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Satellite tracking improves conservation outcomes for nesting hawksbill turtles in Solomon Islands

Richard J. Hamilton [a,b,*], Amelia Desbiens [c,e], John Pita [d], Christopher J. Brown [e], Simon Vuto [f], Willie Atu [f], Robyn James [a,g], Peter Waldie [a], Col Limpus [h]

[a] The Nature Conservancy, Asia Pacific Resource Centre, 48 Montague Road, South Brisbane, QLD 4101, Australia
[b] ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia
[c] School of Biological Sciences, The University of Queensland, Brisbane, QLD 4072, Australia
[d] The Nature Conservancy, Isabel Environmental Office, Buala, Isabel Province, Solomon Islands
[e] Coastal and Marine Research Centre, Australian Rivers Institute, School of Environment and Science, Griffith University, Gold Coast, QLD 4222, Australia
[f] The Nature Conservancy, Honiara Office, Rove, Solomon Islands
[g] School of Social Science, The University of Queensland, Brisbane, QLD 4072, Australia
[h] Threatened Species Operations, Queensland Department of Environment and Science, Ecosciences Precinct, Dutton Park, Qld 4102, Australia

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ABSTRACT

The remote tracking of endangered animals is often justified by the application of movement data to conservation problems, but examples of where scientific findings have rapidly informed conservation actions are relatively rare. In this study we satellite tracked 30 adult female hawksbill turtles (*Eretmochelys imbricata*) that were captured after nesting in the Arnavon Community Marine Park (ACMP), Solomon Islands. Ten hawksbill turtles were tagged in April 2016, ten in May 2017 and ten in November 2018. Our primary aim was to determine if the ACMP boundaries that were demarcated in 1995 were large enough to protect female hawksbill turtles throughout their entire nesting season. Our home range analysis revealed that collectively, tracked hawksbill turtles spent 98.5% of their inter-nesting season within the ACMP, confirming that the original park boundaries were adequate. Our first year's results were shared with community and government stakeholders and assisted in getting the ACMP declared as the Solomon Islands first national park in May 2017. Our fine scale analysis of inter-nesting habitats also highlighted that most hawksbill turtle nests were being laid on an island in the ACMP that did not have a permanent ranger presence and was experiencing persistent poaching. Based on this finding an additional ranger station was established on this uninhabited island and staffed with community rangers in 2017. Our study demonstrates how involving community, government and NGO stakeholders in applied research can lead to results being rapidly utilised to inform policy and conservation practice as soon as they become available.

1. Introduction

All sea turtles are globally listed as threatened species and thus have been the focus of considerable conservation attention (Humber et al., 2014). A challenge for the conservation of sea turtles is that their wide ranges and migratory habits bring them into contact with many human threats (Schofield et al., 2013; Humber et al., 2014; Bell et al., 2020). Tracking their movements across breeding and foraging grounds is therefore important to inform spatial conservation actions (see reviews in Godley et al., 2008; Jeffers and Godley, 2016 and Hays and Hawkes, 2018). Sea turtles are relatively easy to track using satellite telemetry and the advent of the Argos-linked Fastloc-Global Positioning System (Fastloc-GPS) facilitates precise tracking studies, with Fastloc-GPS locations accurate to within 50 m of the true location of the satellite tag (Dujon et al., 2014; Hays and Hawkes, 2018). The fine scale spatial resolution provided by Fastloc GPS satellite tags makes them ideal tools for evaluating whether management actions are protecting turtles across their different life-phases; such as determining if existing marine protected area (MPA) boundaries provide sufficient protection to nesting turtle populations (Schofield et al., 2013; Dawson et al., 2017) or if management zones implemented to reduce vessel strikes on foraging turtles are appropriately placed (Shimada et al., 2017).

* Corresponding author at: The Nature Conservancy, Asia Pacific Resource Centre, 48 Montague Road, South Brisbane, QLD 4101, Australia.
E-mail address: rhamilton@tnc.org (R.J. Hamilton).

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Despite the ability of satellite tracking studies to influence management and policy (e.g. Hays et al., 2019) there are very few real examples of this: a recent review found that of 369 sea turtle tracking studies published between 1982 and 2014, there were only 12 instances where tracking findings resulted in clearly identifiable changes to conservation practice (Jeffers and Godley, 2016). Several exceptions to this are summarised by Hays et al. (2019), including an example of where tracking data from leatherback (*Dermochelys coriacea*) and olive ridley turtles (*Lepidochelys olivacea*) was used to help justify the expansion of two marine protected areas in Gabon, Central Africa (Dawson et al., 2017). Another example is where tracking data on loggerhead turtles (*Caretta carreta*) was utilised when developing a regulatory program to reduce loggerhead turtle bycatch in the gillnet fishery of Baja California Sur, Mexico (Peckham et al., 2007). The low uptake of scientific findings into conservation practice and policy is a widespread problem in conservation (Knight et al., 2008; Laurance et al., 2012), that appears to relate to a suite of factors, such as difficulties in producing time critical research and the lack of proactive dialogue between researchers and conservation practitioners (Laurance et al., 2012).

Here we report how the findings made during the first year of a three-year satellite tracking study of hawksbill turtles (*Eretmochelys imbricata*) resulted in rapid adaptive management and were considered by community and government stakeholders when registering the Arnavon Islands as Solomon Islands first national park (Fig. 1). Hawksbill turtles are listed as Critically Endangered (CR) on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Mortimer and Donnelly, 2008), and the Arnavon Islands supports the largest known rookery for hawksbill turtles in the oceanic South Pacific. By the early 1990s the hawksbill turtle population that nests at the Arnavons had been decimated by 150 years of commercial exploitation (Bennett, 1987; Mortimer, 2002; Hamilton et al., 2015).

The first attempt to conserve the Arnavon Islands rookery occurred in the mid-1970s when the Solomon Islands Ministry of Natural Resources declared the Arnavons as "off limits" to fishers from the nearby communities of Kia, Katapika and Wagina. These early conservation efforts failed to engage the views and voices of the traditional owners of the Arnavons, and the government led conservation project was abandoned in 1982 when an individual burned down the government infrastructure on the Arnavons (Hamilton et al., 2015). In 1991 The Nature Conservancy began to work with local resource owners and Solomon Islands government to re-establish a protected area in the Arnavon Islands, this time with a strong focus on community-involvement and education. Extensive consultations with the communities of Kia, Katupika and Wagina took place between 1991 and 1994 regarding the future of the Arnavons (Mahanty, 2002; Hamilton et al., 2015).

In 1995 the Arnavon Community Marine Conservation Area (ACMCA) was established, protecting 152 km^2 of land and sea (Fig. 1). The name of this conservation area was changed to the Arnavon Community Marine Park (ACMP) when it obtained national park status in 2017. The park's primary aim is to protect the hawksbill turtle population that nests in the ACMP, and the harvesting of turtles and turtle eggs from within the ACMP has been prohibited since 1995 (Mortimer, 2002). Outside of protected areas such as the ACMP, all marine turtles in Solomon Islands (with the exception of the leatherback turtle) can be legally harvested for subsistence purposes, however the sale of any turtle product (meat, eggs or shell) and the harvesting of turtle eggs or a nesting turtle is banned under Solomon Islands legislation (Vuto et al., 2019). The current level of turtle harvesting in Solomon Islands has been estimated at 10,000 turtles each year, a harvest that is made up predominantly of juvenile green and juvenile hawksbill turtles and appears to be unsustainable (Vuto et al., 2019). When the ACMP boundaries were being established in the mid-1990s there was no information on the inter-nesting habitats of the hawksbill turtles that nest in the park, so stakeholders agreed that a precautionary measure would be to protect all coastal waters within 3–4 km of a ACMP nesting beach.

Since 1995 the ACMP has had a management board made up of representatives from the communities of Kia, Wagina, Katupika, Isabel and Choiseul provincial government, The Solomons Islands Ministry of Environment Climate Change Disaster Management and Meteorology (MECDM), the Solomon Islands Ministry of Fisheries and Marine Resources (MFMR) and The Nature Conservancy. Conservation rangers from the communities of Kia, Wagina and Katupika have been stationed on Kerehikapa island year-round since 1995, carrying out turtle monitoring programs within the ACMP and deterring poachers (Fig. 1). These conservation efforts have had some success, with the number of hawksbill turtle nests laid in the ACMP doubling between the early 1990s and 2012 (Hamilton et al., 2015). Despite this, fluctuating levels

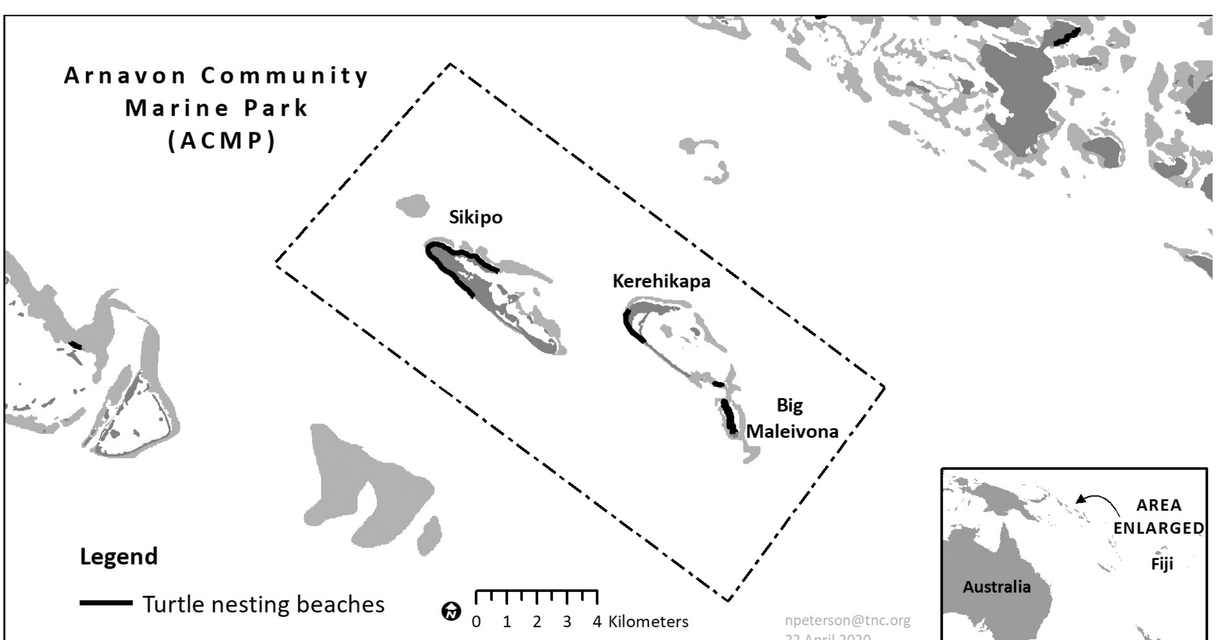

Fig. 1. Location of ACMP. The dotted line shows the protected area boundaries.

of poaching by some Wagina, Kia and Katapika inhabitants have occurred since the establishment of the ACMP in 1995 (Foale et al., 2017). Poachers target high value marine products such as turtles, sea cucumbers and trochus. The scutes from poached hawksbill turtles are illegally sold to buyers in the Solomon Islands capital city Honiara, with the meat consumed locally (Vuto et al., 2019). Incidents of poaching at the Arnavons typically peak when the Solomon Islands Ministry of Fisheries and Marine Resources lifts national moratoriums on sea cucumber fisheries.

In 2010 the Solomon Islands government passed the Solomon Islands Protected Areas Act, which paved the way to register the Arnavons as a national park. Registering the Arnavons as a national park was considered an important step towards curbing poaching and raising greater local, national and international recognition for the conservation work in the Arnavons. Prior to registering the ACMP as a national park the ACMP Board wanted to know if there was a need to expand the park boundaries. To address this question, in 2016 we commenced a satellite tagging study on female hawksbill turtles that nest in the ACMP. We used Fastloc-GPS satellite tags to answer the following questions: 1) Are the existing ACMP boundaries large enough to protect female hawksbill turtles during their entire nesting season when they are most vulnerable to hunting?, 2) Can satellite tracking inform local management actions to reduce threats to nesting hawksbill turtles? and 3) What are the post nesting migration routes and foraging grounds of the hawksbill turtles that nest in the ACMP, and what relevance does this have to conserving ACMP nesters during their other life stages?

2. Materials and methods

2.1. Study site

Satellite tagging was undertaken at the ACMP, a group of small islands and marine habitats that protects important cultural heritage sites (Radclyffe et al., 2019) and an extensive range of marine and terrestrial biodiversity (e.g., Leary, 1993; Leary and Orr, 1997; Green et al., 2006). Flipper tagging of hawksbills turtles that nest on Kerehikapa island began in the mid-1970s (McKeown, 1977), and flipper tagging at the Kerehikapa index beach has occurred annually with varying levels of effort since 1991 (Ramohia and Pita, 1996; Hamilton et al., 2015).

The largest island in the ACMP is Sikopo (7° 26′ S, 157° 58′ E), followed by Kerehikapa (7° 27′ S, 158° 01′ E) and Big Maleivona (7° 29′ S, 150° 03′ E) (Fig.1). Hawksbill turtles' nest throughout the year in the ACMP, with peak nesting activity occurring from approximately May to July, with a second shorter nesting peak occurring from December to January. During the May to July nesting peak approximately 3–4 hawksbill turtle clutches are laid within the ACMP each night (Hamilton et al., 2015). Initial beach surveys that were conducted in the ACMP from the mid-1970s to 1995 revealed that Kerehikapa accounted for 51–65% of all egg clutches laid in the ACMP, however by 2000 greater nesting activity was occurring on Sikopo Island (Mortimer, 2002). The increasing nesting activity on Sikopo has coincided with conservation efforts and the chronic erosion of low-profile nesting beaches on Kerehikapa between 1991 and 2020 (Authors, personal observations). The impacts of sea level rise and storm events have been shown to be extreme in this region of Solomon Islands (Albert et al., 2016). While little is published on mating and courtship in hawksbill turtles, the ACMP is known to be an important hawksbill turtle breeding site, with mating hawksbill turtles observed on numerous occasions over the past 30 years at five locations within the ACMP (John Pita, personal observations, Fig. 3B).

2.2. Turtle capture and transmitter deployment

The Nature Conservancy led this satellite tagging program, which involved a wide range of stakeholders including; staff from MECDM and MFMR, representatives from Choiseul and Isabel Provincial Government, ACMP rangers and ACMP board members, representatives from the local women's group KAWAKI and volunteers.

We equipped 30 nesting female hawksbill turtles with Argos-linked Fastloc-Global Positioning System (Argos-linked Fastloc GPS) satellite tags (SPLASH 10-BF-334D, Wildlife Computers. Redmond, WA, USA) between 2016 and 2018. This included 10 turtles in April 2016, 10 turtles in May 2017 and 10 turtles in November 2018. These tagging periods were chosen to sample hawksbill turtles that had arrived at the beginning of the two peak nesting periods, since our primary interest was to establish if the ACMP boundaries protected nesting hawksbill turtles throughout their entire nesting season. During the 2016–2018 field work two monitoring teams were established on Sikopo and single monitoring teams on Kerehikapa and Big Maleivona. These teams undertook nightly beach surveys from approximately 1900 to 0500 h. When a hawksbill turtle was located monitors waited until it had either completed nesting, or in some cases, had failed to nest and was returning to the sea. Monitors then transferred the turtle to a boat and relocated it to the Kerehikapa field station which was located 0.3–7.4 km away from capture locations. Once back at the Kerehikapa field station turtles were placed in a wooden holding pen. The holding pen was shaded and could be subdivided to prevent multiple turtles from climbing over each other.

The next morning, midline curved carapace length (CCL) was measured, and numbered titanium tags were applied to the proximal location of each front flipper (Limpus, 1992). Titanium flipper tags were not applied to turtles captured in 2018. Satellite tags were attached onto the two anterior vertebral scutes of the carapace with fiberglass cloth, two -part quick-setting epoxy resin (Devcon 5 Minute® Epoxy) and epoxy putty (EA 3463™ 10 min repair epoxy). Tags were programmed to acquire a Fastloc-GPS location every 3 h and the haulout function was enabled. Several weeks prior to deployment each tag was painted with one coat of Interprotect 2000E primer and three coats of Micron66 antifouling paint. After satellite tags had been attached turtles were placed back in the holding pen for approximately 4 h to allow the epoxy resin to fully cure. All turtles were released at the Kerehikapa field station.

2.3. Data preparation

Preliminary filtering of all tracks was applied using the R package SDLfilter (Shimada et al., 2016) to remove spatio-temporal duplicates. All fixes with <5 satellites, a residual error of more than 35 and/or fixes between which velocity exceeded the maximum realistic swimming speed of 5 km h^{-1} (Dujon et al., 2014) were also removed. To investigate inter-nesting, migrating and foraging behaviour, tracks were segmented based on visual assessment of movement within each of these categories. Inter-nesting was defined as the period starting after satellite tag attachment, up until the commencement of migration. The commencement of post nesting migration was determined as the point when turtles showed directional and continuous movement away from the ACMP and an inflection in travel speed to >1 km h^{-1} (Dujon et al., 2017). The cessation of migration and commencement of foraging was detected by a lack of directional movement (i.e. displacement distance from the breeding site staying constant) and the inflection in travel speed decreasing to <1 km hr^{-1} (Dujon et al., 2017).

The satellite tag attached to one turtle (PTT 160052) remained operational across two separate nesting seasons, so it was also possible to estimate this turtle's assumed courtship period. Here we defined the assumed courtship period as being from the day the migrating turtle first arrived back in the ACMP (a known breeding ground for hawksbill turtles), until the day it returned to its core inter-nesting habitat. While we cannot exclude the possibility that this turtle mated prior to arriving back at the ACMP (i.e., during her migration to the ACMP), we do not believe this is the case, given that PTT160052 migrated at a constant speed and in a consistent direction towards the ACMP once leaving her foraging grounds.

2.4. Spatial analysis

When possible, the home ranges across inter-nesting and foraging periods were identified using 50% and 95% volume contours of a utilisation distribution (UD). The home range for one turtle during its presumed courtship period was also identified using the method described above. We assumed the 50% UDs to be representative of each turtle's core activity centre and that the 95% UDs were representative of their overall habitat area. Due to the reduced accuracy of Argos only Fastloc-GPS linked data were used in these calculations. To estimate the UD for each track, we used a movement-based kernel density estimator based on biased random bridges (Benhamou, 2011) implemented with the R package *adehabitatHR* (Calenge, 2006, 2015). This method interpolates regularly spaced steps between location fixes and then estimates the UD across both known and interpolated locations. The interpolation between the known locations is modelled as a biased random walk. The random walk is assumed to follow a bivariate normal distribution with a diffusion coefficient (*D*) that is estimated separately for each turtle's track (Benhamou, 2011). We estimated the diffusion coefficient with a specified maximum time interval between relocations (T_{max}) of 500 min and a distance threshold, L_{min}, of 50 m below which we consider the animal is not moving (Benhamou, 2011). Given *D* for each turtle, UDs were then estimated on a 100 m resolution grid. We set the time lag between interpolated relocations (tau) at 100 min and error around each location (h_{min}) to 50 m.

To obtain accurate estimates of the mean inter-nesting interval between clutches we analysed haul-out data that was obtained from 8 tracked turtles that laid 22 nests (range 1–5 clutches) within the ACMP following tag deployment. Our methodology followed Esteban et al. (2017), with haul-out information obtained from satellite tags that were deployed in 2017 and 2018, as in these years tags were programmed to record a haul-out event when the salt-water switch on the transmitter stayed continuously dry for 20 min (refer to Appendix A, Table A.1, Fig. A.1, Fig. A.2 for additional information). For each turtle, migrations were described by their distance and speed. Total distance travelled was calculated as the sum of linear distances between successive locations and speed (km h) was calculated as the distance divisible by total time between successive locations. Confirmation of foraging habitats was made using satellite imagery in Google Earth and shape files of the great barrier reef (GBR) in Australia.

3. Results

3.1. Turtles

The number of nights required to capture 10 hawksbill turtles was 7 (2016), 5 (2017) and 4 (2018). The satellite tagged hawksbill turtles had a mean CCL = 86.6 cm (SE = ± 0.8, range 78.5–95.5 cm, *n* = 30) with 63% (*n* = 19) of turtles captured on Sikopo, 27% (*n* = 8) captured at Kerehikapa and 10% (n = 3) at Big Malevonia (Appendix A, Table A.2). All 30 satellite tags recorded Argos locations, with Fastloc-GPS locations obtained from 29 satellite tags. These turtles were tracked for a total of 9762 days; individually ranging from 13 to 1392 days (mean ± SE = 325 ± 68 d). The two turtles with the shortest tracking periods were both killed by poachers when they returned to nesting beaches on Sikopo Island. The turtles consisted of first-time tagged turtles (*n* = 27) and known remigrants (n = 3) that had been previously flipper tagged (Appendix A, Table A.2). The shortest recorded remigration interval for these three turtles was six years. PTT 169812 was encountered on Kerehikapa in May 2005 and then on Sikopo in May 2017 when it was satellite tagged. PTT 169813 was encountered on Kerehikapa in June 2010 and May 2017 when it was satellite tagged, and PTT 65512 was encountered on Kerehikapa in November 2006, November 2012 and November 2018 when it was satellite tagged.

3.2. Inter-nesting

The 29 satellite tracked turtles that had functioning Fastloc GPS tags were tracked for 1172 inter-nesting days, with 98.5% (1154.6) of these days spent within the ACMP boundaries (Table 1). The core-use inter-nesting areas (50% UDs) ranged from 0.1–3.5 km^2 with all tracked turtles 50% UDs contained within the ACMP. The overall inter-nesting areas (95% UDs) ranged from 1.2–105.8 km^2 (Table 1). Satellite tracked hawksbill turtles had a modal inter-nesting interval of 14 days [range 12–19 days] (Appendix A; Table A.1, Fig. A.1, Fig. A.2). 21 tracked turtles laid additional clutches (range 1–5 clutches) after tag deployment, with five of these turtles laying clutches on two separate islands within the ACMP. None of the turtles that were satellite tracked for 1172 inter-nesting days laid clutches outside of the ACMP. The distances between the nests laid by an individual turtle ranged from 0.1 to 8.5 km. Many turtles showed strong fidelity to their core-use inter-nesting areas. For example, 83% (10/12) of turtles captured at Sikopo that had not completed their nesting season swam from Kerehikapa (where they were released post tagging) back to Sikopo before their subsequent nesting event. Examples of variable inter nesting movements and known nesting locations for four tracked turtles are shown in Fig. 2.

3.3. Inter-nesting and foraging fidelity and the assumed courtship home range for one female turtle

PTT 160052 provided 5045 Fastloc GPS locations over 1300 days (Table A.1) and was deployed on a turtle that migrated to nearby foraging grounds in the Solomon Islands after it completed its 2016 nesting season (Fig. 3C). This turtle spent 621 days at its foraging grounds before remigrating back to ACMP to complete its 2018 nesting season, then returned to its foraging grounds for another 522 days before the satellite tag ceased to work. The movements of this turtle provided the opportunity examine its fidelity to inter-nesting and foraging areas over different time periods and enabled the calculation of its assumed courtship home range. This turtle showed tight inter-annual fidelity for both its inter-nesting and foraging habitats, with this turtle's 2018 core use inter-nesting home range larger than, but completely overlapping with this turtle's core use inter-nesting area in 2016 (Table 1, Fig. 3A). Similarly, the foraging home ranges that this turtle utilised either side of a breeding migration showed a very high degree of overlap, with the turtle's foraging home ranges larger following the 2018 nesting season (Table 1, Fig. 3D). The assumed courtship period for this turtle covered 15 days over which time 71 Fastloc GPS locations were obtained. The mean 50% and 95% UDs for this turtle's assumed courtship home range were 96.9 km^2 and 502.8 km^2 respectively, three times the size of the ACMP and 1–2 magnitudes larger than its inter-nesting and foraging home ranges (Fig. 3B).

3.4. Migration to foraging areas

Of the 30 satellite-tagged turtles, 28 turtles survived and migrated away from the ACMP towards their foraging grounds. Post nesting migrations covered every month of the year, with 57% (*n* = 16) of turtles reaching their foraging grounds before their tags failed (Appendix A, Table A.3). On average migrating turtles travelled 39 km per day, with a mean migration speed of 1.63 km h^{-1}. Total distance along the migration path for the 16 turtles that reached their foraging grounds ranged from 256 to 3409 km, with an average migration path of 2028 km ± 222 km and an average straight-line migration distance of 1404 km ± 138 km. The mean migration duration for these 16 turtles was 62 days ± 8 days (Appendix A, Table A.3).

93% (*n* = 26) of turtles migrated towards distant foraging grounds in Australia (*n* = 22), Papua New Guinea (n = 2) and New Caledonia (n = 2) while 7% (n = 2) of turtles travelled to nearby foraging grounds in the Solomon Islands (Fig. 4). 57% of the turtles that were tagged in this study followed the same nearshore migratory corridor once departing

Table 1
Home range analysis for hawksbill turtles during their inter-nesting and foraging periods. P = turtles poached within the ACMP.

	Inter-nesting					Foraging			
Turtle ID	Fastloc locations (filtered)	Inter-nesting duration (days)	Time outside ACMP (days)	50% UD (km^2)	95% UD (km^2)	Fastloc locations (filtered)	Foraging duration (days)	50% UD (km^2)	95% UD (km^2)
160053	80	15	0	2.9	22.0				
160054	45	8	0	2.1	10.8	394	196	4.35	22.67
160046	428	84	0	1.8	14.5				
160047	296	59	10.5	3.5	105.8	1805	1275	0.73	4.52
160048	77	14 (P)	0	1.1	11.1				
160050	220	48	0	2.7	19.3	2640	889	0.99	4.55
160051	66	13 (P)	0	0.1	1.6				
160052 (2016)	145	24	0	0.6	5.8	2174	621	0.27	2.51
160052 (2018)	351	88	6.4	1.1	19.4	2077	522	0.46	4.48
160049	84	15	0	1.1	27.3	293	80	2.71	17.61
160055	28	4	0.3	3.0	40.5				
169811	113	17	0	1.6	14.1				
169813	393	68	0	0.1	1.2				
169810	248	41	0.1	1.1	15.0	593	118	0.25	1.61
169816	313	55	0	0.4	8.5	199	200	1.30	8.12
169812	218	34	0	2.2	24.4				
169814	172	31	0	1.3	8.9	1233	569	0.47	3.40
169817	209	43	0	0.6	9.6	810	548	0.60	7.47
169818	254	43	0	2.0	21.3	222	569	0.25	2.20
169819	271	43	0	1.0	12.0				
65519	187	39	0	0.2	3.8				
65510	595	104	0	0.6	12.1				
65512	190	30	0	0.1	3.0	718	125	3.31	23.52
65514	261	44	0	0.3	4.5				
65513	154	23	0	0.6	4.1	517	420	0.33	2.79
65515	341	60	0.1	0.8	8.4	2627	445	0.98	9.86
65511	246	43	0	1.9	17.0				
65518	90	16	0	1.7	9.7	388	75	0.56	4.26
65516	222	44	0	1.7	10.5	316	84	0.57	2.62
65517	151	22	0	0.2	2.8				
Mean ± SE	216 ± 25	39 ± 4	0.6 ± 0.4	1.3 ± 0.2	15.6 ± 3.5	1062 ± 223	436 ± 84	1.1 ± 0.3	7.6 ± 1.8
Total		1172	17.4				6736		

the ACMP, swimming south across the New Georgia Sound to New Georgia Island, migrating around Vangunu Island then swimming past the Kavachi submarine volcano that lies 20 km south of Vangunu Island before dispersing across the Solomon and Coral Seas (insert, Fig. 4).

3.5. *Foraging areas*

Sixteen turtles were tracked on their foraging grounds for a total of 6736 days. The mean 50% and 95% UDs of all foraging turtles were 1.1 km^2 ± 0.3 km^2 and 7.6 km^2 ± 1.8 km^2 respectively (Table 1). Many turtles travelled to foraging grounds on outer barrier reefs of Australia, although several turtles travelled to foraging grounds on nearshore reefs that were adjacent to the Queensland mainland. Examples of the restricted foraging home ranges of three different turtles are shown in Fig. 5.

4. Discussion

The primary aim of this tracking study was to assess whether the ACMP boundaries that were established in 1995 were large enough to protect female turtles during the nesting season when they are most vulnerable to hunting. When the first years tracking results where shared with ACMP board members they concluded that there was no need to spend time and effort in expanding the ACMP boundaries. This enabled the ACMP Board to immediately proceed with the process of registering the ACMP under the Solomon Islands Protected Areas Act, and on May 11, 2017 the ACMP was declared as the Solomon Islands first national park. Having the ACMP declared as a national park was considered an important step towards reducing poaching, because it gave ACMP rangers legally recognised enforcement powers and enables the MECDM to issue fines of up to SBD $10,000 to individual poachers.

Our analysis of all three years of tracking data further supports the ACMP Boards decision. All tracked breeding females had very high fidelity to the ACMP, with 98.5% of the total 1172 inter-nesting days spent within the park. Satellite tracked turtles nested up to six times in a season and none of the turtles nested outside of the ACMP. However, not all turtles were loyal to a single nesting beach, with five hawksbill turtles laying clutches of eggs on both Kerehikapa and Sikopo island within a nesting season, with nests separated by distances of up to 8.5 km. This nesting site plasticity (Hart et al., 2019) had been recorded once before in the ACMP from flipper tag studies (Ramohia and Pita, 1996) and has been documented in hawksbill turtle populations in Australia (Limpus et al., 2008) and the US Virgin Islands (Iverson et al., 2016). The ability to nest at multiple beaches may provide female hawksbill turtles with an evolutionary advantage (Esteban et al., 2017; Hart et al., 2019), by enabling them to seek out alternative nesting locations to their natal beaches when environmental conditions change. The observed nesting site plasticity implies that ACMP nesters could nest outside of the park if cyclones or climate related storm events made ACMP beaches unfavourable for nesting. It is noteworthy that the assumed courtship home range of one turtle was magnitudes larger than its inter-nesting and foraging home ranges. This suggests that the ACMP may not offer adequate protection for the breeding female population during their short courtship period. Very little is known on the courtship home ranges of female turtles and this would be an interesting area to focus future research.

The commencement of this satellite tracking study also highlighted the need to improve protection of the nesting beaches at the uninhabited island of Sikopo. 63% of the turtles tagged in this study were captured on Sikopo and several turtles that were first encountered nesting on

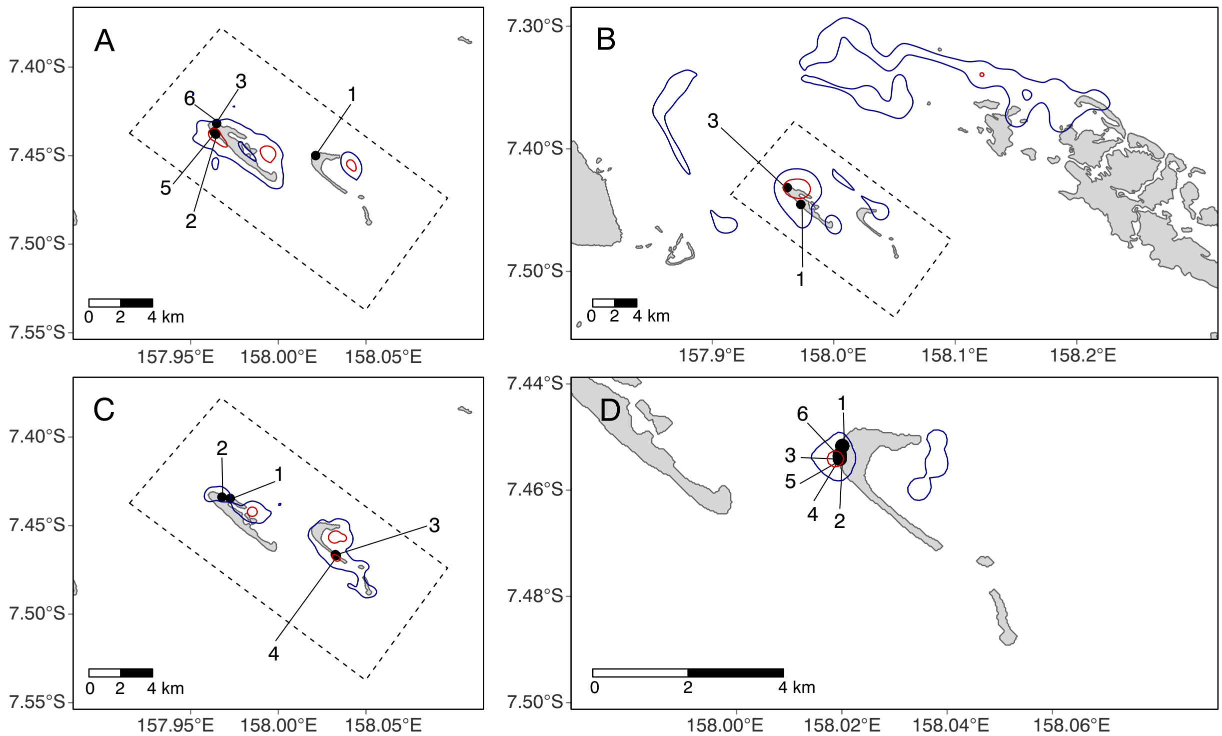

Fig. 2. Inter-nesting areas and known nesting locations for turtles tracked within the ACMP. Red contour line shows the core area of activity (50% UD) and blue contour line shows overall inter-nesting range (95% UD). The dotted line in panel A-C shows the ACMP protected area boundaries. Number "1" shows the initial capture location after a successful nesting event; following numbers show subsequent known nesting events. If an expected upcoming nesting event was missed (i.e. not observed by ACMP rangers and no haulout location obtained), then we assumed that nesting event occurred, but it was not numbered. *Panel A. PTT160046*. Successfully nested on Kerehikapa, then laid 5 subsequent clutches on Sikopo Island. *Panel B*: *PTT 160047*. Captured after successfully nesting on Sikopo. Following release at Kerehikapa, spent 10.5 days outside the ACMP before returning to Sikopo. *Panel C*: *PTT 169819*. Captured after successfully nesting on Sikopo. Following release at Kerehikapa, returned for 2nd nesting at Sikopo then nested a 3rd and 4th time on Kerehikapa Island. *Panel D*: *PTT 169813*. Remigrant turtle captured at Kerehikapa in June 2010 and after laying at Kerehikapa in May 2017. It renested another 5 times on Kerehikapa in 2017, with all 6 nests in very close proximity to each other. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Kerehikapa subsequently nested on Sikopo. For example, one turtle (PTT 160046, Fig. 2A) that was deployed with a satellite tag after nesting on Kerehikapa in 2016 moved and laid a further 5 clutches of eggs on Sikopo beaches before departing for her foraging grounds. Furthermore, two satellite tagged turtles that had been captured after nesting on Sikopo in April 2016 were killed by poachers when they returned to nest on Sikopo beaches two weeks later. To provide better protection for the Sikopo nesting beaches the ACMP Board agreed that there was an urgent need to build and staff an additional ranger station on Sikopo. The Nature Conservancy secured funding for the Sikopo ranger station and by the end of 2017 the ranger station at Sikopo was completed and staffed with community rangers.

As well as providing extensive fine scale data on turtle movements during their nesting seasons, our satellite tagging also revealed previously unknown information on the post nesting migration routes and foraging grounds of the hawksbill turtles that nest in the ACMP. We observed a mean migration distance between nesting and foraging grounds of 2028 km ± 222 km, much further than the mean migration distance reported for any other nesting hawksbill turtle population (e.g. Parker et al., 2009; Gaos et al., 2012; Hawkes et al., 2012; Hays and Scott, 2013; Hoenner et al., 2016; Hart et al., 2019). Previous studies and this research show that many hawksbills that nest at the ACMP make long distance migrations to foraging grounds in Australia, Papua New Guinea and New Caledonia (Vaughan and Spring, 1980; Parmenter, 1983; Mortimer, 2002; Limpus et al., 2008; Hamilton et al., 2015; Bell and Jensen, 2018). We also observed that a small proportion of ACMP nesters travelled to foraging grounds in Solomon Islands that were less than 350 km from the ACMP. Earlier studies from the Dominican Republic and US Virgin Islands have also shown the adult female hawksbill turtles show a range of migratory strategies, with some traveling to nearby foraging grounds and others migrating long distances to international foraging grounds (e.g. Hawkes et al., 2012; Hart et al., 2019). Conversely, some post-nesting hawksbills in Pacific El Salvador and Nicaragua have been shown to be non-migratory, settling in foraging grounds adjacent to their nesting beaches (Gaos et al., 2012).

Hamilton et al. (2015) examined the capture mark recapture histories for 845 individual nesting female hawksbills that were flipper tagged in the ACMP between 1991 and 2012 and concluded that by the early 2000s the mean remigration interval for ACMP nesters was 5–6 years. The long distances between foraging grounds and the ACMP may explain the unusually long mean remigration interval at the ACMP, with even migrations to the relatively close foraging grounds in Papua New Guinea appearing to place significant energetic limitations on the frequency with which turtles can remigrate to the ACMP. Evidence of this comes from this study, where one satellite tracked remigrant (PTT: 65512) that had a nesting remigration interval of six years travelled 1104 km to its foraging grounds in Milne Bay, Papua New Guinea. In contrast, nesting hawksbill turtles in El Salvador and Nicaragua had a mean migration distance between nesting grounds and foraging grounds of 113 km (Gaos et al., 2012), and some of these hawksbill turtles nested on an annual basis (Gaos et al., 2017). It is noteworthy that the only tracked turtle in this study that remigrated back to the ACMP within a two-year time frame foraged in nearby domestic waters, highlighting that the small number of ACMP nesters that forage in the Solomon Islands may contribute disproportionately to the total number of hawksbill nests laid within the ACMP.

This research revealed that many tracked turtles used the same migratory corridor when they were departing the ACMP (Fig. 4), and

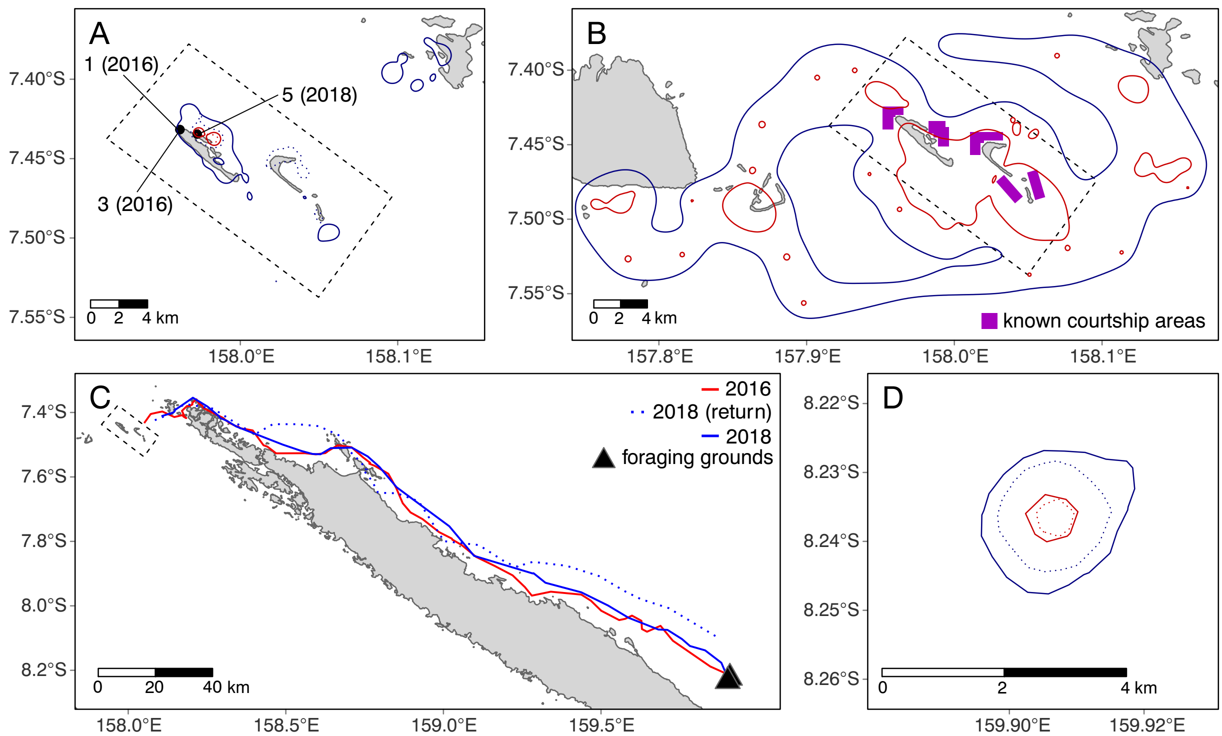

Fig. 3. Movement patterns and home ranges of PTT 160052. Dotted red contour lines show the core area of activity (50% UD) and dotted blue contour lines show and overall area of activity (95% UD) in 2016. Solid red contour lines shows the core area of activity (50% UD) and solid blue contour lines show and overall area of activity (95% UD) in 2018. *Panel A*: Inter -nesting home ranges and known nesting locations in 2016 and 2018. *Panel B*: Assumed courtship home range. *Panel C*: The migration routes taken between nesting and foraging grounds. *Panel D*. Foraging ground home ranges following the 2016 and 2018 nesting seasons. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

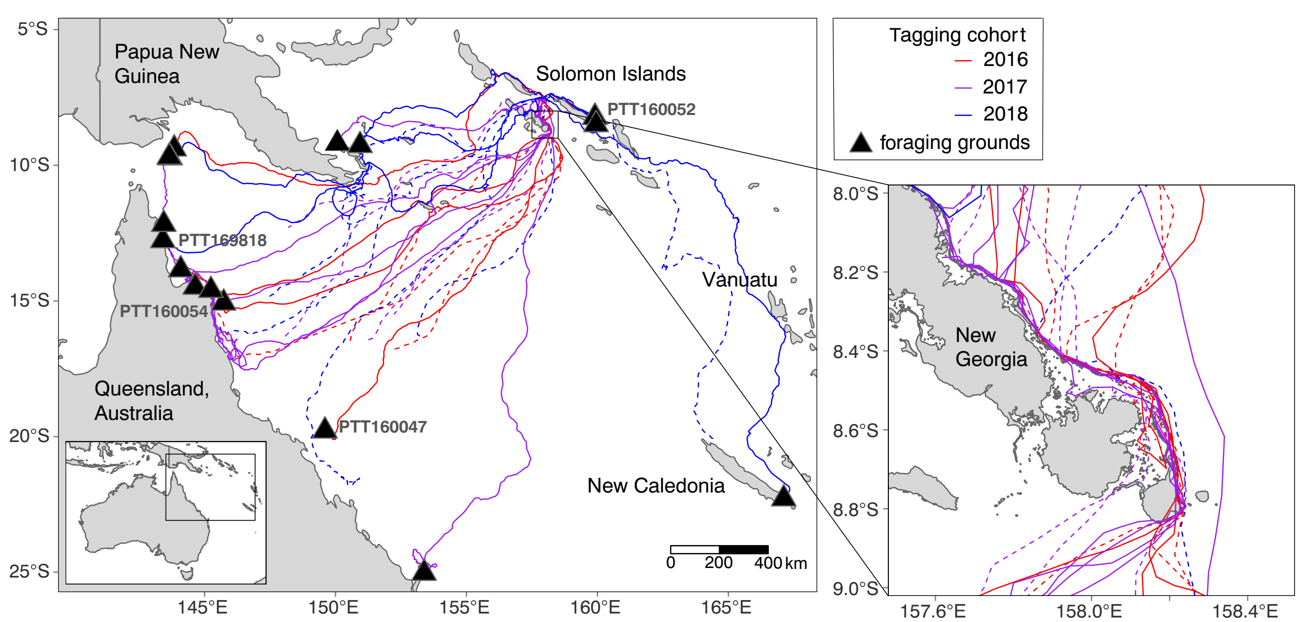

Fig. 4. Post nesting migrations of the 28 satellite tracked turtles. Dashed lines indicate satellite tags that failed prior to the turtle arriving back at its foraging grounds. The insert shows a migratory corridor that was used by 57% (16/28) of turtles after they departed the ACMP. 75% ($n = 6$) of the turtles that survived to migrate in the April 2016 cohort and 80% ($n = 8$) of the turtles that were tagged in May 2017 cohort used this migratory corridor, however only 20% ($n = 2$) of the turtles that were tagged in November 2018 cohort used this corridor.

that greater protection of this nearshore migratory corridor would be beneficial. One management initiative that would provide additional protection to the southern extent of this migratory corridor is the Kavachi Marine Management Area (KMMA). The Wildlife Conservation Society (WCS) is currently working with stakeholders and government to establish the KMMA as a legally designated managed area that encompasses 4580 km^2 of marine habitat (Alec Hughes, personal communication).

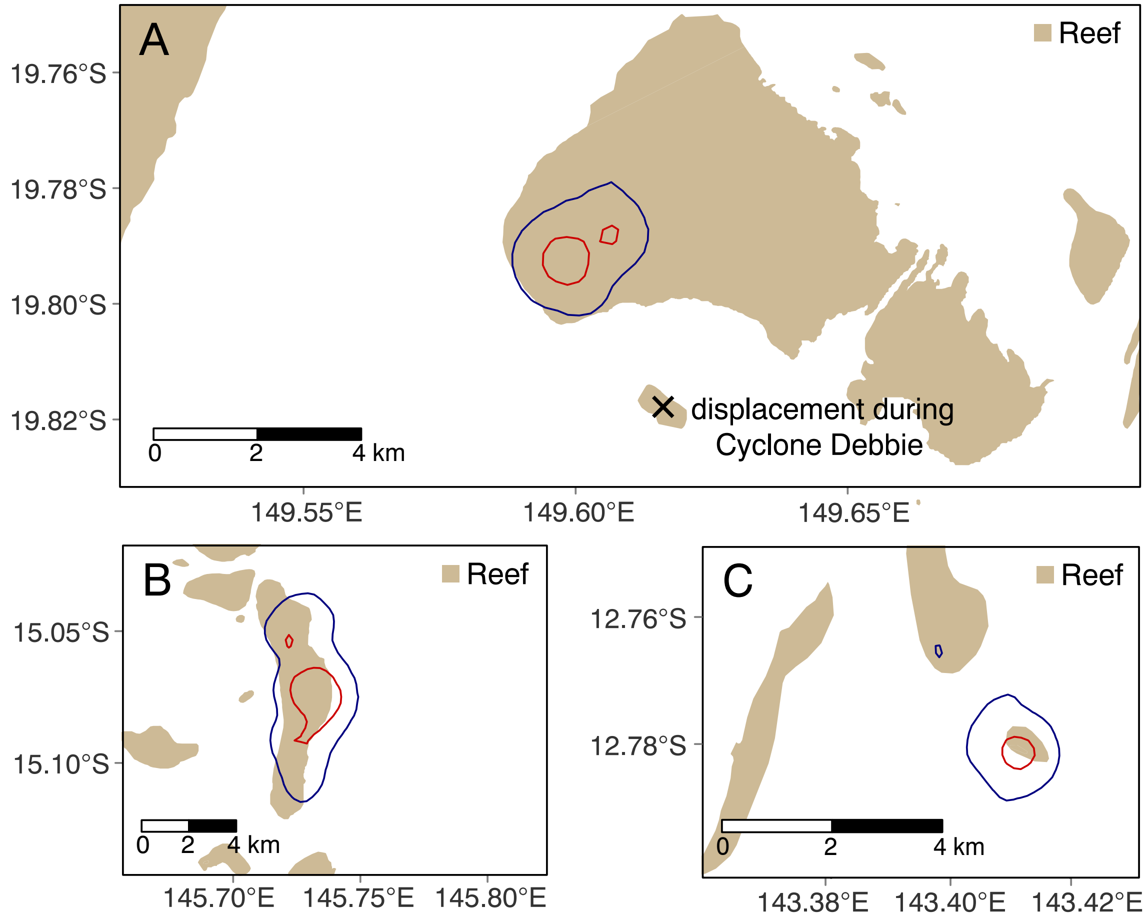

Fig. 5. Foraging ground home ranges. Red contour line shows the core area of foraging activity (50% utilisation distribution) and blue contour line shows overall foraging range (95% UD). *Panel A.* PTT 160047. Tracked on foraging grounds on an outer reef in the central Great Barrier Reef (GBR), Australia for 1275 days. This turtle temporarily migrated from its foraging grounds for four days when Cyclone Debbie passed overhead in March 2017. *Panel B.* PTT 160054. Tracked on foraging ground on an outer barrier reef in the northern GBR, Australia for 196 days. *Panel C.* PTT 169818. Tracked on its foraging ground on an inshore reef in the northern GBR for 569 days. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The satellite tracked ACMP nesters travelled to widely dispersed foraging grounds in Australia, New Caledonia, Papua New Guinea and Solomon Islands, highlighting the challenges of conserving breeding turtles that return to foraging grounds where they may or may not be protected from subsistence harvest. All 16 turtles that were tracked to their foraging grounds displayed fidelity to specific foraging sites (Mean 50% UD 1.1 $km^2 \pm 0.3$ km^2). While foraging ground fidelity is common in sea turtle species (Shimada et al., 2020), we have shown foraging site fidelity for a hawksbill turtle over multiple nesting migrations. The hawksbills nesting in ACMP established foraging sites located on outer barrier reefs, with several turtles also foraging on inshore reefs close to the Queensland mainland. The foraging home ranges of ACMP nesters were smaller than the mean foraging home ranges that were calculated using Fast-loc GPS tags deployed on seven hawksbill turtles within the Gulf of Carpentaria in northern Australia (Hoenner et al., 2016). Some Gulf of Carpentaria turtles foraged within a restricted area while others had much larger foraging home ranges. The small inter-nesting and foraging home ranges observed in this study likely reflect that the complex coral reef habitat at both nesting and foraging sites provided adequate shelter for ACMP nesters (Revuelta et al., 2015). Of the 16 turtles that were tracked to their foraging grounds, 9 (56%) returned to reefs in the northern Great Barrier Reef and the Torres Straits, suggesting that ongoing effective management of these foraging grounds will be vital for the long-term sustainability of ACMP nesters.

5. Conclusion

A primary goal of this study was to utilise Fastloc-GPS satellite tags to obtain fine scale information on female hawksbill turtles inter-nesting movements within the ACMP and use the movement information to improve park management. We found that all tracked female hawksbill turtles had a very high fidelity to the ACMP during their nesting seasons. Based on this finding the ACMP Board concluded that the original park boundaries were sufficient, and they proceeded with getting the ACMP registered as Solomon Islands first national park in May 2017. Results of the tracking study also highlighted the need to improve protection of the main nesting beaches at the uninhabited island of Sikopo. The urgency of addressing this issue became apparent in May 2016 when two satellite tagged turtles were killed by poachers when they returned to nest on Sikopo beaches. Consequent adaptive management actions that were made to address poaching included building an additional ranger station on Sikopo and the recruitment of additional community rangers to staff this station.

Our results also provided detailed and previously unknown information on post nesting migration routes and foraging grounds of ACMP nesters, findings that could help inform management measures far beyond the ACMP boundaries. For example, our tracking study identified a nearshore migratory corridor in Solomon Islands that deserves additional conservation attention and confirmed that reefs in northern Queensland and Torre Straits are important foraging grounds for female hawksbill turtles that nest in the ACMP. Finally, the fact that ACMP nesters were shown to migrate to foraging grounds in Australia, New Caledonia, Papua New Guinea and Solomon Islands underscores the need for regional strategies to effectively conserve highly migratory hawksbill turtles (Hart et al., 2019).

CRediT authorship contribution statement

Richard Hamilton. Conceptualization, Funding Acquisition, Investigation, Methodology, Oversight and Leadership, Project Administration, Supervision, Writing. **Amelia Desbiens**. Data Curation, Formal Analysis, Software, Validation, Visualization, Writing - Review & Editing. **John Pita**. Investigation, Project Administration, Writing - Review & Editing. **Christopher Brown**. Formal Analysis, Software, Validation, Writing - Review & Editing. **Simon Vuto**. Investigation, Project Administration, Writing - Review & Editing. **Willie Atu**. Investigation, Writing - Review & Editing **Robyn James**. Investigation, Writing - Review & Editing. **Peter Waldie**. Investigation, Writing - Review & Editing. **Col Limpus**. Conceptualization, Methodology, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109240.

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