Department of **Biodiversity, Conservation and Attractions**

GOVERNMENT OF WESTERN AUSTRALIA

Inter-nesting and migrations by marine turtles of the Muiron Islands and Ningaloo Coast

Final Report

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Inter-nesting and migrations by marine turtles of the Muiron Islands and Ningaloo Coast, Final Report

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Disclaimer

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Executive Summary

Background: The Department of Biodiversity, Conservation and Attractions (DBCA) undertook a turtle satellite tagging program to determine the spatial use of marine turtles nesting within Ningaloo Marine Park (NMP) and Muiron Islands Marine Management Area (MIMMA).

Aims/Objectives:

- To identify marine turtle inter-nesting habitats, duration of residence, and reproductive outputs.
- To determine marine turtle migration routes, migration timing, and identify post-reproductive foraging grounds.

Methods:

- Local involvement of Woodside volunteers, Traditional Owners and Ningaloo Turtle Program (NTP) volunteers assisted a long-running community-based conservation program.
- Satellite tags were deployed on 13 green turtles and 12 loggerhead turtles over 26/11/18 to 9/12/18.
- Six green turtles and five loggerhead turtles were tagged in the Muiron Islands Marine Management Area.
- Seven green turtles and seven loggerhead turtles were tagged in the Ningaloo Marine Park.
- No nesting hawksbill turtles were encountered during the project.
- Data were analysed using ZoaTrack and QGIS software.
- Tracking histories and depth records were defined from all transmitted locations until each transmitter's final location.
- Track locations were uploaded to a public webpage for community awareness.

Results: Inter-nesting

- Transmitters lasted for 48 to 422 days up to the final location transmitted on 03/02/2020.
- 1450 inter-nesting tracking days recorded 107 inter-nesting intervals between nests. Green turtles averaged 4.8 nests (range 3-8 nests) and loggerheads averaged 3.8 nests (range 2-7 nests).
- Inter-nesting green turtles were tracked in the Marine Park (MP) waters for an average of 67 days (range = 51-78 d).
- Inter-nesting loggerhead turtles were tracked in the MP waters for an average of 49 days (range = 24-78 d.)
- 75-83% of nests were laid in the Ningaloo Marine Park (NMP) or Muiron Islands Marine Management Area (MIMMA).
- Inter-nesting activity was within the NMP or MIMMA for 85% of green turtles and 75% of loggerhead turtles.
- Depth sensors indicated the inter-nesting occupancy was shallower than 10 m for green turtles and ranged between 2-20 m for loggerhead turtles.

- Inter-nesting (IN) green turtles had smaller spatial ranges than loggerhead turtles. Green turtles remained closer to a rookery than loggerheads, the latter ranged more distantly before returning to nest.
- Inter-nesting hotspots for green turtles were mostly in the NMP and for loggerheads were adjacent if not within the NMP.
- Inter-nesting turtles resided mainly within Marine Protected Areas (MPAs) (20/25). 2/13 (15%) of IN green turtles and 3/12 (25%) of IN loggerhead turtles moved outside the park boundaries during IN periods.
- The loggerhead turtles were more likely than green turtles to move east to west across Exmouth Gulf or between offshore islands and the mainland or vice versa.

Results: Migration

- Foraging areas were determined for turtles occupying a location for more than 30 days.
- 24/25 post-nesting turtles were tracked to foraging grounds with over 3788 days of total tracking time.
- For post-nesting migrations, the loggerhead turtles on average undertook more distant (22-2394 km) post-nesting migrations than green turtles (4-544 km).
- Loggerhead turtles had 3x longer migration displacements than green turtles. Loggerhead turtles had higher transit speeds by swimming day and night suggesting that green turtles rested at night on migrations.
- Foraging grounds of NMP/MIMMA contained only 1/13 of tracked green turtles and 1/12 of tracked loggerhead turtles.
- The distant ranges of green turtle foraging grounds spread from Shark Bay up to the Turtle Islands of the East Pilbara. Loggerhead turtles spread further south to Mindaree near Perth and across to Maningrida, Arnhem Land, NT.
- Green turtles had 4/13 Foraging Ground (FG) locations (30.7%) within NMP/MIMMA. Loggerhead turtles had 1/12 FG locations (8.3%) within NMP/MIMMA. Three loggerhead transmitters ceased in 0-4 days after reaching a presumed foraging ground.

Conclusions

- The study adds new quantitative data on regionally significant WA rookeries as documented in the Recovery Plan for Marine Turtles in Australia, specifically the genetic stocks of Northwest Shelf green turtles and Western Australian loggerhead turtles.
- The project details Habitat Critical to Survival for inter-nesting areas of green and loggerhead turtles and augments or modifies the Biologically Important Areas (BIAs) for migration and foraging areas connected with or extended from the Pilbara region.
- Post-nesting migratory paths are spread over 5000+ km of Australian coastlines.
- The results filled knowledge gaps for two species that are conservation assets to State, Commonwealth and Indigenous managers.

- The sample sizes of adult females were adequate to define the rookeries inter-nesting and post-nesting migration phases.
- The fundamental focus of the inter-nesting study did not address foraging areas for juveniles, subadults, or males which remain knowledge gaps important to conservation management of marine turtle species.
- The present study can be leveraged by collaborations with other researchers to expand datasets within the same genetic stock.

Acronyms and Abbreviations

Acronym	Definition
ARGOS	the CLS ARGOS system of satellites
BIA	Biologically Important Area
CALM Act 1984	Conservation and Land Management Act 1984
CAPAD	Commonwealth Collaborative Australia Protective Areas Database
CCL	Curved Carapace Length
CSV	Comma Separated Values file format
DBCA	Department of Biodiversity, Conservation and Attractions
DAWE	Department of Agriculture, Water and Environment
ECF	Estimated Clutch Frequency
EEZ	Exclusive Economic Zone
EPBC Act	Environmental Protection and Biodiversity Conservation Act 1991
FG	Foraging Ground
G	Green Turtle
GEBCO	General Bathymetric Chart of the Oceans
GIS	Geographic Information System
GPS	Global Positioning System
IN	Inter-nesting interval
KML	Keyhole Markup Language is a file format to display geographic data in Google Earth
KUD	Kernel Utilization Distribution
L	Loggerhead Turtle
M	Migration

MIMMA	Muiron Island Marine Management Area
MCP	Minimum Convex Polygon
MPA	Marine Protected Area
MU	Management Unit
NT	Northern Territory
NMP	Ningaloo Marine Park
NTP	Ningaloo Turtle Program
NWS	North West Shelf
PTT	Platform Terminal Transmitter
R	R computer language used in data analysis or graphics
SB	Shark Bay
SHP	SHP file format for spatial software
STO	Seaturtle.org
WA	Western Australia

Definitions

Baseline survey

A baseline survey provides information on the condition and ecology of an area prior to undertaking any development. Baseline surveys gather information that can be used in subsequent impact assessments and to design monitoring programs.

Bathymetry

Bathymetry is the measurement of water depths and the topographic maps of the seafloor resulting from these measurements.

Biologically Important Area

Biologically Important Areas (BIAs) are spatially defined areas where aggregations of individuals of a species are known to display biologically important behaviors such as breeding, foraging, resting or migration. They are an important consideration in decisions made under national environmental protection law.

Continental shelf

The continental shelf is an area of the seafloor averaging less than 200 m deep and includes the underwater, extended edge of a continent and associated coastal plain which generally was exposed at times of lower sea level.

Estimated clutch frequency

ECF is a number of nests deposited by a female in a season determined from tracking patterns of emergences onto land.

Exclusive Economic Zone

The EEZ is a sea zone which extends 200 nautical miles from the Australian coast, over which each state has special rights over the exploration and use of marine resources.

Foraging ground

After breeding season and post-reproductive migration, a foraging ground is the extended (years) localized residence of turtles.

Gas condensate field

Natural gas condensate is a low-density mixture of hydrocarbon liquids that are present as gaseous components in the raw natural gas produced from many natural gas fields.

Habitat Critical to Survival (abbreviated to habitat critical)

Significant Impact Guidelines 1.1 – Matters of National Environmental Significance (MNES) in relation to significant impact. These guidelines define habitat critical to the survival of a species' as areas necessary: for activities such as foraging, breeding or dispersal; for the long-term maintenance of the species (including the maintenance of species essential to the survival of the species); to maintain genetic diversity and long-term evolutionary development; for the reintroduction of populations or recovery of the species.

Heat Map

A spatial analysis yielding a coloured gradient of point intensity to show the hot spots of intensive use.

Home range

An animal's home range is the area that is normally occupied and used by that animal.

Inter-nesting interval

The period between nesting events within a nesting season.

Kalman filter

A statistical filter to exclude unlikely locations and predict a more probable path through time.

KUD

Kernel utilization distribution is a probabilistic zone of spatial occupancy for an animal with 50% KUD defined as a home range core and 95% KUD defined as the used home range.

Marine megafauna

Marine megafauna includes large fauna that live in the marine environment.

MCP

Minimum convex polygon method to calculate spatial occupancy by linking outermost locations.

Migratory species

Migratory species predictably travel from one place to another at regular times of year, often over long distances, for example between feeding and breeding grounds. Migrations are pre-reproductive or post-reproductive movements relative to the breeding events.

Nearshore

The nearshore region extends seaward from the shoreline.

Offshore

The offshore region is an arbitrary term located at a distance from the shore, extending outward to the edge of the continental shelf. For this project we deemed this to be 200 m from the shoreline and extending seaward.

Post-nesting

A period immediately between the last clutch laid for the season and the time of arriving at a foraging ground.

Provincial bioregion

A provincial bioregion is an area which has similar types of plants, animals, and environments when compared to other areas of similar size and were developed under the Commonwealth's Integrated Marine and Coastal Regionalisation of Australia (IMCRA).

PTT

Platform terminal transmitter is a technical term for a satellite tracker tag.

Recapture

Recapture is to capture/count something for a second or subsequent time.

Recovery Plan

The Recovery Plan for Marine Turtles in Australia (Commonwealth of Australia 2017) is cited in full and thereafter referred to generically in lower case as the recovery plan.

Seaturtle.org

A website www.seaturtle.org that facilitates a public interface for public interests in the migrating turtles.

Threatened species

Threatened species are vulnerable or likely to become endangered or extinct in the near future as defined by the EPBC ACT 1999.

Zoatrack

Zoatrack is an analysis platform to archive and analyse animal movement data (zoatrack.org.au).

1 Introduction

Three of the world's seven marine turtle species nest on mainland beaches and islands of the Ningaloo Coast during the summer months from November to March. The Ningaloo Marine Park (NMP) and Muiron Islands Marine Management Area (MIMMA) support significant nesting by thousands of green turtles (*Chelonia mydas*), North West Shelf genetic stock, hundreds of loggerhead turtles (*Caretta caretta*), Western Australian genetic stock, and dozens of hawksbill turtles (*Eretmochelys imbricata*), Western Australian genetic stock. The green and loggerhead rookeries in NMP and MIMMA are major rookeries of the Indian Ocean (Limpus 2009, Casale and Tucker 2017, Commonwealth of Australia 2017) and the hawksbills are at the southern boundary of more populous rookeries centered in the Central Pilbara coast.

In this region, turtles are under threat from habitat loss and disturbance (to nesting, feeding/foraging and breeding), increasing recreational activity, increasing tourism, and from the introduction of feral species, particularly the European red fox. Green, loggerhead and hawksbill turtles are threatened species listed under the IUCN Red List and the Commonwealth Government's Environment Protection and Biodiversity Conservation Act 1999 (EPBC) (refer to **Table 1**). The Recovery Plan for Marine Turtles in Australia (Commonwealth of Australia 2017), hereafter referred to generically as the recovery plan, summarizes other important information on Habitat Critical to the survival of marine turtles and Biologically Important Areas (BIAs) (Commonwealth of Australia 2014).

Nesting turtles return periodically to these regional beach rookeries (R) to nest after migrations (M) from foraging grounds (FG) up to 10's to 2,500 km away. During the breeding phase they will mate and lay multiple clutches of eggs about two weeks apart. The period between clutches is termed the inter-nesting interval (IN) when turtles will seek a quiet location up to 40 km from the nesting beach to prepare the next clutch. After a final nest is deposited, the turtle migrates (M) and returns to a foraging ground (see example illustrated by **Figure 1**). The life history phases involved in this process (the inter-nesting locations, the post-nesting migration corridor and various foraging grounds) defined as Habitat Critical to the Survival of a marine turtle species and are Biologically Important Areas (BIAs) to identify and understand for conservation management of each species and the respective populations in the recovery plan (Commonwealth of Australia 2014).

These rookeries (see **Figure 2 -4**) are an ongoing focus of conservation management and research and monitoring activity by the Ningaloo Turtle Program (NTP). The current collaboration of the Cape Conservation Group (CCG) and the Department of Biodiversity, Conservation and Attractions (DBCA) contributes to the conservation of marine turtles and their associated habitats.

In Phase 1, the Ningaloo Turtle Program (NTP) additional study in January 2018 mapped the distribution of turtle nesting using high resolution imagery of turtle tracks

(Rob *et al.* 2019). Phase 1 identified important turtle nesting beaches along the coast of the Ningaloo Marine Park and the Muiron Islands (north and south) (**Figure 2 – 4).**

The present study (Phase 2) in 2018-2019 revisited the Ningaloo and Muiron coasts to encounter females that were satellite tracked to understand their inter-nesting and post-nesting movements. The satellite telemetry project is the content of the present report.

1.1 Habitat Critical to Survival and Biologically Important Areas

The information in this report provides supporting information to address marine turtle recovery and is relevant to both Australian (EPBC Act 1999) and Western Australian (Biodiversity Conservation Act 2016) legislation. This report will focus on two main descriptions of habitat, "*habitat critical to survival*" (abbreviated to habitat critical for this report) and "*Biological Important Areas*" described in the recovery plan (Commonwealth of Australia 2017) as mandated under the EPBC Act 1999. However, for context it is important to list all the definitions that are used widely within Australian and Western Australian legislation and formal guidelines. Habitat critical to the survival of the species is defined under the EPBC Act *Significant Impact Guidelines 1.1 – Matters of National Environmental Significance* (MNES) in relation to significant impact. These guidelines define habitat critical to the survival of a species' as areas necessary: for activities such as foraging, breeding or dispersal; for the long-term maintenance of the species (including the maintenance of other species essential to the survival of the species of focus); to maintain genetic diversity and long term evolutionary development; for the reintroduction of populations or recovery of the species. It is important to note that "*Habitat Critical*" is different from "*Critical Habitat*" which is defined under Section 207A (EPBC Act 1999) and limited to those habitats listed on the register of critical habitats which at present is limited to five specific areas not related to sea turtles (www.environment.gov.au/cgi-bin/sprat/public/publicregisterofcriticalhabitat.pl). Also, important, but not addressed by this report, are other definitions within the Significant Impact Guidelines which include habitat critical criteria for vulnerable species and criteria for 'important habitat' for migratory species. In addition, for Western Australia, the Biodiversity Conservation Act 2016 also defines critical habitat but has not listed any at this stage for marine turtles. This report will refer to the two categories of habitat described in the recovery plan as Habitat Critical (rookery and inter-nesting) and BIAs (rookery, inter-nesting, migration and foraging ground, hereafter abbreviated as R, IN, M or FG respectively).

1.1.1 Habitat Critical to Survival of Marine Turtles

Habitat critical to survival for marine turtles has only been described for the nesting and interesting phases of the life history in the recovery plan by a panel of experts. Those criteria directly relevant to this report include the following:

- Where relevant, nesting habitat determined to be critical to the survival of marine turtles includes areas that are: geographically dispersed; major and minor rookeries; mainland and island beaches; and winter or summer nesting.
- Inter-nesting habitat critical to the survival of marine turtles is located immediately seaward of designated nesting habitat critical to the survival of marine turtles. The inter-nesting habitat critical buffer for green, loggerhead, hawksbill, olive ridley and leatherback turtles is 20 km and 60 km for flatback turtles.

1.1.2 Biological Important Areas

The Biologically Important Areas (BIAs) are spatially defined areas where aggregations of individuals of a species are known to display biologically important behaviour such as breeding, foraging, resting or migration. BIAs are defined, allocated and managed by the Australian Government Department of Agriculture, Water and Environment (DAWE, established 1 February 2020). BIA maps and descriptions are available in the Conservation Values Atlas at [https://www.environment.gov.au/topics/marine/marine-bioregional-plans/conservation-values-atlas]. BIAs exist for all 6 species of marine turtles in Australian waters. [https://www.environment.gov.au/marine/marine-species/bias#BIA_Species_tables]. The DAWE advised (email 12/03/2020- K. Arthur) of a need to review and update BIAs for marine turtles. For marine turtles, all areas defined as habitat critical in the recovery plan are automatically mapped as BIAs. They operate as a subset and extension of habitat critical. The recovery plans state, "the BIA maps are a dynamic tool which allow for up-to-date information to be stored and referenced in a geospatial environment, building on information used to inform the recovery plan". Currently BIAs for all non-nesting phases of marine turtles are not listed in the recovery plan and the current mapping of these areas as presented in the National Conservation Values Atlas (https://www.environment.gov.au/topics/marine/marine-bioregional-plans/conservation-values-atlas) are not comprehensive and inadequate for systematic conservation planning.

1.2 Aims and outcomes

- To identify marine turtle inter-nesting habitats, duration of residence, and reproductive outputs.
- To determine marine turtle migration routes, migration timing, and identify post-reproductive foraging grounds that could support defining habitat critical or BIAs
- To deliver findings in report form with analysis and GIS layers.
- To provide information to support and update existing habitat critical and BIAs for green and loggerhead turtles (West Australian genetic stocks).

1.3 Study design

- The spatial extent of the project includes the Muiron Islands and mainland Ningaloo Coast.
- The study focuses on green turtles and loggerhead turtles, with hawksbill turtles included if encountered.
- The inter-nesting emphasis requires turtles tracked from relatively early in the season to maximise the number of tracked inter-nesting periods.

1.4 Public Engagement

The creative nicknames assigned randomly to tracked turtles came from a Woodside staff engagement initiative. Nicknames promote public engagement when viewing daily tracking movements visible on seaturtle.org. Support teams that assisted the turtle tagging fieldwork included participation by NTP volunteers, Traditional Owner trainee rangers and Woodside staff.

2 Methods

Satellite telemetry is fundamentally similar for most marine megafauna. Platform terminal transmitters (PTT) are attached to the carapace of turtles and when they are exposed to air, transmit signals to orbiting ARGOS or GPS satellites that triangulate on the signal to estimate a probable location.

The polar orbiting Argos satellites may not always be in a position to accurately determine the locations of individuals. There are seven different accuracy classes with the most precise giving a positional error of less than 150 m. Raw location data are relayed by the Argos system to researchers via email daily.

Satellite telemetry is a proven technology to track migratory fauna and has been relied upon for tracking of marine turtles since the 1980s. Broad overviews on the operations and advantages of satellite telemetry with migrating animals are given by Perras and Nebel (2012).

2.1 Fieldwork location and dates

Nocturnal foot patrols were conducted by Department of Biodiversity, Conservation and Attractions (DBCA) with the assistance of Woodside and NTP volunteers. Surveys occurred within 1-2 hours of high tide until falling tides caused the turtle emergences to decline noticeably. Encounters with turtles were relayed by VHF radios among the patrol crews so that processing gear could be assembled at each turtle emergence. Hawksbill and flatback turtles were not encountered, so the extra PTT tags were deployed with green or loggerhead turtles as randomly encountered (**Table 2**). Metadata on location, date and body size for 13 green turtles and 12 loggerhead turtles in this study are listed in **Table 3.**

Field work began at South Muiron Island (114.349° E, -21.664° S) and North Muiron Island (114.371° E, -21.651° S) from 26 November to 2 December 2018 by staff based on the DBCA vessel Worndoom. Field work continued over 2-9 December

2018 at the Northwest Cape rookeries along the Jurabi coast (114.096° E, -21.809° S) and secondly at Bungelup beach (113.833° E, -22.259° S) by land-based teams.

2.2 Turtle Processing

Nocturnal patrols encounter female turtles when they emerge to nest, generally within a couple hours of nocturnal high tide. After nesting or false crawling was completed the female was contained by a portable wooden corral (**Figure 5**). Standard morphometric measures (curved carapace length and width to nearest millimeter) were taken with a flexible measuring tape. Both front flippers were tagged with titanium tags (Stockbrands WA) as specified by the 2017 Turtle Monitoring Field Guide (DBCA 2017). A 5 mm biopsy was taken from the trailing edge of the rear flipper and preserved in ethanol for later genetic analysis and stable isotope studies. Researchers cleaned the turtle's carapace of biota followed by alternating washes of freshwater and alcohol before adhering a satellite transmitter (Wildlife Computers Fastloc MK10-AF or 10-F) to the carapace with slow setting epoxy (Sikaflex 3). After the epoxy set, researchers added preventative layers of antifouling paint (Interlux Micron 66) to deter algal growth on the PTT. All tags transmitted while on land for >1 hr as a transmission check. Each processing took 2-3 hr per animal and turtles returned into the sea before dawn. Multiple sets of equipment allowed multiple turtles to be processed simultaneously.

2.3 Animal Welfare

All satellite tag attachment procedures were conducted under DBCA Animal Ethics Approval and under Scientific Permits 01-000068-4 and SC001477. Transmitters weighed <1% of body weight and were teardrop shaped to minimize hydrodynamic drag. Field staff worked by red head torches to minimise light disturbance to the turtles. All procedures were conducted by experienced personnel or those under their direct supervision. Decades of turtle tracking studies support that nesting females are minimally disturbed if at all when PTTs are attached and continue to use the same inter-nesting habitats.

2.4 Data Management and Access

Public outreach and education were centered around www.seaturtle.org in the project "Ningaloo and Muiron inter-nesting turtles". Tracking maps were accessible at http://www.seaturtle.org/tracking/index.shtml?project_id=1341 so that DBCA scientists and the general public could review tracks of individual turtles.

DBCA downloaded data daily or weekly from ARGOS account 05377 and exported CSV files for analysis. Project metadata were managed in STAT (Coyne and Godley 2005) and Zoatrack online (Dwyer et al 2015). The embedded R programming in Zoatrack exported results as KML or SHP shapefiles for viewing and further processing in Google Earth Pro 7.3 or GIS software such as ESRI ArcMap or QGIS.

2.5 Spatial analysis of inter-nesting and post-nesting activity

The statistical treatment of animal movements from point location data is complicated because of unequal individual histories for tracking duration and distance (Chapman et al. 2014). Statistical approaches with time series data take a two-step approach for observation error (imprecision of satellite location fixes) by data filtering and address process error (classing IN, M, or FG) from changes in the time/speed/proximity of sequential locations. After filtering, the individual maps reveal each behavioural phase of movement by simple visual inspection or applying an algorithm. Individual track histories were grouped for species comparisons and for island-mainland contrasts.

Location data were filtered by an extended Kalman filter to remove bias from erroneous or lower quality locations (Hays et al. 2019, Auger-Méthé et al. 2020) and the method follows Sibert et al. (2006). Methods of home range analysis include the minimum convex polygon (MSP) as the smallest area convex set that contains the location data (Worton 1995) calculated with adehabitatHR package (Calenge 2006). The kernel utilization distribution (KUD) uses the probability that an animal will be found at a specific geographical location (Seaman and Powell 1996) determined by the adehabitatHR library of functions (Calenge 2006). The contrast enabled by a coarse (MCP) and a finer scale (KUD) method allows management questions to focus on spatial inclusiveness or smaller areas of biological use. Zoatrack generates a heat map of location density in a grid over the study area to visually distinguish areas of high usage. The spatstat package (Baddeley and Turner 2005) generates a white to red colour gradient for increasing density of locations as hotspot clusters.

Green turtles and loggerhead turtle studies in all ocean basins verify the distinctive behavioural phases by cumulative displacement from a rookery in state space models (see **Figure 1**). The telemetry locations identify three distinct behavioural phases of inter-nesting (IN), migration (M), and foraging ground (FG) based on displacements from shore as described in Tucker (2009) and by swim speed calculations and sequential locations. Migratory movements are characteristically unidirectional with higher swim speeds than the relatively low speed randomly directed movements in IN or FG phases.

2.6 Analyses

We conducted analyses with CSV, KML or SHP files and displays within ArcGIS 10.3 (ESRI). Data layers included State Marine Park and Australian Marine Park Boundaries from the Collaborative Australia Protected Areas Database (CAPAD) 2016 and the Commonwealth Marine Reserves 2012 boundary database from Australia Department of Environment and Energy (http://www.environment.gov.au/fed/catalog/main/home.page). We used Zoatrack in conjunction with Google Earth Pro 7.3.2.5776 to visualise and analyse KML layers.

The spatial locations were analysed in conjunction with published bathymetry data and Marine Park boundaries. Spatial summaries reported for turtle locations and depth for IN and FG phases (MCP and KUD) are centroid coordinates (latitude and longitude) of individual home ranges. Displacement measurements (km) are calculated as distance travelled from the turtle release point. Transit movements during migration are reported as kilometers per day (KPD) elapsed from IN last nesting location to FG arrival or a summed displacement distance (km) divided by migration period (days).

Twelve transmitters with a pressure transducer recorded a maximum water pressure calibrated as submergence depths in daily histograms of dive depth in 5 m increments from 2 to 100 m (abridged from Wildlife Computers MK10 Host User Guide (2019). The depth sensors were deployed on 2 island green turtles, 3 mainland green turtles, 2 island loggerheads, and 5 mainland loggerheads.

Bathymetry data were derived from the General Bathymetric Chart of the Ocean (GEBCO_08 Grid 20091120 bathymetry) as a recognized authoritative public data set (https://www.gebco.net/). An onscreen cursor positioned at a centroid of inter-nesting or foraging ground locations uses a single mouse-click to select depth (in meters) from the GEBCO data. The CAPAD marine boundary was used to evaluate a percentage of inter-nesting activity inside or outside NMP.

The data were compiled for GIS layers to indicate important use areas for each species during the inter-nesting periods. We derive estimates for the inter-nesting period length (d) and estimated clutch frequency (ECF). We identified and mapped data layers for beginning dates (dd-mm-yyyy) of migration paths, displacement distances (km), duration of migration (d), arrival dates and locations collected at a foraging ground. Estimated locations used the FASTLOC and Argos positions. We maintained location coordinates and duration of nesting behaviour in Microsoft Excel. Statistical summaries were conducted in SYSTAT 13.2 for the categorical variables of species (G, L) and by nesting behaviour (IN, M, FG).

Estimates of annual female reproductive output can be derived from the inter-nesting intervals during the entire inter-nesting (IN) residency (Tucker 2010). The mean duration of the inter-nesting interval t is calculated as: IN residency from first to last nest (in days) divided by the turtle's nest output during that periods (i.e. estimated clutch frequency). For example, a hypothetical turtle lays a first clutch and each fortnight emerges to lay another nest (nest 1 on night 1, nest 2 on night 15, and so on to final nest 6 on night 75. The female's reproductive output in a 75 day IN residency yielded 6 nests and a 12.5-day inter-nesting interval (75 d /6 nests = 12.5 d IN interval).

The inter-nesting interval is selected by a female to ovulate follicles and shell the next batch of eggs. Inter-nesting habitats are considered habitat critical and have been arbitrarily represented by a 20 km protection buffer around rookeries (Commonwealth of Australia 2017). For further discussions on habitat critical this study investigates the depths of the inter-nesting residence and whether the rest areas are within Marine Park boundaries (Tucker et al. 1996).

2.7 Statistics

Results are reported as means with one standard deviation, sample size and ranges. Data subsets were contrasted by species (green or loggerhead turtles) overall and by island (Muiron Islands) or mainland (Ningaloo coast) rookeries. Statistical summaries were conducted for the categorical variables of species (green - G, loggerhead - L) and by migration phase (IN, M, FG). IN distances were calculated from KUD dimensions for island or mainland rookeries as measured parallel to shore (longshore) and perpendicular to shore (offshore). Parametric statistical tests report the F test degrees of freedom and exact P values of significance. *P* values of 0.05 were accepted to indicate a significant difference. Statistical tests were conducted with POPTOOLS add-in to Microsoft Excel or SYSTAT 13.2.

3 Results

3.1 Transmitter performance

Initial planning expected loggerhead, green and hawksbill turtles for five beaches across 14 encounter nights during an early phase of the turtle season. Intentions were to track up to four hawksbill turtles, but none were encountered. Therefore, the extra PTTs were reallocated on other species. The nesting turtles were encountered opportunistically at a given beach and tide. Six island and seven mainland green turtles can be contrasted with five island and seven mainland loggerhead turtles (**Table 3**).

All transmitters performed to manufacturer specifications and all turtles produced more than adequate numbers of locations at high enough quality for a successful study (transmitter performance with received location classes 3, 2, 1, 0, A, B, Z, - **Table 4)**. Performance reflects the duration of time a turtle spent at the surface, and the satellite constellation over a 24-hr day. Tracking history details (**Table 5)** have transition dates estimated for three reproductive phases (IN, M, FG). All 25 transmitters lasted for the duration of IN residency. All 12 depth sensing tags lasted through inter-nesting, migration, and foraging ground residency. All green turtle transmitters lasted for >30 d of FG calculations, but three loggerhead transmitters ceased early (0,1,4 days) on arrival at foraging grounds so FG statistics were adjusted to 9/12 transmitters. The last transmitter signals were on 03/02/2020.

3.2 Inter-nesting residency

Spatial summaries for IN phases included 100% minimum convex polygons (MCP) and 50% kernel utilization distribution (KUD), inter-nesting depths at the centroid coordinates of calculated IN ranges of green turtles (**Table 6)** and for loggerhead turtles (**Table 7)**.

Inter-nesting MCP estimates were two to three times smaller for green turtles than loggerhead turtles (green turtle mean = 317.5 km^2, loggerhead turtle mean = 907.9 km^2). Inter-nesting green turtles remained close to their original nest site, whereas loggerhead turtles were more likely to swim across Exmouth Gulf and return or between offshore islands to mainland/vice versa. More conservative estimates of spatial use by KUD had large individual variance and so were not statistically different, even though green turtles had lesser IN spatial use (green turtle mean = 62.0 km^2 loggerhead turtle mean = 101.6 km^2).

Tracked animals were categorized by the numbers of locations inside (I), outside (O) or both inside and outside (I+O) Ningaloo's Marine Protected Areas (MPA) (**Table 8**). The inter-nesting residency was largely within the MPA. Eleven of 13 (84.6%) IN green turtles remained within the MPA with site fidelity to a rookery (**Figure 6**) but two (15.4%) shuttled out to spend time in the eastern Exmouth Gulf before returning to nest again within the MPA .Nine of 12 (75%) IN loggerhead turtles remained within the MPA with site fidelity to a rookery while three (25%) ventured out to spend the IN period in the eastern Exmouth Gulf before returning again to nest within the MPA (**Figure 7**).

The inter-nesting spatial use of tracked turtles was summarized by 100% MCP and 50%KUD contours for the green turtle **(Figure 8**) and loggerhead turtles (**Figure 9**). Heat maps for green turtles (**Figure 10**) and loggerhead turtles (**Figure 11**) indicate a close inter-nesting proximity to the rookery. A clear-cut transition of cumulative displacement from the rookery marked inter-nesting behaviour from post-nesting migration (**Figure 12**). Green turtles from island and mainland rookeries had measurable but not statistically different longshore movements (island mean = 3.5 km, range 2-9 km; mainland mean = 7.0 km, range 4-13 km; $F_{1,11}$ = 4.48, P = 0.06) but similar offshore movements (island mean = 1.3 km, range 1-3 km; mainland mean = 2.7 km, range 1-7 km, $F_{1,10}$ = 4.48, P = 0.14).

Loggerhead turtles from island and mainland rookeries had differing longshore movements (island mean = 10.0 km, range 4-27 km; mainland mean = 24.3 km, 2-66 km; $F_{1,11}$ = 0.88, P = 0.037) but similar offshore movements (island mean = 4.3 km, range 2-9 km; mainland mean = 5.0 km, range 1-12 km; $F_{1,11}$ = 0.11, P =0.74). In brief, green turtles maintained higher IN site fidelity than loggerhead turtles at both mainland and island rookeries with the IN dimensions narrower offshore than longshore with both species. IN dimensions were within a 20 km IN habitat critical buffer for island and mainland rookeries of green turtles. The loggerhead IN dimensions exceeded a 20 km buffer only for mainland rookeries and only in the (3/8) longshore, not the offshore dimensions. In sum, inter-nesting females of both species wandered alongshore rather than offshore, excepting females that travelled across Exmouth Gulf between subsequent nests.

The inter-nesting residency was longer for green turtles than loggerhead turtles (66.8 days for green turtles vs.48.5 days for loggerhead turtles) although both species used relatively shallow waters for IN residency (**Table 9**). For IN depths determined by bathymetry, there was no species difference (green turtle mean = 12.8 m, loggerhead turtle mean = 14.0 m, $F_{1,23}$ = 0.014, P = 0.71. The inter-nesting depths did not overlap with existing offshore oil and gas operations. Depth sensors recorded a minor difference between island and mainland greens for time-at-depths but 90% of island nesters and 80% of mainland nesting green females remained in water shallower than 2 m depth (**Figure 13**). Dive sensor data for inter-nesting loggerheads found females of both rookery types occupied waters from 2- 20 m depth (**Figure 14**).

Estimated clutch frequency (ECF) (**Table 9**) was higher with green turtles than loggerhead turtles (P= 0.0304). Green turtle ECF was 4.8 nests (SD ± 1.4) and loggerhead turtle ECF was estimated at 3.8 nests (SD ± 1.3). The estimated clutch frequencies (ECF) were recognized as biased low because any nests laid earlier than the field work dates would be missing from the telemetry locations.

3.3 Post-nesting migrations and foraging ground

The depth sensors recorded the percentage of time-at- depth was shallower for green turtles than loggerheads during post-reproductive migrations. Green turtles migrated in depths shallower than 5 m for 68% of maximum depth records, while loggerhead turtles usually migrated in variable depths usually shallower than 30 m (**Figure 15**). At foraging grounds, the depth sensors showed time-at-depths were relatively shallow for both species (**Figure 16**). Foraging grounds shallower than 10m accounted for 85% of green depth records and 84% of loggerhead depth records.

Spatial summaries are given for FG home ranges of green turtles (**Table 6)** and for loggerhead turtles (**Table 7)**. For the usage areas relative to NMP/MIMMA, the green turtle FG residences were 10/13 outside the Park and loggerhead turtle FG residences were 11/12 outside the Park (**Table 8**). No common migration pattern nor migration routes were detected from the inter-individual differences in migration. Migrations were independent but generally bounding the coastline, or initiated point-point crossings when transiting open water (**Figure 12**). Individuals of both species showed independent migration patterns with green turtles collectively shown by **Figure 17** and loggerhead turtles collectively shown by **Figure 18**.

For green turtles, the post-nesting migrations ranged in distance and duration from 4-468 km and 3-7 days, respectively (**Table 5**). Green turtles migrated to the Exmouth Gulf (5), NMP (1) Coral Bay (2), Carnarvon (2), Shark Bay (1) or northward to Turtle Islands (1), all of which contain extensive seagrass resources.

For loggerhead turtles the post-nesting migrations ranged in distance and duration from 22-2399 km and 3-45 days, respectively (**Table 6**). Loggerhead turtles migrated to foraging grounds in the Ningaloo Marine Park at Coral Bay (1) or beyond (11). Those travelling south of the MPA reached foraging grounds of Shark Bay (2) or Yanchep (1). Those travelling north of the MPA reached Barrow Island (2), Sunday Island (1), Observation Island (1), Cape Lambert (1), Anna Plains (1), Broome (1), or Maningrida (1) in the Northern Territory. Individual green turtle migrations are shown in **Figures 19-31**, and individual loggerhead turtle migrations are shown in **Figures 32-43**.

Notable FG histories were commented in **Table 5**. Observations included transmissions for green turtle Alinta that settled to a foraging ground, was displaced by Cyclone Veronica and subsequently showed site fidelity by returning to the pre-cyclone home range centroid. Green turtle Nika had intermittent signals continuing after reaching the FG, suggesting that antennae damage occurred. Loggerhead Sink maintained sedentary FG residence in Shark Bay for 30 d before the transmitter moved secondarily offshore at distinctly slower pace than migratory swimming. The offshore pelagic depths were uncharacteristic of post-migratory WA loggerheads that occupy coastal shallow waters (**Tables 6, 9**). An interpretation comes from case histories of tiger shark injuries (Heithaus et al. 2002) incurred at the foraging ground, followed by offshore drift of a debilitated turtle. We included Sink's early FG data that showed consistent spatial clustering but excluded dates of the atypical drift offshore. Multiple reasons for transmitter failure are elaborated in a Frequently Asked Questions (www.seaturtle.org/tracking/faq.shtml).

Green turtle migration departures (**Table 9**) began one to two weeks after the loggerhead turtles (loggerhead turtle departures ranged 01/01/2019 to 04/02/2019; green turtle departures ranged from 17/01/2019 to 19/02/2019). The later departures by green turtles are consistent with a later onset, longer duration and higher clutch frequency of their nesting season than the loggerhead turtle season.

Loggerhead turtles undertook longer migrations than green turtles (**Table 9**). Green turtle migrations had a mean displacement of 181.1 km from the rookery, with a range of 4 – 544 km while loggerhead migrations had a mean displacement of 603.5 km with a range 22-2394 km. However, the study showed that the mean transit speed was faster for loggerhead turtles than green turtles. Green turtles have discontinuous migration rates punctuated by nocturnal rests so the green turtle travel rate (14.5 km/d) was overall slower than the loggerhead turtle continuous travel rate (31.5 km/d).

Arriving to a home FG after reproduction, some species differences in foraging residency could be expected for herbivorous green turtles settling to seagrass and carnivorous loggerhead turtles in search of benthic prey. However. mean foraging ground depth as determined by bathymetry was not statistically different by species (green turtle mean = 5.3 m, loggerhead mean =- 9.0 m, $F_{1,22}$ = 3.57, P = 0.07) (**Table 9**). The foraging ground depths did not overlap with offshore oil and gas operations.

The FG home range estimates by the inclusive method (MCP) were about three times smaller for green turtles than loggerhead turtles (green turtle mean = 307.7 km^2, loggerhead turtle mean = 950.4 km^2). The conservative estimates of foraging home ranges by KUD were not statistically different because of the large variability even though green turtles had lesser area of spatial use (green turtle mean = 98.6 km^2, loggerhead turtle mean = 351.1 km^2).

The migratory routes of tracked turtles extended to or transited through other WA, NT or Commonwealth marine protected areas. Migratory corridors and foraging grounds extended to or through 11 protected areas south of Ningaloo and 17 protected areas north of Ningaloo. The FG were more distant for loggerhead turtles than green turtles from the NMP/MIMMA (**Table 9**).

4 Discussion

4.1 Summary

The aims of inter-nesting and post-nesting movement studies were achieved. The field work was guided by nesting surveys from the Ningaloo Turtle Program (Rob et al. 2019). The identified hotspots of nesting allowed us to deploy the PTTs on 25 females. The tracking of individuals identified inter-nesting hotspots, spatial ecology, and reproductive output for two of three species of turtles. Inter-nesting residencies were noted for 25/25 females, and post-migration movements concluded for 22/25 females at a foraging ground with residence for a minimum of 30 days. The opportunistic encounters of females tracked per species gave a representative fraction of all the region's breeders but presents an underestimate of distribution patterns unless combined with other studies for larger sample sizes.

The newfound spatial knowledge offers conservation insight inside and beyond the NMP/MIMMA boundaries. Marine habitat classifications were beyond the scope of the present study. However, new insights may develop when the identified marine turtle foraging grounds are later aligned to SEAMAP Australia (seamapaustralia.org) subtidal habitat maps.

New data revealed species differences in migrations from rookeries used in common. Migrations by green turtles were more localized than the loggerhead turtles. Green turtles used foraging grounds between Shark Bay and Turtle Islands, but loggerhead turtles swam southward as far as Perth (WA) or northeast to Maningrida (NT). The extensive migrations by post-nesting loggerhead turtles demonstrate a clear value for cross-jurisdictional approaches to effectively manage threats across their distribution.

4.2 Inter-nesting

Currently, inter-nesting habitat critical are defined by 20 km radius for rookeries of loggerhead, green, hawksbill, olive ridley and leatherback turtles and by a 60 km radius for flatback turtles (Table 6 in Commonwealth of Australia 2017, **Figure 1**). The new data from the present study raises questions if a 20 km IN buffer zone is overly wide and whether a less than 20 km IN buffer zone would serve nesting turtles on the Ningaloo coasts. The IN areas used by both species were generally within a 20 km buffer zone of the habitat critical for the inter-nesting phase (Commonwealth of Australia 2017). The inter-nesting tracks also highlighted eastern Exmouth Gulf hotspots that have no marine park protection. These areas are integral to ensuring continued rookery production and should receive further investigation. From 15-25% of inter-nesting tracks for both species were external to the NMP/MIMMA boundaries (**Table 8**). For loggerheads, 3/12 (25%) of IN activity was outside NMP/MIMMA and into Exmouth Gulf or Shark Bay commercial fishery zones of the WA Fishing Industry. The inter-nesting turtles that moved out and back into park boundaries also highlighted the importance of the eastern Exmouth Gulf

The Australian continental shelf is particularly narrow along the Ningaloo reefs so bathymetry may be influencing the availability of inter-nesting habitat use at Northwest Cape and Muiron Islands rookeries. The island rookeries had narrower buffers than mainland rookeries in their seaward extent of inter-nesting residency. However, it may be warranted to extend a landward (eastward) coverage of the MIMMA for turtles that shift toward the shallower mainland depths during the inter-nesting period. Our study raised questions if an effective Habitat Critical buffer could be considered based on bathymetry or depth contours (as illustrated by **Figures 13, 14**) rather than an arbitrary distance from shoreline.

Biologically Important areas (BIAs) are underestimated if no turtles were tracked into or across an area. An under-represented area may result from tagging too few females for a representative sample (Sequeira et al. 2019). A larger sample of tracked individuals would be unlikely to improve IN BIAs of individuals in close fidelity to rookeries (**Figure 10, 11**) but likely reveal additional FG BIAs at the wide spatial scale of migration endpoints (**Figures 17, 18**).

Our study is consistent with inter-nesting research elsewhere on these species. Inter-nesting studies of green turtles in Western Australia at Barrow Island and Sandy Island (Pendoley 2005) recorded inter-nesting distributions generally within 7 km of the nesting beach. Inter-nesting green turtles tracked for 20-83 days at the offshore Lacepede Islands of Western Australia were within 8 km of the rookery, and highest density of locations with a median distribution of <2 km. (Waayers et al. 2011). Inter-nesting loggerheads in Queensland were generally with 10 km longshore of a mainland rookery and limited to 1-2 km of the coast rather than offshore oriented (Tucker et al 1996).

4.3 Post-nesting migration and foraging grounds

As yet no Habitat Critical to Survival for post-nesting migration or foraging grounds have been defined for marine turtles in the recovery plan (Commonwealth of Australia 2017, p. 29). BIAs are conceived as a dynamic spatial tool that can be updated as information becomes available in between successive recovery plans. However, existing data for updating an existing BIA are limited, proposed conservatively or not recently updated (Northwest Atlas, and Commonwealth database National Conservation Values Atlas (http://www.environment.gov.au/webgis-framework/apps/ncva/ncva.jsf)) which highlights the ongoing need for improved baseline knowledge. This study provides information that could support additions or amendments to current post-nesting BIA life history phases for green turtles (North West Shelf genetic stock) and loggerhead turtles (Western Australian genetic stock).

The present tracking study reports a similar range of migration distances (10s to 1000s km) and directions along coastal depths <100 m undertaken by these two species in the East Indian Ocean region (Limpus 2009, Waayers et al. 2019). However, other studies underway have seen international open ocean migrations (Waayers et al. 2019), so the 2018 sample of NMP/MIMMA turtles did not fully capture all FGs known by tracking technology.

The post-nesting migration tracks reveal previously unknown links to other marine parks intrastate and interstate. The FG for loggerhead turtles were more likely than green turtles to be distant from the MPA of NMP/MIMMA. The FG residency outside MPAs by green or loggerhead turtles may place them at risk of commercial fisheries during migration or residency (Commonwealth of Australia 2017). After leaving Ningaloo's Marine Park boundaries, loggerhead turtles migrated longer distances and for longer durations to reach FG than green turtles. In principle, the herbivorous green turtles occupy stations at seagrass or algal patches (Thomson et al. 2015), compared to loggerhead turtles known to deplete benthic prey patches and range in search of novel benthic prey (Thomson et al. 2012) The migratory routes of tracked turtles ranged through or ended in marine parks of WA, Commonwealth, and Northern Territory both north (17) and south (11) of the inter-nesting areas.

WA tracking studies document FG ranges up to 3884 km for green turtles to Indonesia (AIMS/DBCA in prep) and up to 6470 km for loggerhead turtles to Papua New Guinea (Mau et al. 2012). These tracking distances are similar scales to WA flipper tag recoveries for green turtles 34-2506 km and loggerhead turtles of 13-2949 km (DBCA Marine Turtle database, unpubl. data). Comparable migration records from flipper tag recoveries document Eastern Australia migrations by loggerheads migrating from 11-2620 km and by greens from 2-2612 km (Limpus et al. 1992). For WA loggerheads, foraging ground studies on males have included Shark Bay but without related rookery information (Olsen et al. 2012). Migration tracking projects are currently at the analysis stage on green turtles (Luciana et al., in prep), hawksbill turtles (Fossette et al. in prep) and loggerhead turtles (DBCA et al, in prep) to consolidate the multiple tracking studies based in Western Australia (Waayers et al. 2019).

4.4 Conservation Context

There is substantial variability in nesting numbers between years for NMP and MIMMA green and loggerhead turtles, but no consistent trends of overall decline or increase (Coote 2018). The variability makes it difficult to identify which known threats have effects on regional turtle stocks (Limpus 2009, FitzSimmons and Limpus 2014).

The most current documentation of threats to turtle stocks is listed (**Table 10**) by the Recovery Plan for Marine Turtles in Australia (Commonwealth of Australia 2017). For the NWS green turtle stock and the WA loggerhead stock, acute chemical discharge (driven by unplanned hydrocarbon releases) was a common threat rated as a high risk. For green turtles, habitat modification was listed as a high threat (moderate for loggerheads) and for this area, salt production and tourism development are potential pressures. Artificial light pollution was also high risk for NWS greens. For loggerheads, also rated as high risk were domestic fishing bycatch and climate change (moderate for NWS greens). Pressures listed as moderate for either or both NWS greens and WA loggerheads were marine debris, chronic chemical discharge, international take, habitat modification (dredging/ trawling), indigenous take, vessel disturbance, noise and recreational activities. For all these pressures, information on species distribution and habitat use is essential baseline information to assess risk and provide mitigation options. This study, in a data poor area, yielded results to understand the potential impact of these threats and enable planning for response strategies.

The risk of an offshore petroleum spill is low likelihood, but with severe consequences (Lutcavage et. al. 1997), and the risk increases with rising levels of shipping activity related or unrelated to oil and gas industries (Shigenaka 2010). The offshore petroleum industry has combined hazards of rigs, drilling platforms, wells, off-loads and pipeline corridors. The oceanographic current models in the region (Taylor and Pearce 1999, Woo et al. 2006) show that nesting sites and foraging sites are downstream from existing oil and gas infrastructure (Department of Industry and Science 2015, Vander Zanden et al. 2016, Wallace et al. 2020).

The present study documented Habitat Critical for nesting and inter-nesting turtles inside and outside of the NMP and MIMMA which showed turtles did not use vicinities of offshore oil and gas infrastructure during inter-nesting nor during migration and foraging. However, onshore and nearshore staging areas for pipeline assemblies are planned on the Northwest Cape (Learmonth Pipeline Fabrication Facility [https://www.epa.wa.gov.au/proposals/learmonth-pipeline-fabrication-facility]) that may temporarily overlap with Habitat Critical if undertaken during November to March. Further analyses could be completed to understand what factors (depth, distance to shore,
ocean currents, seasonal variation) influence the location of the migratory corridor for each species.

A major benefit of linking tracking data of this and previous studies would be to increase confidence in applied conservation. The present study has provided new insight into overlaps of foraging areas and trawl fields in the Exmouth Gulf (Kangas and Thomson 2004) and spatial information to assess coastal developments, such as the light pollution pressures (Kamrowski et al. 2012), increased shipping activity (Shigenaka 2010) and port infrastructure that are common to all resource production facilities (oil and gas, iron ore and salt). The tracked turtles revealed that Ningaloo rookeries are mostly distant from international harvests outside Australia’s Exclusive Economic Zones but still exposed to take if foraging grounds are near traditional Indigenous harvest areas. Climate change remains a major and uncertain pressure for turtles globally.

The West Australian green turtle regional population is one of the seven subpopulations in Australia, estimated at around 20,000 (Commonwealth of Australia 2017). The three distinct genetic stocks of green turtles in the Northwest Region of Australia are the North West Shelf stock, the Scott Reef stock and the Ashmore stock (Dethmers et al. 2006).

The Southeast Indian Ocean loggerhead genetic stock of Western Australia constitutes one of the largest in the world (Limpus 2009, Casale and Tucker 2017). The WA stock is the largest in Australia, one of only four populations in the Indian Ocean, and when combined for WA rookeries, represents the third or fourth largest population in the world (Limpus 1997), with estimates between 1,000-2,100 (Baldwin et al. 2003: Prince 1994). The WA rookeries for loggerheads receive protection from commercial fishing for most of Ningaloo Marine Park, the Ningaloo Coast World Heritage Area, the Shark Bay Marine Park and Shark Bay World Heritage Area (Hamann et al. 2013).

However, loggerhead turtles in and outside the region interact with long line, trawling and lobster pot fisheries (Limpus 2009). Loggerhead turtle/fishery interactions have been reported throughout the extent of the Commonwealth long-line fisheries operational ranges. Loggerhead turtles are also occasionally found by Indigenous communities and rangers in ghost nets washed up on Northern Territory beaches. Mortality associated with ghost nets is not well quantified for this species. The importance of NMP/MIMMA for these two species is emphasized by 75% of loggerhead turtles and 85% of green turtle IN tracks overlapping the MPA before migration. After migration, only 8% of FG for the species were overlapping the MP boundary so attention shifts to threats outside the protection of Parks.

5 Conclusions and recommendations

Green turtle, loggerhead turtle and hawksbill turtle movement studies in Western Australia lag our understanding for flatback turtles particularly in terms of sample sizes (Waayers et. al. 2019). This present study adds substantial new information and the first quantitative analysis for green and loggerhead turtles. Many studies appear as metadata in a recent review (Waayers et al. 2019). The Indian Ocean tracking review (Waayers et. al. 2019) outlines how a broader analysis by tracking efforts combined from multiple locations for each species would offer a better insight for the North West Shelf (Sequeira et al. 2019).

Updates from the present study to the tracking review by Waayers et al. (2019) now tally 106 tracked green turtles and 58 tracked loggerheads in coastal WA from a combination of government, academic and conservation group projects. A meta-analysis using combined results would provide valuable information to update habitat critical and BIAs for inter-nesting, migration and foraging phases for green and loggerhead females across the Pilbara, including Exmouth Gulf.

- This study improved understanding of patterns of movement and habitat use during inter-nesting and migration of NMP and MIMMA nesting green and loggerhead turtles.
- Findings support the adequacy of the current Habitat Critical to Survival for the inter-nesting phases of green and loggerhead turtles and provided information to refine these areas.
- Migratory paths are mapped for NMP nesting loggerhead and green turtles.
- NMP/MIMMA nesting turtles come from foraging grounds spread over 5000+ km of Australian coastlines.
- The study filled knowledge gaps for two species that are conservation assets to State, Commonwealth and Indigenous managers and findings have been shared with managers.

- The study did not address foraging areas for juveniles, subadults, or males which remain knowledge gaps important to conservation management of marine turtle species.

A number of collaborative studies are underway to collate species focused data sets and provide regional scaled insights in the behaviour and movement of marine turtle species in WA waters A key identified value of the Ningaloo Turtle Program is the long-term monitoring of sites for three turtle species. However, the broader benefits and values of the NTP is to understand and respond to long-term changes in habitat, species resilience, pressures and spatial shifts of activity. Managers will need to understand what is happening to respond appropriately and effectively. Combining the NTP data including the additional studies, (Phase 1) and the insights from satellite tracking of nesting female turtles (Phase 2) will enhance marine turtle behaviour and movement understanding and nesting activity in a region influenced by global climate variability and weather (Le Nohaïc et al. 2017).

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Table 1. Conservation status of marine turtles nesting within NMP or MIMMA as listed under the IUCN Red List and the Commonwealth Government's Environment Protection and Biodiversity Conservation Act 1999 (EPBC).

Turtle species	IUCN Red List	EPBC Act Status
Chelonia mydas (green turtle)	Endangered	Vulnerable
Caretta caretta (loggerhead turtle)	Endangered	Endangered
Eretmochelys imbricata (hawksbill turtle)	Critically Endangered	Vulnerable

Table 2. Deployments by location and species to evaluate inter-nesting habitat use during 2018 field trip to Muiron Islands Marine Management Area and Ningaloo Marine Park.

Location & GPS coordinates	**Green Turtles**	**Loggerhead Turtles**
South Muiron Island (-21.373° S, 114.344° E)	5	4
North Muiron Island (-21.660° S, 114.346° E)	1	1
Northwest Cape (-21.801° S, 114.071° E)	7	3
Bungelup (-22.282° S, 113.831° E)	0	4
Totals	13	12

Table 3. Metadata for tracked turtles during 2018 field trips to Muiron Islands and Ningaloo Marine Park.

Argos ID-NIckname	Species	Date	Beach	Curved Carapace Length (cm)
66276 Maverick	green	27/11/2018	S. Muiron	98.8
66273 Goodjawandjin	green	27/11/2018	S. Muiron	100.2
66313 Harmony	green	27/11/2018	S. Muiron	100.3
C6342 Nyaja	green	27/11/2018	S. Muiron	107.8
66323 Dani	green	28/11/2018	S. Muiron	98.4
66318 Adwaitaa	loggerhead	28/11/2018	S. Muiron	92.0
66271 Wilari	loggerhead	28/11/2018	S. Muiron	97.0
66268 Turtley Fabulous	loggerhead	29/11/2018	S. Muiron	86.5
66302 Elise	loggerhead	29/11/2018	S. Muiron	90.1
66294 Turtle Eclipse of the Heart	loggerhead	1/12/2018	N Muiron Island	94.8
66261 Babaneek	green	2/12/2018	N Muiron Island	99.8
66301 Nika	green	3/12/2018	Hunters	104.5
66326 Wartortle	green	3/12/2018	Mauritius	101.0
66263 Wayambeh	green	4/12/2018	Mauritius	89.2
66321 Dilga	green	4/12/2018	Mauritius	98.5
66262 Alinta	green	4/12/2018	Mauritius	98.7
66264 Sioban Chelonii	loggerhead	4/12/2018	Mauritius	97.6

66304 Katyin	green	5/12/2018	Mauritius	99.5
66259 Tortue Geniale	loggerhead	5/12/2018	Mauritius	95.5
66272 Ngajuri	loggerhead	6/12/2018	Bungelup	93.0
66288 Wittwer	loggerhead	6/12/2018	Bungelup	94.8
66319 Nhulyi	loggerhead	6/12/2018	Bungelup	100.0
66260 GeeGeike	loggerhead	7/12/2018	Bungelup	87.6
67906 Gemma	green	8/12/2018	Mauritius	99.0
66303 Sink	loggerhead	8/12/2018	Mauritius	105.5

Table 4. Transmitter performance for Muiron Islands and Ningaloo green turtles and loggerhead turtles.

Green turtles	Locs	3	2	1	0	A	B	Z	-	Deploy date	Last location	Tracking (d)	Displacement (km)
66273 Goodawandjin	2422	111	108	116	119	375	1593	0	6	27/11/2018	17/04/2019	141	72
66276 Maverick	5552	119	100	193	485	790	3864	1	66	27/11/2018	27/12/2019	395	157
66313 Harmony	3499	163	79	83	134	413	2626	1	46	27/11/2018	1/12/2019	369	58
66342 Nyaja	4920	194	199	410	698	851	2568	0	46	27/11/2018	31/12/2019	399	468
66323 Dani	3309	95	88	206	344	520	2056	0	34	28/11/2018	25/09/2019	301	51
66261 Babaneek	3571	226	154	158	169	506	2355	3	42	02/12/2018	2/09/2019	274	84
66301 Nika	1312	71	65	66	49	199	862	0	150	03/12/2018	29/04/2019	147	348
66326 Wartortle	2224	52	39	86	173	375	1499	0	8	03/12/2018	2/05/2019	150	4
66262 Alinta	3376	206	184	355	461	579	1590	1	16	04/12/2018	13/08/2019	252	544
66263 Wayambeh	2959	214	131	154	148	458	1852	2	34	04/12/2018	20/07/2019	228	19
66321 Dilga	3822	101	156	204	428	664	2269	0	40	04/12/2018	26/09/2019	296	119
66304 Katyin	4264	106	127	219	359	674	2776	3	50	05/12/2018	1/10/2019	300	51
67906 Gemma	6227	218	262	531	900	1272	3044	0	40	08/12/2018	3/02/2020	422	380
Loggerhead turtles													
66271 Wilari	2507	53	130	385	881	361	697	0	28	28/11/2018	3/07/2019	217	1129
66318 Adwaitaa	2189	42	63	204	574	347	959	0	72	28/11/2018	19/10/2019	325	2399
66268a Turtley Fabulous	548	46	26	69	133	98	176	0	0	29/11/2018	15/01/2019	47	22
66302 Elise	3726	161	147	556	984	711	1167	0	42	29/11/2018	28/10/2019	333	738

66294 TurtleEclipseoftheHeart	2878	96	169	518	707	429	959	0	24	1/12/2018	16/09/2019	289	309
66264a Sioban Chelonii	585	36	47	70	137	88	207	0	0	04/12/2018	21/01/2019	48	52
66259 Tortue Geniale	5534	59	99	693	1515	1234	1933	1	50	05/12/2018	29/01/2020	420	160
66272 Ngajuri	6087	350	403	1170	965	1086	2112	1	60	06/12/2018	1/12/2019	360	455
66288 Wittwer	844	73	48	78	62	152	430	1	2	06/12/2018	25/01/2019	50	63
66319 Nhuly	1168	15	27	90	498	191	347	0	0	06/12/2018	26/03/2019	110	237
66260 GeeGeike	1750	58	61	254	541	310	526	0	2	07/12/2018	4/05/2019	148	994
66303 Sink	763	42	46	121	171	103	280	0	2	08/12/2018	25/02/2019	79	685
Total	76036	2907	2958	6989	11635	12786	38747	14	860				

Table 5. Tracking history of Muiron Islands and Ningaloo green turtles and loggerhead turtles for inter-nesting (IN), migration (M) and foraging ground (FG) residences. Note that three loggerheads had transmitters that recorded only 0-4 days of FG residency which are considered underestimates. An asterisk in the sensor column denotes twelve females with depth sensors, and a rookery abbreviation GI = greens on island, GM = greens on mainland, LI = loggerhead on island, LM = loggerhead on mainland.

Green turtles	Sensor (*)	Deploy date	Depart IN	IN (d)	Arrive FG	M (d)	FG (d)	Tracking (d)	Displacement (km)	Comment
66273 Goodawandjin	GI	27/11/2018	02/02/2019	67	05/02/2019	3	71	141	72	
66276 Maverick	*GI	27/11/2018	29/01/2019	63	09/02/2019	11	321	395	157	
66313 Harmony	GI	27/11/2018	17/01/2019	51	21/02/2019	35	283	369	58	
66342 Nyaja	GI	27/11/2018	02/02/2019	67	21/02/2019	19	313	399	468	
66323 Dani	GI	28/11/2018	14/02/2019	78	18/02/2019	4	219	301	51	
66261 Babaneek	*GI	02/12/2018	27/01/2019	56	02/02/2019	6	212	274	84	
66301 Nika	GM	03/12/2018	03/02/2019	62	11/02/2019	8	77	147	348	FG intermittent
66326 Wartortle	GM	03/12/2018	11/02/2019	70	19/02/2019	8	72	150	4	
66262 Alinta	*GM	04/12/2018	18/02/2019	76	15/03/2019	25	151	252	544	Cyclone displaced, FG fidelity
66263 Wayambeh	*GM	04/12/2018	12/02/2019	70	22/02/2019	10	148	228	19	
66321 Dilga	GM	04/12/2018	13/02/2019	71	18/02/2019	5	220	296	119	
66304 Katyin	GM	05/12/2018	19/02/2019	76	24/02/2019	5	219	300	51	
67906 Gemma	*GM	08/12/2018	6/02/2019	60	17/02/2019	11	351	422	380	
Loggerhead turtles	sensor	Deploy date	Depart	IN	Arrive	M	FG	Tracking	Displacement	Comment

			IN	(d)	FG	(d)	(d)	(d)	(km)	
66271 Wilari	*LI	28/11/2018	25/01/2019	58	11/03/2019	45	114	217	1129	
66318 Adwaitaa	LI	28/11/2018	14/02/2019	78	29/04/2019	74	173	325	2399	
66268a Turtley Fabulous	*LI	29/11/2018	08/01/2019	40	11/01/2019	3	*4	47	22	<30 d FG
66302 Elise	LI	29/11/2018	07/01/2019	39	02/02/2019	26	268	333	738	
66294 TurtleEclipseoftheHeart	LI	1/12/2018	26/01/2019	56	11/02/2019	16	217	289	309	
66264a Sioban Chelonii	*LM	4/12/2018	14/01/2019	41	20/01/2019	6	*1	48	52	<30 d FG
66259 Tortue Geniale	*LM	5/12/2018	29/01/2019	55	01/02/2019	3	362	420	160	
66272 Ngajuri	*LM	6/12/2018	23/01/2019	48	05/02/2019	13	299	360	455	
66288 Wittwer	*LM	6/12/2018	22/01/2019	47	25/01/2019	3	*0	50	63	<30 d FG
66319 Nhuly	LM	6/12/2018	05/02/2019	61	12/02/2019	6	42	110	237	
66260 GeeGeike	*LM	7/12/2018	10/01/2019	34	04/02/2019	25	89	148	994	
66303 Sink	LM	8/12/2018	1/01/2019	24	11/01/2019	10	45	79	685	FG predation?

Table 6. Green turtle inter-nesting and foraging ground summaries.

Foraging ground travel direction abbreviations are S= South, N= North, L=local region defined by Muiron and within Exmouth Gulf.

Green turtles	IN MCP 100% (km^2)	IN KUD 50% (km^2)	IN Depth (m)	IN Centroid (lat, lon)	FG MCP (km^2)	FG KUD (km^2)	FG Depth (m)	FG Centroid (lat, lon)	MPA IN/OUT	Migration trajectory Rookery to foraging ground Direction, Figure
66273 Goodawandjin	162.1	5.5	10	-21.679, 114.351	111.4	7.3	4	-22.311, 114.395	O	S Muiron-SE Exmouth Gulf (L-Figure 15)
66276 Maverick	109.2	4.1	10	-21.674, 114.335	158.1	11.0	2	-23.025, 113.778	I	S Muiron-Coral Bay (S-Figure 16)
66313 Harmony	109.8	38.3	13	-21.673, 114.334	364.1	100.9	2	-22.221, 114.411	O	S Muiron-SE Exmouth Gulf (L-Figure 17)
66342 Nyaja	35.7	21.7	7	-21.686, 114.338	22.9	3.7	12	-25.719, 113.071	0	S Muiron -W Shark Bay (S-Figure 18)
66323 Dani	379.3	279.9	10	-21.678, 114.33	683.8	214.2	2	-21.937, 113.933	I	S Muiron-Ningaloo (L-Figure 19)
66261 Babaneek	96.9	80.2	9	-21.637, 114.346	239.3	38.2	5	-22.330, 114.363	O	N Muiron-SE Exmouth Gulf (L-Figure 20)
66301 Nika	121.8	7.4	17	-21.803,	314.1	42.4	2	-24.91,	O	Ningaloo-Carnarvon

				114.104				113.655		(S-Figure 21)
66326 Wartortle	155.1	74.8	10	-21.806, 114.114	1021.8	621.7	8	-21.648, 114.700	O	Ningaloo-Serrurier (L-Figure 22)
66262 Alinta	41.4	9.0	13	-21.810, 114.089	117.9	31.5	9	-19.860, 118.874	O	Ningaloo-Turtle Islands (N-Figure 23)
66263 Wayambeh	118.9	18.3	8	-21.814, 114.024	59.4	5.5	5	-21.972, 114.555	O	Ningaloo-Onslow (L-Figure 24)
66321 Dilga	173.4	94.8	35	-21.811, 114.042	130.3	23.5	2	-22.860, 113.765	I	Ningaloo-Coral Bay (S-Figure 25)
66304 Katyin	1292.6	148.8	14	-21.803, 114.071	843.6	153.8	6	-21.976, 114.576	O	Ningaloo-Onslow (L-Figure 26)
67906 Gemma	1331.3	23.7	11	-21.812, 114.066	233.8	28.3	10	-25.224, 113.763	O	Ningaloo-Carnarvon (S-Figure 27)

Table 7. Loggerhead turtle inter-nesting and foraging ground summaries.

Foraging ground direction abbreviations are S= South, N= North, L=local region defined by Muiron and within Exmouth Gulf.

Loggerhead turtles	IN MCP 100% (km^2)	IN KUD 50% (km^2)	IN Depth (m)	IN Centroid (lat, lon)	FG MCP (km^2)	FG KUD (km^2)	FG Depth (m)	FG Centroid (lat, lon)	MPA IN/OUT	Migration trajectory Rookery to foraging ground Reference
66271 Wilari S	28.4	6.8	8	-21.696, 114.332	75.4	13.1	5	-31.703, 115.679	O	S Muiron-Yanchep (S-Figure 28)
66318 Adwaita S	2379.6	164.9	9	-21.656, 114.337	399.9	98.1	16	-11.868, 134.149	O	S Muiron-Maningrida, NT (N-Figure 29)
66268a Turtley Fabulous S	379.3	70.3	5	-21.675, 114.344	*14.0	*7.5	*12	-21.745, 114.548	O	S Muiron- Observation Island (L-Figure 30)
66302 Elise S	297.9	21.6	17	-21.669, 114.337	279.7	53.2	17	-19.478, 121.042	O	S Muiron-Anna Plains (N-Figure 31)
66294 TurtleEclipseoftheHeart S	46.7	7.8	16	-21.657, 114.347	437.6	25.1	9	-20.545, 117.155	O	N Muiron-Depuch Island (N-Figure 32)
66264a Sioban Chelonii S	2436.5	500.6	6	-21.802, 114.092	100.9	238.3	3	-21.684, 114.574	O	Ningaloo-Sunday Island (L-Figure 33)
66259 Tortue Geniale	169.0	18.1	17	-21.801, 114.063	216.9	10.5	5	-20.999, 115.273	O	Ningaloo-S Barrow (N-Figure 34)
66272 Ngajuri S	468.2	17.6	22	-22.301, 113.813	77.0	3.3	2	-26.377, 113.847	O	Bungelup-S Shark Bay (S-Figure 35)

66288a Wittwer S	28.3	20.3	34	-22.280, 113.826	103.4	617.1	2	-22.840, 113.765	I	Bungelup-Coral Bay (S-Figure 36)
66319 Nhuly S	157.2	9.8	4	-22.258, 113.842	9578.6	2901.1	11	-20.856, 115.517	O	Bungelup-E Barrow Island (N-Figure 37)
66260 GeeGeike	26.3	8.1	25	-22.282, 113.820	211.3	23.9	17	-17.831, 122.074	O	Bungelup-Broome (N-Figure 38)
66303a Sink S	1897.5	673.5	6	-21.797, 114.100	*	*	*	-26.149, 113.226	O*	Ningaloo-Shark Bay (*Foraging predation?) (S-Figure 39)

Table 8. Species comparisons of residency for inter-nesting (IN) and foraging ground (FG) phases with the boundaries of the Ningaloo Marine Park and Muiron Island Marine Management Areas. With respect to NMP/MIMMA boundaries, the abbreviations are I for inside the boundaries, O for outside the boundaries, and I+O for inside and outside the boundaries. The number and percentage of species are given for IN/FG histories by I-I, I+O/O and I/O.

Species	Residence	Inter-nesting Number and Percentage	Foraging Ground Number and Percentage
Green	I	11/13 (84.6%)	3/13 (23.1%)
	I+O	2/13 (15.4%)	0/13 (0%)
	O	0/13 (0%)	10/13 (76.9%)
Loggerhead	I	9/12 (75%)	1/12 (8.3%)
	I+O	3/12 (25%)	0/12 (0%)
	O	0/12 (0%)	11/12 (91.7%)

Table 9. Statistical comparisons of marine turtle species of the Ningaloo Marine Park and Muiron Island Marine Management Areas. Statistical means and standard deviation (SD) are given followed by the exact *P* value. Statistical significance was assigned at $P < 0.05$. Acronyms are inter-nesting (IN)), migration (M), and foraging ground (FG) for behavioural phases; 100% minimum convex polygon (MCP) and 50% kernel utilisation distribution (KUD).

Comparison	Green (N=13)		Loggerhead (N=12)		*P* value Statistic
	Mean	SD	Mean	SD	
Estimated Clutch Frequency (nests)	4.8	1.4	3.8	1.3	0.03
IN residency (days)	66.8	20.2	48.5	14.2	0.03
IN depth (m) bathymetry	14.8	3.6	13.3	3.0	0.03
IN MCP (km^2) 100%	317.5	449.3	907.9	1220.6	0.11
IN KUD (km^2) 50%	62.0	78.7	101.6	165.2	0.05
M displacement (km)	181.1	4-544	603.5	22-2394	0.04
M transit speed (km/d)	14.5	10.5	31.5	17.6	0.00
FG residency (days)	204	96.3	135	126.8	0.13
FG adjusted for 3 early transmitter failures (days)	204	96.3	179	115.3	0.56
FG depth (m) bathymetry	5.3	3.5	8.9	5.7	0.07
FG MCP (km^2) 100%	307.7	301	950.4	2719.5	0.43
FG KUD (km^2) 50%	98.6	169.7	351.1	822.5	0.32

Table 10. Summary of the threat risk assessment process undertaken for each genetic stock of marine turtle in Australian waters. Threats are prioritized based on the number of stocks found to be at 'high' or 'very high' risk from a threat. G-NWS: North West Shelf Green turtle stock; LH-WA: Western Australia Loggerhead stock (From Commonwealth of Australia 2017).

Species Stock	G-NWS	LH-WA
Stock Status	→	→
THREAT		
A. Climate change and variability	[blue]	[yellow]
B. Marine debris – entanglement	[blue]	[blue] U
B. Marine debris – ingestion	[green] U	[blue] U
C. Chemical and terrestrial discharge - acute	[yellow]	[yellow]
C. Chemical and terrestrial discharge – chronic	[blue]	[green]
D. International take – outside Australia's jurisdiction	[blue] U	[blue]
D. International take – within Australia's jurisdiction	[blue] U	[green]
E. Terrestrial predation	[blue]	[blue]
F. Fisheries bycatch – international	[blue]	[blue]
F. Fisheries bycatch – domestic	[blue]	[yellow]
G. Light pollution	[yellow]	[blue]
H. Habitat modification – infrastructure/coastal development	[blue]	[blue]
H. Habitat modification – dredging/trawling	[blue]	[blue]
I. Indigenous take	[blue]	[blue]
J. Vessel disturbance	[blue]	[blue]
K. Noise interference – acute	[blue] U	[blue]
K. Noise interference – chronic	[blue] U	[blue] U
L. Recreational activities	[blue]	[green]
M. Diseases and pathogens	[green]	[green] U
	[green]	[green]
	[green]	[green]

Stock Status: ? = unknown, → = stable, ↗ = recovering, ↘= early stages of decline, ↓ = declining
Risk rating: pink = very high, yellow = high, blue = moderate, green = low, U = unknown
* Historical guano mining

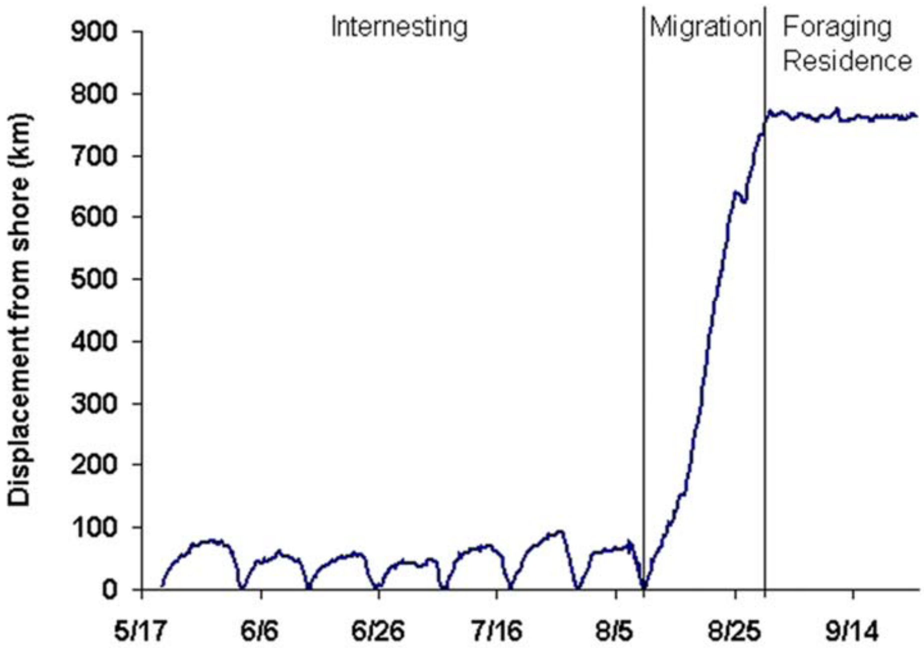

Figure 1. Reproductive phases of inter-nesting (IN), migration (M) and foraging ground (FG). Adapted from Tucker (2009).

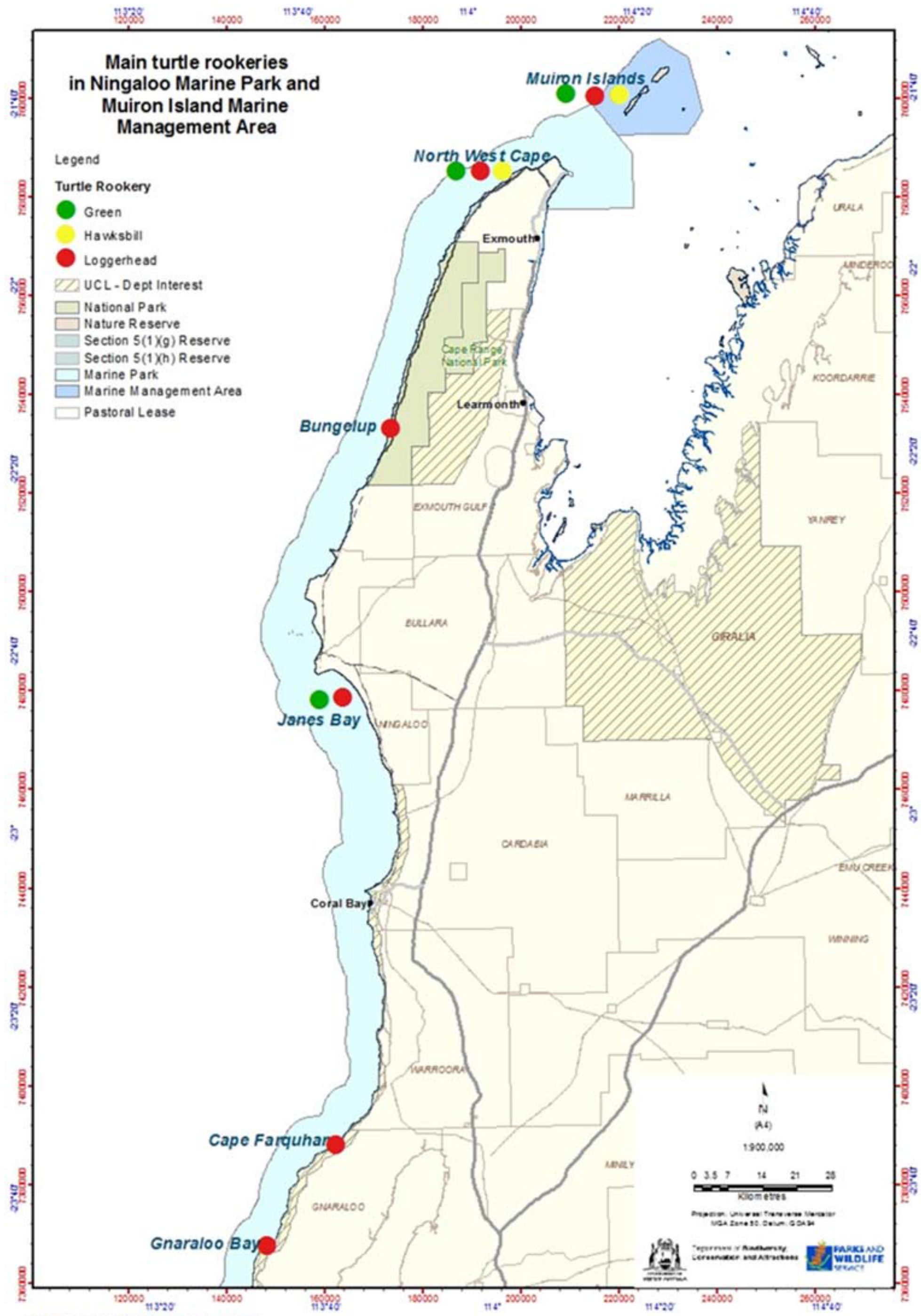

Figure 2. Turtle beaches of the Muiron Island and Northwest Cape identified in Rob et al 2019 (Figure reproduced by DBCA permission).

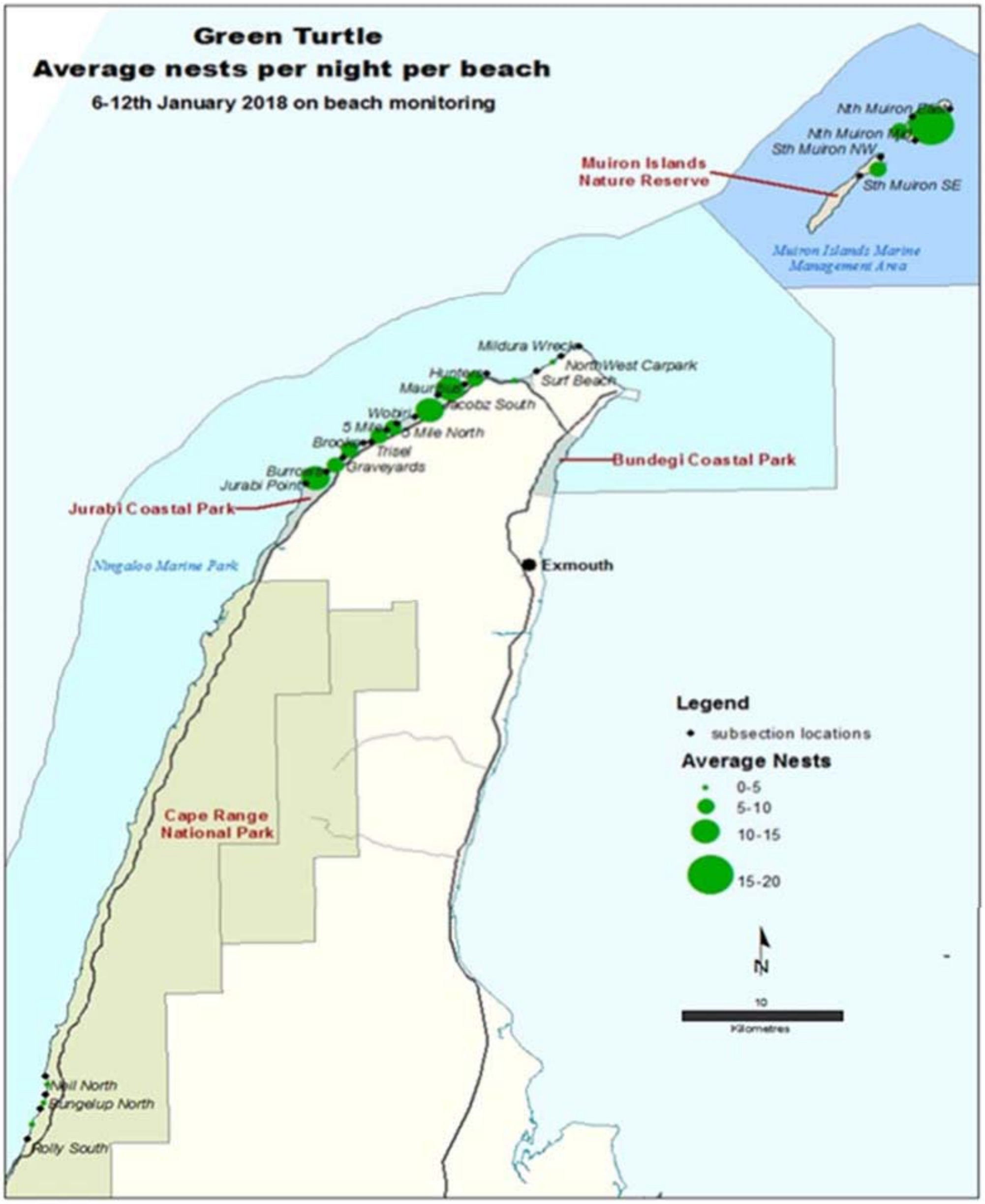

Figure 3. Track density for green turtles of the Muiron Islands and Northwest Cape as identified in Rob et al. 2019 (Figure reproduced by DBCA permission).

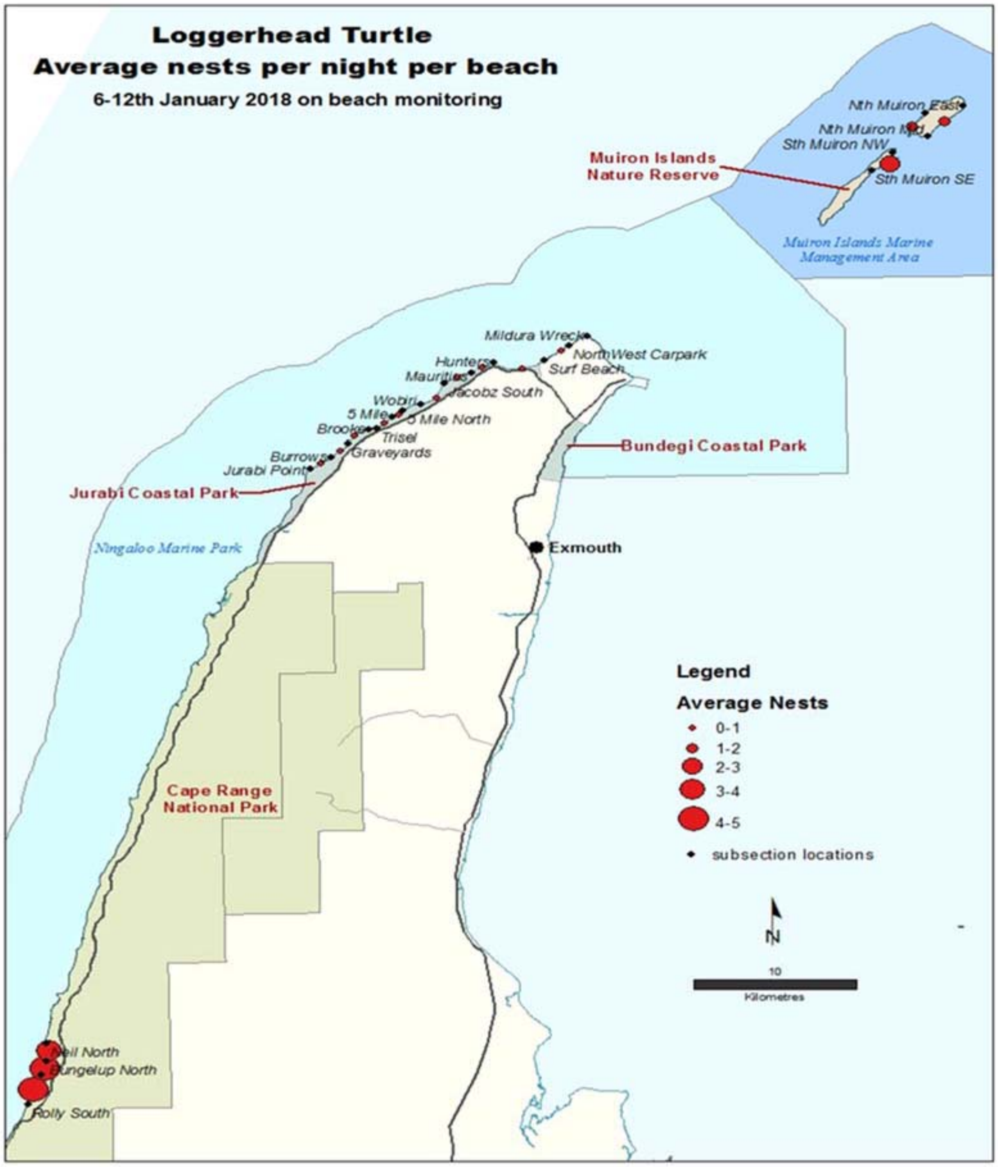

Figure 4. Track density for loggerhead turtles of the Muiron Islands and Northwest Cape as identified in Rob et al. 2019 (Figure reproduced by DBCA permission.

Figure 5. A green turtle inside a portable plywood corral bearing a satellite tracker attached by epoxy and painted with anti-fouling paint. Because turtles are less sensitive to red wavelength light, staff are operating by red head torches. Image was taken with long digital exposure, so no flash photography was used. Image – DBCA.

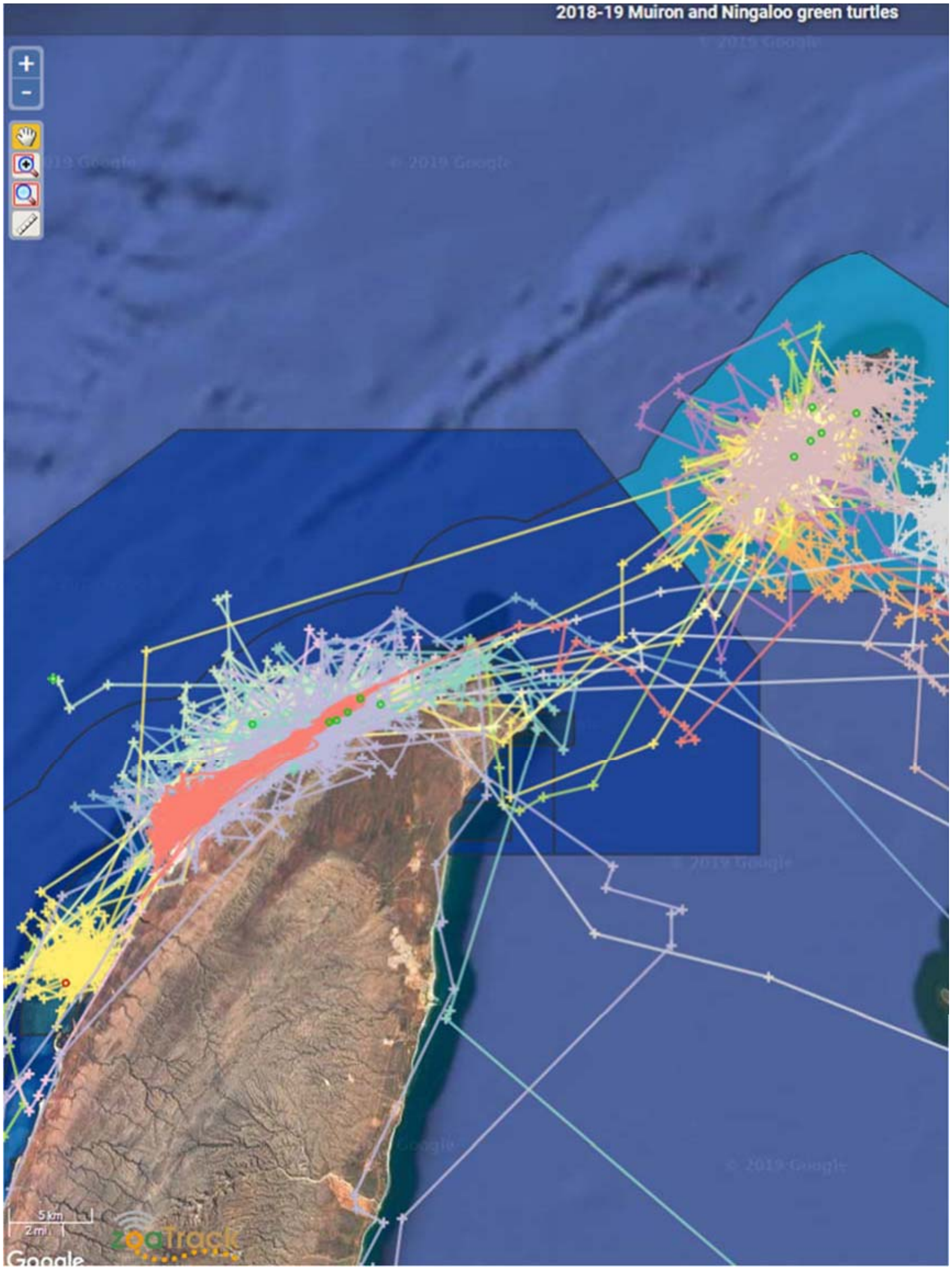

Figure 6. The 2018-2019 green turtle inter-nesting locations overlaying the Marine Park Boundaries. Green circles show deployments, red circles show final displacements. Blue boundary shows Ningaloo Marine Park and Muiron Island Management Area.

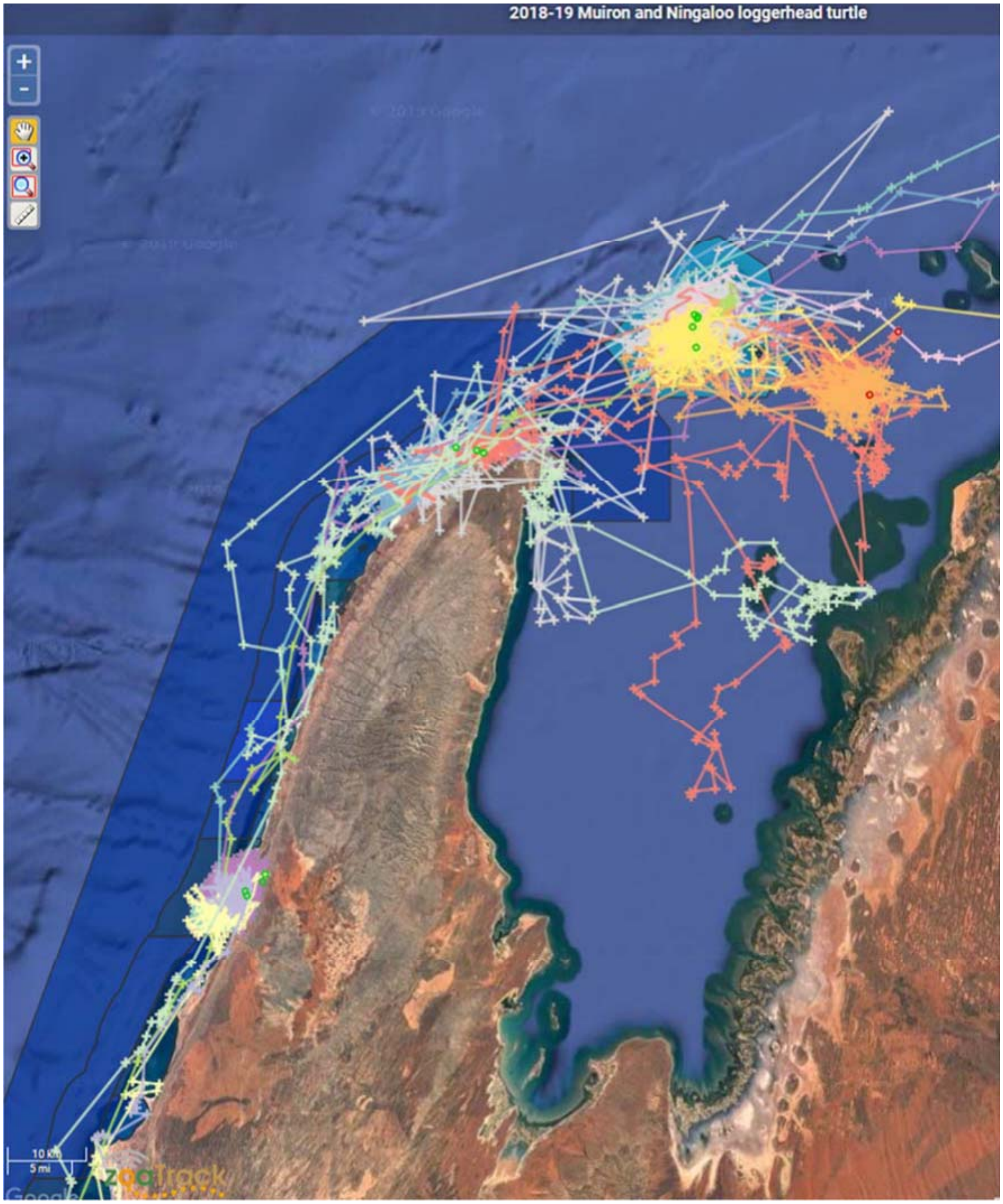

Figure 7. The 2018-2019 loggerhead turtle inter-nesting locations overlaying the Marine Park Boundaries. Green circles show deployments, red circles show final displacements. Blue boundary shows Ningaloo Marine Park and Muiron Island Management Area.

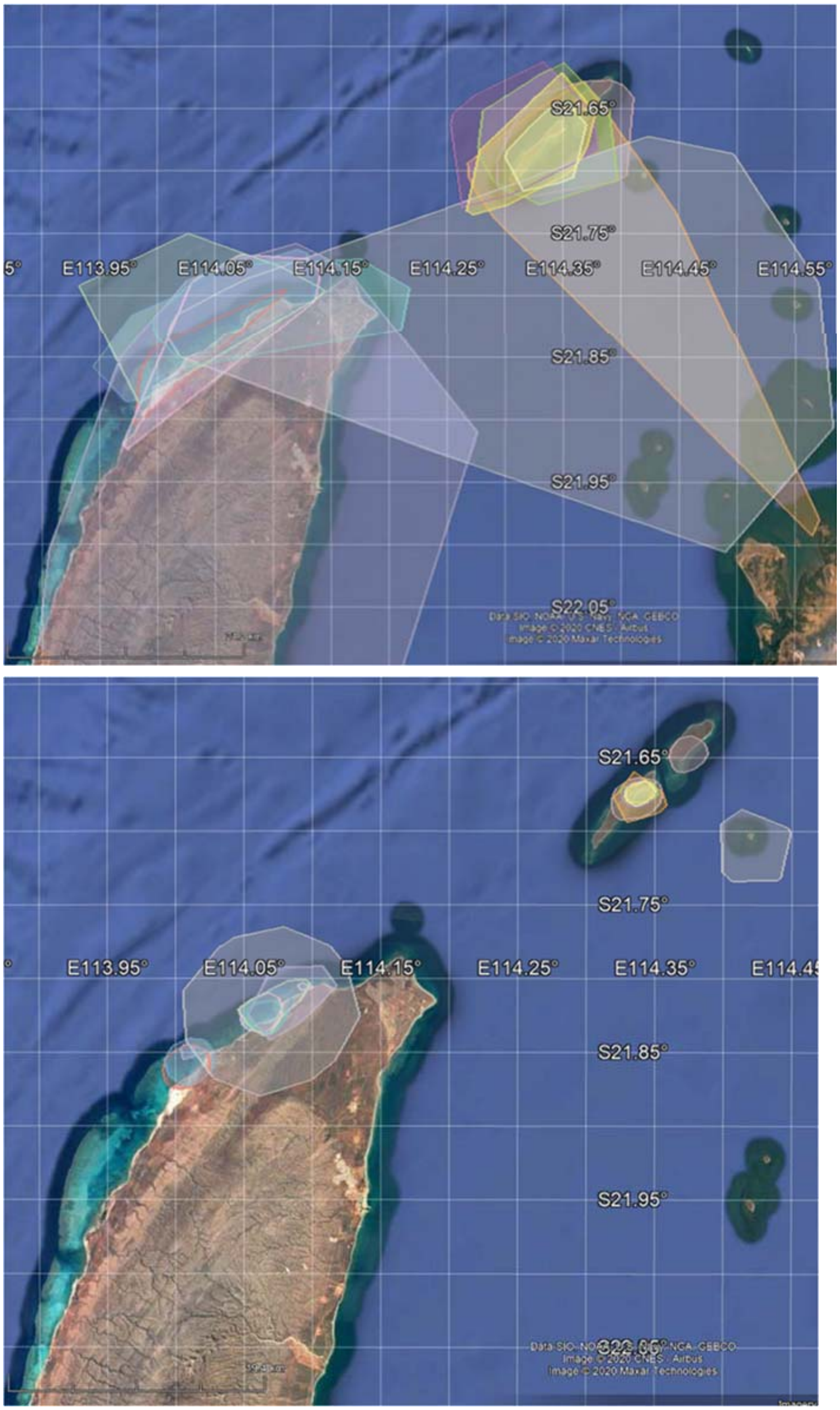

Figure 8. Spatial comparisons of green turtles for 100% minimum convex polygon (top panel) and 50% core ranges KUD (bottom panel). A scale bar is at the bottom of each image

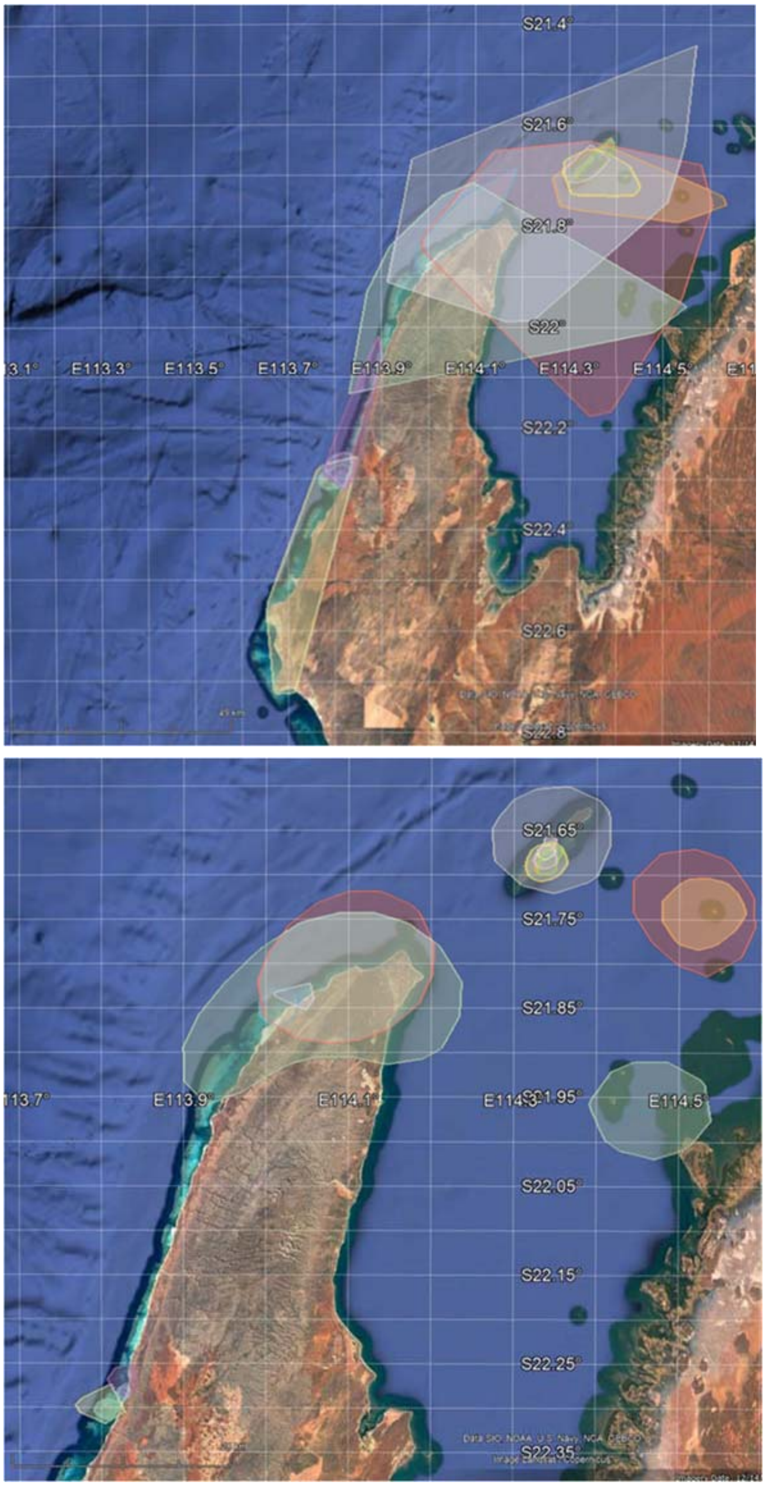

Figure 9. Spatial comparisons of loggerhead turtles for 100% Minimum convex polygon (top panel) and 50% core ranges KUD (bottom panel). A scale bar is at the bottom of each image.

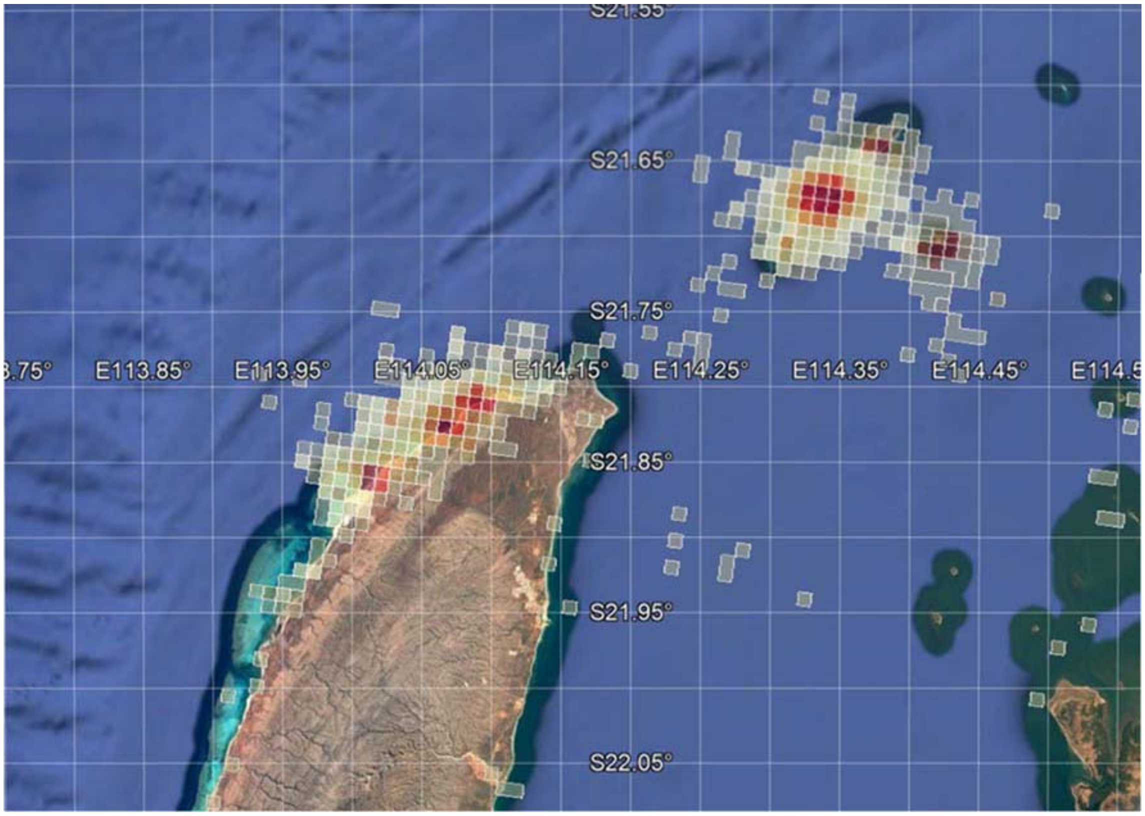

Figure 10. Combined heat map for inter-nesting green turtles

The heatmap color gradient scale displays a location density with redder colour indicate higher density of turtle locations. Pixel sizes are scaled smaller than shown by **Figure 11** because no Bungelup locations were included to the south.

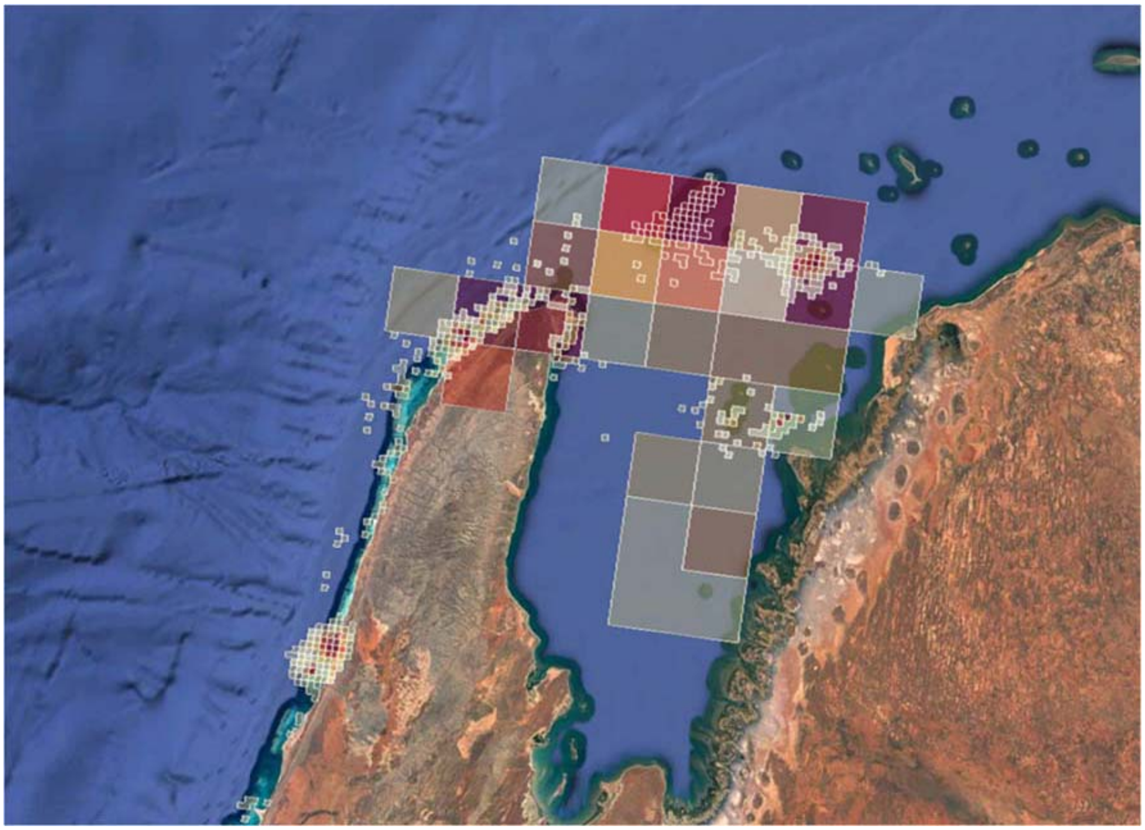

Figure 11. Combined heat map for inter-nesting loggerhead turtles.

The heatmap color gradient scale displays a location density with redder colour indicate higher density of turtle locations. Pixel sizes are scaled larger than shown by **Figure 10** because of additional Bungelup locations were included to the south.

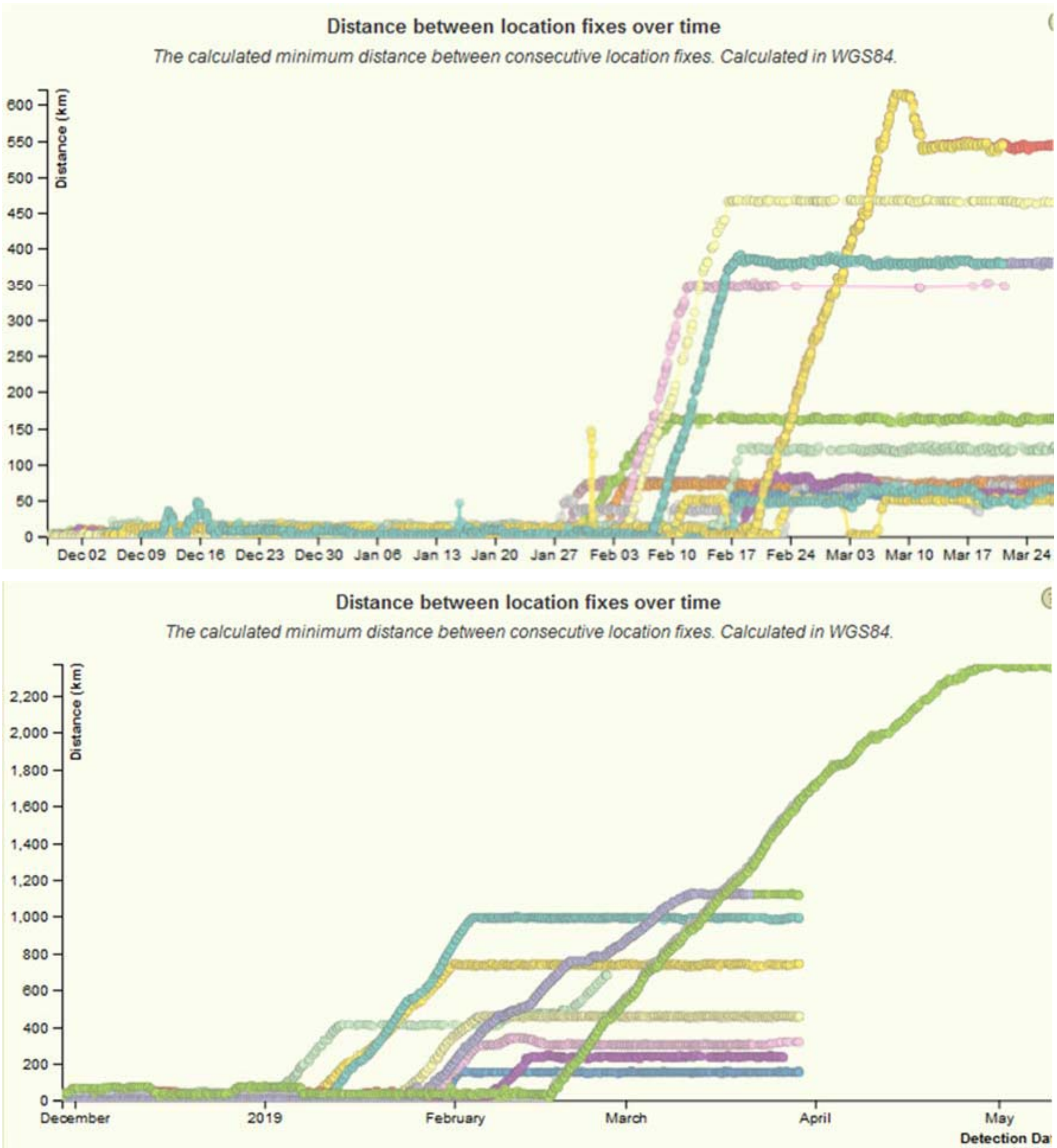

Figure 12. Cumulative distance from original tagging site for green turtles (upper panel) and loggerhead turtles (lower panel).

These empirical determinations are simple state-space models for the individual turtles in **Table 5**. The inter-nesting (IN) residence represented an extended proximity near the original tagging site. The migration (M) phase was defined by increasing distance in transit from the original site as individuals departed at unique times, migration durations and distances. The third phase of foraging ground (FG) is a plateau of cumulative distance as the turtles arrived at pre-reproductive residences and re-establish home ranges.

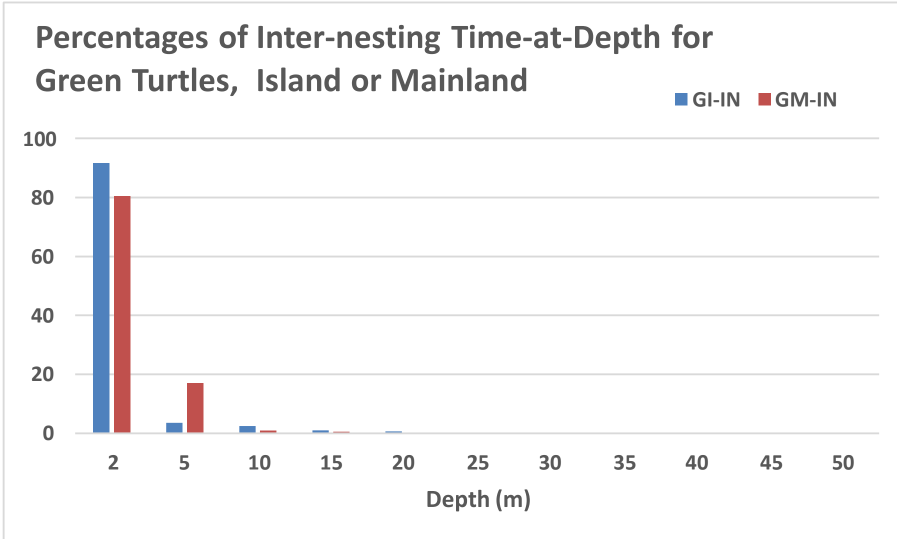

Figure 13. Percentages of inter-nesting time-at-depth used by green turtles nesting on island or mainland rookeries.

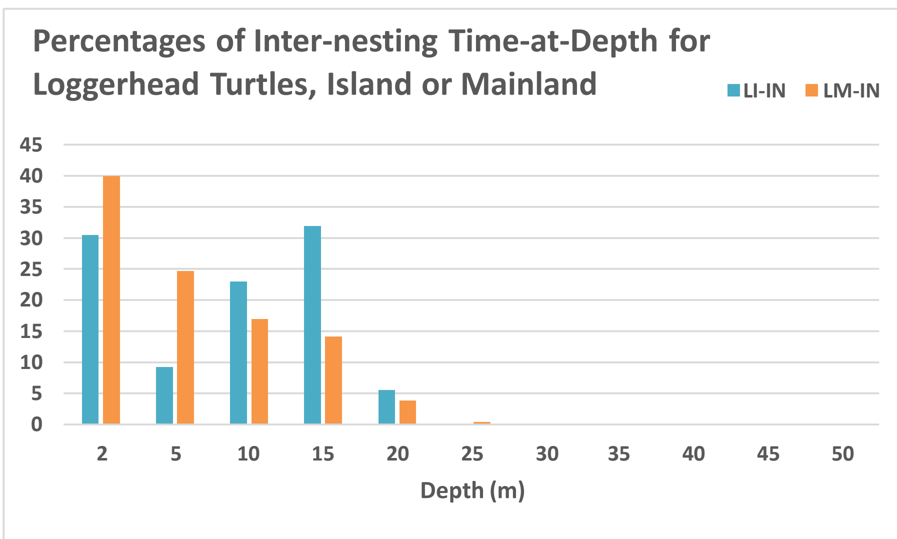

Figure 14. Percentages of inter-nesting time-at-depth used by loggerhead turtles nesting on island or mainland rookeries.

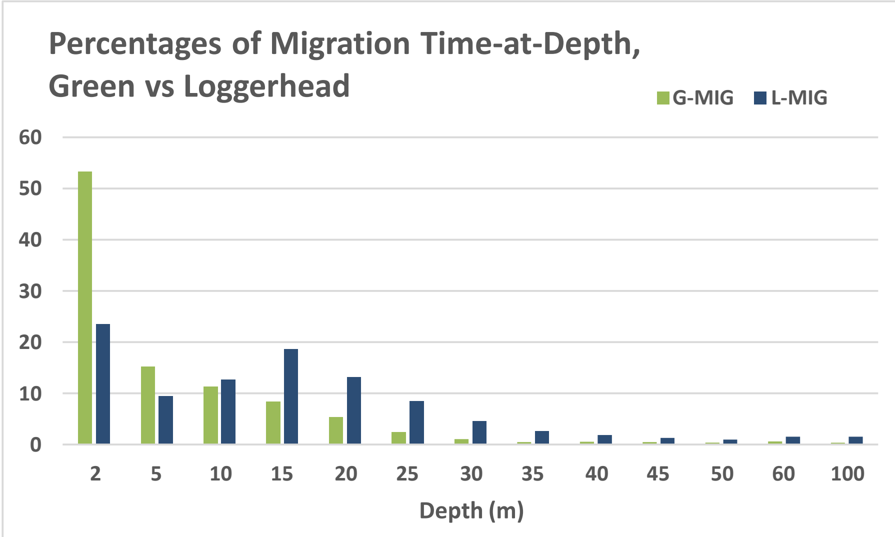

Figure 15. Percentages of migration time-at-depth used by green and loggerhead turtles.

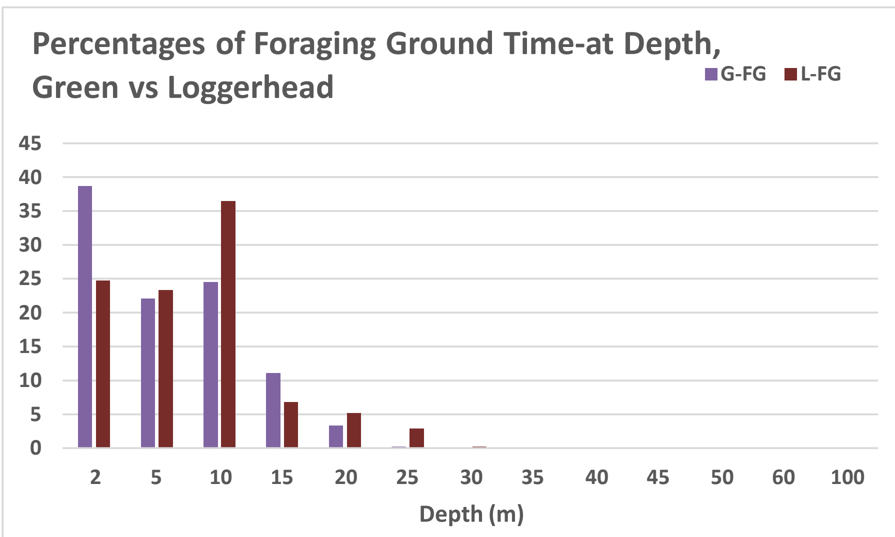

Figure 16. Percentages of foraging ground time-at-depth used by green and loggerhead turtles.

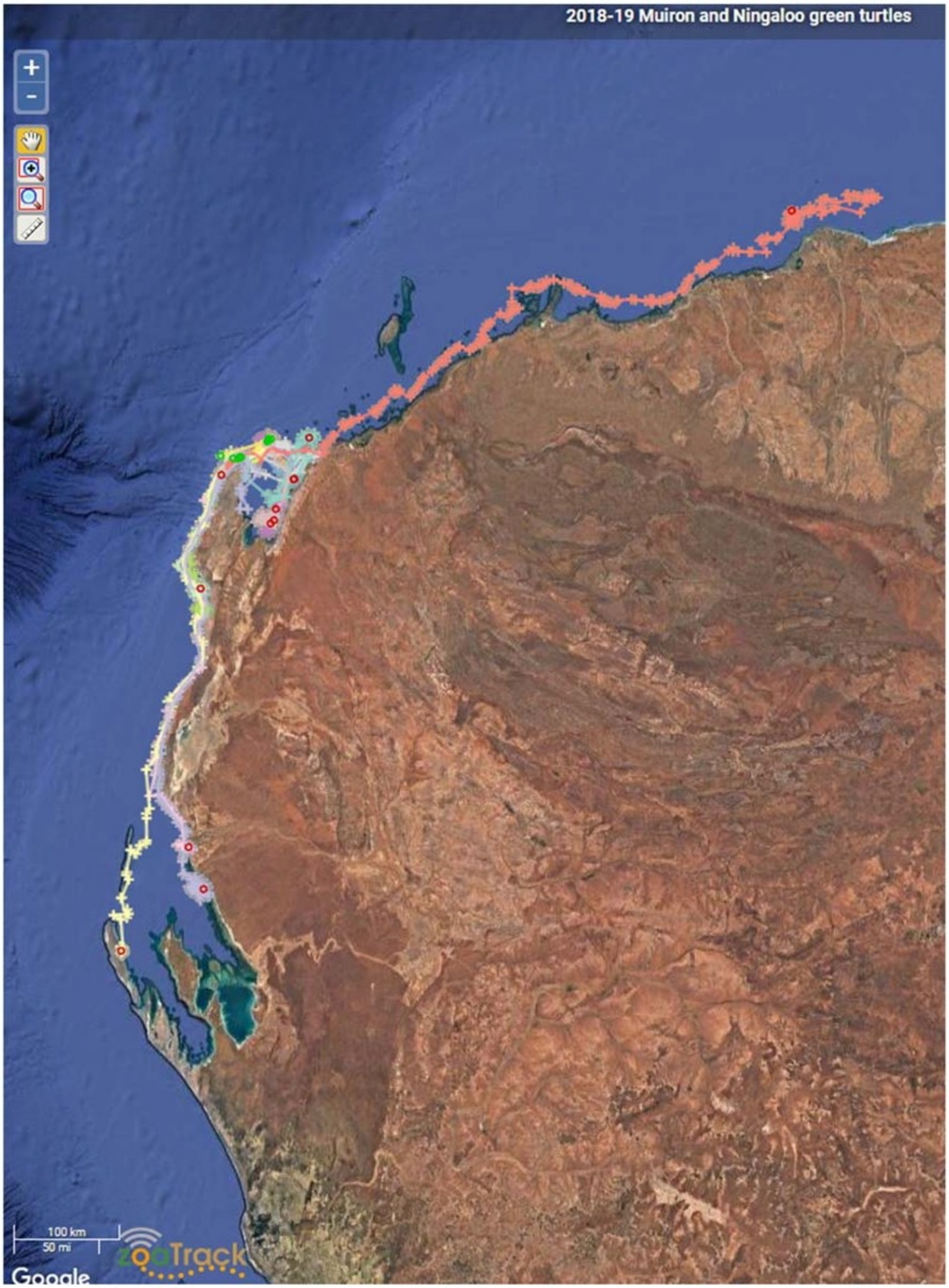

Figure 17. The 2018-2019 green turtle migrations to foraging ground locations beyond the Marine Park Boundaries.

Green circles show deployments, red circles show final displacements.

Figure 18. The 2018-2019 loggerhead turtle migrations to foraging ground locations beyond the Marine Park Boundaries. Green circles show deployments, red circles show final displacements.

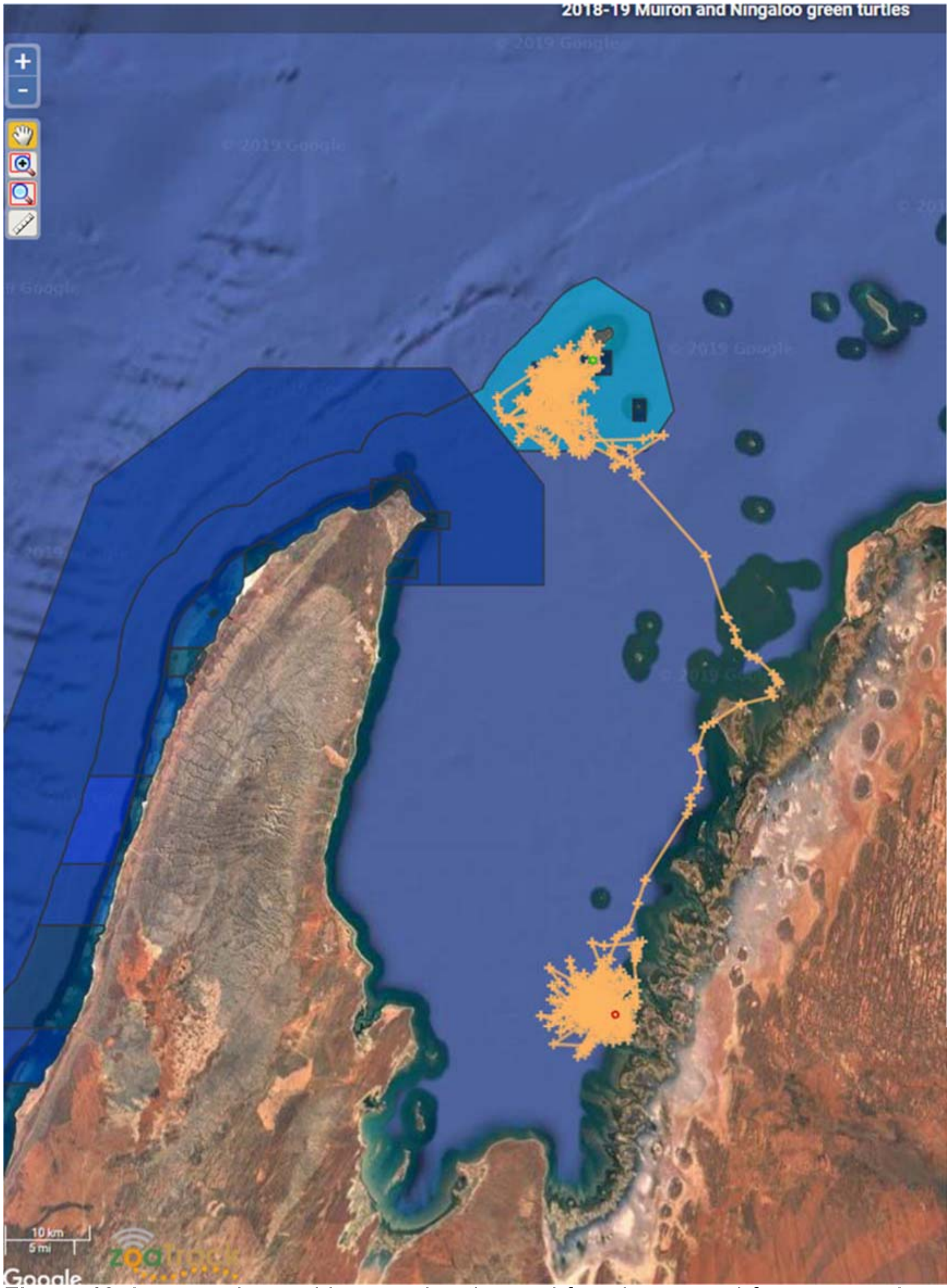

Figure 19. Inter-nesting residence, migration and foraging ground for green turtle G-66261 Babaneek.

Green circles show deployments, red circles show final displacements.

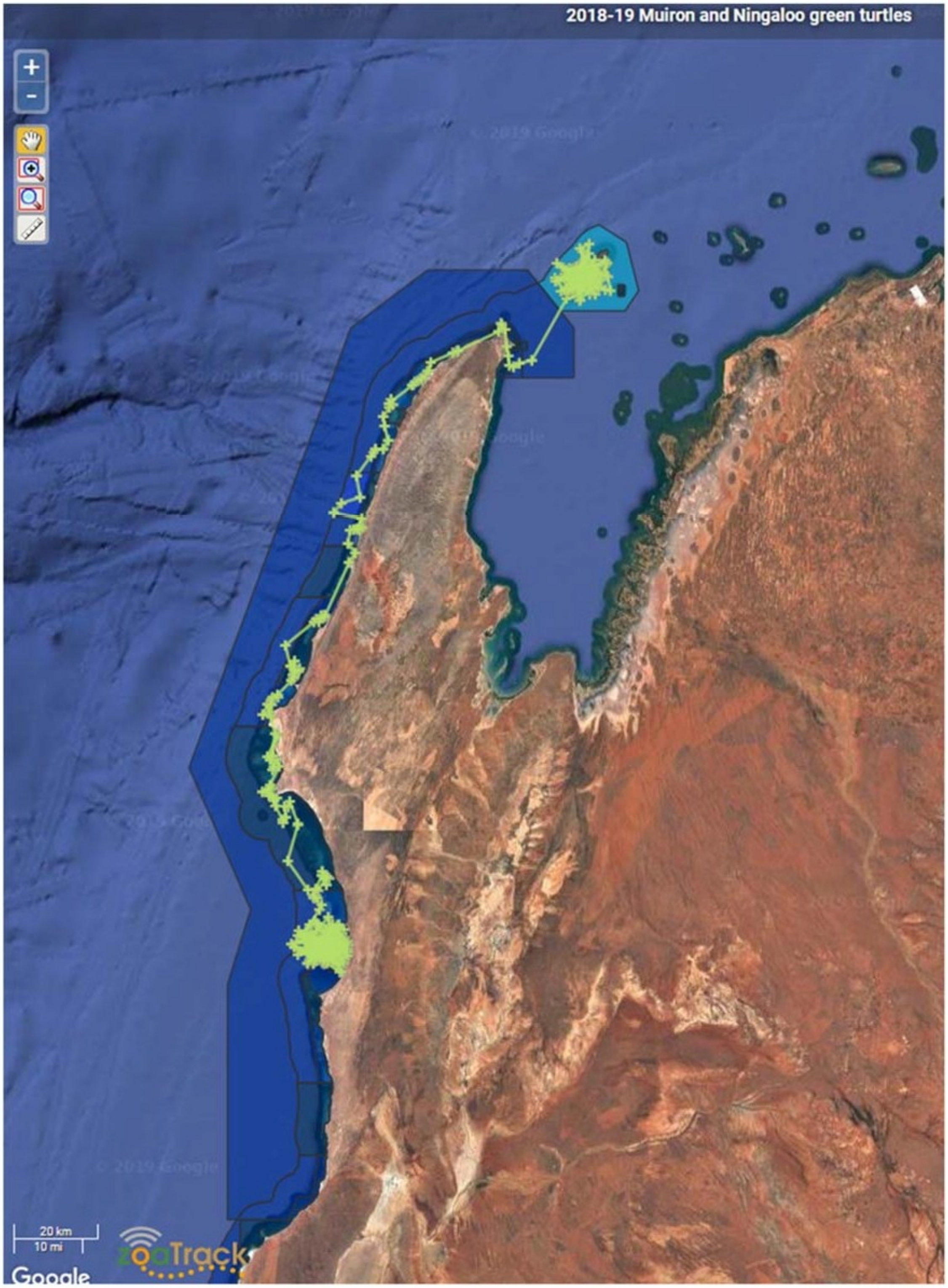

Figure 20. Inter-nesting residence, migration and foraging ground for green turtle G-66262 Alinta.

Green circles show deployments, red circles show final displacements.

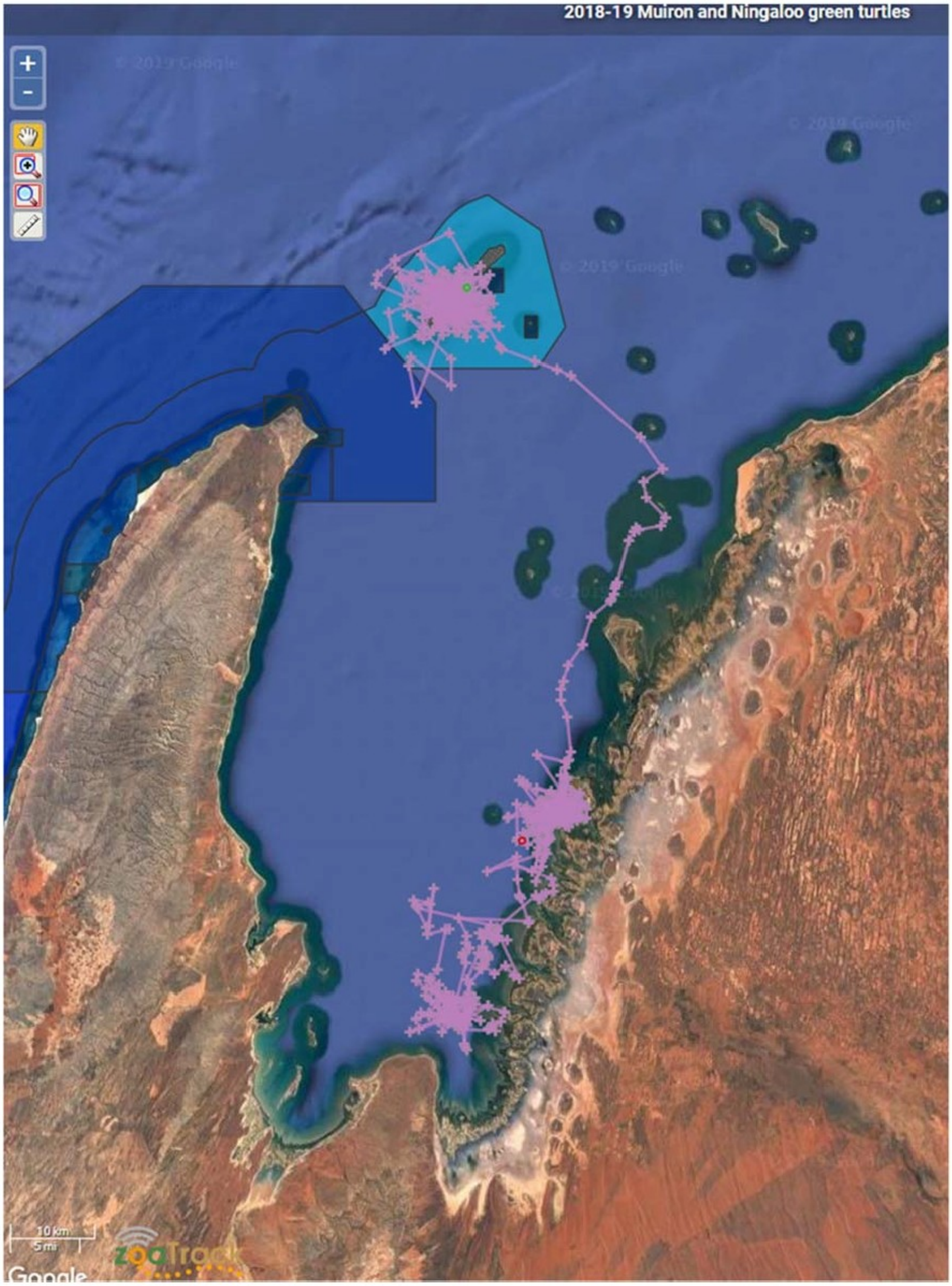

Figure 21. Inter-nesting residence, migration and foraging ground for green turtle G-66263 Wayambeh.

Green circles show deployments, red circles show final displacements

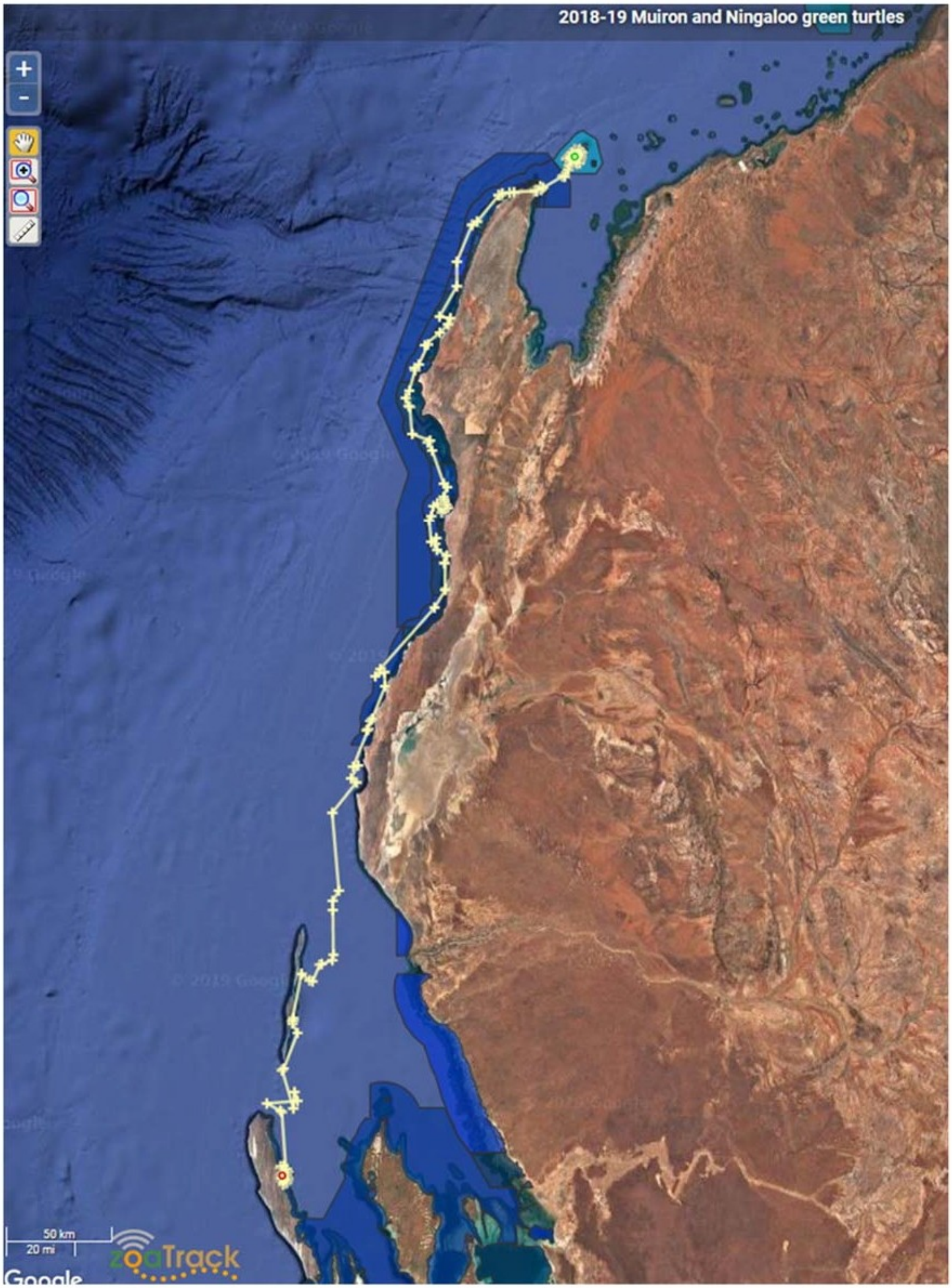

Figure 22. Inter-nesting residence, migration and foraging ground for green turtle G-66273 Goodawandjin.

Green circles show deployments, red circles show final displacements

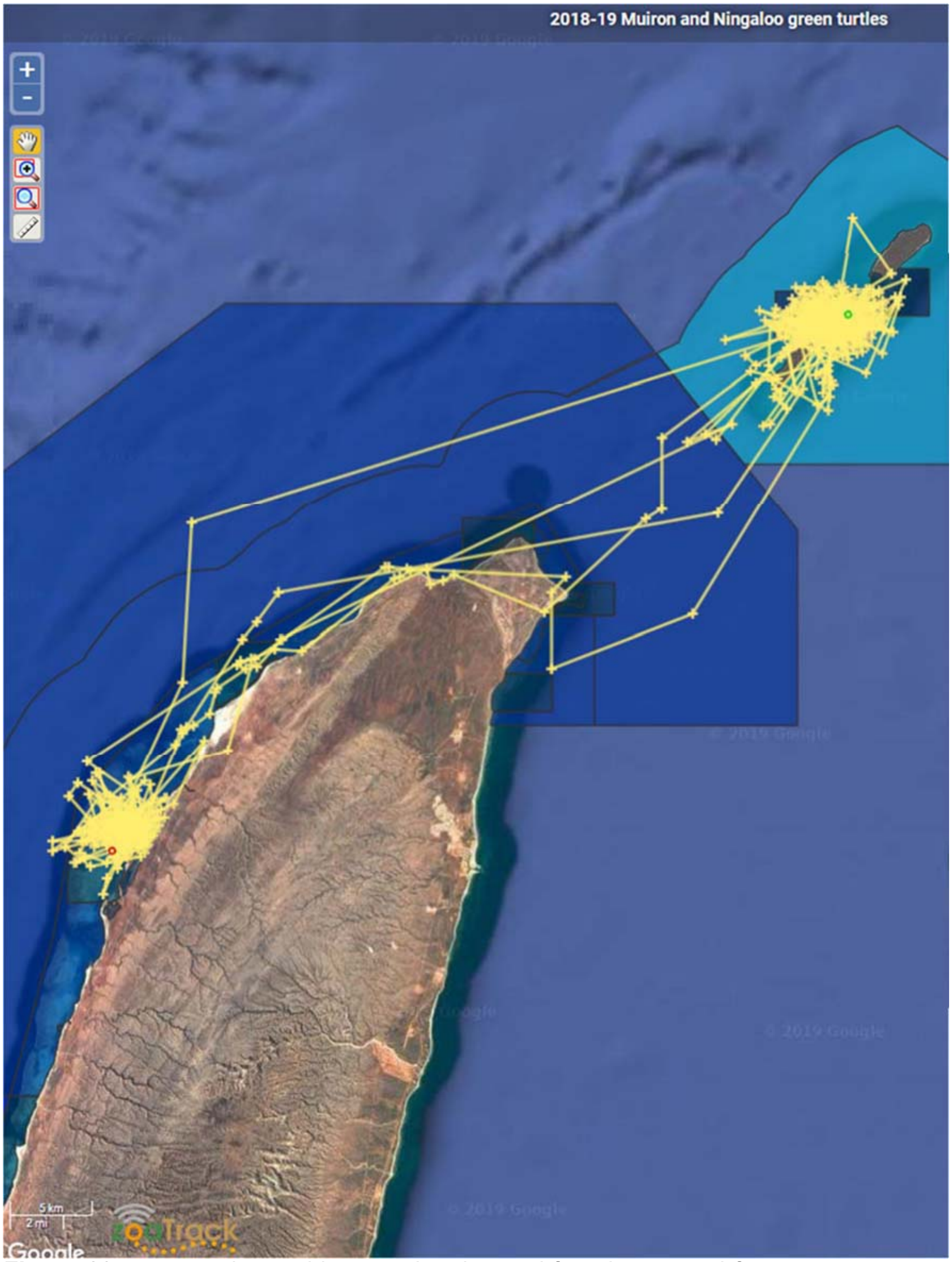

Figure 23. Inter-nesting residence, migration and foraging ground for green turtle G-66276 Maverick

Green circles show deployments, red circles show final displacements.

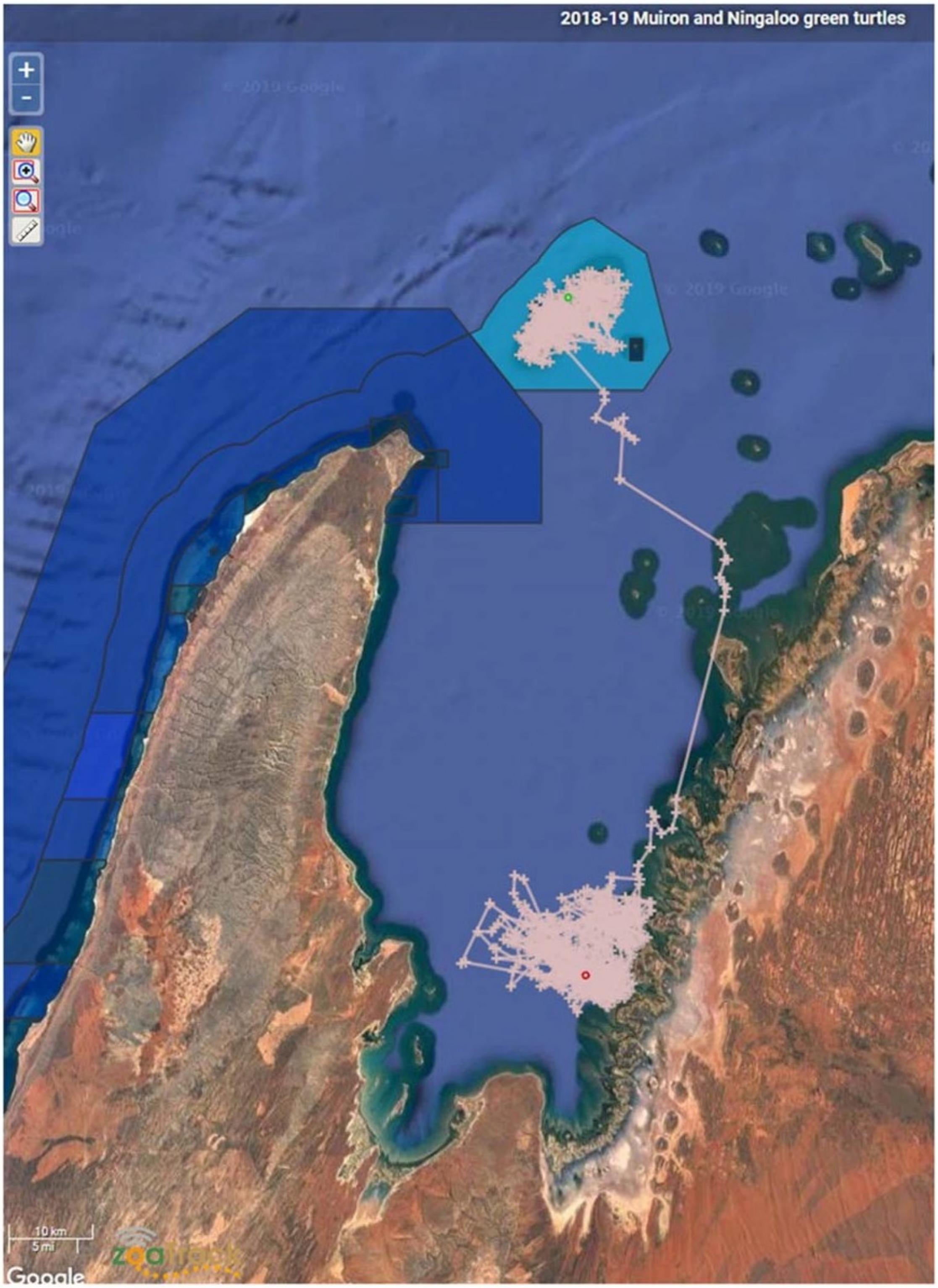

Figure 24. Inter-nesting residence, migration and foraging ground for green turtle G-66301 Nika.

Green circles show deployments, red circles show final displacements.

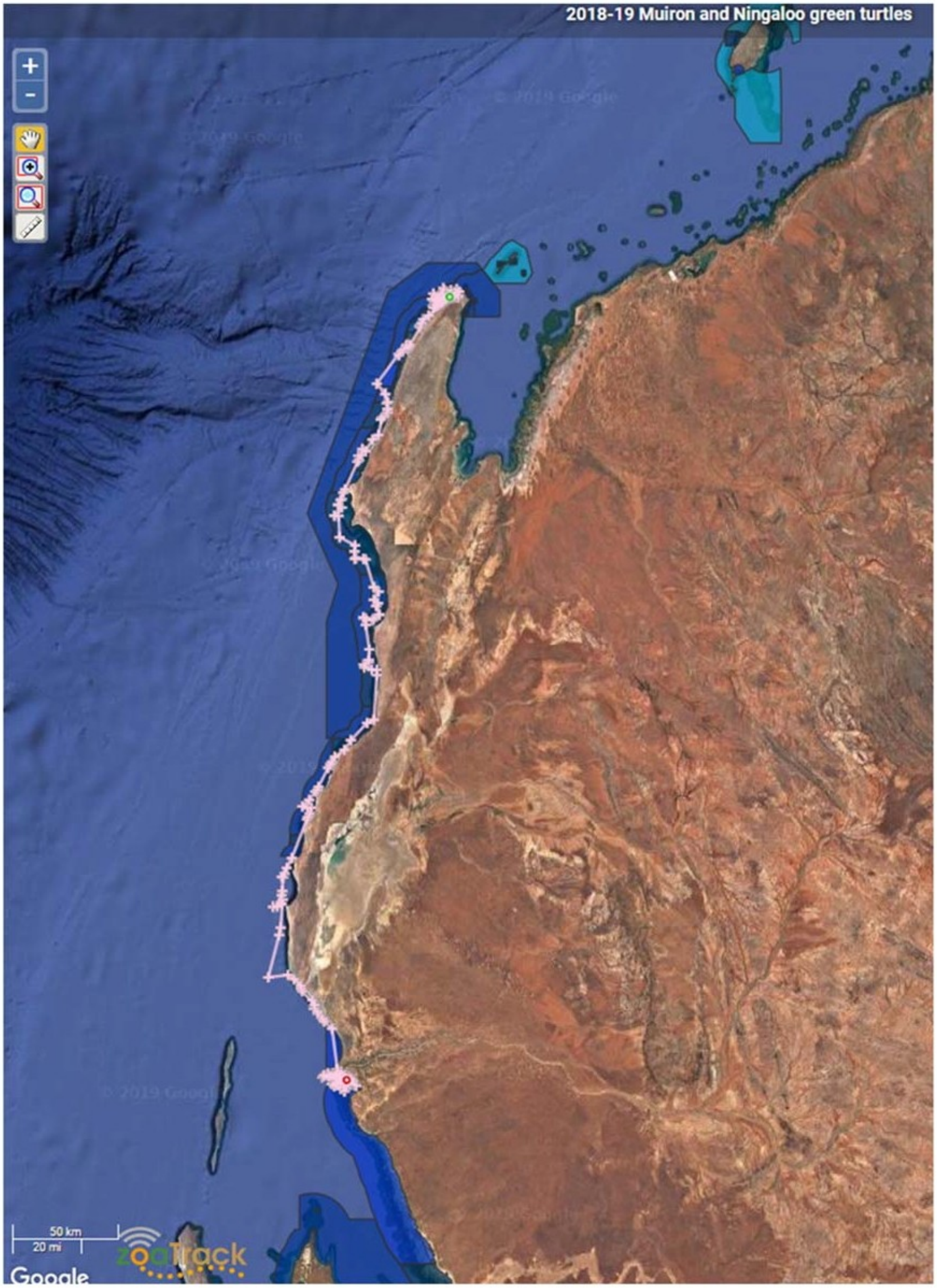

Figure 25. Inter-nesting residence, migration and foraging ground for green turtle G-66304 Katyn.

Green circles show deployments, red circles show final displacements.

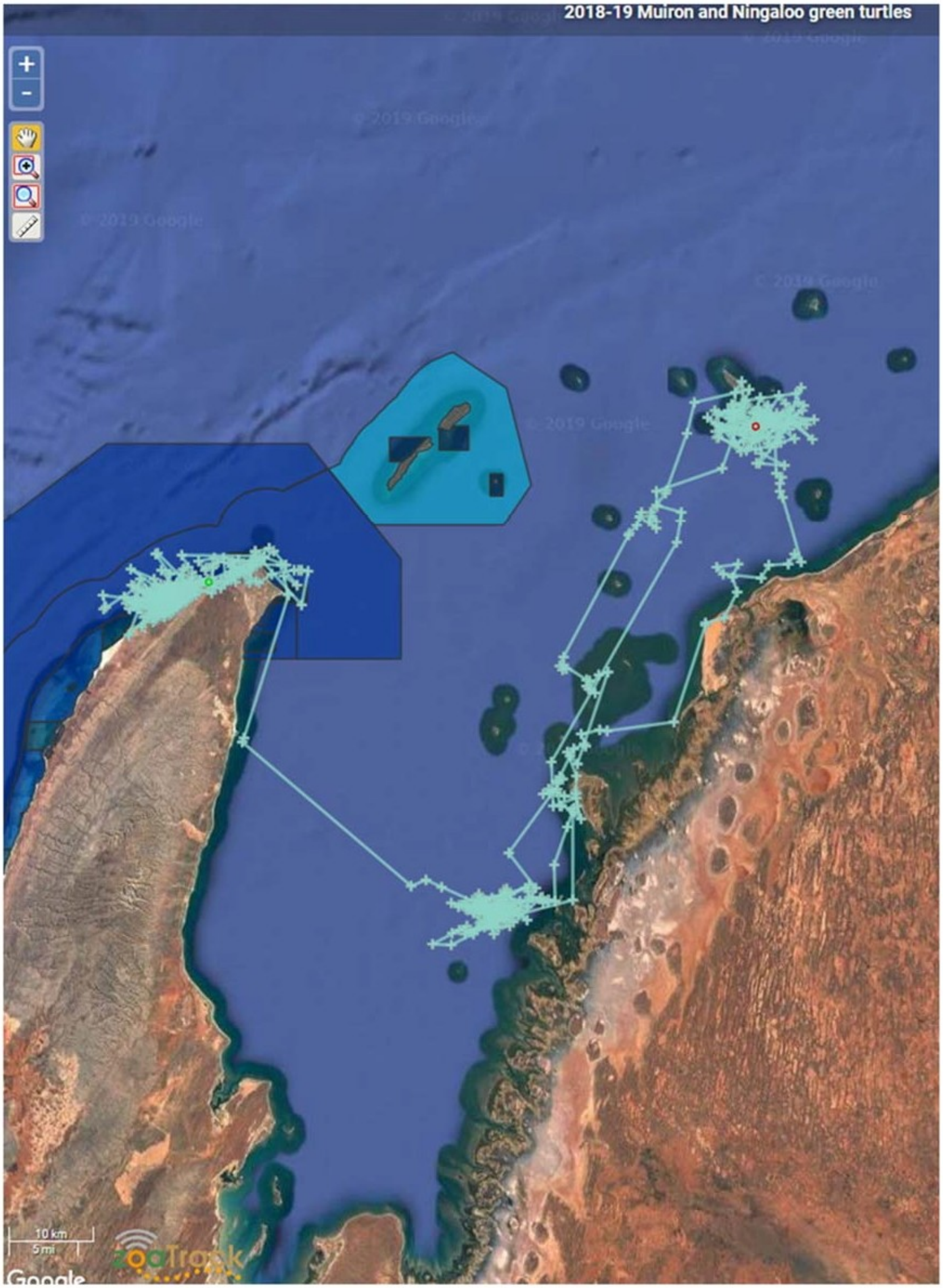

Figure 26. Inter-nesting residence, migration and foraging ground for green turtle G-66313 Harmony. Green circles show deployments, red circles show final displacements.

Figure 27. Inter-nesting residence, migration and foraging ground for green turtle G-66321 Dilga

Green circles show deployments, red circles show final displacements.

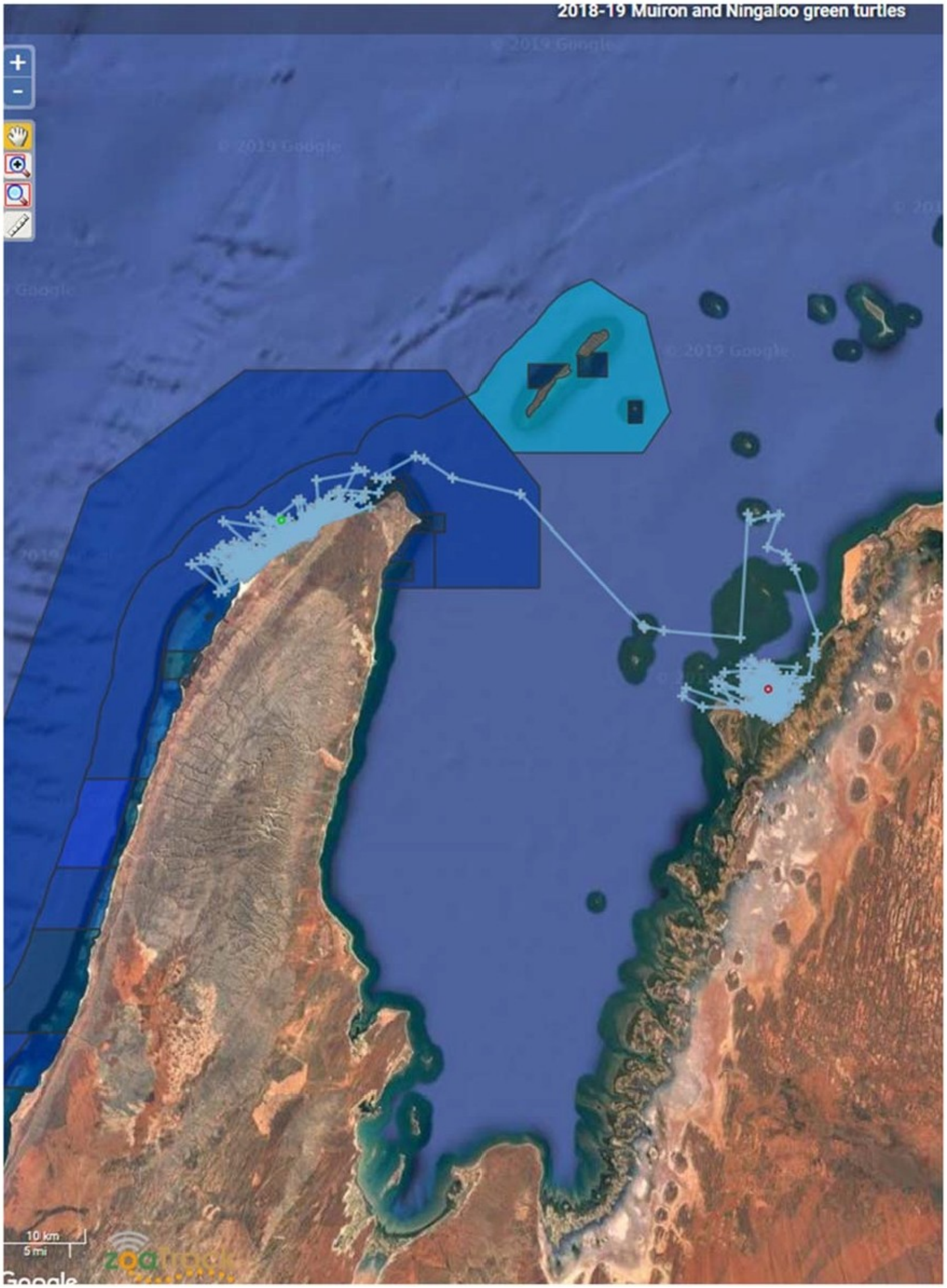

Figure 28. Inter-nesting residence, migration and foraging ground for green turtle G-66323 Dani.

Green circles show deployments, red circles show final displacements.

Figure 29. Inter-nesting residence, migration and foraging ground for green turtle G-66326 Wartortle.

Green circles show deployments, red circles show final displacements.

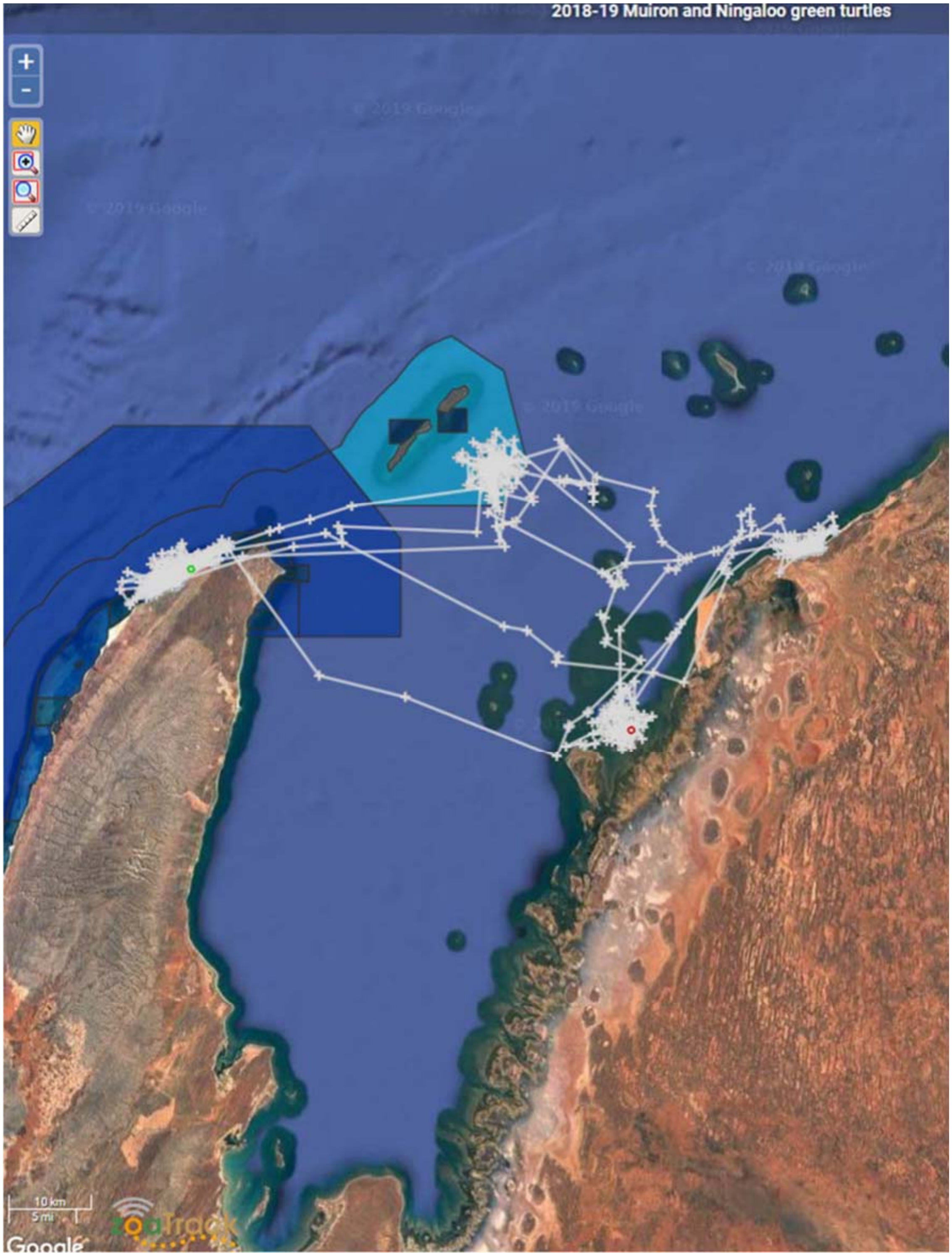

Figure 30. Inter-nesting residence, migration and foraging ground for green turtle G-66342 Nyaja.

Green circles show deployments, red circles show final displacements.

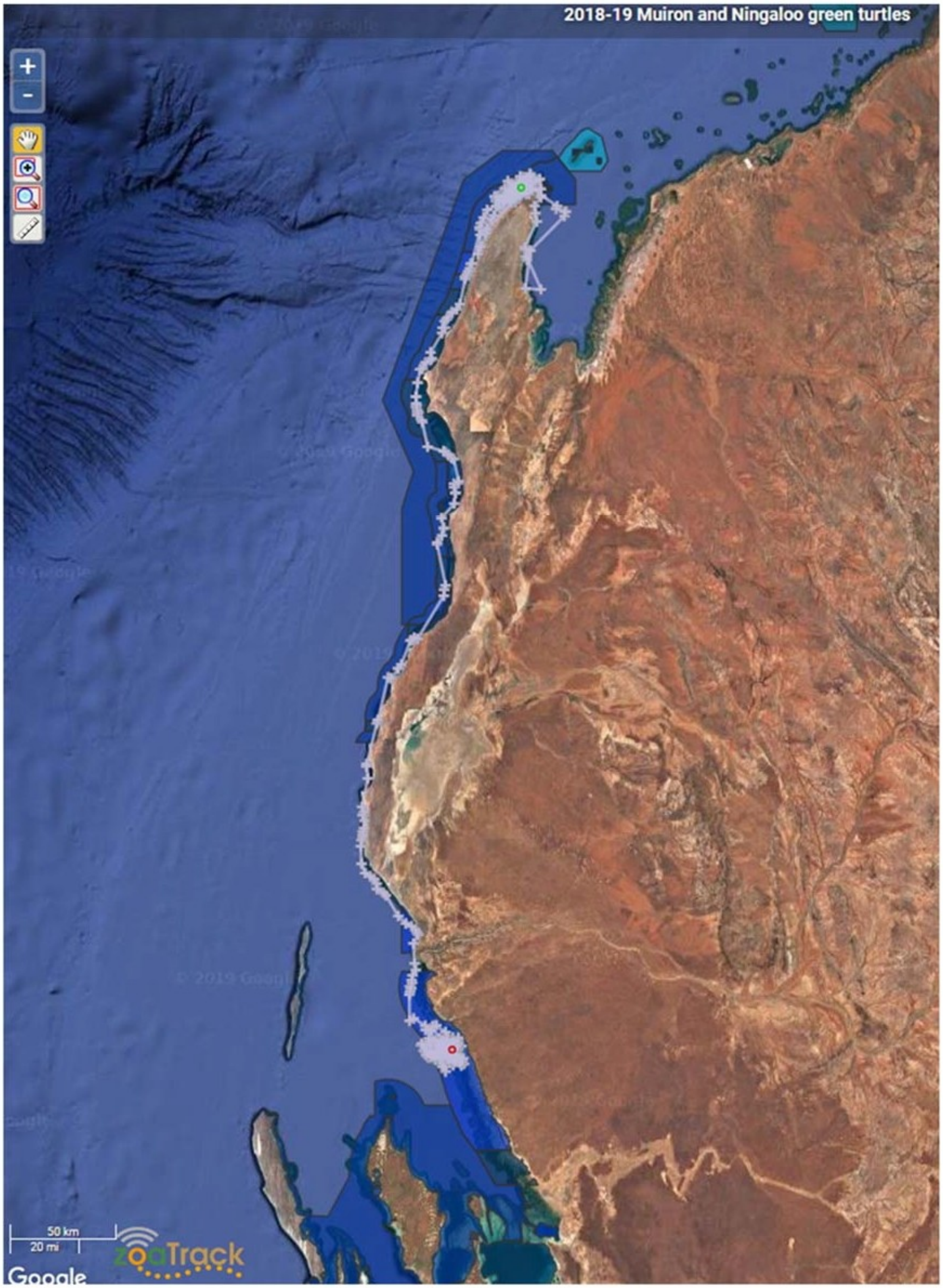

Figure 31. Inter-nesting residence, migration and foraging ground for green turtle G-67906 Gemma

Green circles show deployments, red circles show final displacements.

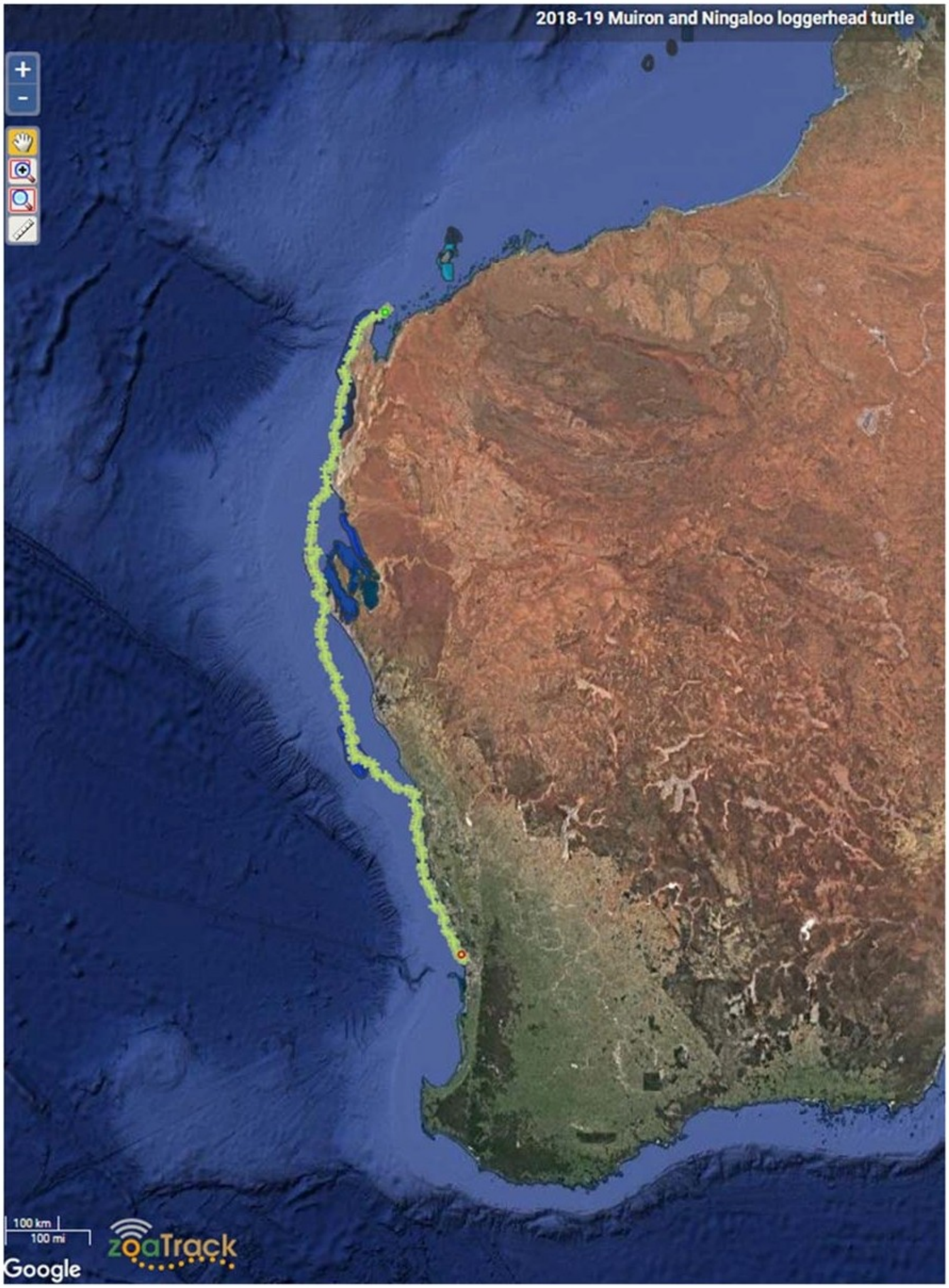

Figure 32. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66259 Tortue Geniale

Green circles show deployments, red circles show final displacements

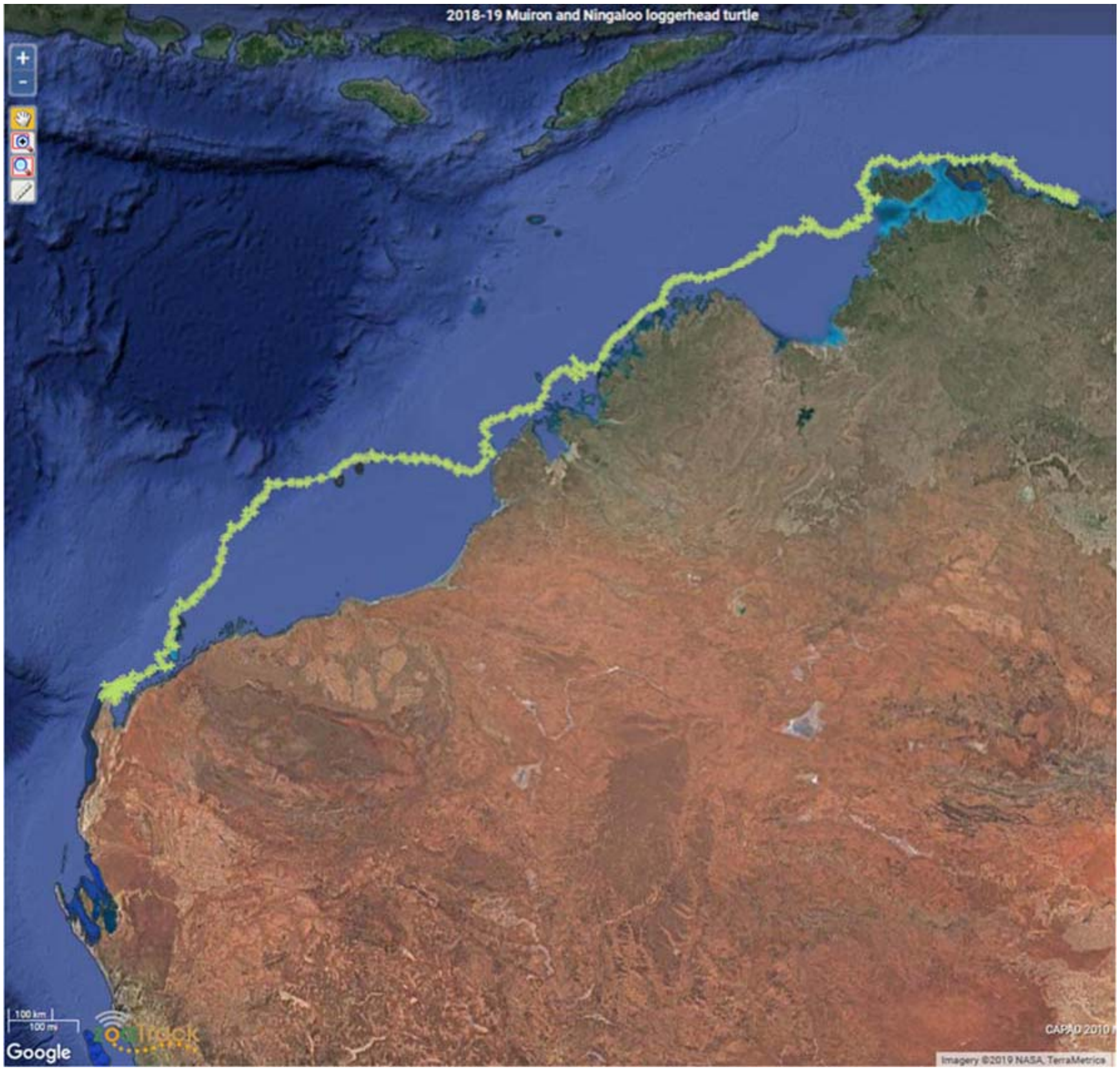

Figure 33. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66260 Gee Geike.

Green circles show deployments, red circles show final displacements.

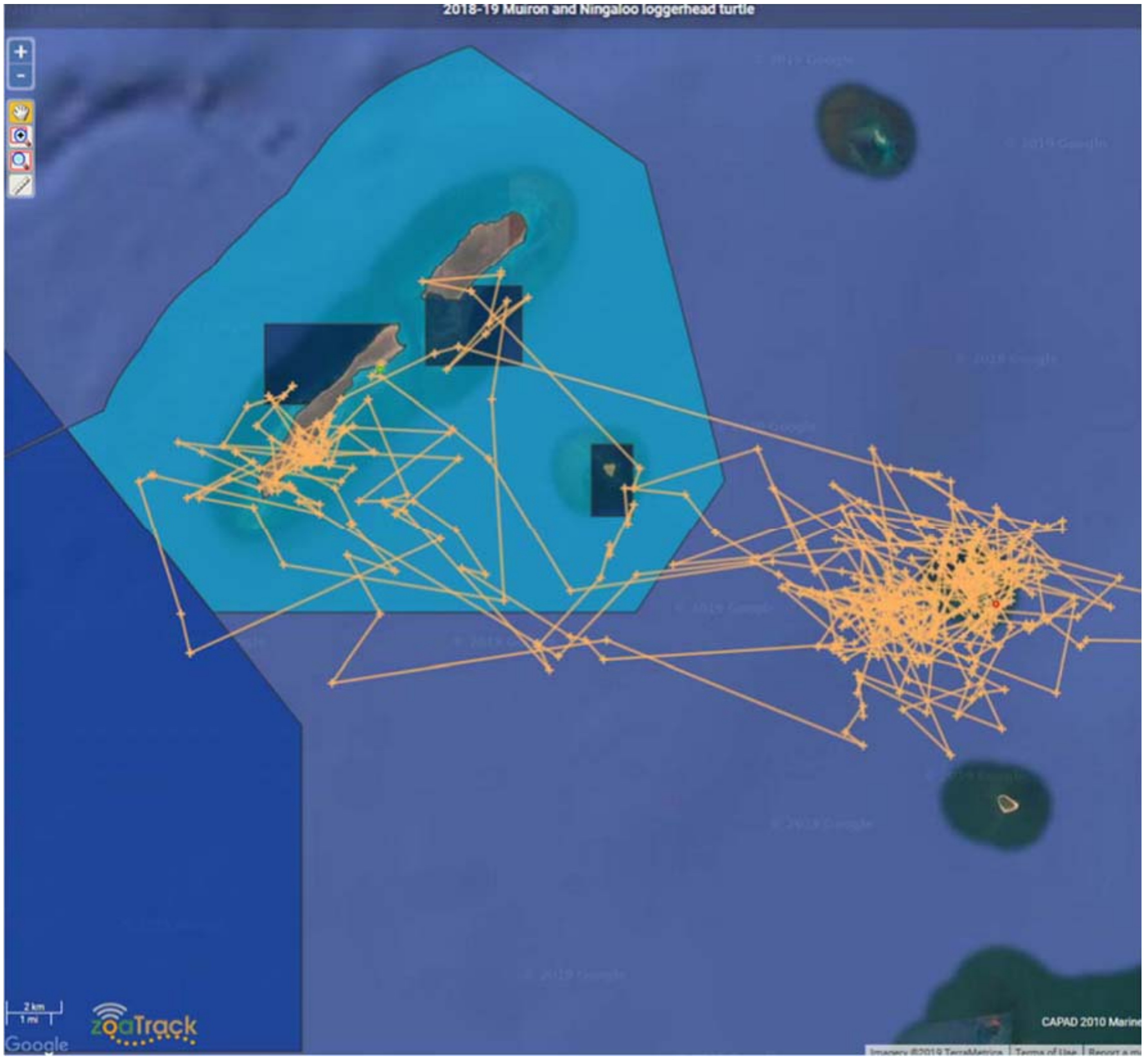

Figure 34. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66264 Sioban Chelonii.

Green circles show deployments, red circles show final displacements.

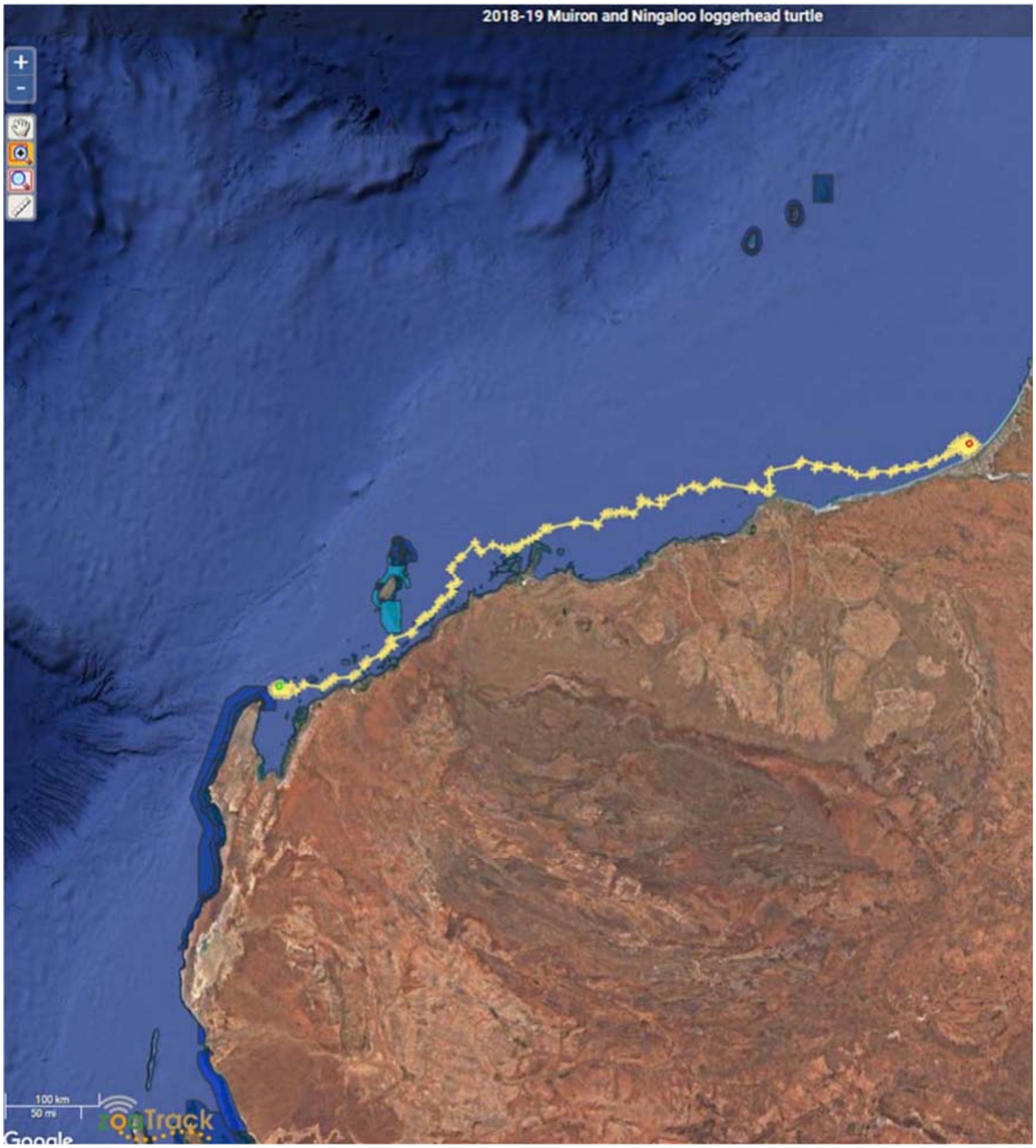

Figure 35. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66268 Turtley Fabulous.

Green circles show deployments, red circles show final displacements.

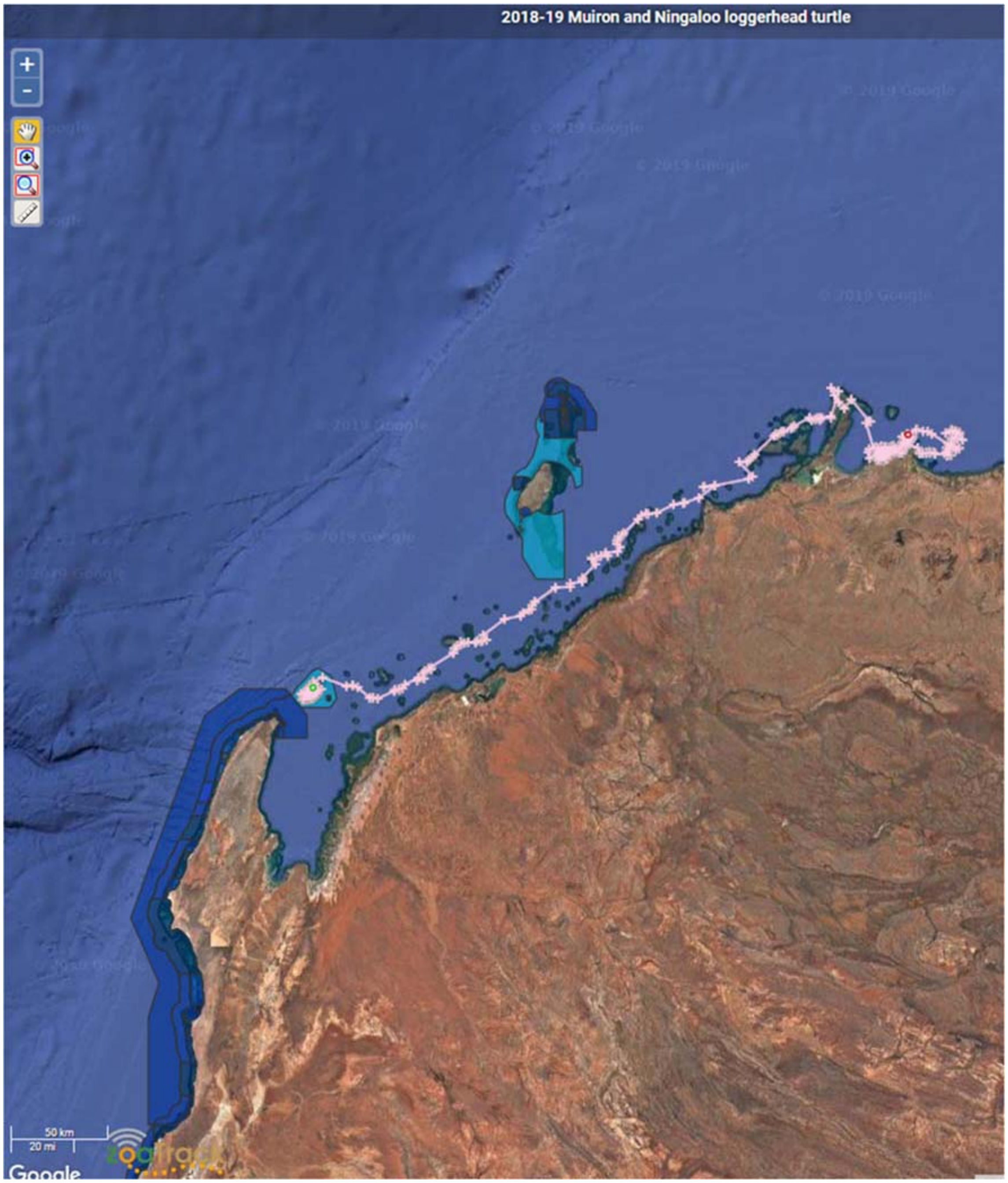

Figure 36. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66271 Wilari.

Green circles show deployments, red circles show final displacements.

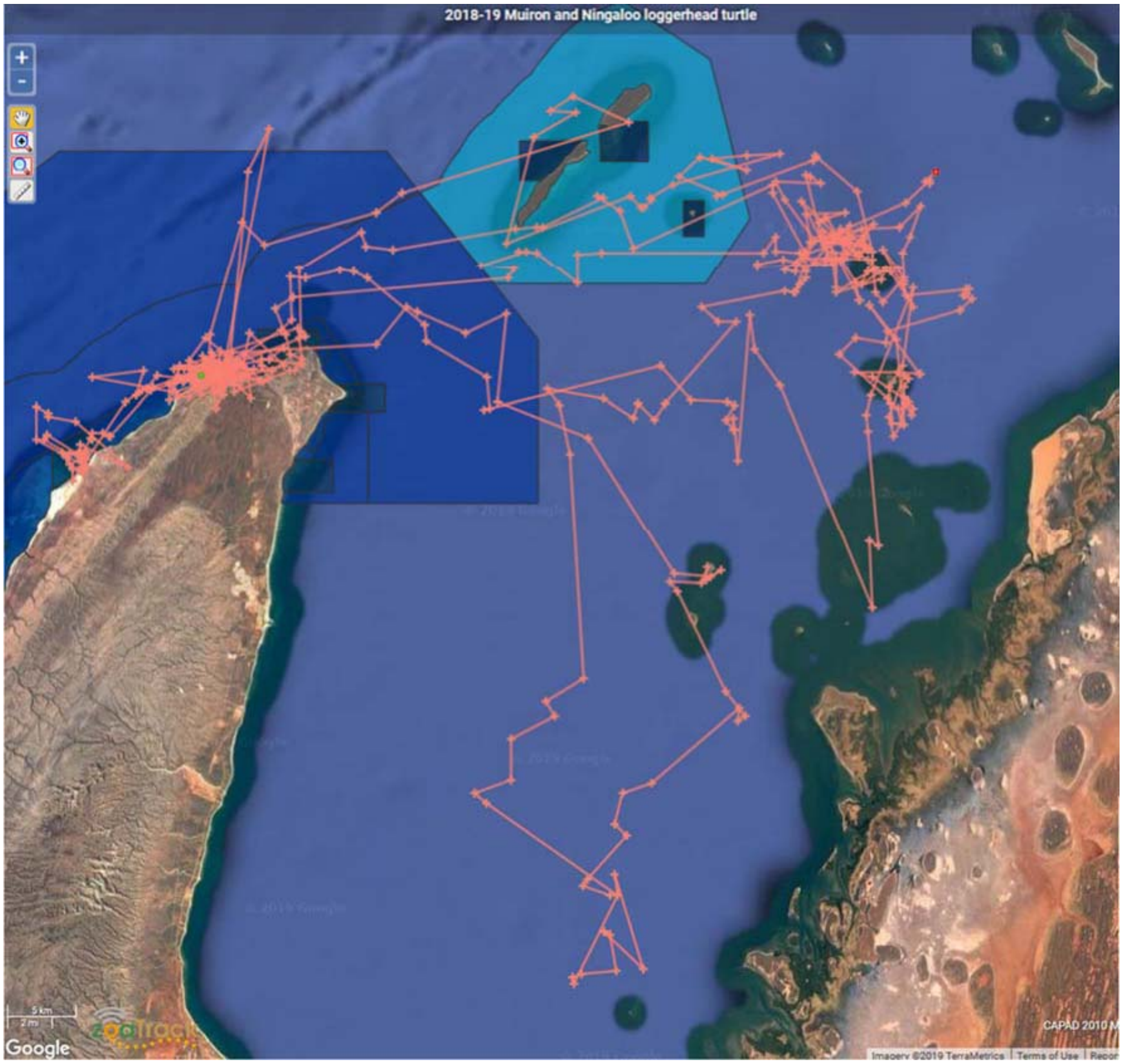

Figure 37. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66272 Ngajuri.

Green circles show deployments, red circles show final displacements.

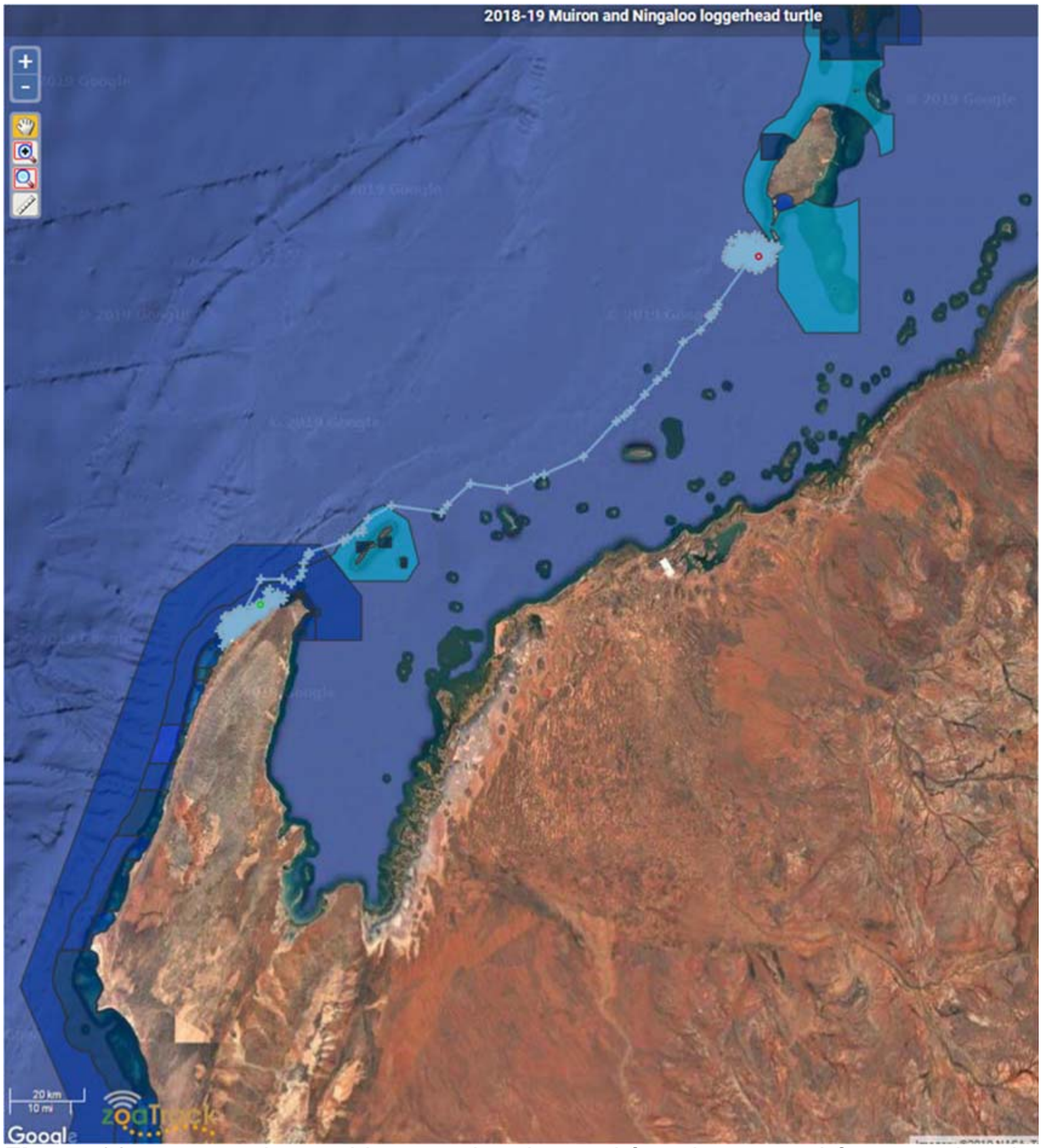

Figure 38. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66288 Wittwer

Green circles show deployments, red circles show final displacements.

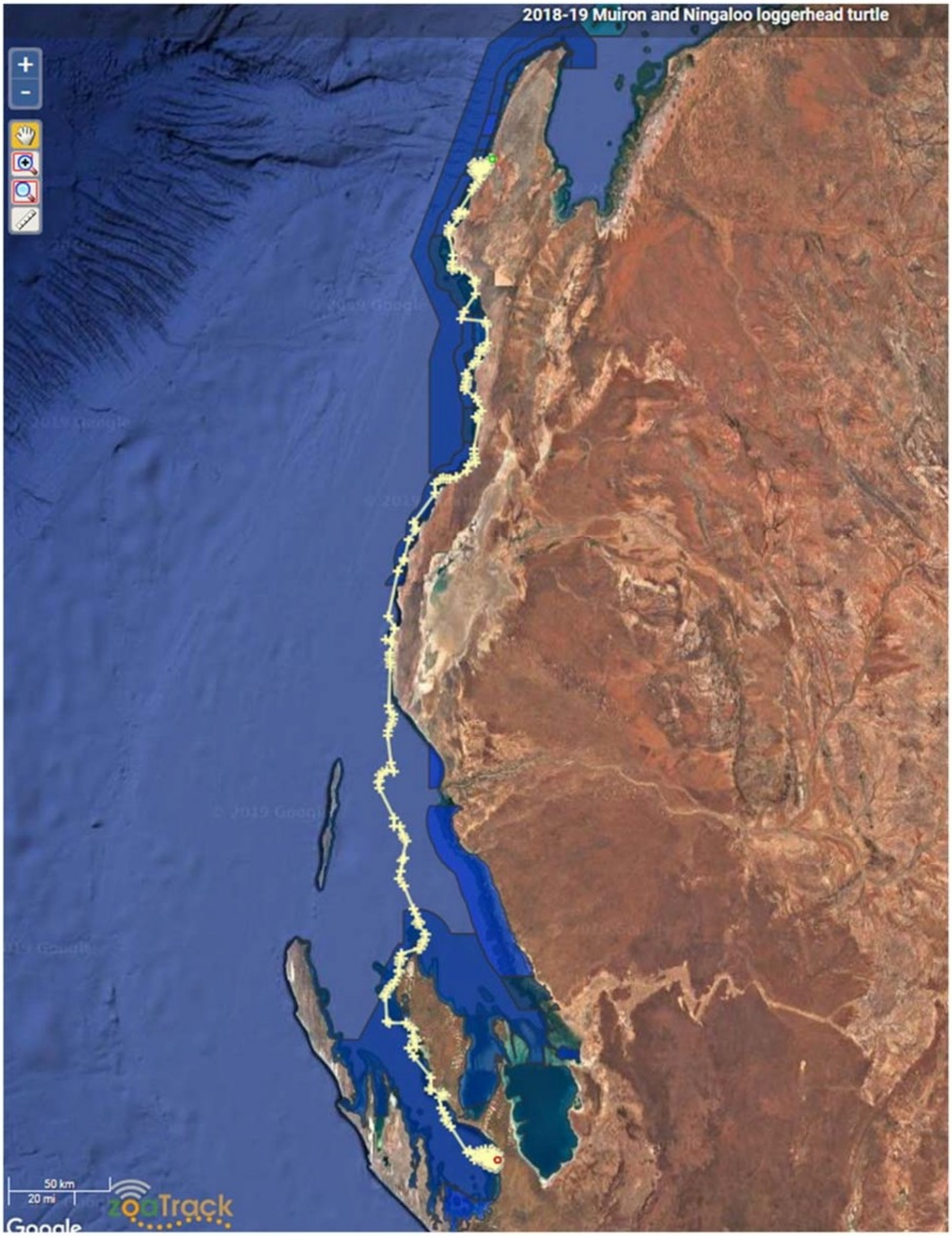

Figure 39. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66294 Total Eclipse of the Heart.

Green circles show deployments, red circles show final displacements.

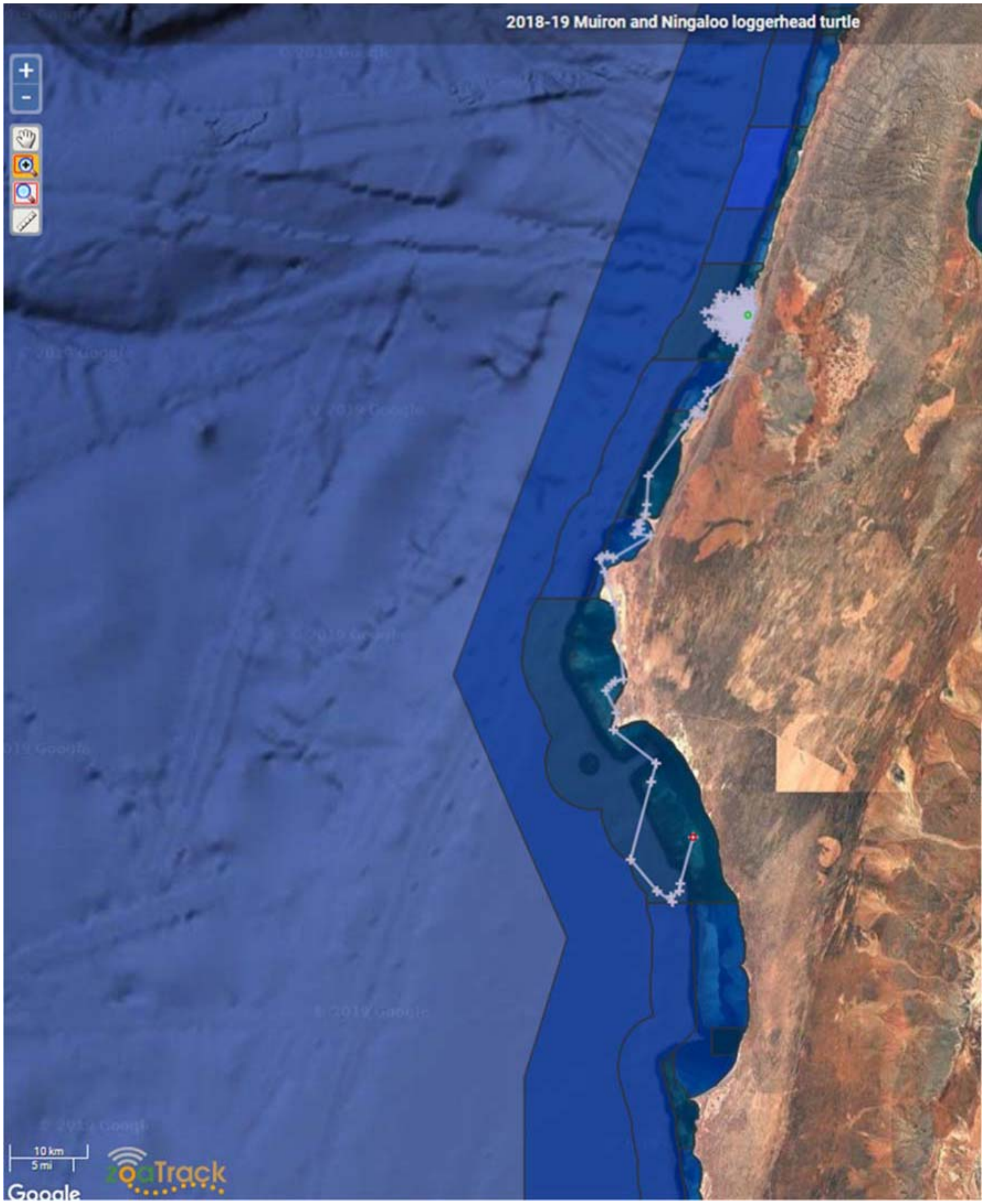

Figure 40. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66302 Elise.

Green circles show deployments, red circles show final displacements.

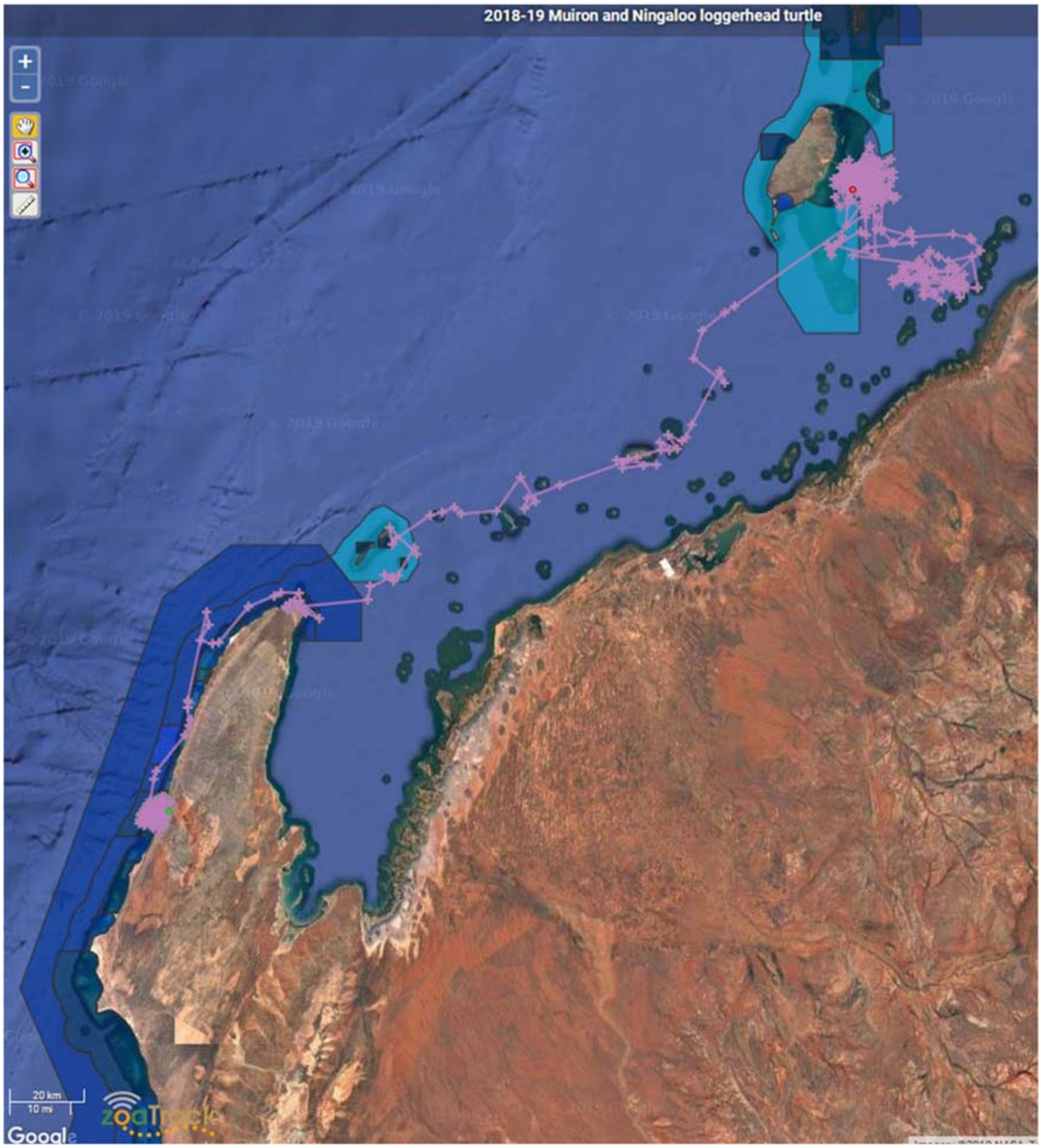

Figure 41. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66303 Sink.

Green circles show deployments, red circles show final displacements.

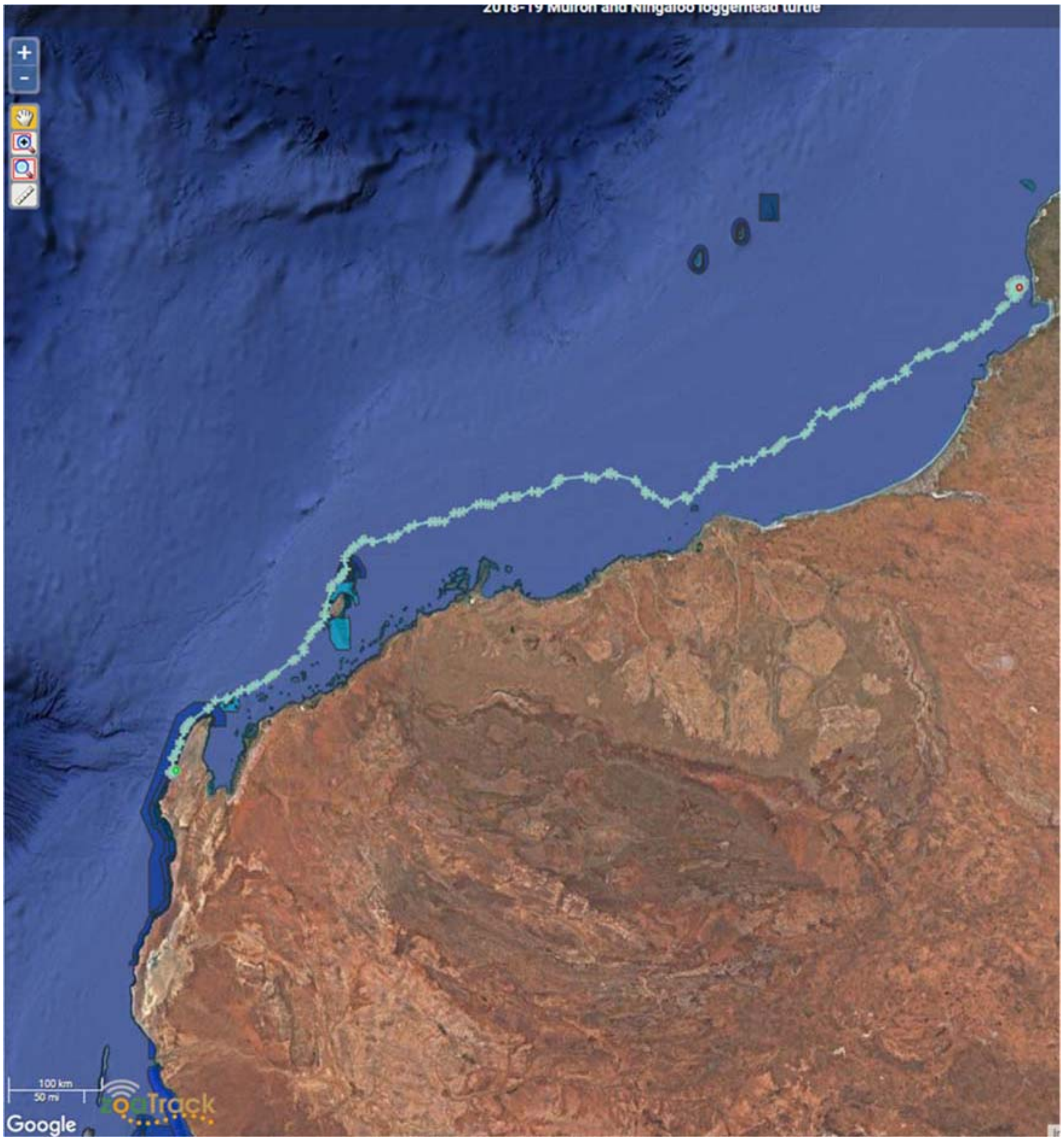

Figure 42. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66318 Adwaita.

Green circles show deployments, red circles show final displacements.

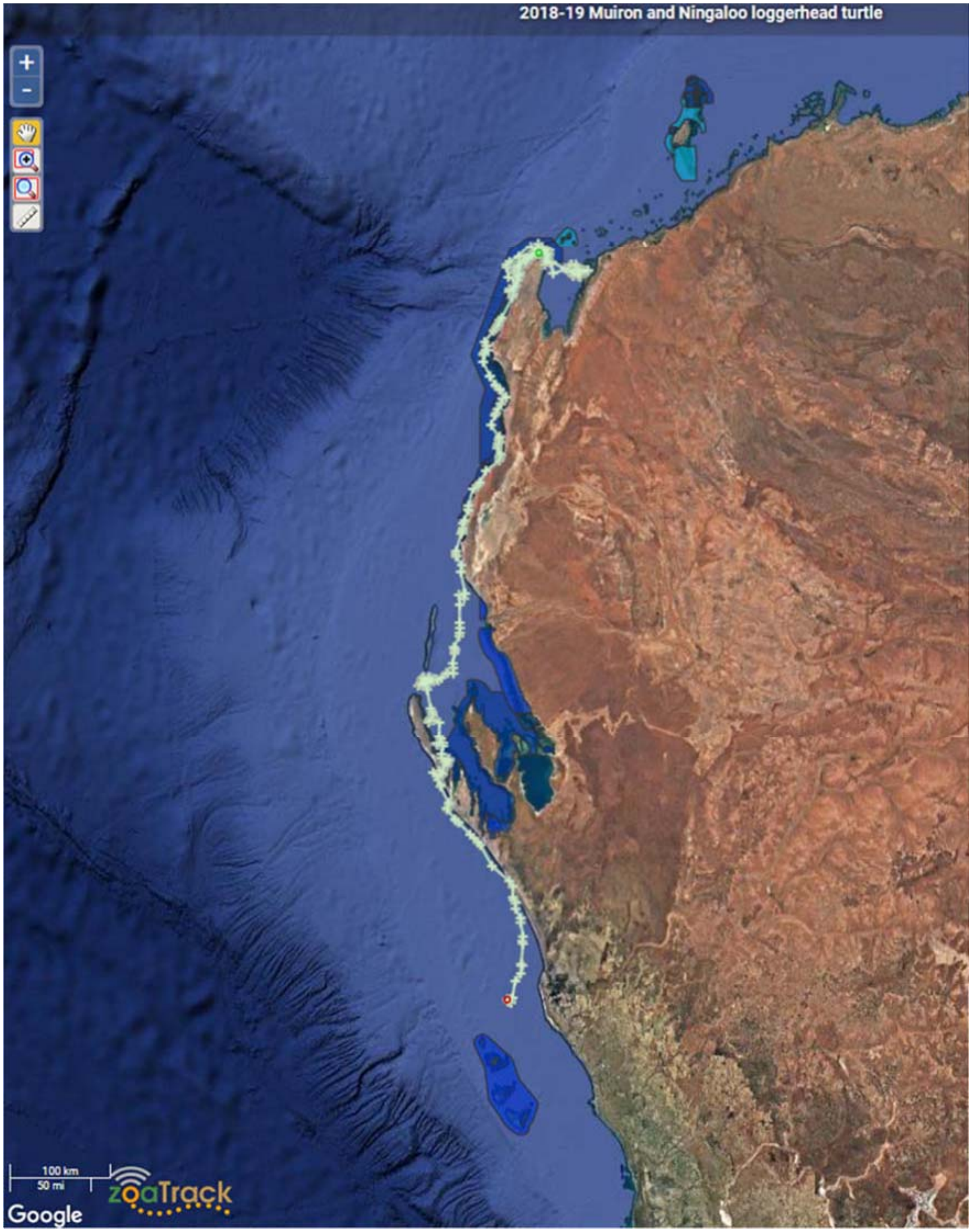

Figure 43. Inter-nesting residence, migration and foraging ground for loggerhead turtle G-66319 Nhuly.

Green circles show deployments, red circles show final displacements.

Appendix 1.

Twelve transmitters included pressure transducers which recorded two parameters: % Time-at-Depth (m) and maximum water pressure calibrated as submergence depths and recorded in daily histograms. The depth sensor tags were deployed on 2 island green turtles, 3 mainland green turtles, 2 island loggerheads, and 5 mainland loggerheads (as documented in **Table 5**). The first column of abbreviations indicates GI = green island rookery, GM= green mainland rookery, LI =loggerhead island rookery, LM = loggerhead mainland rookery, and an abbreviation suffix indicates a behavioural state for IN = inter-nesting, MIG = migration and FG = foraging ground. The number in parentheses is total days recorded in that behaviour for that species.

Time-at-Depth (TAD) histograms are the % of time spent in a specified depth bin. A total of 2488 histograms were obtained that recorded 14 depth bins by 12 turtles with 3 behaviours. The summed histograms per species and behaviour are the data documented below that are best interpreted by viewing **Figures 13, 14, 15,** and **16**. Note that each bin value is the upper limit of the bin. For example, with bin settings of 2, 5, 10,15, … meters, a reading of 5.1 would appear in the 10-meter bin (abridged explanations adapted from Wildlife Computers MK10 Host User Guide (2019)).

Species/ Behaviour	% Time at Depth bin (m) histogram													
Days 2488 d	2	5	10	15	20	25	30	35	40	45	50	60	100	>100
GI-IN 119 d	91.6	3.5	2.4	1.0	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GM-IN 206 d	80.4	17.0	0.9	0.5	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
G-MIG 17 d	53.3	15.2	11.4	8.4	5.4	2.4	1.1	0.5	0.5	0.5	0.4	0.6	0.4	0.0
G-FG 533 d	38.7	22.0	24.5	11.1	3.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LI-IN 98 d	30.4	9.2	23.0	31.9	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LM-IN 225 d	40.0	24.7	17.0	14.1	3.8	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L-MIG 310 d	23.5	9.4	12.6	18.7	13.1	8.4	4.6	2.6	1.9	1.3	1.0	1.5	1.5	0.0
L-FG 1290 d	24.8	23.3	36.4	6.8	5.2	2.9	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.0