Fig. 4b).

Only juvenile turtles were tagged at Wiggins Island preventing within size-class comparison with Pelican Banks where KUD was calculated for only two juveniles. Juvenile turtles tagged at Wiggins Island had a significantly longer detection span (306 ± 144 days) than animals tagged at Pelican Banks (186 ± 142 days) (Student's t -test, $p = 0.007$). This resulted in a higher RI (0.86 ± 0.15) at

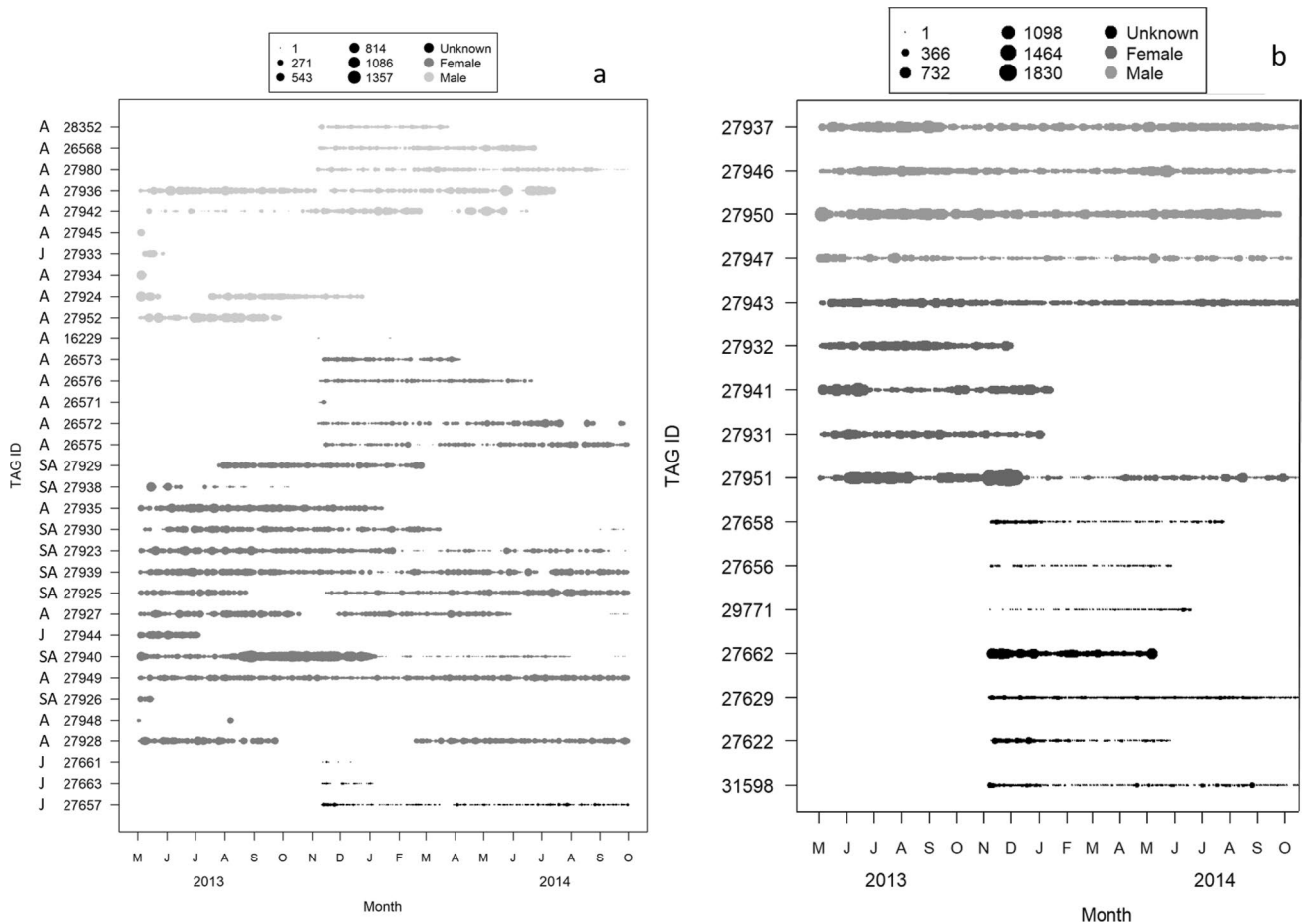


Fig. 3 Detection history for turtles tagged at Pelican Banks (a) and Wiggins Island (b). Size of circles denotes number of daily detections. Colours denote sex, letters denote age-class of animals tagged

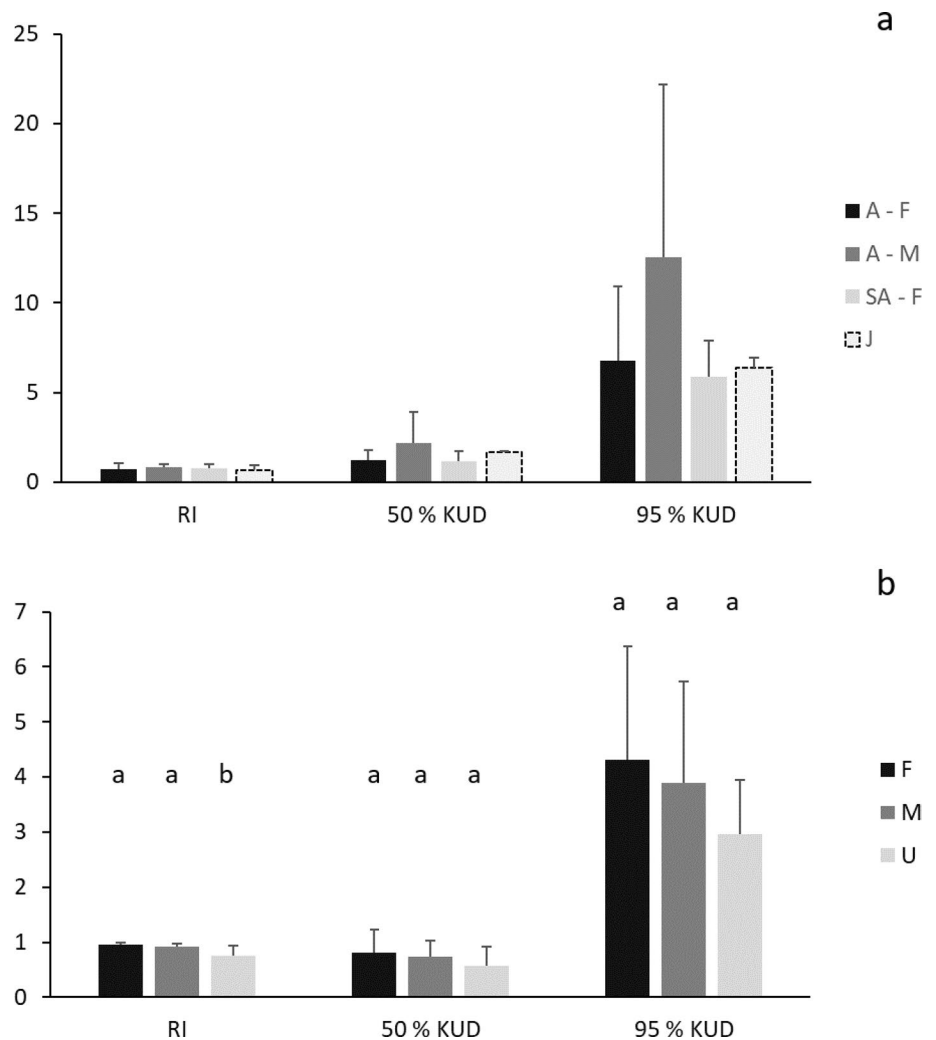
at Pelican Banks (A = adult, SA = sub-adult, J = juvenile). All animals tagged at Wiggins Island were juveniles

Wiggins Island compared to Pelican Banks (0.75 ± 0.25) (Student's *t*-test, $p = 0.001$). The 50 and 95% KUD area of turtles tagged at Wiggins Island (0.70 ± 1.12 and 3.7 ± 1.65 km², respectively) were significantly smaller than turtles tagged at Pelican Banks (1.5 ± 1.13 and 8.3 ± 6.5 km², respectively) (Student's *t*-test $p = 0.05$). Overall, juvenile turtles had slightly higher RI (0.84 ± 0.15 SD) than adults (0.77 ± 0.25) (Student's *t*-test, $p = 0.23$). Both the 50 and 95% KUD area in juveniles (0.80 ± 0.45 km² and 3.94 ± 1.78 km², respectively) were significantly smaller than 50 and 95% KUD home range estimates of adults and sub-adult combined (1.54 ± 1.17 km² and 8.49 ± 6.76 km², respectively). Six turtles moved between Pelican Banks (where they were tagged) and Wiggins Island with these animals having a significantly larger 50% KUD (2.2 ± 0.7 km²) and 95% KUD area (14.7 ± 3.5 km²) (Student's *t*-test, $p < 0.01$), respectively, than the home range of animals that remained at either Pelican Banks or Wiggins Island. One adult male (tag ID = 27952) departed Pelican Banks 5 days after tagging and was detected at Wiggins Island for the remaining 144

days. Two other adult males and one adult female moved between Pelican Banks and Wiggins Island two and three times, respectively. One juvenile female moved from Pelican Banks to Wiggins where it spent 10 days before returning to Pelican Banks for the remainder of its detection. The time spent at either Wiggins Island or Pelican Banks between movements varied within and between animals. Turtles spent as few as 3 and as many 65 days at one site before moving to the other site.

Continuous detections of acoustic tags on individual receivers indicated that at least six acoustic tags detached from turtles during the monitoring period. The shortest known periods that a tag was attached before detaching was 91 days and the longest 395 days with average detachment time of 270 (± 105 SD) days. Premature detachment of tags makes it difficult to be certain whether animals that stopped being detected had departed the array or moved outside detection range; however, for animals that departed within 3 months it is reasonable to assume they had shifted location. At Pelican Banks, five adults (22%), two sub-adults

Fig. 4 Mean (\pm SD) Residence Index, 50 and 95% KUD area (km^2) for male, female and unsexed turtles at Pelican Banks (A) and Wiggins Island (B). The Y-axis represents both RI (range of 0–1) and KUD area in km^2 . Letters denote significant of two sample *t*-test between sexes. Different letter denotes a significant difference between sexes ($p < 0.05$). There was no statistical difference between sexes and age-classes at Pelican Banks



(25%) and one juvenile (20%) had departed the array within 3 months. None of the juveniles tagged at Wiggins Island had departed the array within 7 months.

Diurnal and tidal influence on KUD size and overlap

The core home range area (50% KUD) of turtles at Pelican Bank during the day ($1.67 \pm 1.48 \text{ km}^2$) was slightly larger than the core area at night ($1.30 \pm 0.91 \text{ km}^2$) (Student's *t*-test, $p = 0.39$). There was a high degree of overlap between day and night core area (mean \pm SD UDOI: 0.35 ± 0.01). At Pelican Banks, the core area at high tide was slightly larger ($1.39 \pm 0.94 \text{ km}^2$) than low tide area ($1.19 \pm 0.55 \text{ km}^2$) (Student's *t*-test, $p = 0.35$). Despite similar sized core areas, there was very little spatial overlap of core home range at high and low tide at Pelican Banks (mean \pm SD UDOI: 0.06 ± 0.09). The 50% KUD at high tide covered the intertidal flats and seagrass beds, whereas the 50% KUD at low tide was confined to the sub-tidal seagrass beds and deeper channels (Fig. 6a). For turtles at Wiggins Island, day core

area (0.76 ± 0.33) was slightly higher than night core area ($0.69 \pm 0.41 \text{ km}^2$), but the difference was not significant (Student's *t*-test, $p = 0.59$) and there was a high degree of overlap between day and night core areas (mean \pm SD UDOI: 0.23 ± 0.07). At Wiggins Island, core area during high tide (1.76 ± 1.24) was significantly larger than low-tide core area (0.78 ± 0.39) (Student's *t*-test, $p = 0.008$). Despite larger size core area at high tide, overall the location of core areas at low and high generally overlapped (mean \pm SD UDOI: 0.15 ± 0.09) with low tide 50% KUD slightly further offshore in deeper water (Fig. 6b). However, in a few animals there were distinct high- and low-tide areas and no overlap in UDOI.

Habitat preference

When at Pelican Banks, turtles spent the majority of their time on seagrass or intertidal sand, but this could largely be explained by habitat area given that electivities were clustered around zero, although it was negative for the other two

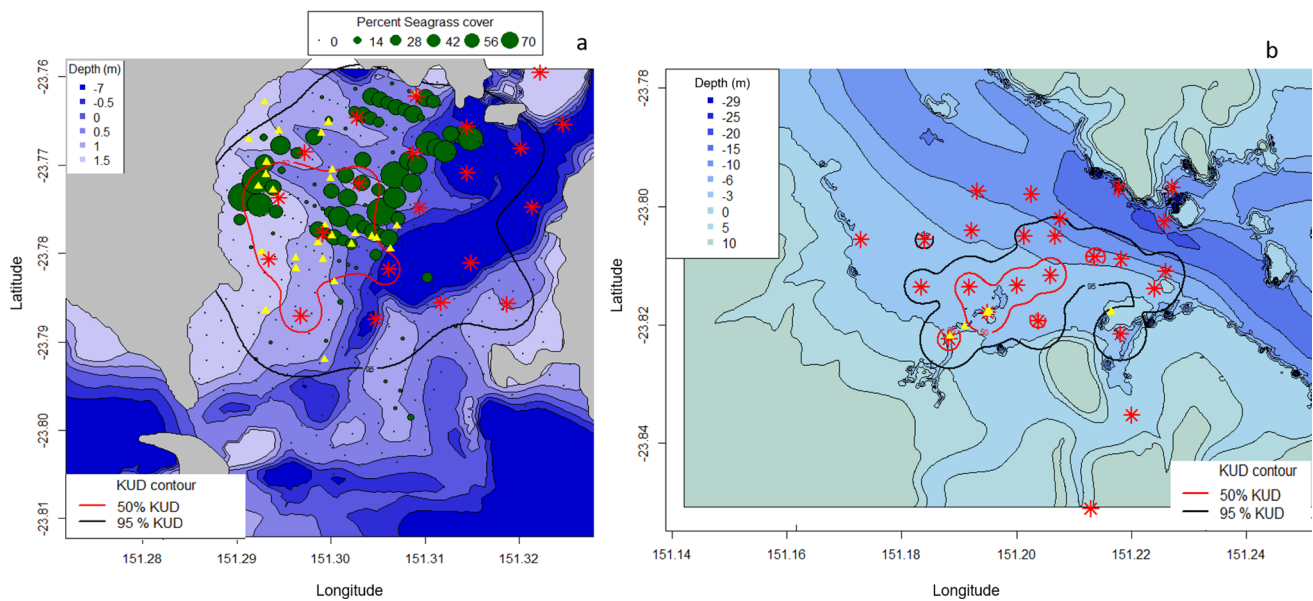


Fig. 5 The cumulative 50 and 95% KUD contours for 33 green turtles tagged at Pelican Banks (a). The cumulative 50 and 95% KUD contours for 16 green turtles tagged at Wiggins Island (b). Receivers are shown as red asterisks, tag location of individual turtles as yellow

triangles and the 50 and 95% KUD contours by red and black lines, respectively. The percent seagrass cover at Pelican Banks is shown. Shading depicts depth at each study site

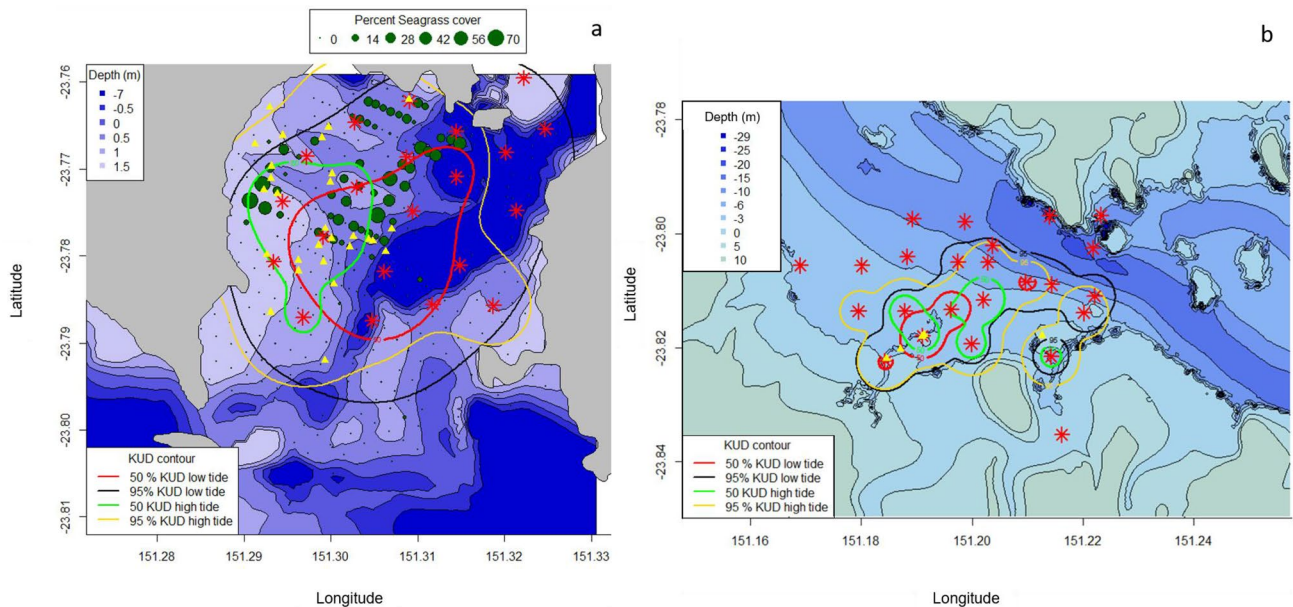


Fig. 6 The cumulative 50 and 95% KUD contours for detection of turtles 1 h either side of low tide (red and black lines for 50 and 95% KUD, respectively) and 1 h either side of high tide (green and yellow lines for 50 and 95% KUD, respectively) at Pelican Banks (a)

and Wiggins Island (b). Capture locations of individuals are shown as yellow triangles. Receivers shown as red asterisks. The percent seagrass cover at Pelican Banks is shown. Shading depicts depth at each study site

habitats (rocky reef and to a lesser extent channel) (Fig. 7a, b). Habitat utilization differed significantly between high- and -tide (MANOVA, Pillai–Bartlett = 0.94, $F_{3,13} = 72.5$, $p < 0.001$, 16 individuals, 4 habitats; Fig. 7c). For individual

habitats, utilisation was higher for seagrass at high tide and for rocky reef and channel at low tide (Wilcoxon signed rank test, $p < 0.001$ for each of seagrass, rocky reef and channel, $p > 0.05$ for intertidal sand). Habitat utilization did not differ

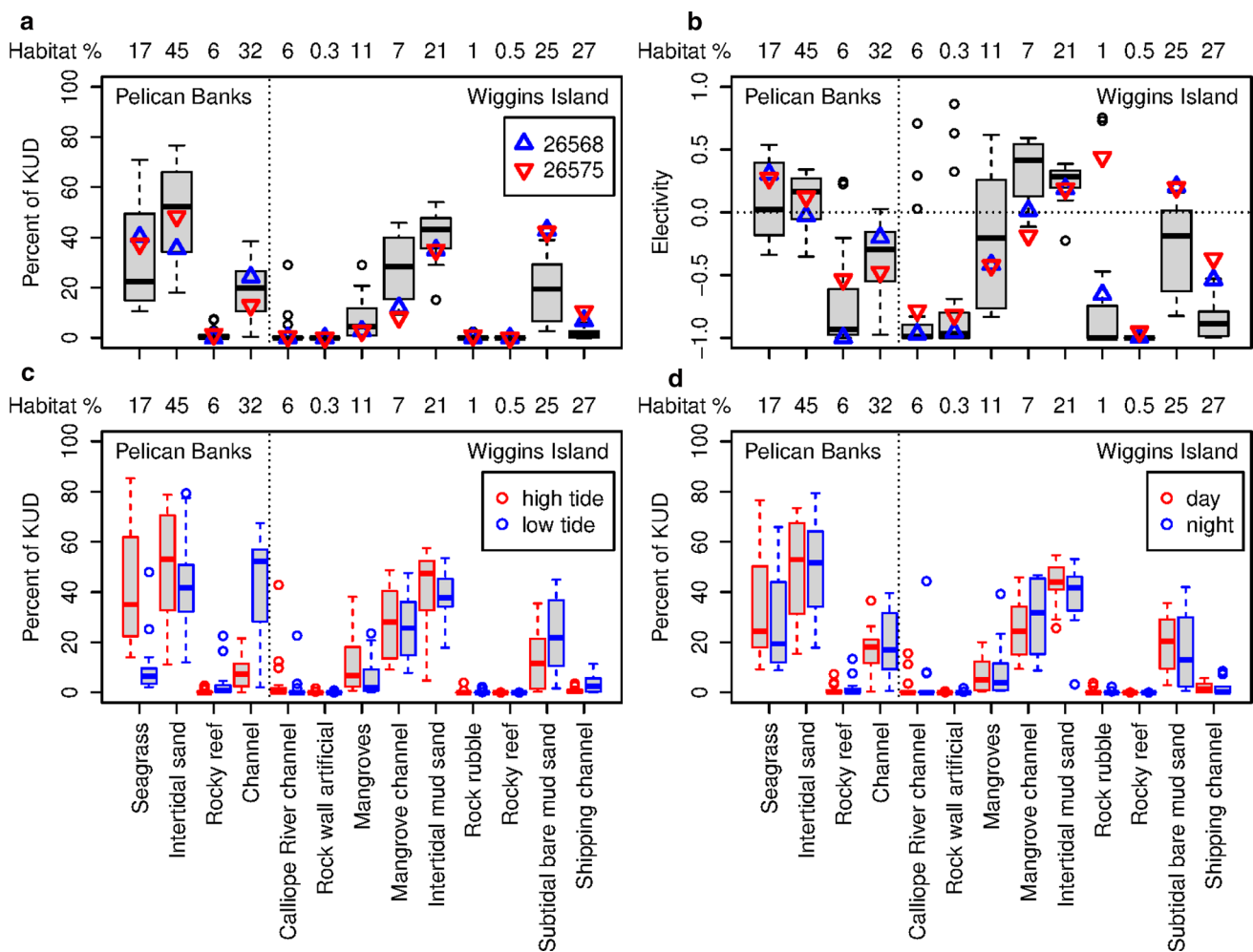


Fig. 7 a Box and whisker plot of habitat utilisation (a) and electivity (b) for habitat types at Pelican Banks and Wiggins Island. All detections of animals tagged at each site were used to calculate utilisation. Triangles show utilisation and electivity for two individuals that were tagged at Pelican Banks but spent more than 30 days at both Pelican Banks and Wiggins Island. Utilisation for these individuals was

calculated when they were respectively at Pelican Banks or Wiggins Island. Habitat utilisation for c high and low tide and d daytime and night-time. The percentage of the array area covered by each habitat type is shown above each plot (the array area here defined as the area within 600 m of any receiver)

significantly between day and night (MANOVA, Pillai–Bartlett=0.29, $F_{3,13} = 1.75$, $p = 0.2$, 16 individuals, 4 habitats; Fig. 7d). (This was consistent with the high UDOI between day and night KUDs).

At Wiggins Island, intertidal mud/sand and mangrove channels (channels leading into the mangroves) were the only habitat types for which turtles showed a preference (Fig. 7a, b). From there, electivity declined through subtidal bare mud/sand (and adjacent small habitats) to the shipping channel. The Calliope River channel (with the adjacent artificial rock wall) was avoided by all but a few individuals. Habitat utilization differed significantly between high and low tide (MANOVA, Pillai–Bartlett=0.81, $F_{5,11} = 9.3$, $p < 0.01$, 16 individuals, 6 habitats; Fig. 7c). For individual habitats, utilisation was higher for Calliope River channel and mangroves at high tide and for subtidal bare mud/sand

and shipping channel at low tide (Wilcoxon signed rank test, $p < 0.001$ for each of mangroves, subtidal bare mud/sand and shipping channel, $p < 0.01$ for mangroves and $p > 0.05$ for mangrove channel and intertidal mud/sand). Habitat utilization did not differ significantly between day and night (MANOVA, Pillai–Bartlett=0.44, $F_{5,11} = 1.72$, $p = 0.2$, 16 individuals, 6 habitats; Fig. 7d). (This is again consistent with the high UDOI between day and night KUDs).

Of the six animals that moved between Pelican Banks and Wiggins Island, one adult male (tag ID 26568) and one adult female (tag ID 26575) were detected at both sites for more than 30 days enabling estimates of habitat use at both Pelican Banks and Wiggins island. At Pelican Banks, both animals showed a preference for seagrass beds with electivity values for each habitat within the range of values of resident individuals (Fig. 7a). When these individuals moved

to Wiggins Island, their habitat preference shifted to intertidal mud/sand and bare subtidal mud/sand < 10 m deep. At Wiggins Island, for preferred habitat, the electivity values of both animals for bare subtidal mud/sand < 10 m deep was outside the range of resident turtles.

Nesting movement

One of the adult females turtles that was captured at Pelican banks in May 2013 and tagged with an acoustic (27928) and flipper tags (QA 34792) was recorded daily within the Pelican Banks array between 2 May and 25 September 2013 at which time the animal disappeared from the array for nearly 5 months. On the 18 February 2014, it was again recorded and thereafter it was detected daily until the last download of acoustic receivers in mid-September 2014. This animal was recorded nesting on Lady Musgrave Island in the Capricorn Bunker Group on 31 December 2013 (Limpus pers. comm.) with the acoustic detections providing data on when the animal left and returned to its foraging ground between nesting.

Discussion

We monitored long-term movement of juvenile, sub-adult and adult green turtles using acoustic telemetry in Port Curtis, Australia's largest port. Turtles were monitored for up to 502 days in inshore habitat adjacent to mangroves and significant port development (Wiggins Island) and at a relatively undisturbed site with intertidal and sub-tidal seagrass beds (Pelican Banks). Turtles at both sites were confined to a small area with juveniles having a smaller average 50% KUD (0.80 km²) than adults and sub-adults (1.54 km²). Turtles at Pelican Banks showed a strong preference for seagrass beds with animals moving onto intertidal seagrass beds at high tide resulting in little overlap between high- and low-tide KUD's. Turtles at Wiggins Island showed a strong preference for channels leading into the mangroves and intertidal mud and sand covered substrate.

Diet was not directly investigated in the current study; however, Prior et al. (2016) conducted last bite analysis and stable isotope analysis of skin and blood samples from all animals that we tagged in November 2013 ($n = 12$ at Pelican Banks, $n = 7$ at Wiggins Island). Turtles at Pelican Banks primarily consumed seagrass, whereas epiphytic red algae found growing on mangrove roots and rocks dominated the diet of animals at Wiggins Island. Despite turtles having multiple centres of activity within their home range, we found no evidence of separate day and night locations with tide being the primary driver of habitat selected. Despite small home range and specific habitat preferences, our data demonstrate that more than 24% of the turtles tagged at

Pelican Banks departed the array within a few months of tagging with these movements not related to reproduction.

Turtle movement

The results of the current study have demonstrated green turtles in Port Curtis have a small core area (less than 1.6 km²) with juveniles occupying smaller areas than sub-adults and adults. The average 50 and 95% KUD area was 0.80 ± 0.45 km² and 3.94 ± 1.78 km² for juveniles and 1.54 ± 1.17 km² and 8.49 ± 6.76 km² for adults and sub-adults, respectively. Only juveniles were monitored at Wiggins Island and the small number of juveniles tagged at Pelican Banks did not enable comparison of age-classes between the sites. Nonetheless, these estimates of home range are within the range of other studies using a variety of methods from tag returns, visual observations, active boat based acoustic telemetry, satellite telemetry and passive acoustic telemetry (Mendonca 1983; Hirth et al. 1992; Renaud et al. 1995; Brill et al. 1995; Whiting and Miller 1998; Seminoff et al. 2002; Makowski et al. 2006; MacDonald et al. 2012; Hazel et al. 2013; Christiansen et al. 2017; Crear et al. 2017; Griffin et al. 2020; Shimida et al. 2020). These studies have estimated 50% KUD and or Minimum Convex Polygon (MCP) between 0.18–4.04 km² and 95% KUD estimates less than 10 km². The largest green turtle home ranges have been described by Seminoff et al. (2002) who reported home ranges of 12 green turtles in Bahia de los Angeles, Gulf of California, Mexico from 5.84 to 39.08 km². The large size of home ranges in these animals was attributed to the large distance between macroalgal food resources and benthic shelter.

We have demonstrated that turtles at Pelican Banks had significantly larger home ranges than individuals at Wiggins Island. Turtles at Pelican Banks were primarily adults compared to only juveniles at Wiggins Island suggesting that adults forage over larger distances than juveniles. This is consistent with findings of Whiting and Miller (1998); however, MacDonald et al. (2012) demonstrated that larger adults had a smaller home range than juveniles which they attributed to adults having a better knowledge of habitat. Reasons for any differences between home range size of individuals from Pelican Banks and Wiggins Island are likely to be complex since, in addition to differences in the body size and, therefore, age of individuals at the two sites, habitat types and habitat preferences were very different. At Pelican Banks, turtles moved to intertidal seagrass beds with the flood tide and remained at these habitat until the flooding tide forced them back into the subtidal channel where they remained at low tide. The use of the sub-tidal channel at low tide was attributed to turtles being forced off the intertidal seagrass beds as these areas became too shallow. Tide-related movement has been described previously with turtles observed moving into intertidal foraging areas as water

depth allowed them to access these areas and then retreating to deeper water on the ebb tide (Limpus et al. 1994). The strong preference for seagrass beds was also reflected in dietary analysis of turtles at Pelican Banks. Prior et al. (2016) sampled all of the animals we tagged at Pelican Banks in November 2013 using oesophageal lavage and stable isotope analysis. Last bite analysis showed that animals at Pelican Banks fed almost exclusively on seagrass (*Zostera muelleri* and *Halophila ovalis*). Given that most animals monitored at Wiggins Island were adults, habitat preference of juveniles and sub-adults may be different. However, for the juveniles and sub-adults we monitored, KUDs were similar in shape and size with no distinct preferences for other habitats.

At Wiggins Island, there was more individual variability in habitat preference with mangrove channels and intertidal sand/mud flats having the highest electivity. A few individuals also used the Calliope River channel, rock rubble and artificial rock wall but overall, these habitats were largely avoided. The relatively minor change in electivity values in the mangrove channel at high and low tide were most likely a result of some individuals remaining within a 2- to 4 m-deep hole at the top of the mangrove drain during low tide resulting in detections at low tide despite surrounding intertidal areas being dry. Future research would require additional receivers to be placed along the edge of the mangrove forest to better understand tidal movements. Visual observations and our capture method of blocking off channels draining the mangrove forest during the ebb tide indicates that the animals are accessing the mangrove forest on the flood tide and retreat as water depth drops. Oesophageal lavage and stable isotope analysis of turtles tagged at Wiggins Island demonstrated that red algae were the dominant food source of these turtles (Prior et al. 2016). The dominant species (*Catenella nipae*, *Chondria* sp., *Hypnea* sp., and *Bostrychia tenella*) found in lavage samples support the observed tidal related movement with these species known to be associated with mangrove vegetation (Cribb 1996). Furthermore, the presence of pieces of mangrove bark and root in the diet of these turtles suggests that turtles were foraging on epiphytic algae on mangroves. The area of highest habitat use at Wiggins Island was largely devoid of hard substrate and we did not find seagrass in this area. It stands to reason that turtle's main food supply is the epiphytic algae growing on mangrove roots that is only available at high tide. Epiphytic red algae documented growing on mangrove roots and trunks has been recorded in the diet of green turtles captured adjacent to mangrove forests (Limpus et al. 2005). While seagrass was visually absent from Wiggins Island during our study, historically this area has supported seagrass beds (Davies et al. 2015) and changes in food availability due to reduced water quality in Port Curtis may result in turtles using alternative habitats over longer time periods.

We did not find any evidence of turtles using different day and night time areas or any difference in the size of day and night core areas as has been identified in other studies of this species (Seminoff et al. 2001; Makowski et al. 2006; Hazel et al. 2009; Christiansen et al. 2017; Chambault et al. 2020; Griffin et al. 2020). Smaller nocturnal and non-overlapping day and night core areas have been proposed as a mechanism to reduce predation of turtles by sharks at night when the chance of predation was perceived to be greater (Makowski et al. 2006; Heithaus et al. 2007; Hazel et al. 2009; Christiansen et al. 2017). Although large Carcharhinid sharks are present in Port Curtis, we did not observe any sharks during our study. We attribute the lack of diurnal changes in habitat use to tide-mediated foraging. At both sites, food resources were primarily available at high tide and presumably the need to feed at high tide is more important than seeking shelter at night. Hazel et al. (2013) noted that availability of suitable areas to rest during the day may preclude moving to rest at night and it possible that in our study turtles rest at low tide when access to intertidal foraging habitat is restricted. The large degree of variability in turtle movement indicates regional plasticity in behaviour that results in subtle differences in home range size, habitat preferences and diurnal patterns presumably influenced by local environmental factors including predation (Heithaus et al. 2007), tide (Limpus et al. 1994, 2005; Limpus and Limpus 2000; current study), food availability (Shimida et al. 2020; current study), depth (Hays et al. 2000) and combinations of all these factors.

Long-term residency

Animals tagged at Pelican Banks were more likely to move out of the array than animals tagged at Wiggins Island. While the extent of movement away from the array at Pelican Banks cannot be inferred from acoustic telemetry, ten turtles tagged with acoustic tags in this study were also fitted with satellite tags (Babcock et al. 2015). Three females that departed Pelican Banks after tagging reveal the extent of movement away from this area outside of the breeding season. All three animals moved more than 100 km away from Port Curtis. One immature pubescent female (tag ID = 27926) departed Pelican Banks 15 days after it was tagged, then moved 271 km south to Hervey Bay where it remained for 200 days, before moving 55 km north for 4 days before moving back to Hervey Bay where it remained until the tag stopped transmitting.

An adult female (tag ID = 27926) left Pelican Banks 1 day after it was released and over a period of 5 days moved 182 km north to a small inlet where it remained for 77 days before moving 313 km south to Baffle Creek where it remained for 62 days when the tag stopped transmitting. Another adult female (tagID = 16229) departed the array 1 day after tagging and over 6 days moved 240 km north to

Shoalwater Bay where it remained for 65 days before moving 435 km south to Elliot Heads where it remained for 20 days before the tag stopped transmitting. The core area of home range of all three turtles between long-distance movements was highly restricted, with the 50% KUD area ranging from 0.79 to 2.76 km². While it is common for animals to move tens of kilometres between foraging areas (Whiting and Miller 1998; current study) and even between reefs (Gredzens et al. 2014), the scale of movement demonstrated by three of the satellite tagged animals at Pelican Banks is unprecedented for green turtles previously monitored on the east coast of Australia (Gredzens et al. 2014; Shimida et al. 2020). The departure of at least three animals combined with high proportion (27%) of animals leaving the foraging area at Pelican Banks after tagging in May 2013 may be due to the decline in food resources following record floods caused by ex-tropical cyclone Oswald which resulted in significant seagrass loss throughout Port Curtis and surrounding areas (McCormack et al. 2013). Flint et al. (2014) examined the health of 56 live turtles and 11 stranded turtles from Port Curtis in 2011 and showed live animals were twice as likely to present in an unhealthy state compared to animals from Moreton Bay or Shoalwater Bay. Flint et al. (2014) concluded that the cumulative impacts of natural and anthropogenic disturbances were contributors to the increased stranding events observed in Port Curtis during this period. It has been suggested that relocating home range is very rare in green turtles (Shimida et al. 2020), with evidence that rather than relocating, animals may simply endure temporary degradation of food resources within foraging areas that is aided by their low metabolic rate and slow use of stored fat reserves (Hays et al. 2002). Increased stranding and reduced health support the hypothesis of animals remaining in degraded environments; however, our data also show unprecedented levels of movement away from impacted habitats up to 2 years after significant flooding and reduced seagrass coverage at Pelican Banks. The lack of movement away from Wiggins Island may be related to the fact that animals in this area were feeding primarily on red algae which were less affected by changes in water quality than seagrass.

Recent research on sub-adult and juvenile turtles has demonstrated that turtles greater than ~78 cm CCL were more likely to move away from their developmental foraging sites due to an ontogenetic emigration towards foraging and reproduction areas used by adults (Chambault et al. 2018; Siegwalt et al. 2020). Chambault et al. (2018) demonstrated that for turtles tagged in the Caribbean, ten individuals approaching sexual maturity moved large distances movements (average distance of 4394 km) away from tagging site compared to animals less than 78.5 cm CLL who remained resident. Of the animals that departed our study area outside of the reproductive season, more than half were adults, 33% were juveniles and only one was a sub-adult female

approaching sexual maturity suggesting movements away from Port Curtis were not due to ontogenetic changes in habitat that are very uncommon in Australia. Our results and those of Shimida et al (2020) suggest that the use of developmental foraging grounds by juveniles, followed by extensive migrations to adult foraging/reproductive areas is location specific and possibly influenced by the proximity of courtship and nesting areas to suitable foraging grounds.

Evidence of turtles shifting habitat

We demonstrated that six turtles tagged at Pelican Banks were also detected at Wiggins Island for periods of a few days to more than 130 days. While movements of a tens of kilometres between foraging areas have been identified previously (Whiting and Miller 1998; Gredzens et al. 2014), our electivity analysis provides direct evidence that animals were utilising very different habitat types in the two locations. Stable isotope analysis of blood and skin tissues taken from a subset of the turtles we tagged Pelican Banks and Wiggins Island (Prior et al. 2016) support this with strong evidence that turtles were shifting their diet based on different results from blood (relatively recent diet) and skin (diet from months previously). While the size of our arrays at Pelican Banks (18 km²) and Wiggins Island (15 km²) were larger than 95% KUD, there were periods when turtles were absent from the array with this being more common at Pelican Banks (mean RI=0.76) than Wiggins Island (mean RI=0.86). For turtles at Pelican Banks that were absent for a period before returning, seven individuals were absent for 14–30 days, one for 30 days and three for more than 60 days with one of these an adult female that recorded nesting at Lady Musgrave Island before returning to the array. Of the seven turtles that were absent for periods of 14–30 days, four and one individual were absent for two and three periods, respectively, during the monitoring period. These periods of absence suggest that at for least for a small proportion (27%) of the turtles tagged, they most likely have an additional foraging area within their home range that was outside the detection range of the array. Whiting and Miller (1998) demonstrated that adult green turtles in Repulse Bay, Queensland moved up to 25 km between foraging sites and attributed these movements to availability and quality of food resources. Given high rates of emigration at Pelican Banks, a similar food-related mechanism is likely in our study.

Movement in relation to vessel activity

Highest commercial shipping traffic occurred in the deep shipping channels to the north of Wiggins Island. At Pelican Banks, commercial traffic was limited to vessels of shallower draft travelling at slow speed. The turtles we tagged at Wiggins Island were not detected in the channel, resulting

in virtually no overlap between 50 and 95% KUD's of turtles and areas of high commercial shipping traffic. Previous research has demonstrated limited movement of turtles to deeper channels adjacent to shallower feeding grounds between Renaud et al. 1995; MacDonald et al. 2012). Around Wiggins Island, there was no seagrass on the intertidal and subtidal flats or any other obvious source of food such as epiphytic algae outside of the mangrove forest, suggesting that absence of food may have caused animals to remain close to available food sources.

At Pelican Banks, there was a greater degree of overlap of turtle home ranges with the channel and channel edge which was most likely due to the presence of seagrass across a depth gradient. Despite the home range of animals at Pelican Banks encompassing the channel, very few animals crossed over to the eastern side of the channel nearer to Facing Island, which may partially be explained by the reduced density of seagrass in this area of Pelican Banks. The use of intertidal areas by both turtles and small recreational craft during high tide results in overlap and increased risk of vessel strike. Increased vessel speed has been demonstrated to put dugongs, turtles and other marine species at higher risk of collision or disturbance (Hazel and Gyuris 2006; Hazel et al. 2007; Hodgson and Marsh 2007) and we frequently observed recreational vessels travelling in excess of 15 knots over the intertidal flats at Pelican Banks and to a lesser extent at Wiggins Island.

Acoustic telemetry for monitoring turtle movement

In this study we demonstrate that external acoustic tags are a suitable method for obtaining data on residency, home range and habitat use for marine turtles. These findings are consistent with those of Hazel et al. (2013). While a few tags detached within 6 months, of those tags known to have detached, the mean time to detachment was 270 days. The longest detection span of an acoustic tag in this study was 502 days with more than 50% of tags detected for at least 1 year. This attachment period is significantly longer than that demonstrated by Smith et al. (2019). These authors tagged juvenile green turtles with external acoustic tags using similar methods to those in the current study and showed that 50% of tags had detached within 150 days with almost all tags detaching within 1 year. The significantly shorter attachment period in Smith et al. (2019) is potentially due to differences in attachment with their tags attached using thin diameter wire and 8 mm holes compared to our 3 mm holes and 3 mm bolts. Regardless of the methods used to externally attach acoustic tags, long-term attachment methods where the tag is surgically implanted into either the peritoneal cavity of fish and elasmobranchs (see Pillans et al. 2014, 2020) or in terrestrial monotremes (Bino et al. 2018) will ensure long-term (up to 10 years) detections of

individuals required to monitor population level changes that occur over time scales currently not captured by either satellite or acoustic telemetry in marine turtles. Future studies should attempt to develop methods of internally implanting acoustic tags in marine turtles.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Animal ethics All green turtle capture, handling and tagging were approved by the Queensland Government Department of Agriculture, Forestry and Fisheries (DAFF) Animal Ethical Committee, Queensland Australia (Application SA-2012-11-395). The treatment of animals complies with the Queensland Environmental Protection Agency and complied with Australian laws and regulations.

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