FLATBACK TURTLE, *Natator depressus*, SEVEN YEAR REVIEW: 2013-2014 to 2019-2020 BREEDING SEASONS AT CURTIS, PEAK AND AVOID ISLANDS

Colin J. Limpus, Nancy N. FitzSimmons and Milani Chaloupka

Queensland Government

Department of
Environment and Science

Cover photographs:
Scenes from the census of nesting Flatback turtles, *Natator depressus,* 2013 – 2020. Photographs taken by Nancy FitzSimmons

This report should be cited as:

Colin J. Limpus, Nancy N. FitzSimmons, and Milani Chaloupka (2021). Flatback Turtle, *Natator depressus*, Seven Year Review: 2013-2014 to 2019-2020 Breeding Seasons at Curtis, Peak and Avoid Islands. Brisbane: Department of Environment and Science, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 83 pp.

This report has been produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. The study was undertaken under a Consultancy Agreement (CA12000291 [130032]) between Gladstone Ports Corporation and the Queensland Department of Environment and Science to monitor marine turtle nesting at Peak, Avoid and Curtis Islands.

This publication has been compiled by the Queensland Department of Environment and Science (DES).

FLATBACK TURTLE, *Natator depressus*, SEVEN YEAR REVIEW: 2013-2014 to 2019-2020 BREEDING SEASONS AT CURTIS, PEAK AND AVOID ISLANDS.

Colin J. Limpus, Nancy N. FitzSimmons and Milani Chaloupka

Contents page

EXECUTIVE SUMMARY

This report summarises the results of monitoring the eastern Australian (eAust) Flatback turtle nesting population at Curtis, Peak and Avoid Islands during a seven-year period from the 2012-2013 to the 2019-2020 breeding seasons. For each of these seasons a two-week mid-season census was conducted at all three islands. During the 2016-2017 season a near complete season census was conducted on Avoid Island and Curtis Island. Additionally, intermittent monitoring has been done on Curtis Island since 2017-2018.

Number of nesting females and nests

- There was a range of 25 - 58 individual nesting Flatback turtles and 30 - 53 clutches of eggs laid at Curtis Island during the two-week census periods.
- There was a range of 121 – 218 individual nesting Flatback turtles and 114 - 211 clutches of eggs laid at Peak Island during the census periods.
- There was a range of 29 - 78 individual nesting Flatback turtles and 32 - 79 clutches of eggs laid at Avoid Island during the census periods.
-

Recruitment of new females into the annual breeding population

- Curtis Island had highly variable levels of recruitment, from 14.3% – 32.3%, with rates >20% across three years of the study, which is regarded as a high level.
- Recruitment of new nesting females into the breeding population at Peak Island during the census period varied from 10.7% – 19.3%, with relatively low values recorded for four years.
- After five years (including data from 2007-2008 and 2012-2013) of tagging turtles at Avoid Island the recruitment rate stabilised below 20% and ranged from 15.4% – 23.9% in the last four years of the study.

Remigration intervals and rookery fidelity

- The most common remigration interval for nesting females at all rookeries was two or three years. Mean yearly remigration intervals varied among the rookeries and there was an increase in the remigration interval indicated for Peak Island
- It is likely that re-capture intervals will under-estimate actual remigration intervals as not all turtles breeding in a season will be encountered during the census period.
- Nesting females continue to display high fidelity to each island. Only seven of the 1095 (0.6%) tagged turtles encountered at the three rookeries during the study were originally tagged while nesting at a different eAust Flatback rookery.

Demographic parameters

- Nesting Flatback turtles at all three islands show normal demographic features for the eastern Australian Flatback turtle stock in terms of female size, clutch size and egg and hatchling size. The size of experienced females and clutch size were both larger at Curtis Island than at Peak Island or Avoid Island.
- At Curtis, Peak and Avoid Islands, new recruits to the nesting population were smaller than females with a past breeding history. The size of new recruits was the same at the three rookeries.

- The start to the nesting season was recorded at Curtis Island, with the earliest nesting starts ranging from 8 - 23 October. The latest nesting crawl recorded on Curtis Island occurred in the first week of February.
- The first emergence of hatchlings occurred during the last week of November or first week of December.
- The average incubation period from laying to hatchling emergence to the beach surface was under 54 days in all years as recorded at all three rookeries. This indicates a female-bias to hatchling production of clutches laid within the census periods.

Population trends

- There was a substantial decline in the number of turtles and number of clutches laid at Curtis Island during the study. This has occurred since 2013 even though the recruitment of new adults into the nesting population has been at a relatively high rate over much of the same period.
- There was a substantial decline in the number of clutches laid at Peak Island during the study and an observed decrease in the numbers of tagged turtles since 2016.
- At Avoid Island there has been an observed decrease in the numbers of tagged turtles since 2016.
- The observed declines in the number of tagged turtles were significantly correlated between all pairs of rookeries and declines in clutch size were significantly correlated in one-way ANOVA tests (between Peak Island and Curtis Island or Avoid Island.
- At present the observed declines in the number of nesting turtles do not appear to reflect a decrease in population size for the Peak Island and Curtis Island populations based on demographic analyses (Limpus 2022a). Too few years of data at Avoid Island precluded demographic analysis.

Hatchling production

- Curtis Island: Mean nesting success averaged 72%, with only two years below 70%. Incubation success of undisturbed clutches of eggs was good, ranging from 75% - 89% across all years. Emergence success ranged from 64% - 86%, and in only one year was the mean below 75%. These values include clutches that were relocated to prevent inundation.
- Peak Island: Mean nesting success averaged 61%, with only one year above 70%. This is due to turtle attempting to nest in sectors where there is not enough sand. Incubation success ranged from 56% - 89%, with two years below 70%. Hatchling emergence ranged from 39% - 89%, with four years below 70%. The lowest success occurred in 2017/18, largely due to invasive roots in nests which decreased incubation success and entrapped hatchlings in the nest. Removal of weed species alleviated much of this problem.
- Avoid Island: Mean nesting success averaged 66%, with only two years above 70%. This is due to turtles encountering fallen trees and logs, buried branches and steep dune slopes in some areas. Incubation success ranged from 62% - 86%, with two years below 70%. Hatchling emergence ranged from 57% - 86%, with two years below 70%. The lowest success occurred in 2017/1 and 2018/19

which was largely due to the formation of a swale on the upper beach slope that resulted in the inundation of several nests.

Temperature profiles and weather events

- Cyclone Dylan in January 2014, which caused extensive erosion and loss of clutches, was the most significant cyclone to affect the three rookeries during the study. At Avoid Island, it took two years for beach sand to re-establish, but downed trees and the eroded dune face continued to reduce nest success throughout the study.
- Queensland experienced record heatwave conditions during the 2016-2017 and 2018-2019 summers. The extent to which this affected sand temperature at nest depth depended on the extent and frequency of rainfall events, which were observed to lower sand temperatures by as much as five degrees for several days.
- Heat wave conditions resulted in observations of heat stress mortality in several years at Peak Island and Avoid Island of hatchlings preparing to emerge from the nest and of emerged hatchlings. This was particularly apparent at Peak Island from 2016-2017 to 2018-2019.
- Based on sand temperature measurements and incubation period to hatchling emergence values, it is predicted that a female biased hatchling sex ratios will have been produced at all three rookeries, with a strong bias in several years.

Management considerations

- Existing management of feral animals by Queensland Parks and Wildlife Service (QPWS) within the Curtis Island National Park is maintaining Flatback turtle clutch loss to predators such as pigs, dogs and foxes at a negligible level.
- Continued management of invasive plants in the turtle nesting habitat at Peak Island would benefit improved hatchling production.
- Existing management by Trust for Nature at Avoid Island is providing important protected habitat for the eastern Australian nesting population of Flatback turtles in an area free of large terrestrial predators of their eggs and well removed from the impacts of urban and industrial development.
- Major concerns include:
    - a predicted feminisation of the population due to a female biased hatchling production,
    - light pollution which is observed to affect turtles at the Curtis Island rookery,
    - a need for continued monitoring of the nesting females to understand the apparent contradiction between the observed reductions in the number of nesting turtles versus the demographic analyses indicating increasing population trends.

CHAPTER 1. INTRODUCTION

This study has been conducted under an agreement between the Gladstone Ports Corporation (GPC) and the Queensland Department of Environment and Science (DES) to continue monitoring of Flatback turtle (*Natator depressus*) nesting and the success of incubation and hatchling emergence at the South End Beach, Curtis Island, Peak Island and Avoid Island (Figure 1.1) for the duration of the 2013-2014 to 2019-2020 breeding seasons. This monitoring is supported by GPC's Ecosystem Research and Monitoring Program (ERMP). This report covers seven years of monitoring these rookeries under this program.

These three rookeries are part of the eastern Australian Flatback turtle population, also referred to as the eAust Flatback stock or management unit (Figure 1.2). (FitzSimmons and Limpus, 2014a). This population is distinct from all other Flatback rookeries to the west of Torres Strait (FitzSimmons and Limpus, 2014a; FitzSimmons *et al*. 2019). Flatback turtle are essentially endemic to Australia, as they only nest in Australia and their foraging areas are mostly restricted to Australian continental shelf waters. The biology of the eAust Flatback turtle population has been reviewed (Limpus, 2007; Limpus *et al*. 2013).

Curtis Island is a moderate sized rookery that is located near substantial industrial development and potential light pollution. It is one of the index nesting areas that has been monitored annually across decades for this species. Peak Island has previously supported the largest nesting aggregation for Flatback turtles within the eAust stock and is an established index beach for long-term monitoring of Flatback turtles. Avoid Island is a moderate sized rookery located towards the northern extent of the population's nesting range (Limpus *et al*. 2002) in a remote area that is not influenced by industrial development or light pollution from the mainland.

Monitoring of the rookeries is ongoing and conducted to determine the size of the nesting population and population trends over time, the proportion of newly recruiting females, the size of females, clutch size, egg size, incubation and emergence success, hatchling size and condition and variability in hatchling production in different areas of the beaches monitored. To assess the impacts of artificial light, data are collected on the orientation ability of females when they ascend the beach to lay eggs and descend afterwards, and of hatchlings as they travel to the water's edge. Additionally, data are collected on beach sand temperatures at nest depth to determine the likely sex ratio of hatchlings. These data will be reported elsewhere.

CHAPTER 2. GENERAL METHODS

Standard methodologies of the Queensland Turtle Conservation Project (QTCP) within the DES Aquatic Threatened Species Program were followed to monitor nesting females and their clutches (Limpus *et al*. 1983; Limpus, 1985). Statistical procedures follow Zar (1984). Proportional data were presented as the value ± 95% confidence interval.

Any variation to the methods followed during the seven years of monitoring at these islands can be found in the yearly reports (FitzSimmons and Limpus 2014b, 2015, 2016; Limpus *et. al*. 2017, 2018, 2019, 2022b; Pople *et al*. 2016; Twaddle *et al*. 2014, 2015).

Monitoring teams included DES staff and QTCP Volunteers with prior training for the methodologies being implemented.

Nesting activity

Data on nesting activity were recorded at all three rookeries during a minimum of the two-week, mid-season census period:

- At Curtis Island, in addition to the standard census period since 2017-2018 intermittent monitoring of the turtle nesting by local volunteer members of the study team occurred throughout most of the nesting season.
- At Avoid Island in addition to the standard census period on all eastern beaches, referred to as South Beach, Middle Beach and North Beach, additional monitoring on South Beach was conducted during some seasons for 2 - 9 additional nights.
- During the 2016-2017 nesting season nesting activity and hatchling emergence was monitored for the entire season at Curtis Island (14 October 2016 – 13 April 2017) and for nearly the entire season at Avoid Island (28 October 2016 – 1 March 2017).
- The 14-day mid-season census is referred to as the ‘census period’.

Nightly monitoring began at least two hours before high tide and continued for at least two hours after low tide, or longer if turtles were still active on the beach. Procedures included:

- Encountered turtles left the beach with a minimum of two titanium tags (manufactured by Stockbrands Australia) in the front left and right flippers at a designated tagging position (Limpus, 1992), generally proximal to the flipper scute closest to the body. If scar tissue from previous tagging made this position unsuitable for tagging, tags were applied distally to this scute.
- Passive Integrated Transponder (PIT) tags (Parmenter, 1993) were injected into the upper left (or occasionally right) shoulder (just below the carapace) of nesting females. PIT tags were manufactured by Animal Electronic I.D Systems or Smartrac.
- Curved carapace length (CCL ± 0.1 cm) was measured from the skin/carapace junction at the anterior edge of the nuchal scale, along the midline, to the posterior junction of the two post-vertebral scutes at the rear of the carapace using a

flexible fibreglass tape measure. Any barnacles living along the midline of the carapace were removed prior to measuring.

- Any damage to the turtle or unusual features were recorded and photographed if possible (Figure 2.2).
- A nest tag (flagging tape ~20 cm long) with the date of laying and a tag number of the turtle (Limpus, 1985) was placed in the nest during oviposition for most clutches. The nest tag enabled identification of individual clutches of eggs when excavated following hatchling emergence some two months later. The vast majority of this plastic material was removed from the beach during excavation of clutches following hatchling emergence.
- A subset of clutches of eggs were counted and 10 eggs were selected to represent a cross-section of eggs from top to bottom of the nest. Each selected egg was weighed (± 0.1 g) on a digital balance and measured for maximum and minimum diameter (± 0.1 mm) with Vernier callipers. To minimise movement induced mortality of eggs all handled eggs were returned to their respective nests within two hours of being laid and with the minimum of rotation (Limpus *et al*. 1979).
- Nest locations were recorded using a hand-held GPS (global positioning system) unit (± 4 m). Habitat type of the nest location was recorded including the beach profile location and vegetation type near the nest.
- To identify marked nests after hatchling emergence, somewhat different techniques were used at each rookery in addition to GPS locations:
    - At Curtis Island, all clutches were marked with two timber marker pegs (25 mm x 25 mm x 400 mm) that were labelled with a unique nest number. One marker peg was placed two hand spans from the nest, and the second maker peg was placed one hand span from the first marker peg, in line with the nest.
    - At Peak Island, nest locations were recorded as GPS locations and identified with nest tapes placed with the eggs. Data were collected from emerged clutches when hatchling tracks were visible.
    - At Avoid Island, initially nest locations were mapped by measuring to trees that were identified by GPS and on hand-drawn maps. In 2017, sector numbers were established on trees or posts on South Beach and North Beach and these were used for measuring distances to nests.

Rescuing doomed eggs

DES supports the rescue of doomed turtle eggs for highly threatened populations when eggs are laid in areas considered to be at risk of loss from predation, flooding or erosion during incubation (Pfaller *et al.* 2008). Eggs may also be rescued where coastal lighting is likely to disrupt hatchling ocean finding behaviour and cause hatchlings to move inland away from the sea. Doomed clutches of eggs were relocated to safer incubation sites either higher up the dunes or to an adjacent dark area of the beach in response to the identified threats. Eggs are relocated (within two hours of oviposition and with the minimum of rotation) to artificial nests that are 55-60 cm deep with a 50 cm radius “body pit” from which surface vegetation has been cleared within 2 hours of oviposition and with the minimum of rotation (Limpus *et al.* 1979).

Incubation and emergence success

Nests were excavated after hatchlings had emerged for assessing incubation success and hatchling emergence success. Previously marked nests were located using GPS locations, and measurements from marker trees, posts or pegs and confirmed by the presence of nest tags. Nests were dug no sooner than 24 hours after hatchling emergence or after eight weeks if hatchlings had not emerged. Procedures included:

- If hatchling emergence was observed and when logistically feasible, a sample of 10 hatchlings (+ any 'live in nest') were weighed (± 0.1 g), measured (± 0.1 mm) with Vernier callipers and the scale pattern counted.
- Observations of heat stress were noted that included:
    - dead hatchlings in the neck of the nest that were not otherwise trapped by roots from emerging,
    - dead hatchlings that had emerged but died in the vicinity of the nest, with no signs of predation.
- The number of hatched eggs was determined by counting the number of eggshell fragments that were larger than 50% of that expected from an entire egg.
- Clutches were assessed for any signs of predation by crabs or other animals and counts were made of any hatched live or dead hatchlings within the nest.
- Un-hatched eggs were opened to determine whether the embryo had developed to an observable stage or whether it appeared to be undeveloped.
- Incubation success was calculated as: (hatched eggs/estimated clutch count) x 100%.
- Emergence success was calculated as: (hatched eggs – [live + dead hatchlings]/estimated clutch count) x 100%.
- Counting error, the accuracy of counting broken eggshells was calculated as: estimated clutch count following hatchling emergence minus clutch count made when the eggs were laid.
- The depth to the bottom of the egg chamber was measured (± 5 mm) and observations on the nest environment were made with respect to erosion and water inundation.

Environmental Monitoring

Vemco Minilog II temperature data loggers have been deployed for a number of years at turtle nesting beaches in Queensland to measure sand temperatures at 50 cm depth at 30 min intervals. These temperature recording instruments can record temperature continuously for up to 10 yr. Temperature data loggers were deployed at various times and locations at these three rookeries to monitor long-term temperature variability in the nesting habitats.

Cyclone data and daily or monthly temperature and rainfall data at selected recording stations were obtained via the Australian Bureau of Meteorology (BOM) website.

Temperature variation across nesting seasons

Bureau of Meteorology (BOM) summary data for all of Australia indicated that the annual mean temperature anomalies for the duration of the study ranged from +0.94

– 1.52°C and included eight of the 10 highest anomalies since records commenced in 1910 (Figure 2.3).

There was substantial variation in monthly mean maximum temperatures across the seven years based on records from the Gladstone Airport (#39326), St Lawrence (#33210) and Yeppoon (#33204) recording sites, which span the geographic range of the monitored beaches (Figure 2.4). Temperatures were generally the highest at St Lawrence and the lowest at Yeppoon. Notably high monthly mean temperatures were observed in February 2017 and December 2019 (Figure 2.4). A BOM report (BOM, 2020) identified the summer of 2019-2020 as a summer of record-breaking temperatures and heatwave conditions stating "2019 was the warmest December on record Australia-wide and for all mainland States except Victoria. 2019−2020 went on to be the second-warmest summer on record Australia-wide, and for area-averaged Queensland, the Northern Territory, and Western Australia".

Rainfall variation across nesting seasons

Rainfall data were summarised for the monthly rainfall totals from BOM weather stations that were nearest to the Avoid Island, Peak Island and Curtis Island rookeries (Figure 2.5). Not all weather stations had complete data records so if the nearest station did not have complete records then the next nearest stations were included to derive a complete data set with averaged values. For Avoid Island, records were used from Carmila-The Valley #33071, Carmila-Beach Road #033186, Orkable West Hill #33095, and St Lawrence #33210. For Peak Island, data were taken from Yeppoon-The Esplanade #33024 and Sevendsen Beach #33260 on Great Keppel Island. For Curtis Island, data were taken from Gladstone Airport #39326.

Cyclone activity across nesting seasons

Cyclones caused nest inundation or beach erosion during three of the monitored nesting seasons. Information about the cyclones was sourced from the BOM, 15 April 2021 at: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/past-tropical-cyclones/.

- 31 January 2014: Tropical Cyclone Dylan crossed the Queensland coast near Bowen as a category 2 cyclone. This cyclone "combined with a ridge of high pressure situated to the south of the system to cause increased tides and strong to gale force winds along a large stretch of the Queensland east coast in the days leading up to Dylan's landfall. Dylan also caused heavy rainfall along parts of the central Queensland coast".
- 20 February 2015: Severe Tropical Cyclone Marcia crossed the Queensland coast at Shoalwater Bay as a category 5 cyclone. Erosion occurred at the monitored beaches, with BOM noting "A large storm surge was recorded across the Capricorn coastline, with significant beach erosion…" A storm surge of 2.0 m was recorded at Port Alma. The extent of beach erosion by the cyclone was mitigated by it crossing the coast during a low tide.
- 12-13 February 2020: Tropical Cyclone Uesi tracked south through the Coral Sea, passing approximately 1,000 km east of the central Queensland Coast as a category 3-2 Cyclone. Uesi caused abnormally high tides and large

waves along the New South Wales and southeast Queensland coast. “Maximum wave heights of 5-6 metres were generally recorded along areas of the southeast Queensland coast during the event”.
- 13-15 March 2020: Tropical Cyclone Gretel tracked “in a consistent south-eastward direction across the Coral Sea region” as category 2-1 Cyclone. Gretel caused abnormally high tides and large surf about the southeast Queensland and northern New South Wales coasts

Hatchling sex ratio theory

The sex of marine turtle hatchlings is determined by the temperature of the nest presumably during the middle third of incubation (Reed, 1980; Yntema and Mrovosky, 1982). The pivotal temperature, the theoretical temperature that will result in equal proportions of male and female hatchlings for the eAust Flatback turtle population is 29.3^{o}C (Limpus, 2007), with higher temperatures producing females and lower temperatures producing males. If Flatback turtle eggs incubate at a constant temperature of 29.3^{o}C, hatchlings should emerge from their eggs approximately 52 days after the eggs were laid (DES unpublished data). Therefore, incubation duration can also be informative about the sex of hatchlings. Allowing for the time taken for hatchlings to dig to the surface from the hatched eggs, the pivotal period from laying to hatchling emergence to the beach surface (period to emergence) should be approximately 54 days. Longer periods to emergence should be indicative of cooler nests when the sex is determined and hence increased male ratio among hatchlings. A shorter period to emergence should be indicative of warmer nests and increased female ratio. Rainfall will influence this as cool rain results in a decline in sand temperatures at nesting beaches. In contrast, sand temperatures increase in the short term in the absence of rain as a result of reduced evaporative cooling within the sand (Reed, 1980).

CHAPTER 3. CURTIS ISLAND STUDY

Study Area

South End Beach, Curtis Island (23°45'S, 151°18'E), has supported a medium density nesting population of the Flatback turtle, *Natator depressus*, a turtle found only in Australian continental shelf waters. This large sand island situated off the coast of Gladstone extends for ~100 km to the north. The small South End village lies on the south-eastern tip of the island (Figure 3.1). The majority of the turtle nesting for the island occurs on the adjacent South End Beach, which is approximately 5 km in length. In some years, there is occasional nesting by green turtles (*Chelonia mydas*) and/or loggerhead turtles (*Caretta caretta*).
While the rookery has been monitored intermittently since 1969 (Limpus, 1971a), it has been monitored annually since 1994 with support from the Gladstone Ports Corporation (Limpus et. al. 2006, 2013, 2017, 2018, 2019). Curtis Island has one of the longest histories of monitoring of Flatback turtle breeding in Australia, and hence the world.

Methods specific to Curtis Island

South End Beach was monitored on a daily basis during the 14-day census periods each year. Additional data were collected during nightly monitoring of nesting turtles, or from daytime monitoring of nesting activity outside of the census periods for 1-2 weeks in 2013-2014 and 3-4 weeks in 2014-2015 and 2015-2016. Monitoring of nesting turtles was done for the duration of the nesting period in 2017-2018, 2018-2019 and 2019-2020. Monitoring in 2016-2017 was done for the entire breeding season of nesting through to the end of hatchling emergence. Intermittent data collection was also done by the community during most years, which often provided data on the dates of the first and last clutches and first hatchling emergence.

During the monitoring by the turtle teams, nests that were considered to be at risk from flooding were relocated further up the dune within one hour of being laid and their eggs counted. In addition to the evening monitoring, the beach was examined once or twice daily depending on tides to count nesting crawls, to locate hatchling emergence and identify daylight nesters. Various vehicles were used to patrol the beach over the years.

Sand temperature data from the two Vemco Minilog II temperature data loggers that have been deployed in open sunny areas within the nesting habitat at opposite ends of South End Beach, Curtis Island since the 2016-2017 breeding season were not downloaded during the 2019-2020 breeding season.

During the 2013-2014 season, fox exclusion devices (FEDs) made from standard plastic garden mesh were laid horizontally at the beach surface over a series of nests to prevent foxes from digging into clutches of turtle eggs (Figure 2.1). These plastic mesh (100 mm grid size) panels were approximately 1x1 m^2 square. They were placed over clutches of turtle eggs within two hours of the eggs being laid. Each mesh panel was held down by 25x25x400 mm timber pegs, one in each corner of the panel.

For each clutch protected with a FED, a clutch laid on the same or following night was left unprotected as a set of control clutches. All clutches laid during the nesting census period, both those with FEDs and the unprotected clutches, were identified using adjacent markers on the beach surface. When beach was monitored for incubation and emergence success, the effectiveness of FEDs in protecting the clutches from fox predation was assessed (Figure 3.2).

Trapping, baiting, or shooting of feral canids (foxes and dogs) was conducted on several occasions from 2014 until early 2017. The success of those efforts allowed a reduction in the use of FEDs, thus FEDs were deployed for the entire period of monitoring as follows:

- 2013-2014: 43 nests covered by FEDs
- 2014/-2015: 20 nests covered by FEDs
- 2015-2016: 26 nests covered by FEDs
- 2016-2017: 4 nests covered by FEDs
- 2017-2018: no FEDS used
- 2018-2019: no FEDS used
- 2019-2020: no FEDs used

RESULTS

Nesting activity, nesting success and recruitment

Dates for the first nesting activity ranged from 8 to 23 October and the last nesting activity occurred from 11 January - 2 February. Within the census periods the average number of tracks per night ranged from 2.6 - 5.1 across the seven years (Figure 3.3, Table 3.1). Across years, the overall average number of tracks per night was 4.0 (SD = 0.81; Table 6.1) and since 2017, the values have been below the average value.

The number of tagged turtles during the yearly census ranged from 25 - 58, with an average value of 37.4 (SD =10.0) (Figure 3.4, Tables 3.1, 6.1). Since 2017, the values have been below the average value. During 2016, when nesting activity was monitored for the entire season, 49 tagged turtles were observed.

For the duration of the study only two turtles were observed that had originally been tagged elsewhere. Turtle K97501 observed in 2016-2017 was tagged as a nesting turtle at Peak Island in 2008 and last seen there in 2012. Turtle QA50621 observed in 2017-2018 was tagged at Mon Repos in 2014 and only observed there once. A third turtle QA50817 observed in 2016-2017 is thought to have originally tagged at Facing Island.

Recruitment rates of estimated 1st time nesters (turtles not previously tagged) were higher than the 10 - 20% range reported in Limpus (2007) for the three years of the study. Across all years, values ranged from 14.3 to 32.3, with an average of 21.6 (SD = 6.4, Figure 3.4, Tables 3.1, 6.1).

The average number of clutches laid per night ranged from 2.1 - 3.8 with a yearly average value of 2.8 (SD = 0.52) (Figure 3.5, Tables 3.1, 6.1). Across years the average number of clutches was per night was correlated (R^2 = 0.86, p = 0.0025) to the average number of tracks per night. An average of 39.9 clutches (SD = 8.7, range = 30 - 58) were laid within the census periods over the seven years (Figure 3.5, Tables 3.1, 6.1).

Average nest success, which is based on the proportion of nests in which eggs were laid relative to the number of nesting crawls, ranged from 59.7% - 82.1%, with an average value of 71.5% (SD = 6.5%) (Figure 3.5, Tables 3.1, 6.1).

Nesting females: size, fecundity

Females that were experienced nesters were consistently larger than new recruits. Taking the average of the yearly mean CCL values, experienced nesters averaged 94.7 cm (SD = 0.57) and new recruits averaged 92.1 cm (SD = 0.95) (Tables 3.1, 6.1).

Remigration interval, the number of years between recorded breeding seasons, averaged across the years of the study between 2.8 - 3.5 yr, providing a yearly average of 3.3 yr (SD = 0.28) (Tables 3.1, 6.1). These data suggest a trend towards somewhat longer (>3 yr) average remigration intervals since 2016. Graphing the distribution of individual remigration intervals did not show an obvious trend across years with the majority of turtles having remigrated after two (in 2014, 2015, 2017) or three years in (2013, 2016, 2018, 2019) (Figure 3.6).

A problem in the interpretation of the remigration data is the extent to which nesting turtles are missed during the census in a given year, which would over-estimate the remigration interval. Across the years of the study there were from 2 - 8 (mean = 3.9) nests laid by turtles that were missed during the census.

Inter-nesting intervals between a successful nesting and the subsequent return to lay another clutch varied from an average of 13.0 - 15.5 d, with a mean across seven years of data of 14.2 (SD = 0.70) d (Tables 3.1, 6.1). Return intervals for turtles that crawled out of the water but failed to lay eggs varied from a mean of 0.60 – 1.6 d, with a mean across years of 0.84 d (SD = 0.33) (Tables 3.1, 6.1).

There was an average of 51.6 - 62.8 eggs per clutch over the seven years, with a yearly average of 55.3 (SD = 3.6) eggs. Summary data on clutch egg size and nest depths are given in Tables 3.1 and 6.1.

Health and injuries

During the seven years of the study there were two turtles recorded that had fresh injuries in the 2016-2017 season. One turtle had an extensively fractured rear carapace, thought to have occurred when it would have been dropped onto the deck from a trawl net (Figure 2.3). The other turtle had healed fractures from propeller damage, which had not been observed when previously encountered in 2013 (Figure 2.3). In 2014-2015, there was a turtle that died from suffocation due to inhalation of fine sand. While filling below a steep dune she was covered by sand and took deep breathes while under the sand. She was rescued but died while returning to the water. Cause of death was verified by a veterinarian.

Nest and hatchling disturbance and depredation and island fauna

Causes of concern at Curtis Island have been the inundation of clutches laid below the high tide level, observed predation of clutches by dogs and foxes, and possible trampling of nests by horses and cows.

Relocation of clutches during the entire period of monitoring occurred in all years as follows:

- 2013-2014: 17 of 76 clutches, representing 22.4% of clutches
- 2014-2015: 26 of 40 clutches, representing 65.0% of clutches
- 2015-2016: 7 of 45 clutches, representing 15.6% of clutches
- 2016-2017: 37 of 163 clutches, representing 22.7% of clutches
- 20172018: 3 of 138 clutches, representing 2.2% of clutches
- 2018-2019: 5 of 91 clutches, representing 5.5% of clutches
- 2019-2020: 4 of 109 clutches, representing 3.8% of clutches

Given the wide variation in the number and percent of clutches relocated, it is not possible to attribute the proportion of variation to changes in turtle behaviour, or changes in the assessment of possible inundation made by the different monitoring teams. Summed across all years, 15.0% (99 of 659) of clutches were relocated throughout the study.

The success of the feral animal control by Queensland Parks and Wildlife Service (QPWS) was apparent in the reduction of predation over the duration of the study as follows:

- In 2013-2014, when 43 of the 76 clutches laid during the entire monitoring had been covered by FEDs, it was not possible to get complete data on the success of the FEDs because 14 of them had been eroded by storm activity of Tropical Cyclone Dylan. Of the remaining 29 nests, none had evidence of dogs or foxes digging in the vicinity. One of the paired control nests without a FED, of which 18 had not been eroded, one had been destroyed by dogs. At least eight other clutches were destroyed by dogs, representing at least 11.8% of clutches.
- In contrast, there was no evidence of dogs or foxes present during the 2014-2015 monitoring.
- In 2015-2016, there was no evidence of foxes, but two clutches were dug into by a dog that had killed hatchlings.
- In 2016-2017, no tracks of dogs or pigs were observed throughout the season. Fox tracks were observed from 21 December to 30 January, leading to predator control actions. Foxes disturbed 27 clutches (16.6%), during incubation or at hatchling emergence, four clutches were disturbed multiple times. One fox and one dog were trapped on 30 January 2017 and no sign of fox predation was recorded after that.
- In 2017-2018, there were 3 of 35 (8.6%) clutches were predated by dogs after hatchling emergence.

- In 2018-2019 and 2019-2020, there was no evidence of canid tracks or predation.

Clutches

Clutch size varied from an average of 51.6 – 62.8 eggs per year, with a yearly average of 55.3 (SD = 3.6) eggs per clutch (Tables 3.1, 6.1). Average egg diameters ranged from 5.04 to 5.32 cm per year, with a yearly average of 5.19 cm (SD = 0.08 cm) (Table 3.1, 6.1). Average egg weights ranged from 71.7 – 77.0 g per year, with a yearly average of 75.8 g (SD = 1.8 g) (Tables 3.1, 6.1). Nest depth to the top of the nest upon laying ranged from 34.9 – 44.8 cm per year, with a yearly average of 42.0 cm (SD = 3.6 cm) (Tables 3.1, 6.1). Nest depth to the bottom of the nest ranged from 55.4 – 62.0 cm per year, with a yearly average of 58.4 cm (SD = 2.7 cm) (Table 3.1, 6.1).

Incubation duration

The incubation period to hatchling emergence was obtained for several clutches each year. The average incubation period to hatchling emergence to the beach surface ranged from 47.0 – 52.0 d with a yearly average of 48.4 d (SD = 1.6) (Tables 3.1, 6.1), which is less than expected (54 days) if clutches were incubated at pivotal temperature during the critical middle third of incubation. Within the census periods the range in the period to emergence only included durations of 54 days or greater in 2013-2014 and 2014-2015. Since then, durations of 54 days or greater have only occurred outside of the census periods.

Incubation and emergence success

Incubation success varied from an average of 74.7 – 87.7% per year, with a yearly average of 83.0% (SD = 5.3%). Hatchling emergence success ranged from 64.2 – 86.4%, with a yearly average of 79.5% (SD = 7.0%) (Figure 3.7, Tables 3.1, 6.1). Several clutches were lost to erosion in years of cyclone activity.

Sand Temperature monitoring

Rainfall and air temperature data recorded at the BOM weather stations at Gladstone Airport (#39326), were obtained to compare variation in monthly values throughout the study (Figures 2.4a, 2.5c). Air temperatures during the breeding season were highest in February during most years and there was a spike in temperature in December 2019. The most prominent peak in rainfall occurred in March 2017, which coincided with a drop in sand temperatures late in the season.

Temperature data loggers were deployed on South End Beach, situated within the nesting habitat of the frontal dune within open sunny locations at opposite ends of the beach

Temperature data are summarised as follows:

- 2013-2014, 2014-2015: Two temperature data loggers were deployed in 2014 but were later stolen.
- 2015/-206: Data loggers were replaced, but not successfully downloaded.

- 2016-2017: Data collected from 1 November 2016 - 15 March 2017 at the southern end of South End Beach indicated that the temperature rose above pivotal temperature of 29.3°C on 4 December, after which there were three drops in temperature below 29.3°C until finally staying above 29.3°C on 11 January. The drops in temperature lasted from 1.5 - 6 d.
- 2017-2018: The temperature at the southern end of South End Beach rose above minimum incubation temperature of 25°C around 8 October, and above the pivotal temperature of above 29.3°C on 19 December. This was followed by three rainfall events which resulted in temperatures that fluctuated 1 - 2°C above and below 29.3°C from 2 February until 8 March when the temperature stayed below 29.3°C.
- 2018-2019: Temperature data from both data loggers on the South End Beach were downloaded on 23 January. Temperatures at the southern end of the beach did not rise above pivotal temperature of 29.3°C but was near 29.3°C on three occasions in January. Temperatures at the northern end of the beach rose above 29.3°C on 21 November but fluctuated about 2°C above and below 29.3°C until 12 January when it rose above 29.3 °C, until 23 January.
- 2019-2020: Temperature data were not downloaded.

Recording of temperatures prior to the commencement of the nesting season, showed that the 1st clutches were not laid until after the sand at nest depth had risen above the minimum incubation temperature of 25°C and that all clutches had emerged prior to the temperature dropping below 25°C.

High rainfall events were shown to contribute to cooling sand temperatures at nest depth by several degrees. In 2018-2019 this was associated with three tropical cyclones in the Coral Sea.

DISCUSSION

Nesting activity

This study has contributed another seven years of data to a long-term annual monitoring program since 1994 with support from the GPC (Limpus *et al*. 2006, 2013, 2017, 2018, 2019). Apparent trends within the seven-year study were a decrease since 2016 in the number of tagged turtles and clutches laid, and the related parameters of the number of tracks and clutches per night, which was a cause for concern. A post-hoc trend analysis using a linear regression indicated this was a significant decline ($y = 75.4 – 4.32x$, $p = 0.012$) in the number of tagged turtles observed during the census periods. However, analysis of capture-mark-recapture data across 27 years indicated a stable nesting female population from 1993 onwards, with a possible increase since 2016 and an estimated size of approximately 138 adult females in the total population (Limpus *et al*. 2022a).

A large range in recruitment rates (16-33%) was observed across the years, with the highest rate observed in 2019-2020 after a decline in the previous two years. Given the problems of determining actual recruitment rates of first-time nesters into the population from field data a modelling approach (Pradel temporal symmetry) was used to better determine recruitment (Limpus *et al*. 2021). That analysis found that recruitment rates before 2010 were lower than after 2010 and that the long-term mean per capita recruitment rate was 11.3%. The increased apparent recruitment rate observed during the study may be indicative of the suggested increase in population size, however the apparent decline in the number of observed turtles indicates that continued long-term monitoring is needed.

Nesting success, the proportion of nests in which eggs were laid relative to the number of nesting crawls, was very good at Curtis Island, with values since 2017 all above 70%. Throughout the study there was no significant disturbance of nesting turtles when they came ashore.

Nesting females

Flatback turtles nesting at Curtis Island continued to be almost exclusively turtles that were originally tagged while nesting at Curtis Island as recorded previously (Limpus *et al*. 1984). Over the seven years of the study a total of 193 turtles were encountered throughout all monitoring, and of these, only three turtles (1.6%) had been tagged originally nesting elsewhere. Conversely, satellite tracking of 11 nesting Flatback turtles at Curtis Island in 2014 - 2015 suggested three of the turtles also nested at nearby beaches, two at Facing Island, immediately to the south of Curtis Island, and one at Rodds Bay, approximately 43 km to the south (Hamann *et al*. 2015). The strong fidelity of Flatback turtles to nest at the Curtis Island rookery reinforces the need to protect this beach, and the satellite telemetry data reinforces the value of community programs that monitor local beaches.

As observed previously, experienced nesters were consistently larger than new recruits, suggesting that nesting Flatback females continue to grow after they commence egg laying. This size difference ranged from 1.0 – 4.4 cm across the different breeding seasons. Although mean sizes vary between the two categories, there is a broad overlap in sizes.

Average yearly recapture intervals suggested remigration intervals of three years throughout the study, but the distribution of recapture intervals for each year showed that during three breeding seasons the most common interval was two years, and for two breeding seasons similar numbers of turtles were observed after two or three years. Two breeding seasons with a mode value in three-year recapture intervals were in 2016 and 2019. A problem in the interpretation of the remigration data is the extent to which nesting turtles are missed during the census in a given year, which would over-estimate the remigration interval. One indication of this problem was that for 2 - 8 nests per census the female was not encountered during the census. Additionally, in 2016 when monitoring occurred over the entire season 29.6% (16 of 49) of turtles were only encountered outside of the census period. Modelling of capture-mark-recapture data since 1993 indicated that the yearly recapture probability had a wide range from 13% - 83% (mean = 45%), (Limpus *et al*. 2021). Therefore, many turtles that nest in a given year were missed during the monitoring, particularly as the only data collected is during the census period. A generalised additive mixed regression model was fitted to the Curtis Island long-term dataset and no statistically significant trends based on age, year, cohort or carapace size was found (Limpus *et al*. 2021).

Inter-nesting intervals, the time between laying successive clutches ranged from an average of 13.0 – 15.5 d over the seven years of the study. There were no apparent trends over the duration of the study.

Health and injuries

Flatback turtles nesting at Curtis Island continue to show a low incidence of fresh injuries due to boat collisions and probable injuries from being captured in trawl nets and being dropped onto the boat deck. There was one death due to nesting activity and no evidence of fibropapillomas during the study.

Nest and hatchling disturbance and depredation and island fauna

Incubation success at Curtis Island has relied to a significant extent on the successful relocation of nests that were laid below the high tide level. For the duration of the study 659 nests were observed and of those 99 clutches (15%) were relocated. Across the study there was a large variation in the proportion of clutches relocated (2% - 65%) but it is unknown whether this represents changes in turtle behaviour, or changes in the assessment of possible inundation made by the different monitoring teams. Importantly, 49 of the relocated clutches were moved outside of the census period, emphasising the importance of the monitoring that was done in addition to the census.

Feral animal control by QPWS has been successful in reducing the fox and dog predation during the study. Predation by dogs destroyed at least 11.8% of clutches in 2013-2014, two clutches in 2015-2016 and three clutches (8.6% of clutches observed) in 2017-2018. During the 2016-2017 breeding season, the importance of continual monitoring for tracks and predation was demonstrated when fox tracks and 27 disturbed clutches were observed the end of December, which instigated successful predator control for the rest of the season. Early in the study fox excluder devices were installed, with a total of 92 FEDs placed during the first three years of monitoring, 20 of which were installed outside of the census periods. From the 2017-2018 breeding season onwards, FEDs were not considered needed.

Clutch abundance, size and success

During the study, 30 - 58 clutches per year were laid within the census period, with a decline observed between most years. A post-hoc trend analysis using a linear regression indicated this was a significant decline ($y = 55 – 3.789x$, $p = 0.012$) in the number of clutches laid, as expected given the observed decline in the number of tagged turtles.

For the four breeding seasons (2016-2017 to 2019-2020), where activity by nesting turtles was monitored across the duration of the season, it was possible to determine the proportion of clutches laid within the census periods. During that time, 279 clutches were observed within census periods and 365 clutches were found outside of the census. Therefore, the census values represent on average 43.3% of the clutches laid for an entire season. In 2016-2017 it was determined that females laid on average 2.65 clutches per season.

Clutch size variation when there were at least 30 clutches measured suggested a decline across the study. A post hoc one-tailed t-test indicated that clutch size in 2013-2014 to 2015-2016 was larger than those in 2016-2017 to 2018-2019 (p = 0.001), although a post-hoc trend analysis using a linear regression did not indicate a significant trend (y = 57.3 – 0.94x, p = 0.060). Conducting the same tests on egg diameter across the years of the study also suggested a decline (one-tailed t-test, p = 0.047) and a significant linear decline (y = 5.32 - 0.031x, p = 0.033). There were no linear trends in egg weight (p = 0.14). We recommend a more detailed analysis that includes all available data and continued monitoring of these parameters.

Incubation success as reported for Curtis Island ranged from 74.7 – 87.7%, and hatchling emergence ranged from 64.2 – 86.4%. This indicates the success of QPWS management of feral predators (pigs, dogs, and foxes) and large grazing stock (cattle and horses) and the monitoring team's relocation into safer incubation locations of clutches at risk of loss through erosion or flooding. In all years except 2017/18 emergence success exceeded 77%, indicating that Curtis Island South End dune sands constitute a very good incubation medium.

Incubation duration, sand temperatures and estimated sex ratios

Given that the pivotal temperature for Flatback clutches is 29.3°C and the expected incubation period to hatchling emergence for clutches incubated at pivotal temperature should be approximately 54 days. With sand temperature data recorded 1 November 2016 - 23 January 2019, pivotal temperatures were first reached across a range of dates and locations from 21 November to 19 December, and on the southern end of South Beach in 2018-2019 pivotal temperature was not reached by 23 January. Similarly, there was considerable variation in the proportion of time that clutches incubated above pivotal temperature, with temperature notably higher in 2016-2017 than in 2017-2018, largely in response to major rainfall events. Average periods to emergence each year were less than 54 days, indicative of strongly biased female hatchling production. This has been particularly apparent since 2016-2017 when all clutches laid within the census period had durations less than 54 days. In most years, production of male hatchlings would have occurred in clutches laid early in the season, or when significant rainfall events occurred that coincided within the middle third of the incubation period when sex is determined.

It is well established that extreme variability in size of the annual Green turtle nesting population at beaches in the SW Pacific is driven by environmental variability (ENSO climate cycle. Limpus and Nicholls, 2000) impacting on the proportion of the adult female population in the dispersed foraging areas that prepare for breeding in any one year. Similar environmental impacts on the proportion of the adult female Flatback foraging population that prepares for breeding could account for the apparent disparity in results between the long term CMR analysis that indicated an increasing adult female population at Curtis Island (Limpus *et al*. 2021) and the current short term analysis of number of tracks from nesting turtles, the number of clutches laid and number of nesting females annually which indicates a possible decline in the population. Long term rigorous CMR studies are the most informative for the understanding population function and trends.

CHAPTER 4. PEAK ISLAND STUDY

Study Area

This chapter provides a summary of results from monitoring marine turtle nesting activity at Peak Island during the 2013-2014 to 2019-2020 breeding seasons Peak Island, 23.333°S, 150.933°E, is a continental island in Keppel Bay and lies approximately 15 km off the mainland coast southeast of Yeppoon in eastern Australia (Figure 4.1). Tenure of the island is "National Park (Scientific)", which is the strongest level of land management protection under the *Nature Conservation Act 1992*. Peak Island is also surrounded by a one-kilometre-wide Preservation Zone within the Great Barrier Reef Coast Marine Park and the Great Barrier Reef Marine Park. The island is managed by the Department of Environment and Science (DES) in accordance with the Keppel Bay Islands National Park (Scientific) and adjoining State Waters Management Plan. As a consequence, the turtle nesting habitat of Peak Island and the immediately adjacent inter-nesting habitat are managed to provide the highest level of habitat protection available to any turtle nesting population. The island is closed to visitation by the general public and is uninhabited except by the turtle monitoring team during annual monitoring visits. There is no built structure on the island. The principal nesting beach on Peak Island is on the north-western corner that faces westerly towards the mainland. Only 300 m of this beach provides access to sand dunes suitable for turtle nesting. The dune nesting habitat on the small beach on the north-eastern side of the island is inaccessible because of an erosion bank while the accessible sandy beach on the south-eastern side of the island has rocks under the sand at dune level preventing successful egg chambering.

Peak Island has supported one of the largest populations of nesting Flatback turtles in the eAust stock (Limpus *et al*. 2013) and is recognised as an index beach for long-term monitoring of Flatback turtles within the eAust stock. Census of the Peak Island Flatback turtle nesting population commenced in the 1980-1981 breeding season (Limpus *et al*. 1981). Monitoring of turtle nesting at Peak Island was led by Dr C. J. Parmenter of Central Queensland University during 1981-2006 (Parmenter 1993). Monitoring recommenced in 2008 within the Queensland Turtle Conservation Project and has continued to the present with funding support from the GPC ERMP (Twaddle *et al*. 2014, 2015; Pople *et al*. 2016; Limpus *et al*. 2017, 2018, 2019).

Methods specific to Peak Island

• At Peak Island, the nesting beach is subdivided into 25 m sectors identified by numbered posts to allow comparisons across sectors. Sectors 0 - 5 are fronted by inter-tidal rocks with a sandy beach above the high tide level. Sectors 14 - 17 are fronted by extensive inter-tidal rocks which extend to exposed rocky rubble above the high tide level and into the dunes. The remainder of the beach has a sandy approach to the dunes (Figure 4.1).
• The work program at Peak Island was not designed to collect data for the duration of the Flatback turtle nesting season. Each year an adult tagging census was conducted. Additional trips to quantify incubation and emergence success were timed for also determining incubation to emergence durations for several clutches. Trips of various dates were as follows:

- 2013-2014 Tropical Cyclone Dylan and rough seas in February prevented the trip
- 2014-2015 Monitored 16 - 23 January, 9 nights
- 2015-2016 Monitored 27 January -3 February, 8 nights, evacuated due to adverse weather
- 2016-2017 Monitored 23 January -2 February, 11 nights
- 2017-2018 Monitored 16 - 29 January, 14 nights
- 2018-2019 Monitored 17 - 31 January, 15 nights
- 2019-2020 Monitored 16 - 29 January, 14 nights

• A Vemco Minilog II temperature data logger was placed in a sunny location at Sector 10 post on 26 November 2014 but was no longer present in November 2016. A replacement temperature data logger was set at the same location in late January 2017. This was downloaded on 26 November 2017 and 29 January 2020.

RESULTS

Nesting activity, nesting success and recruitment

It is not known when the first nesting activity of any season occurred at Peak Island. Within the census periods the average number of tracks per night ranged from 16.5 - 25.7 across the seven years (Figure 4.4, Tables 4.1, 6.1). Across years, the overall average number of tracks per night was 20.5 (SD = 3.7), and since 2017 the values have been below the average value.

The number of identified turtles during the yearly census ranged from a maximum of 218 in 2013 and a minimum of 121 in 2018, with an average value of 177.7 (SD = 33.7) (Figure 4.5, Tables 4.1, 6.1). Since 2017 the values have been below the average value.

For the duration of the study there was only one tagged turtle that had been tagged while nesting elsewhere in a previous season. Turtle T9619 observed in 2013-2014 had originally been tagged in 1985 at Wild Duck Island.

Recruitment rates of estimated 1st time nesters (turtles not previously tagged) were below 20% for the duration of the study. Concern was raised in 2017-2018 and 2018-2019 when recruitment dropped below 11%, which was at the bottom of the range reported for Flatback turtles nesting at Peak Island, Wild Duck Island and the Woongarra Coast (10% - 20%) reported in Limpus (2007). Across all years, values ranged from 10.7 to 19.3, with an average of 14.2 (SD = 3.3), and in 2019-2020 recruitment rose to 16.1% (Figure 4.5, Tables 4.1, 6.1). Given a possible decline in the annual recruitment of new breeding females into the Peak Island nesting population over the past 11 years (Figure 4.12), this recruitment parameter should continue to be monitored. This decline in recruitment should be regarded as of high concern for this population.

Average nesting success, which is based on the proportion of nests in which eggs were laid relative to the number of nesting crawls, ranged from 48.3.% - 71.7%, with an average value of 60.8% (SD = 7.9%) (Figure 4.6, Tables 4.1, 6.1). The average number of clutches laid per night ranged from 8 - 15.1 with a yearly average value of 12.3 (SD = 2.7) (Figure 4.4, Tables 4.1, 6.1). The average number of clutches per night was weakly correlated (R^2 = 0.74, p = 0.01) to the average number of tracks per night (Figure 4.4, Table 4.1). An average of 172 clutches (SD = 36.8, range = 114 - 211) were laid within the census periods over the seven years (Figure 4.6, Tables 4.1, 6.1).

Nesting activity was typically low (<10 activities per sector) in Sectors 1- 4, with a broad range of nesting success. Sectors 5 - 6 had low to medium (~10 - 15 activities) nesting activity and Sectors 7-13 generally had high levels of activity and the greatest number of nests. Initially there was none or little activity in Sectors 14-15 none in Sector 16 and very low nesting success. There was a general increase in nesting activity in those sectors, including years with very high nesting activity, but very low nest success. Nesting success in Sectors 14 (57%) and 15 (32%) were notably higher than in previous years during the 2019 -2020 season.

Nesting females: size, fecundity

Females that were experienced nesters were consistently somewhat larger than new recruits. Taking the average of the yearly mean CCL values, experienced nesters averaged 94.1 cm (SD = 0.35) and new recruits averaged 92.3 cm (SD = 0.54) (Tables 4.1, 6.1).

Remigration interval, the number of years between recorded breeding seasons, averaged across the years of the study between 2.17 - 3.6 yr, providing a yearly average of 3.0 yr (SD = 0.31) (Tables 4.1, 6.1). These data suggest a trend towards somewhat longer (>3 yr) average remigration intervals since 2018. Graphing the distribution of individual remigration intervals showed the majority of turtles remigrated after two years in 2013 – 2017, two and three years in 2018 and three years in 2019 (Figure 4.7).

A problem in the interpretation of the remigration data is the extent to which nesting turtles are missed during the census in a given year, which would over-estimate the remigration interval. During the study, there were from 1 - 23 (mean = 5.6. SD = 7.3) nests laid by turtles that were missed during the census.

Inter-nesting intervals between a successful nesting and the subsequent return to lay another clutch varied from an average of 12.2 - 13.3 d, with a mean across three years of data of 12.2 (SD = 0.44), although this was based on a small sample size (n = 37). Return intervals for turtles that crawled out of the water but failed to lay eggs varied from a mean of 0.83 – 1.3 d, with a mean across years of 1.20 d (SD = 0.15).

There was an average of 50.4 - 55.4 eggs per clutch over the seven years, with a yearly average of 52.1 (SD = 1.5) eggs. Summary data on clutch egg size and nest depths are given in Table 4.1.

Health and injuries

During the seven years of the study there were no turtles recorded that had fresh injuries. One turtle was rescued that had fallen down an erosion bank. None of the nesting Flatback turtles were recorded with fibropapilloma tumours.

Nest and hatchling disturbance and depredation and island fauna

Large terrestrial predators of turtle eggs (pigs, dogs, foxes, varanid lizards and humans) are absent from the island. However, in some years an excessive number of clutches were invaded by roots from grasses and vines resulting in increased incubation failure and entrapment of hatchlings within the nest. Typically, there was also some loss of eggs from predation by *Ocypode* crabs.

In the 2017-2018 report it was noted that "at daylight, up to four white bellied sea eagles, *Haliaeetus leucogaster*, patrolled long the beach daily. Later in the morning, small flocks of Torresian crows, *Corvus orru*, would drive off the sea eagles and commence patrolling along the beach and continue throughout the day, utilising trees and elevated positions as resting stations. Crows regularly were observed "dropping" on hatchlings on the beach and carrying the hatchlings in their beaks to feeding stations. This is the first season that crows have been recorded as active predators of the Flatback hatchlings at Peak Island. While the rate of hatchling predation by crows remains unquantified, we have the impression that they contributed to a significant level of hatchling loss for the season. By day and night, there were numerous small (less than 1.5 m) carcharinid sharks of multiple species patrolling the shallows against the shoreline. These sharks preyed intensely on hatchlings as they entered the sea. These sharks were also present during the census period. That intensity of avian predation of hatchlings was not observed in the following season.

In some years, flooding of nests during high tides reduced incubation success.

Clutches

Summary data on clutch size, size of eggs and nest depths are given in Tables 4.1 and 6.1. Clutch size varied from an average of 50.4 – 55.4 eggs per year, with a yearly average of 52.1 (SD = 1.5) eggs per clutch. Average egg diameters ranged from 5.14 - 5.24 cm per year, with a yearly average of 5.20 cm (SD = 0.03 cm). Average egg weights ranged from 75.1 – 78.5 g per year, with a yearly average of 76.7 g (SD = 0.99 g). Nest depth to the top of the nest upon laying ranged from 30.6 – 35.3 cm per year, with a yearly average of 32.8 cm (SD = 1.8 cm). Nest depth to the bottom of the nest ranged from 45.5 – 56.4 cm per year, with a yearly average of 50.5 cm (SD = 3.7 cm).

Incubation and emergence success

Incubation success varied from an average of 55.9 – 88.8% per year, with a yearly average of 75.0% (SD = 10.1%). Hatchling emergence success ranged from 39.1–88.7%, with a yearly average of 66.8% (SD = 14.0%) (Figure 4.8, Tables 4.1, 6.1).

The lowest values occurred during the 2017-2018 season, which had the lowest incubation and hatchling emergence success recorded since 2008. In that year there were a combination of factors contributing to the very low success. Fourteen turtles were observed digging into previously laid nests, which affected 8.9% of clutches during the census and a 21% egg loss within those clutches. Root invasion of 65 clutches resulted in increased incubation failure and entrapment of emerging hatchlings reduced emergence success (Figure 4.2). In January, an excessive number of dead eggs and hatchlings were observed that were killed during heat wave conditions (Figure 4.2). There was some additional loss due to crab predation of eggs and nest inundation. Each of these issues were noted across several years of the study. Several clutches were lost to erosion in years of cyclone activity (Figure 4.2).

Incubation duration

The incubation period to hatchling emergence was obtained for several clutches during five years of the study. In 2013-2014, weather conditions due to Tropical Cyclone Dylan prevented the trip occurring. In 2015-2016, the hatchling trip was delayed, and impending stormy weather resulted in the team being evacuated after eight nights and no period to emergence data were determined. The average period to emergence to the beach surface ranged from 47.8 – 52.7 d with a yearly average of 50.2 d (SD = 1.7) (Tables 4.1, 6.1). This is less than expected (54 days) if clutches were incubated at pivotal temperature during the critical middle third of incubation. Within the census periods, the range in period to emergence included durations of 54 days or greater.

Sand Temperature monitoring

Rainfall and air temperature data recorded at the nearest BOM weather stations were obtained to compare variation in monthly values throughout the study (Figures 2.4b, 2.5b). Air temperature data were obtained from Yeppoon (#33204). Rainfall data were incomplete for Yeppoon therefore average values were obtained by including data from Great Keppel Island (#33260). Air temperatures during the breeding season were consistently the highest in 2016-2017 and 2019-2020. Large peaks in rainfall occurred in March 2014, 2017 and 2020, and in February 2015.

A temperature data logger was placed in a sunny location by sector post 10 at a depth of 50 cm in 2014. Temperature data at nest depth are summarised as follows:

- 2013-2014: no data
- 2014-2015: Data were recorded from late November to late January. Temperatures were above the pivotal temperature of 29.3°C for the duration except for a five-day period in mid-December when temperatures dropped to a low of 24.5°C.
- 2015-2016: Temperatures rose above the pivotal temperature of 29.3°C around 23 November and stayed there into January when the data ceased. Temperatures were above the upper optimal temperature of 32°C for much of December and into January.
- 2016-2017: The previous data logger was lost and replaced the end of January 2017. At that point, temperatures were above the pivotal temperature of 29.3°C until around 19 March when they dropped below 29.3°C for the rest of the season.

- 2017-2018: The temperature was below the pivotal temperature of 29.3°C for all of October until mid-December, when it rose above 29.3°C and stayed there until February. Mid to late January was very hot, with nest temperatures above 32°C, resulting in observed heat stress deaths of hatchlings in the upper nest chamber and on the beach. In February to March there were two drops in temperature below 29.3°C for ~3 - 5 d each due to substantial rainfall. By April temperatures remained below 29.3°C. These data suggest a male bias to hatchling production from early in the season until the peak nesting period, followed by a mostly female biased sex ratio.
- 2018-2019: Temperatures at the beginning of the season were below the pivotal temperature through November. They fluctuated between 28°- 31.5°C in December before staying above 29.3°C until 29 January when the data were downloaded.
- 2019-2020: The data logger was not downloaded.

Elevated temperatures were noted in some years that resulted in substantial embryo deaths and hatchling deaths within the nests and after emergence.

- In the 2016-2017 season, 33 clutches were identified as having reduced success due to heat stress
- In the 2017-2018 season, this was particularly apparent in nests laid in the dunes, as there was a pervasive smell of dead animals coming from the nests and hatchlings were observed dying while crossing the beach. Elevated sand temperatures and a majority of periods to emergence of <54 days suggested a strongly female biased season. However, the early season clutches should have produced a male-biased sex ratio based on sand temperatures at nest depth being below the pivotal temperature.

DISCUSSION

Nesting activity

Limpus *et al*. (2013) identified a downward trend in the number of nesting turtles at Peak Island over recent decades, which was particularly apparent in the low numbers of nesters in 2017-2018 thru 2019-2020. A post-hoc trend analysis using a linear regression indicated the observed decline was not significant (y = 226 – 12.07x, p = 0.071). Analyses of capture-mark-recapture data across 29 years indicated an increasing trend in population size since 2000, with an expected increase of 2.9% per year, and estimated long-term abundance of approximately 537 adult females (Limpus *et al*. 2021). The discrepancy between observed numbers of nesting turtles and the modelling results emphasises the value of continued long-term monitoring to determine factors impacting annual nesting population size.

Recruitment of turtles not previously tagged fluctuated between the 10% -20% range previously reported for the eAust Flatback population Limpus (2007). Given the problems of determining actual recruitment rates of first-time nesters into the population from field data a modelling approach (Pradel temporal symmetry) was used to better determine recruitment (Limpus *et al*. 2021). That analysis found that recruitment rates fluctuated around 16.5%, which is close to the most recent value recorded in 2019-2020. However, given that recruitment dropped below 11% in 2017-2018 and 2018-2019, this parameter should continue to be monitored.

Nest success, the proportion of nesting crawls that result in eggs being laid, was low and consistently below 70% except in 2013-2014. This is mostly the result of turtles emerging at several sectors of the beach having little or no sand available to support nesting activity. Throughout the study there has been some variation in nesting activity and nest success across sectors, such as a recent improvement at sectors 14 and 15, but overall nest success remains low. This low nest success has existed for at least the last decade.

Nesting females

Flatback turtles nesting at Peak Island continue to demonstrate the strong fidelity of the eAust genetic stock to particular rookeries, with only two turtles having been tagged while nesting elsewhere. A total of 657 tagged turtles were encountered, thus only 0.3% of turtles had been tagged elsewhere.

As observed previously, experienced nesters were consistently larger than new recruits, suggesting that nesting Flatback females continue to grow slowly after they commence egg laying. This size difference ranged from 1.0 – 2.6 cm per season, but with a broad overlap in sizes.

Average yearly recapture intervals suggested remigration intervals that fluctuated around a three-year interval. Field-based recapture intervals are expected to over-estimate actual remigration rates, largely due to turtles missed during a two-week census period. Modelling of capture-mark-recapture data since 1980 derived a long-term recapture probability of 39% per year that fluctuated widely from 3% - 73% (Limpus *et al*. 2021). Therefore, many turtles that nest in a given year were missed during the monitoring. The distribution of individual recapture intervals across the study suggested an increased frequency from 2 - 3 yr. A post-hoc trend analysis using a linear regression indicated the observed increase was significant ($y = 2.46 + 0.13x$, $p = 0.021$). Given the implications that an increased remigration interval would results in a reduction in individual fecundity, and the unknown effects of climate change, continued long-term monitoring of this parameter is needed.

Health and injuries

Flatback turtles nesting at Peak Island continue to show a low incidence of fresh injuries due to boat collisions and probable injuries from being captured in trawl nets or being dropped onto the boat deck. There was no evidence of fibropapillomas during the study.

Nest and hatchling disturbance and depredation and island fauna

Terrestrial predators of turtles or turtle eggs are not present on Peak Island. In some years predation of hatchlings by sea eagles, *Haliaeetus leucogaster*, or Torresian crows, *Corvus orru*, may result in significant losses. Additionally, carcharinid sharks were observed to prey intensely on hatchlings as they entered the sea. Levels of predation on Flatback turtle hatchlings is not quantified for the eAust population and data collected on this parameter would be valuable for population modelling.

Clutch abundance, size and success

During the study, 114 - 211 clutches per year were laid within the census period, with a decline observed in the last three years. A post-hoc trend analysis using a linear regression indicated there was a significant decline during the study ($y = 228.1 - 14x$, $p = 0.046$).

Yearly average clutch size, egg diameter and egg weight fluctuated somewhat (2%-10%) during the study and were within the range previously reported (Limpus 2007). There were no significant trends identified by ad-hoc regression analyses ($p > 0.1$).

Incubation success was highly variable (55.9% – 88.8%), though in most seasons it was at or exceeded 70%. Variation in emergence success was even greater (39.1% - 88.7%) and only exceeded 70% in three years. Reduced success in several seasons of was attributed to root invasion from grasses and vines. Some removal of weed vegetation occurred prior to the 2018-2019 season, which saw a reduction in the percentage of nests with observed invasion of roots and a consequently higher hatchling emergence success in that season and in 2019-2020. Management of non-native weed species (Limpus and Limpus, 2018) to reduce root invasion of nests may be warranted.

Elevated temperatures were a significant contributor to reduced emergence success as well at the death of emerged hatchlings, particularly in 2016-2017 and 2017-2018. A more extensive monitoring of sand temperatures at this index beach should be a priority.

Additionally, in some years, flooding of nests during high tides reduced incubation success. Throughout the study duration some effort has been made to counter this issue by the relocation of 51 clutches, and this practice should be continued.

Period to emergence, sand temperatures and estimated sex ratios

As outlined in the methods, the pivotal temperature for Flatback clutches is 29.3°C and the expected incubation period to hatchling emergence for clutches incubated at pivotal temperature should be approximately 54 days. Sand temperatures were obtained for 3 - 4 months of the breeding seasons in 2014-2015, 2017-2018 and 2018-2019 and the final two months of 2016-2017. These data showed temperatures were above pivotal temperatures for most of the period that eggs were incubating, indicative of a strong female bias to hatchling production. Average period to emergence data were all below period to emergence at pivotal temperature. In all years, some clutches had durations greater than 54 days, thus some male hatchlings were produced. Male hatchling production is dependent on clutches laid early in the season, or when significant rainfall events occurred that coincided within the middle third of the incubation period when sex is determined.

CHAPTER 5. AVOID ISLAND STUDY

Study Area

This chapter provides a summary of results from monitoring marine turtle nesting activity at Avoid Island during the 2013-2014 to 2019-2020 breeding seasons. Avoid Island was first identified as a significant Flatback turtle breeding site during an aerial survey in 1971 (Limpus, 1985) and again in 2000 and 2001 (Limpus *et al*. 2013). The nesting population was first monitored during the mid-nesting season in 2007-2008 (Jones and Venz, 2008). The island's turtle breeding has now been monitored for eight consecutive seasons commencing in 2012 with the last seven seasons of monitoring supported by GPC ERMP.

Avoid Island, 21.9744ºS, 149.6500ºE, is a continental island located just north of Broad Sound and lying approximately 18 km from the nearest mainland shore and approximately 125 km southeast of Mackay on the mainland coast of eastern Australia. The Queensland Trust for Nature (QTFN) owns the island and manages it as a designated nature refuge. Avoid Island sits within a Habitat Protection Zone of the Great Barrier Reef Coast Marine Park and the Great Barrier Reef Marine Park. The island is closed to visitation by the general public and is uninhabited except by the turtle monitoring team during annual monitoring visits, associated classes visiting for environmental education, and periodic visits by QTFN personnel and volunteers for maintenance. As a consequence, the turtle nesting habitat of Avoid Island and the immediately adjacent inter-nesting habitat are managed to provide a high level of habitat protection to the turtle nesting population. There is a house, built in the 1970s, on the highest point on the island, and a shed. There are 4wd tracks that circle the island and a grass airstrip, which are maintained with a tractor mower. QTFN installed solar power and two composting toilets on the island in 2015, which substantially improved the living situation.

The Island is approximately 1.6 km long and 0.4 km wide and has undulating terrain with a rise on the northern end of the island (Figure 5.1). There are three main nesting beaches (South Beach, Middle Beach, North Beach) on the eastern side of the island that are bordered by rocky outcrops. Each beach is fronted by tidal sandy mud flats with scattered rocky shelves. These beaches are backed by dunes, which are highest at South Beach. Nesting activity occurs on the beach slope and dunes. Other beaches on the island are either too narrow or rocky to provide suitable nesting habitat, though occasional nesting occurs on West Beach, the largest westerly facing beach.

Avoid Island supports a moderate density of nesting Flatback turtles of the East Australian (eAust) stock (FitzSimmons and Limpus, 2014a) and has been selected as an index beach for long term monitoring of Flatback turtles within the eAust stock. An initial census of the Avoid Island Flatback turtle nesting population was conducted during the 2007-2008 breeding season (Jones and Venz, 2008) and annual monitoring commenced in the 2012-2013 breeding season (FitzSimmons, 2013; FitzSimmons and Limpus, 2014b, 2015, 2016; Limpus *et al*. 2017, Limpus *et al.* 2018, 2019, 2022b).

Methods specific to Avoid Island

Nightly monitoring occurred during the census periods on all eastern beaches, referred to as South Beach (A3), Middle Beach (A2) and North Beach (A1) (Figure 5.1). Additional nightly monitoring on South Beach occurred outside of the census period during most seasons, as well as daily track counts and identification of nests on North and Middle beaches. This provided additional data that were included in the yearly reports on the presence of individual females, body size of new recruits versus experienced nesters, return and inter-nesting intervals, and period to emergence data. This additional monitoring occurred over most of the 2016-2017 nesting season from 28 October 2016 – 1 March 2017. In other years, data were collected for additional nights as part of projects to attach satellite tags, and while running short courses for school groups. This led to an additional 29 nights of monitoring during the seven years.

Initially nest locations were mapped by measuring to trees that were identified by GPS and on hand-drawn maps. In 2017, sector numbers were established on trees or posts on South Beach and North Beach. These continued to be used throughout the study.

Temperature data loggers (Vemco Minilog II) were established in open and shaded locations on the top of the 1st dune and on the upper beach slope, each buried at 50 cm depth. These resulted in variable success due to failure of data loggers, or damage to data loggers after Tropical Cyclone Dylan. In 2018, the data logger in the shaded dune location was removed due to no turtles nesting in such locations during the previous years of monitoring. Instead, during the 2018-2019 and 2019-2020 seasons a temporary data logger was placed near the high tide level on North Beach in locations where nests were frequently been recorded (Figure 5.3). That data logger was removed at the end of the hatchling emergence trips.

Field trips to determine incubation success and hatchling emergence varied in duration across the nesting seasons. Initially this was done as a five-day trip timed to occur after the hatchlings in all marked nests would have emerged. In 2013-2014, Tropical Cyclone Dylan caused severe erosion of nest sites prior to the monitoring trip and only four nests were found. In 2014-2015, Tropical Cyclone Marcia was forming during the monitoring trip and the team was evacuated after three days. For the 2017-2018 season, the duration of the hatchling trip was increased to 13 days to obtain additional data on the period to emergence and to collect measurement data on hatchlings. In 2018-2019, the hatchling trip ran for 15 days, and in 2019-2020, for 12 days. In addition to collecting data on marked nests, data were collected from emerged clutches found opportunistically.

RESULTS

Nesting activity, nesting success and recruitment

It is not known when the first nesting activity of any season occurred at Avoid Island. The earliest dates that track counts were made were at the end of October, with observations of 17 tracks on 27 October 2016, and 47 tracks on 31 October 2018, suggesting a mid-October start.

Within the census period, the average number of tracks per night ranged from 10.2 in 2015 to a low of 3.5 in 2018 across the seven years (Figure 5.5, Table 5.1). Across years the overall average number of tracks per night was 7.0 (SD = 2.0) (Table 6.1), and since 2017 the values have been below the average value.

Numbers of identified turtles during the census ranged from a maximum of 78 turtles in 2016-2017 and a minimum of 29 in 2018-2019, with an average value of 60.7 (SD = 17.4) (Figure 5.6, Tables 5.1, 6.1). The numbers of turtle observed numbers before 2017 were all above average, but since 2017-2018 the values have been below the average (range 29 - 52). During the longer monitoring period for the 2016-2017 season, (beginning on 27th October), 76 turtles were observed during the census, and a total of 92 turtles were observed for the duration of monitoring, indicating that within the census period, 82.6% of the turtles had been observed.

Because only 49 turtles had been tagged in 2007-2008, and an additional 60 new recruits were tagged in 2012-2013, it was expected that the percentage of new recruits would start at a high percentage that would drop and stabilise over the seven years. There was a continuous decline in the percentage of new recruits from 66.7% in 2013 to 26.3% in 2015-2016 (Figure 5.6, Table 5.1). Since 2016-2017, values have ranged from 15.4% to 23.9%. No other species of turtle was recorded as nesting during this study.

The average number of clutches laid per night ranged from 2.2 - 6.4 with a yearly average value of 4.6 (SD = 1.3) (Figure 5.5, Tables 5.1, 6.1). These values followed the general pattern across seasons as the average number of tracks per night. The average number of clutches per night was closely correlated (R^2 = 0.92) to the average number of tracks per night but with less magnitude to the variation (Figure 5.5).

Average nest success, which is based on the proportion of nests in which eggs were laid relative to the number of nesting crawls, ranged from 59.0% - 75.8%, with an average value of 66.0% (SD = 5.9%) (Figure 5.7, Tables 5.1, 6.1). As in previous years, turtles had difficulty nesting near trees due to low hanging branches, buried branches or roots, or attempting to nest in areas that were not suitable due to tidal debris or washed-out gullies (Figure 5.2).

In all years, the majority of nesting activity occurred at South Beach, with an average of 81.9% of tracks (range 75.5 - 90.0%) and 83.9% of nests (range 74.2 - 93.6%) laid there. Nesting activity at North Beach accounted for an average of 14.2% of tracks (range 5.9 – 24.5%) and 13.7% of nests (range 5.1 – 25.8%). Middle Beach had an average of 3.1% tracks (range 0 – 6%) and 1.9 % of nests (range 0 – 3.8%). Across the seven years there were a total of five nesting attempts on the west side of the island, none resulted in clutches being laid.

The preferred nesting habitat on South Beach was between the base of dune and the mean higher high water. Relatively few clutches per season were laid in the 1st dune (0 - 5 nests), with a maximum of 7.7% of all clutches in 2019. At North Beach, most nesting occurred in the middle and south end of the beach on the upper portion of the beach slope. Nesting at Middle Beach was limited to a few areas just above higher high water where it was possible to dig a nest in coarse sand and dirt.

Nesting females: size, fecundity

Females that were experienced nesters were consistently somewhat larger than new recruits. Taking the average of the yearly mean CCL values, experienced nesters averaged 93.6 cm (SD = 0.34) and new recruits averaged 91.9 cm (SD = 1.0) (Tables 5.1, 6.1).

Remigration interval, the number of years between recorded breeding seasons, averaged between 2.1 - 3 years from 2016-2017 to 2019-2020 providing a yearly average of 2.6 yr (Tables 5.1, 6.1). Because monitoring on a yearly basis did not start until 2012-2013, remigration intervals prior to 2016-2017 would be biased to one or two-year intervals, so they were not included in the summary data. The data suggest a trend towards somewhat longer average remigration intervals since 2018-2019. Graphing the individual intervals for each year showed a relative increase in three-year intervals in 2018-2019, which became the most common interval in 2019-2020 (Figure 5.8).

A problem in the interpretation of the remigration data is the extent to which nesting turtles are missed during the census in a given year, which would over-estimate the remigration interval. During the study there were from 2 - 8 (mean = 3.9) clutches per year laid by turtles that were missed during the census. During the 2016-2017 season with a near complete monitoring of the nesting activity 17.4% of turtles were not observed during the census and 12.0% of all turtles were only observed once. Therefore, remigration intervals for some turtles may be an over-estimate

For the duration of the study only one turtle was observed that had originally been tagged as a nester at Wild Duck Island. This was turtle T38567, tagged in 1988 and observed at Avoid Island in 2012-2013, 2016-2017 and 2018-2019.

Inter-nesting intervals between a successful nesting and the subsequent return to lay another clutch varied from an average of 12.8 - 13.9 d, with a mean across years of 13.2 d (Tables 5.1, 6.1). Return intervals for turtles that crawled out of the water but failed to lay eggs varied from a mean of 0.7 – 2.8 d, with a mean across years of 1.2 d (SD = 0.70) (Tables 5.1, 6.1).

There was an average of 34.9 - 51.9 eggs per clutch over the seven years, with a yearly average of 47.2 (SD = 6.0) eggs. Summary data on clutch egg size and nest depths are given in Tables 5.1, 6.1.

Health and injuries

For the duration of the study, there was one turtle observed with a fresh injury that indicated a healing fracture. At least 3 - 4 turtles were observed with healed injuries from a propeller strike, one turtle showed evidence of a recent shark attack, and two turtles were missing half of a front flipper that was healed (Figure 2.2). None of the nesting Flatback turtles were recorded with fibropapilloma tumours.

Nest and hatchling disturbance and depredation and island fauna

Nesting turtles rarely disturbed previously laid clutches. In 2015-2016, one clutch was disturbed, and during the (nearly) whole of season monitoring in 2016-2017, three clutches were dug into. No mammalian or reptilian terrestrial predators of marine turtle eggs or hatchlings were recorded on Avoid Island. Crab predation was observed in every year

While potential avian predators of turtle hatchlings were present on the island, none were recorded taking turtle hatchlings during this season. Across all clutches dug, 10 nests had a total of 11 eggs predated by crabs, with a mean of 0.14 eggs taken per clutch (SD = 0.39, n = 77). The crab species responsible for this predation was *Ocypode cordimanus*.

Clutches

An average of 61.9 clutches (SD = 15.1, range = 32-79) were laid within the census periods over the seven years (Figure 5.7, Tables 5.1, 6.1).

Summary data on clutch size, size of eggs and nest depths are given in Tables 5.1 and 6.1. Clutch size varied from an average of 34.9 – 51.9 eggs per year, with a yearly average of 47.2 (SD = 6.0) eggs per clutch. Average egg diameters ranged from 4.77 to 5.18 cm per year, with a yearly average of 5.08 cm (SD = 0.18 cm). Average egg weights ranged from 72.0 – 78.8 g per year, with a yearly average of 76.1 g (SD = 2.5 g). Nest depth to the top of the nest upon laying was only measured in 2016/17 and it averaged 48.5 cm (SD = 3.87, n = 4). Nest depth to the bottom of the nest upon excavation ranged from 56.3 – 61.5 cm per year, with a yearly average of 59.7 cm (SD = 1.7 cm).

Period to emergence

The incubation period to hatchling emergence was obtained for several clutches from 2016-2017 to 2019-2020. The average incubation period to hatchling emergence to the beach surface ranged from 46.7 – 50.2 d with a yearly average of 47.7 d (SD = 1.5) (Tables 5.1, 6.1). These values are less than expected (54 days) if clutches were incubated at pivotal temperature during the critical middle third of incubation. Within the census periods the period to emergence data included durations of 54 days or greater except in 2017-2018 and 2019-2020.

Incubation and emergence success

Incubation success varied from an average of 62.0 – 86.4% per year, with a yearly average of 76.1% (SD = 9.1%). Hatchling emergence success ranged from 56.9 – 86.4%, with a yearly average of 73.3% (SD = 10.6%) (Figure 5.9, Tables 5.1, 6.1).

The three main environmental factors observed to reduce incubation and emergence success were nest inundation during high tides, heat stress and cyclones. Inundation killed embryos, heat stress killed embryos, hatched but not emerged hatchlings, and emerged hatchlings and cyclones eroded nest locations and increased problems with inundation (Figure 5.2)

Sand temperature monitoring

Bureau of Meteorology rainfall and air temperature data recorded at weather stations at Carmila, 27 km to the northwest, and St Lawrence, 44 km southwest, were used to compare variation in monthly values throughout the study (Figures 2.4c, 2.5c). Rainfall data were incomplete for the closest weather stations therefore average values were used from stations near Carmila (#33071, #033186, #33095) and St Lawrence (#33210). The nearest station for temperature data was at St Lawrence.

Considerable variation in total monthly rainfall was recorded for each month of the nesting season (Figure 2.5c). The difference in maximum and minimum rainfall per month ranged from 153 – 1049 mm.

Mean monthly air temperatures at St Lawrence were consistently at or above 29°C throughout the nesting season each year. A spike in temperature was observed in February 2017 and temperatures were consistently above average for much of the 2019-2020 nesting season (Figure 2.4c).

Temperature data loggers were placed on the beach slope South Beach in 2012 but were uncovered by Tropical Cyclone Dylan in January 2014. Two new data loggers were placed on the dune slope in a sunny and shaded location in 2014 and in 2015 additional data loggers were placed on the beach slope at the base of the dunes in 2015. During the 2017-2018 season, the data loggerhead on the dune failed and it was not replaced because no turtle had been observed nesting in a shaded dune location. In 2018-2019 and 2019-2020, a data logger was temporarily placed for the duration of the nesting season near the high tide level at North Beach in the vicinity of nests.

Temperature data are summarised as follows:

- 2013-2014: Temperatures in the sunny dune location were above pivotal temperature when the data loggers were placed at the end of November, other than an approximate two-week period in the beginning of February. In the shaded dune location temperatures fluctuated around the pivotal temperature. Although hatchling production would have been biased to female hatchlings, some male hatchlings would have been produced.
- 2014-2015: Temperatures in the sunny dune location were below pivotal temperature for most of the nesting season. This is not readily understood based on the BOM temperature and rainfall data and given that this data logger failed later in 2015 and gave unrealistically low temperatures, the 2014-2015 data are considered unreliable. In the shaded dune location temperatures fluctuated around the pivotal temperature, which could have produced males, although no turtles were observed to nest in similar habitat.
- 2015-2016: No data were recorded successfully.
- 2016-2017: Sand temperatures in the mostly sunny area at the base of the dune reached the pivotal temperature in the second week of November and stayed above it until the recording stopped on 4 December 2017. Sand temperatures in the shaded area at the base of the dune fluctuated around

pivotal temperature and then rose above pivotal temperature in the first week of December. BOM temperature and rainfall data indicated that the period from mid-January until early March 2017 was very dry with isolated days with a few millimetres of rain and was also the period of elevated daily air temperatures for the summer. Under these conditions the surface sand temperatures, particularly during the middle of the day and early afternoon, can be expected to reach lethal levels for turtle hatchlings.

- 2017-2018: When the data loggers were initialised in early November, the sand temperature at nest depth was already above pivotal temperature at all sites. The sand temperatures on the upper dune and the beach in mid-November to early December dropped during two brief cooling spikes that brought the sand temperatures below the Flatback pivotal temperature. Sand temperatures at all three monitoring sites remained above the pivotal temperature for the remainder of the breeding season. It is expected that the hatchling sex ratio was strongly skewed to females for almost the entire breeding season.
- 2018-2019: At the beginning of the nesting season the data loggers reached pivotal temperature at different dates: 25 October 2018 for sunny dune and sunny beach slope, and 8 November 2018 for shaded beach slope habitats. Three periods of heavy rain brought temperatures below the pivotal temperature for variable lengths of time of approximately: 6 days (sunny dune), 11 days (sunny beach slope), 14 days (open beach at North Beach) and 24 days (shaded beach slope). For the remaining time periods, temperatures at nest depth were above pivotal temperature at all sites. It is expected that for most of the breeding season hatchling sex ratio was strongly female biased, but that cooler periods due to rain would have produced some male hatchlings in all nesting habitats.
- 2019-2020: At the beginning of the nesting season the data loggers reached the pivotal temperature (29.3°C) for Flatback turtles, and then stayed above it, on 9 November 2019 for the sunny beach slope and 16 November 2019 for the sunny dune habitat. The shaded beach slope was only above pivotal temperature from 12 - 18 and 20 - 26 January 2020. The data logger on North Beach was already at pivotal temperature when it was placed on 10 December. Maximum temperatures recorded from the four data loggers ranged from 30.3° – 32.6°C. Four periods of rain that brought temperatures down were recorded, but they only dropped below pivotal temperatures on two occasions in the shaded beach slope habitat of South Beach and once on the open beach at North Beach. It is expected that male hatchlings would have only been produced early in the season or in some nests on the shaded beach slope.

DISCUSSION

Avoid Island supports a moderate-sized population of nesting Flatback turtles. The island is located towards the northern extremity of the breeding range for the eAust stock. It was chosen as a control site for comparative monitoring with respect to the Curtis Island and Peak Island rookeries because Avoid Island has no mammalian or reptilian predators of eggs, it is free of uncontrolled human disturbance of the nesting turtles and the nesting and adjacent inter-nesting habitat has not been modified by anthropogenic activities. Monitoring of nesting activity at Avoid Island was initiated in the 2007-2008 season and reinstated for the 2012-2013 season, thus there have been eight consecutive years of monitoring.

Nesting activity

From the 2012-2013 to 2016-2017 breeding season the number of tagged turtles encountered during the census was relatively stable, fluctuating between 68 - 88 turtles. Those number dropped to between 29 - 52 turtles and is a cause for concern. As expected, a post-hoc trend analysis using a linear regression indicated the observed decline was not continuous enough to be significant ($y = 89.6 – 6.6x$, $p = 0.087$). Analyses of capture-mark-recapture data since 2012/13 indicated the population has fluctuated significantly around a long-term mean of around 68 observed turtles (Limpus *et al*. 2021). The long-term mean abundance of nesting females was estimated to be approximately 319 turtles. This analysis concluded that monitoring for several more seasons is required for more robust estimations of these parameters.

The duration of the study provided data on the number of years needed for a new monitoring project to reach a stabilisation of the recruitment rate of first-time breeding females into the adult nesting population. Initially in 2007-2008 there were 49 turtles tagged and 78 turtles were tagged in 2012-2013. At the beginning of this study, the proportion of turtles without tags was 67%, which dropped to 50% and 26% in the successive years. Since then, the observed recruitment rate has stabilised between 15% - 24%, suggesting that most of the experienced nesting turtles at Avoid Island have been tagged. These values are on the higher end of the range reported in Limpus (2007). The analysis of recruitment using a modelling approach was not possible given the limited years of data (Limpus *et al*. 2021).

The relatively low nesting success as Avoid Island appeared to have several causes. On South Beach much of the middle section of the beach has numerous Casuarina trees that have fallen over, some during cyclone Dylan, creating obstacles for turtles, and there are few slopes that allow access to the first dune. On all three beaches there are areas of shallow sand, or gravelly areas with deposits of pumice, that preclude successful nest digging. Additionally, we observed on numerous occasions that many Flatback turtles were particularly sensitive to natural disturbance and would leave the beach when seeking a nesting location, such as encountering a driftwood log, being brushed by an overhanging Casuarina branch blowing in the wind or encountering the dune slope.

Throughout the study the majority (~82%) of nesting activity occurred on the eastern side of the island at South Beach, with significant (~14%) nesting activity on North Beach and minor (~3%) nesting on Middle Beach. The upper beach slopes on South Beach and North Beach provided a good incubation environment in most years. Access by turtles to the higher dunes on South Beach was restricted for several years after Tropical Cyclone Dylan, and only a few clutches per year have been laid near the dune crest.

No other species of turtle was recorded as nesting during this study.

Nesting females

A total of 245 tagged turtles were encountered over the seven-year study, and only one (0.4%) had been tagged elsewhere. This was turtle T38567, tagged in 1988 and observed at Avoid Island in 2012-2013, 2016-2017 and 2018-2019, thus providing a 30-year breeding history. The only other immigrant turtle (T27540) to Avoid Island was observed in 2007-2008 and it also had been tagged at Wild Duck Island in 1988 and it had last been seen there in 1992.

Experienced nesters were mostly larger than new recruits, although this varied across years from 0.3 – 3.8 cm, and there was a broad overlap in sizes.

Average yearly recapture intervals indicated that the most common remigration interval was two years, but with an increased proportion of three-year intervals the last two years of the study. Field-based recapture intervals are expected to over-estimate actual remigration rates, largely due to turtles missed during a census period. Modelling of capture-mark-recapture data since 2012 derived a long-term recapture probability of 25% per year that fluctuated widely from 7% - 58% (Limpus *et al*. 2021). Therefore, some turtles that nest in a given year were missed during the monitoring.

Data on inter-nesting intervals, the time period between laying successive clutches was limited to only three years of data at Peak Island and six years of data at Avoid Island. Post-hoc tests (two-samples Z tests) for differences in means indicated that the remigration yearly inter-nesting intervals were longer at Curtis Island than at Peak Island and Avoid Island, which were similar.

Health and injuries

Flatback turtles nesting at Avoid Island continue to show a low incidence of fresh injuries and no evidence of fibropapillomas during the study.

Nest and hatchling disturbance and depredation and island fauna

No mammalian or reptilian terrestrial predators of marine turtle eggs or hatchlings were recorded on Avoid Island. Very few clutches were dug into by nesting turtles during the course of the study, crab predation by *Ocypode cordimanus* of turtle eggs was low and few instances of their predation of hatchlings was reported. While potential avian predators of turtle hatchlings were present on the island, including sea eagles, *Haliaeetus leucogaster,* and beach stone curlew, *Esacus magnirostris*, the latter of which was recorded preying in ghost crabs.

Clutch abundance, size and success

During the study there was a large range (32 - 79) in the number of clutches laid per year, with a decline observed in the last three years. A post-hoc trend analysis using a linear regression was not significant (y = 89.6 – 64.3x, $p = 0.087$), given the stability in clutch numbers the first four years of the study. Clutch size also varied considerably, with a 33% variation in clutch size (34.9 – 51.9 eggs). These values were mostly below values previously reported for the eQld population (Limpus 2007).

Yearly average egg diameter and egg weight fluctuated somewhat (~9%) during the study and were within the range previously reported (Limpus 2007).

Incubation success was >80% for all seasons except in 2017-2018 and 2018-2019 (62%, 64%). Similarly, emergence success was >70 except in 2017-2018 and 2018-2019 (57%, 61%). Reduced success in those seasons of was mostly attributed to changes to the beach profile that resulted in a depressed swale area on the upper beach slope that was inundated on the higher high tides, and which resulted in standing pools of water, sometimes for extended periods during rain events. In those years the success of ~10 nests each were substantially affected by inundation, which accounted for 16 – 29% of the clutches laid in those years. The extent to which this is an issue depends upon how weather events shape the beach profile, and whether turtles can access the higher beach slope or dunes. Erosion of nests due to cyclones occurred in 2013-2014 due to Tropical Cyclone Dylan, but it was not possible to quantify the extent of the loss. A large proportion of the season's clutches would have been incubating and nearly all nests laid below the dunes were eroded.

There were indications of heat stress in nests during five years of the study in which emerging hatchlings had died near the surface or were found compromised at the time the nest was dug, or of emerged hatchlings that had died near the nest from heat exposure. This was most apparent in 2016-2017 and 2019-2020.

Period to emergence, sand temperatures and estimated sex ratios

As outlined in the methods, the pivotal temperature for Flatback clutches is 29.3°C and the expected incubation period to hatchling emergence for clutches incubated at pivotal temperature should be approximately 54 days. Average yearly period to emergence data were less than this in the years that data were collected (2016-2017 onwards).

Sand temperature at nest depth exceeded pivotal temperature early in the nesting season at different times across the study, ranging from the last week of October to the first week of December. This also depended on whether the data loggers were in a sunny versus partially shaded location, with the shaded locations typically reaching pivotal temperatures about two weeks after those in the sunny locations. In some years periods of high rainfall reduced sand temperatures below pivotal temperatures, generally from a few days to one week, and on one occasion up to two weeks in a shaded location.

Considering the period to emergence and sand temperature data, Avoid Island is producing a strongly female biased hatchling population, but some males are produced early in the season, particularly in partially shaded locations and when there are major rainfall events.

Existing management at Avoid Island is providing an important island nesting site that is free of predation by pigs, dogs and foxes on beaches not impacted by urban or industrial development. It is highly recommended that the TFN supports continued monitoring to determine population trends and stay alerted to possible issues affecting the nesting population at Avoid Island.

CHAPTER 6. ROOKERY COMPARISON

Comparisons among rookeries were considered to better understand which attributes recorded during the monitoring were similar across all rookeries, which trends were shared, and what differences among rookeries were observed. To compare mean yearly values among rookeries one-way ANOVAs were conducted. If significant results were found, paired t-tests were run. To test for similarities in trends across years, correlation analyses were done.

Trends in nesting activity

Tests for correlations in the yearly number of nesters between rookeries showed significant correlations among all rookeries ($p < 0.05$). Additionally, the yearly number of clutches was correlated ($p <, 0.01$) among rookeries, though at a higher threshold *p*-value for the Curtis and Avoid islands relationship ($p = 0.056$). These similarities across years, with observed declines in the number of nesters among the rookeries, suggests they are responding in similar ways to a shared environment. Contrary to these observations, analyses of capture-mark-recapture data indicated a 2.9% increase per year since 2000 for the Peak Island rookery, a possible increase since 2016 at Curtis Island, and fluctuations in population size at Avoid Island (Limpus *et al*. 2021).

One hypothesis to explain the discrepancy between these two approaches is that remigration intervals may have increased, thus turtles are observed less frequently at the nesting beach. The use of regression analyses to test for significant trends in the remigration intervals showed positive trends through time that were significant for Peak Island, which supports the hypothesis, but results were non-significant at Curtis Island and Avoid Island. Testing for correlations in yearly remigration intervals were not significant between any rookery. It is problematic to determine remigration intervals, as opposed to observed recapture intervals, due to nesting turtles that did not lay within the observed periods, or that nested elsewhere, or were missed. Where monitoring is restricted to two weeks, a higher remigration rate would be expected due to missed turtles, in comparison to longer monitoring where there are more opportunities to encounter individual turtles. Systematic monitoring is needed to make comparisons, so it will be important to continue having (as a minimum) consistent two-week mid-season monitoring at all index beaches. Finding consensus between the observed field data and the analysis of population size and trends (Limpus *et al*. 2021) will require additional years of monitoring to extend the observations and analyses.

Because of community monitoring outside of the census period, Curtis Island was the only rookery that could provide data on the first nesting activity. This ranged from 8 – 23 October. A post-hoc trend analysis using linear regression indicated a declining, non-significant ($p = 0.10$) trend of females commencing nesting earlier in the season.

Nest success at the three rookeries ranged from 48.3% - 82.1%, with wide variation between successive years. Post-hoc ANOVA analysis indicated significant (*p* =

0.044) differences among the rookeries, with the largest pairwise difference suggested (p = 0.064) between Curtis Island and Peak Island. Peak Island had generally lower nest success due to turtles emerging at several sectors of the beach having little or no sand available to support nesting activity. Avoid Island nest success was generally low due to fallen trees, partially buried branches and areas of steep dune slopes.

Nesting females

Flatback turtles within the eAust genetic stock have continued to display fidelity to particular rookeries. Of the 1095 tagged Flatback turtles encountered across all study sites only seven (0.6%) had migrated between rookeries. Satellite tagging studies have shown that at least some turtles use more than one rookery within a season (Hamann *et al*. 2015). Given that nesting by the eAust Flatback population occurs on numerous islands and mainland beaches that are not monitored, the extent of movement among rookeries will be underestimated.

There was a large range in the proportion of new recruits observed at Curtis Island, which declined from 2013-2014 to 2016-2017 and then increased. A similar trend was observed at Peak Island, and these trends were significantly correlated (p = 0.040). The proportion of new recruits at Avoid Island dropped below 20% in 2016, indicating that most experienced nesting turtles had been tagged.

Analysis of inter-nesting intervals indicated that turtles spent more time (1- 2 d) between laying successive clutches at Curtis Island in comparison to Peak Island and Avoid Island, although the data from Peak Island was limited.

Population genetic analysis of turtles sampled at Curtis Island, Peak Island, and Wild Duck Island found that estimates of gene flow, which consider the contribution of males and females, links these rookeries as a single population (FitzSimmons *et al*. 2019). This will occur if the turtles from these rookeries overlap at mating locations. When only the female component of gene flow using mtDNA is considered, then Peak Island is genetically differentiated, yet Wild Duck and Curtis are genetically similar. One hypothesis to explain this is that when a beach is colonised, if there are few colonisers then they are likely to have a different composition of genetic variants, which may persist if there is little gene flow among rookeries.

Nesting female size and fecundity

Across all rookeries the seasonal average size of experienced nesting females was larger than that of newly recruited females, but with a large overlap in the sizes of turtles in the two categories. Additionally, a Bayesian approach to fitting models to female size at each rookery uncovered a trend of increasing body size through time (Limpus *et al.* 2021). ANOVA analyses found significant differences (F = 10.00, df = 20, p = 0.0012) in the yearly mean size of experienced turtles, with Curtis Island turtles being larger than the Avoid Island and Peak Island turtles (paired T-tests; p = 0.0024 and p = 0.029). In contrast, there were no differences in the yearly mean size of new recruits among the rookeries (F = 0.23, df = 20, p = 0.79).

The differences in the size of experienced females could be due to differential use of foraging grounds, in which the larger turtles preferentially use more productive foraging grounds or they expend less energy during foraging and migrations. Satellite tracking of post-nesting Flatback turtles from Curtis and Avoid Islands have shown a large range in foraging grounds used by the eAust population, from about 40 km south of Curtis Island to the top of the Cape York Peninsula (Hamann *et al*. 2015a; Shimada *et al.* 2020). It will take a more detailed analysis to determine if there are differences in the foraging grounds used by the different rookeries.

Flatback turtle eggs at the three rookeries were of similar diameter (F = 0.90, df = 1, p = 0.44) and weight (F = 0.073, df = 11, p = 0.93) based on ANOVA analyses of yearly mean data. Clutch size varied across the rookeries (F = 5.89, df = 20, p = 0.018) due to there being yearly mean values at Curtis Island that were larger than those at Avoid Island (T = 3.24, p = 0.018). The number of clutches laid per female was determined in 2016-2017 to be 2.65 at Curtis Island and 2.73 at Avoid Island.

Health, injuries and survivorship

There was a low incidence of fresh injuries at each of the rookeries. No nesting turtles were observed to have fibropapilomas. Observed injuries included damage from propeller cuts, carapace fractures that were consistent with a turtle being dropped onto a deck from a trawl net, and carcharinid injuries. Observed injuries at a nesting beach do not take into account injuries serious enough to result in mortality. Estimates of adult female survivorship based on mark-recapture data varied among the rookeries (Limpus *et al*. 2021). Peak Island nesting turtles had the lowest recorded survival rate (87%) of any analysed Flatback population, Curtis Island nesters had one of the highest rates (94.9%), and a very high rate for Avoid Is (98%) was considered unreliable (Limpus *et al*. 2021, for comparisons with other species see Pfaller *et al*. 2018). The extent of variation in adult female survival rates may indicate issues for Peak Island turtles either within the inter-nesting habitat or in their use of particular foraging grounds. To date, no satellite tagging of Peak Island turtles has been conducted, and this appears to be an important knowledge gap.

Nest and hatchling disturbance and depredation and island fauna

At Avoid and Peak Island there are no terrestrial mammals or reptiles that prey on turtles or hatchlings. Elevated avian predation of hatchlings was observed at Peak Island by sea eagles, *Haliaeetus leucogaster*, Torresian crows, *Corvus orru,* and beach thick-knees, *Esacus magnirostris*, in some seasons and there was nearshore predation of hatchlings by carcharinid sharks. Crab predation by *Ocypode cordimanus* on eggs and emerged hatchlings occurs at each of the rookeries, but the overall loss is very low. The most significant current predation issue for these island rookeries was fox and dog predation at Curtis Island of incubating clutches or at hatchling emergence. A successful island-wide pest management program was instigated in 2012, and it will be important to continue with a monitoring program for canids throughout the season to instigate predator control as needed. Trampling of nests by feral cattle and horses, or disturbance by inappropriate vehicle use at Curtis Island was a concern during the 2015-2016 season, and this needs to be monitored on a regular basis (Queensland Government. 2019).

Levels of predation on Flatback turtle hatchlings is not quantified for the eAust population and data collected on this parameter would be valuable for population modeling.

Incubation and emergence success

Incubation success reported for the three rookeries cannot be directly compared. At Curtis Island and average of 14 (22%) clutches were relocated each season due to the possibility of nest inundation during the study, thus the success of the nests is expected to be higher than if clutches were left in place. At Peak Island, nest locations were not mapped by measuring to marker posts but relied on GPS readings and observations of hatchling emergence. Therefore, failed nests were not included in the data, nor were nests in which only few hatchlings emerged. In some years it was noted that rain or windy conditions made it difficult to locate emerged clutches, which may have also favoured data collection from only the more successful nests. At Avoid Island, nest locations were mapped and located by measuring distances to the nests and included failed nests with no emergence of hatchlings. Notwithstanding these methodological differences, an ANOVA analysis did not detect significant differences in incubation or emergence success at the three rookeries ($p = 0.23$).

An increasing concern at all rookeries is lethal heat stress to pre-emergent hatchlings that are near the surface and of hatchlings that have emerged. Although this was an issue at all rookeries in some years there was no correlation in yearly incubation success between any of the rookeries ($p = 0.23 – 0.99$), as there are site-specific issues. Heat stress was documented as a particular problem at Peak island in part due to it being west-facing beach. A more extensive monitoring of sand temperatures at this index beach should be a priority.

Inundation of nests during high tides was an issue at all rookeries. Relocation of clutches at risk of inundation was done at Curtis Island in al years and at Peak Island in some years. Assessment of clutches at risk of inundation and relocation to areas with high incubation success is a practice that should continue. Knowledge gained of incubation success at Avoid Island will now allow a more accurate assessment of nest locations.

At Peak Island, incubation and emergence success was highly variable. Entrapment of hatchlings in the nest and reduced incubation success was due to root invasion by grasses and vines, including weed species. Removal of weed vegetation appears to be a successful strategy tool and management of non-native weed species (Limpus and Limpus, 2018) to reduce root invasion of nests may be warranted.

Environmental monitoring and hatchling sex ratios

There are three notable issues with elevated temperatures within the nest during the incubation period for marine turtle clutches: mortality, increased female sex ratio and sublethal effects to hatchling fitness. Optimal incubation temperatures are between 25 °C - 32°C, with a pivotal temperature of 29.3°C for Flatbacks at which a 50:50 ratio of female and male hatchlings is expected. At the extreme, nest temperatures above 33 - 35°C, are expected to be lethal, and although our monitored sand temperatures did not exceed 33°C, nest temperatures can be elevated several degrees due to embryonic metabolic heating during late incubation (reviewed in Howard *et al*. 2014). Studies of elevated temperatures on Flatback hatchling mortality and fitness are limited, though suggest tolerance to short periods of elevated temperatures (Hewavisenthis and Parmenter, 2002; Howard *et al*. 2015).

Monthly mean maximum temperatures from the BOM stations closest to the rookeries provided insights into the temperature variation across the three rookeries and the quantification of heat wave conditions. Determining sand temperatures at nest depth is crucial for estimating hatchling sea ratios and requires the placement of temperature probes at a 50 cm depth. It was apparent that having temperature probes placed in open and shaded locations on the upper beach slope and the dune at Avoid Island contributed to a better understanding of the temperature ranges at that rookery. Additional temperature probes are needed at Curtis and Peak islands. There were several issues with the temperature probes including being lost due to cyclones, stolen at Curtis Island, probe failure, software and hardware issues during deployment, and a lack of opportunity to upload data at the very end of the season. A new model of temperature probe is now in use within the DES turtle studies that allows a WiFi connection to upload data. This would alleviate most of the problems and allow a rapid assessment of temperatures and data quality.

Rainfall will influence the period to emergence as cool rain results in a decline in sand temperatures at nesting beaches. The mid-summer Flatback turtle nesting season typically coincides with a summer peak annual rainfall. Rainfall results in a decline in sand temperatures at nesting beaches and sand temperatures increase in the short term in the absence of rain (Reed, 1980). In the absence of rain, dry surface sand conditions will favour higher sand temperatures as a result of reduced evaporative cooling within the sand.

Monthly total rainfall data from the BOM stations closest to the rookeries allowed an approximate comparison of the relative amount of rainfall received by the three rookeries (Figure 2.5). This suggested that across the seven years Curtis Island tended to have the highest rainfall in October and the least rainfall in February through April. Avoid Island tended to have the most rainfall from November through March and the least rainfall in October. Peak Island tended to have the least rainfall in October through January and only the highest rainfall in April. This relative lack of rain at Peak Island may have contributed to the greater heat stress to clutches and hatchlings observed in some years.

Hatchling sex ratio theory

As explained previously, if Flatback turtle eggs incubate at a constant temperature of 29.3^{o}C, hatchlings should emerge approximately 52 days after the eggs were laid (DES unpublished data). Therefore, the period to emergence can also be informative about the sex of hatchlings. Allowing for the time taken for hatchlings to dig to the surface from the hatched eggs, the pivotal period from laying to hatchling emergence to the beach surface should be approximately 54 days. Longer incubation period from laying to hatchling emergence should be indicative of cooler nests when the sex is determined and hence increased male ratio among hatchlings. A shorter period to emergence should be indicative of warmer nests and increased female ratio.

Mean period to emergence data within the census periods for all years at all locations were shorter than 54 days, indicative of a biased female hatchling ratio for the eAust Flatback turtle population. However, when monitoring occurred over a longer period there was a range in period to emergence that exceeded 54 days, indicative of a male-biased hatchling production in some nests laid outside of the census period.

In general, nest depth temperatures rose above pivotal temperature between early November and mid-December, suggesting that nests laid early in the season would be biased towards the production of male hatchlings. At most locations, in most years, temperatures stayed above pivotal temperature until sometime in March, except when there were major rain events which dropped the temperature below 29.3°C for several days. If these shorter duration rainfall events happen during the critical middle third of incubation, then an increase of male hatchlings would occur.

Summary- eAust Flatback Population

In summary, several observations indicate similarities across rookeries indicative of a single panmictic population. These included:

- correlations between the number of nesting turtles across the seven years, which included a significant decline in the annual number of nesting turtles at Curtis Island,
- correlations among the number of clutches across the seven years, which included a significant decline in the annual number of clutches at Curtis and Peak Island,
- similar sizes of newly recruiting females,
- the proportion of new recruits was correlated across years for the Curtis and Peak Island rookeries, with a larger proportion of new recruits at Curtis Island. There were insufficient data from Avoid Island to test this,
- similar egg diameters and weights at the three rookeries,
- similar number of clutches per female at Curtis and Avoid Island, and
- a low frequency of migration between rookeries that would contribute to gene flow within the population.

Indications of variation among rookeries included:

- mean yearly remigration intervals that were different among all rookeries with the greatest intervals at Peak Island and the least intervals at Avoid Island,
- the Peak Island remigration intervals showed a significant increasing trend with time,
- the yearly mean size of experienced turtles which were larger at Curtis Island than at Peak Island or Avoid Island,
- the yearly mean number of eggs per clutch that were greater at Curtis Island than at Peak Island or Avoid Island.
- the inter-nesting interval was greater at Curtis Island that at Peak Island and Avoid Island.

Major concerns for the eAust Flatback population are:

- There were observed declines in the number of nesting turtles at all three rookeries, for the last three years of the study, which contrasts with the results from analyses of mark-recapture data. Previous fluctuations, with two-three-year declines have been observed in the past (Limpus 2007), so it is imperative to see if the numbers of nesting turtles increase.
- Strongly female biased hatchling sex ratios were predicted for several years at each of the rookeries. The recurring strongly female biased hatchling sex ratio should be viewed with concern (Hamann *et al*. 2007; Limpus, 2008; Poloczanska *et al*. 2009). Increased effort is warranted for identifying if there are other nesting beaches within the breeding range of the eAust Flatback turtle genetic stock that consistently produce large numbers of male hatchlings. If not, then management options could be considered that can counter the consequences of global warming that is feminising this marine turtle nesting population.
- Flatback turtles do not instinctively know the way to the ocean. As they leave the nest, hatchlings orient to move towards the horizon at the lowest angle of elevation from their viewpoint and they move away from elevated dark horizons (Limpus, 1971b; Limpus and Kamrowski, 2013). Although not investigated in the present study, the extremely bright sky glow emanating from Gladstone and Port Curtis (Kamrowski *et al*. 2012; Pendoley Environmental, 2012) has negative impacts on the breeding success of marine turtle nesting on the Curtis Coast (Shimada *et al*. 2021).
  - It is expected that the bright sky glow inland of the nesting beach will result in an elevated mortality of hatchlings dispersing out to sea from the beaches as has been recorded for green turtle hatchlings dispersing from Heron Island, impacted by the tourist resort and research station lighting (Truscott *et al*. 2017).
  - It is expected that with the increased bright sky glow behind South End Beach since the construction since 2010 of the three LNG port facilities on Curtis Island and the Wiggins Island Coal Terminal could be causing the reduction in adult female numbers visiting the beach for breeding.

  Significant reduction of the intensity of the sky glow created by Gladstone and Port Curtis industrial facilities is warranted.

  At Peak Island, sky glow is seen from Gladstone, Rockhampton and the Keppel Bay Coast that may also be of concern.

Recommendations for monitoring and management

As listed in the Marine Turtle Recovery Plan for Australia, the index beaches for the eAust Flatback Population are Peak Island, Wild Duck Island, Curtis Island and Avoid Island. We recommend the continuation of monitoring at these rookeries, with the Queensland Trust for Nature (QTN), taking over the monitoring at Avoid Island.

Curtis Island is a minor rookery of the eAust Flatback population. Monitoring of the rookery commenced in 1993 and has been nearly continuous. This rookery has the advantage of being able to involve the local community in intermittent monitoring throughout the season. Recommendations for monitoring at Curtis Island are:

- continued two or three-week mid-season census of nesting turtles.
- continued identification of nest locations for an unbiased determination of incubation and emergence success,
- placement of four temperature data loggers, at nest depth in varied microhabitats, that can be uploaded via WiFi,
- continued two-week hatchling trips to determine period to emergence, incubation success and emergence success,
- continued relocation of nests assessed as being at risk of inundation,
- continued support for intermittent monitoring by the local community, particularly for determining the number of tracks and clutches/night and observing feral animal tracks,
- continued pest management actions and monitoring for nest disturbance throughout the season.

Peak Island is the second largest rookery of the eAust Flatback population. Monitoring of the rookery commenced in 1980 and has been nearly continuous. Recommendations for monitoring at Peak Island are:

- continued two-week mid-season census of nesting turtles,
- accurate mapping of a proportion of nest locations for an unbiased determination of incubation and emergence success,
- placement of four temperature data loggers, at nest depth in varied microhabitats, that can be uploaded via WiFi,
- continued two-week hatchling trips to determine period to emergence, incubation success and emergence success,
- removal of weed vegetation to reduce root invasion of nests,
- relocation of nests assessed as being at risk of inundation,
- monitoring of predation on hatchlings, and
- conducting a satellite tracking study to determine inter-nesting habitat use, migration corridors and foraging habitats.
- research to determine nest temperatures 10-20 cm below the surface and monitor pre-emergent hatchlings to understand their behaviour when heat stressed, why some hatchlings emerge during the daytime into lethal temperatures, and how to anticipate this and minimise mortality

Avoid Island is the third largest rookery of the eAust Flatback population. Monitoring of the rookery was first done in 2007/08 and has been continuous since 2012/13. The Island is owned by QTFN and is managed as a permanent nature refuge. This rookery has the advantage of being a control site as the island is remote from urban or industrial development. The continued systematic monitoring of nesting activity at Avoid Island for several more years would provide adequate data to estimate population trends and survivorship. Recommendations for QTFN monitoring at Avoid Island are:

- continued two-week mid-season census of nesting turtles on the North, Middle and South beaches,
- continued mapping of nest locations to allow an unbiased determination of incubation and emergence success from marked nests,

- continuation of temperature monitoring with four data loggers at nest depth in varied microhabitats, with replacement to newer models that can be uploaded via WiFi,
- continued hatchling trips of 1 - 2 weeks duration to determine incubation success and emergence success, and when possible, period to emergence,
- relocation of nests assessed as being at risk of inundation,

During the 2016-2017 breeding season, monitoring at Curtis Island was conducted over the entire season, and at Avoid Island monitoring was done for most of the season.
What was most valuable in doing full season monitoring came from:

- determining the number of clutches laid by females,
- determining what percentage of the season’s nesting females were observed within the census period,
- determining what percentage of the season’s clutches were laid within the census period,
- obtaining a more reliable estimate of the proportion of new recruits, as late arrivals to the breeding season have a higher proportion of new recruits,
- obtaining period to emergence data for the entire season as a proxy to estimate the sex ratio of hatchlings, and
- obtaining data on inter-nesting intervals, as these may be affected by increased temperatures with climate change, due to increased metabolic rates.

It will be important to continue collecting this additional season-long data periodically, with Curtis Island being the most feasible logistically. Season-long data has been collected since 1968 at the Mon Repos rookery, but this rookery has a long-term mean of only six individuals nesting per year (Limpus *et al*. 2022a), so additional season-long data from the larger rookery at Curtis Island is needed for greater data reliability.

6. Acknowledgements

These Flatback turtle projects were conducted as part of the Turtle Conservation Project of the Threatened Species Unit, Department of Environment and Science. The project was funded in part by grants from Gladstone Ports Corporation’s Ecosystem Research and Monitoring Program and from Eco Logical Australia.

The Curtis Island and Peak Island projects received logistical assistance from the Gladstone Queensland Parks and Wildlife Service staff.

The Avoid Island project was conducted as a cooperative project between the Queensland Trust for Nature (QTFN) and the Turtle Conservation Project of the Threatened Species Unit, Department of Environment and Science. Renee Rossini of QTFN provided logistic support, organised transport and organised accommodation for the field studies.

These studies could not have been completed without the assistance of the numerous Queensland Turtle Conservation volunteers, who often worked long hours in challenging conditions. The assistance of staff and volunteers is gratefully acknowledged.

Photos were provided by Duncan Limpus, Maree Mclaren, Lucy Pople, Linda Reinhold, Bill Tompkins, and Helen Twaddle

7. References

Bureau of Meteorology (BOM) (2020). Special Climate Statement 73 – Extreme heat and fire weather in December 2019 and January 2020. (Australian Bureau of Meteorology: Melbourne).

FitzSimmons, N. N. (2013). Avoid Island Flatback Turtle (*Natator depressus*) Nesting Study 2012-2013. Final Report to Queensland Trust for Nature. (20 February 2013).

FitzSimmons, N. N. and Limpus C. J. (2014a). Marine turtle genetic stocks of the Indo-Pacific: identifying boundaries and knowledge gaps. Indian Ocean Newsletter **20**: 2-18.

FitzSimmons, N. N. and Limpus, C. J. (2014b). Marine Turtle Nesting Populations: Avoid Island Flatback Turtles, 2013-2014 breeding season. Brisbane: Department of Environment and Heritage Protection, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 16 pp.

FitzSimmons, N. N. and Limpus, C. J. (2015). Marine Turtle Nesting Populations: Avoid Island Flatback Turtles, 2014-2015 breeding season. Brisbane: Department of Environment and Heritage Protection, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 19 pp.

FitzSimmons, N. N. and Limpus, C. J. (2016). Marine Turtle Nesting Populations: Avoid Island Flatback Turtles, 2015-2016 breeding season. Brisbane: Department of Environment and Heritage Protection, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 20 pp.

FitzSimmons, N. N., Pittard S. D., McIntyre N., Jensen M. P., Guinea M., Hamann M., Kennett, R., Leis, B., Limpus C. J., Limpus, D. J., McCann, M. J., McDonald, A. J., McFarlane, G., Parmenter, C., J., Pendoley, K., Prince, R. T., Scheltinga, L., Theissinger, K., Tucker, A. D., Waayers, D., Whiting, A., Whiting, S. (2019). Phylogeography, genetic stocks, and conservation implications for an Australian endemic marine turtle. Aquatic Conservation **30**: 440-460.

Hamann, M., Limpus, C. J., and Read, M. A. (2007). Vulnerability of marine reptiles to climate change in the Great Barrier Reef. In: Climate Change and the Great Barrier Reef: a vulnerability assessment. Eds. Johnson, J. E., and Marshall, P. A., pp. 465-497. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Townsville. 18 pp.

Hamann, M., Wildermann, N., Daff, K., and Limpus, C., J. (2015b). Annual report on the inter-nesting use by flatback turtles off the Curtis Island coast - 2014-2015 nesting season. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 19 pp.

Hewavisenthi, S.,and Parmenter, C. J. (2002). Incubation environment and nest success of the flatback turtle (*Natator depressus*) from a natural nesting beach. *Copeia* **2002**: 302-312.

Howard, R., Bell, I., and Pike, D. A. (2014). Thermal tolerances of sea turtle embryos: current understanding and future directions. *Endangered Species Research* **26**: 75-86.

Howard R., Bell, I., and Pike, D. A. (2015). Flatback turtle (*Natator depressus*) embryos are resilient to climate change. *Journal of Experimental Biology* **218**: 3330-3335.

Jones, M. and Venz, H. (2008). Queensland Turtle Conservation Project: Avoid Island Flatback Turtle Study, 2007-2008. Version 1: Report to EPA Tenure Actions Branch and Queensland Trust for Nature. 31 pp.

Kamrowski, R. L., Limpus, C., Moloney, J., and Hamann, M. (2012). Coastal light pollution and marine turtles: assessing the magnitude of the problem. *Endangered Species Research* **19**: 85-98.

Limpus, C. J. (1971a). The flatback turtle, *Chelonia depressa* Garman in southeast Queensland, Australia. *Herpetologica* **27**: 431-436.

Limpus, C. J. (1971b). Sea turtle ocean finding behaviour. Search **2**: 385-387.

Limpus, C. J. (1985). A study of the loggerhead turtle, *Caretta caretta*, in eastern Australia. *PhD thesis, University of Queensland*: Brisbane

Limpus, C. J. (1992). Estimation of tag loss in marine turtle research. *Wildlife Research* **19**: 457-69.

Limpus, C. J. (2007). A biological review of Australian marine turtles. 5. Flatback turtle *Natator depressus* (Linneaus). (Queensland Environmental Protection Agency, Brisbane.) ISBN 978-0-9803613-2-2.

Limpus C. J. and Kamrowski R. L. (2013). Ocean-finding in marine turtles: the importance of low horizon elevation as an orientation cue. *Behaviour* **150**: 863-893.

Limpus, C. J. and Limpus, D. J. (2018). Plant species within the marine turtle nesting habitat of Peak Island. (Queensland Department of Environment and Science: Brisbane)

Limpus, C. J., Baker, V., and Miller, J. D. (1979). Movement induced mortality of loggerhead eggs. *Herpetologica* **35**: 335-338.

Limpus, C. J., Parmenter, C. J., Parker, R., and Ford, N. (1981). The flatback turtle, *Chelonia depressa*, in Queensland: the Peak Island rookery. *Herpetofauna* **13**: 14-18.

Limpus, C. J., Parmenter, C. J., Baker, V. and Fleay, A. (1983). The Crab Island sea turtle rookery in north eastern Gulf of Carpentaria. *Australian Wildlife Research* **10**: 173-184.

Limpus, C. J., Fleay, A., and Baker, V. (1984). The flatback turtle, *Chelonia depressa* in Queensland: reproductive periodicity, philopatry and recruitment. *Australian Wildlife Research* **11**: 579-87.

Limpus, C. and Nicholls, N. (2000). ENSO regulation of Indo-Pacific Green turtle populations. In "Applications of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems." (Eds. Hammer, G., Nicholls, N., and Mitchell, C.) Pp. 399-408. (Kluwer Academic Publishers: Dordrecht.)

Limpus, C. J., Clifton, D., Griffin, K., Kemp, L., Gallagher, L., Gallagher, L., Fisher, S., and Parmenter, C. J. (2002). Survey of marine turtle nesting distribution in Queensland, 2001 and 2002: Broad Sound to Repulse Bay, Central Queensland. (Queensland Parks and Wildlife Service: Brisbane.)

Limpus, C. J., McLaren, M., McLaren, G., and Knuckey, B. (2006). Queensland Turtle Conservation Project: Curtis Island and Woongarra Coast Flatback Turtle studies, 2005-2006. *Conservation Technical and Data Report* **2006**.

Limpus C.J., Parmenter, C.J., and Chaloupka, M. (2013). Monitoring of Coastal Sea Turtles: Gap Analysis 5. Flatback turtles, *Natator depressus*, in the Port Curtis and Port Alma Region. Department of Environment and Heritage Protection Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 26 pp.

Limpus, C. J., FitzSimmons, N. N., Sergeev, J. M., Ferguson, J., Hoffmann, F., Phillot, A., Pople, L., Ross, A., Tompkins, B., Turner, T. and Wenk, L. (2017). Marine turtle nesting populations: flatback turtle, *Natator depressus*, 2016-2017 breeding season at Curtis Peak and Avoid Islands. Brisbane: Department of Environment and Heritage Protection, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 70 pp.

Limpus, C. J., FitzSimmons, N. N., Hoffmann, F., Hoffman E., Laws, J., Limpus D. J., McLaren M., Sergeev, J. M., Shapland F., and Turner, T. (2018). Flatback turtle, *Natator depressus*, 2017-2018 breeding season at Curtis Peak and Avoid Islands. Brisbane: Department of Environment and Science, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 67 pp.

Limpus, C. J., FitzSimmons, N. N., French, K., Hoffmann, F., Hoffman E., Limpus D. J., McLaren M., McLaren, G., Robertson, C., Shapland F., and Turner, T. (2019). Flatback turtle, *Natator depressus*, 2018-2019 breeding season at Curtis Peak and Avoid Islands. Brisbane: Department of Environment and Science, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 73 pp.

Limpus, C. J., Chaloupka, M., Ferguson, J., FitzSimmons, N. N. and Parmenter, J. C. (2022a) The Flatback turtles, *Natator depressus* in Queensland: population size and trends. Brisbane: Department of Environment and Science, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 56 pp.

Limpus, C. J., FitzSimmons, N. N., French, K., Hoffmann, F., Hoffman E., Limpus D. J., McLaren M., McLaren, G., Robertson, C., Rossini, R., and Turner, T. (2022b). Flatback turtle, *Natator depressus*, 2019-2020 breeding season at Curtis Peak and Avoid Islands. Brisbane: Department of Environment and Science, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 68 pp.

Parmenter, C. J. (1993). A preliminary evaluation of the performance of passive integrated Transponders and metal tags in a population study of the flatback sea turtle (*Natator depressus*). *Wildlife Research* **20**, 375-381.

Pendoley Environmental (2012). Gladstone Baseline Sky Cam Light Monitoring 2011. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation’s Ecosystem Research and Monitoring Program.

Pfaller, J. B., Limpus, C. J., and Bjorndal, K. A. (2008). Nest-site selection in individual loggerhead turtles and consequences of doomed-egg relocation. *Conservation Biology* **23**: 72-80.

Pfaller, J. B., Chaloupka, M., Bolten, A. B., and Bjorndal, K. A. (2018). Phylogeny, biogeography and methodology: a meta-analytic perspective on heterogeneity in adult marine turtle survival rates. *Scientific Reports* **8**: 5852.

Poloczanska, E. S., Limpus, C. J., and Hays, G. C. (2009). Vulnerability of marine turtles to climate change. *Advances in Marine Biology* **56**: 151-211.

Pople, L., Reinhold, L. and Limpus, C. J. (2016). Marine Turtle Nesting Population: Peak Island Flatback Turtles, 2015-2016 breeding season. Brisbane: Department of Environment and Heritage Protection, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation Ecosystem Research and Monitoring Program.

Queensland Government 2019. Curtis Island National Park Management Statement 2019. Prepared by Department of Environment and Science, 33 pp.

Reed, P. C. (1980). The sex ratio of hatchling loggerhead turtles - progeny of two nesting adult females. *B.Sc.Hon. Thesis, James Cook University of North Queensland:* Townsville.

Shimada, T., Thums, M., Hamann, M., Limpus, C. J., Hays, G. C., FitzSimmons, N. N., Wildermann, N., Duarte, C. M., Meekan, M. G. 2020. Optimising sample sizes for animal distributions analysis using tracking data*. Methods in Ecology and Evolution* doi.org/10.1111/2041-210x.13506.

Shimada, T., Limpus, C. J., FitzSimmons, N. N., Ferguson, J., Limpus, D., and Spinks, R. K. (2021). Industrial and residential sky glow disrupts the orientation of hatchling and adult flatback turtles on nesting beaches. Brisbane: Department of Environment and Science, Queensland Government.

Truscott, Z., Booth D. T., and Limpus C. J. (2017). The effect of on-shore light pollution on sea turtle hatchlings commencing their off-shore swim. *Wildlife Research* **44**(2): 127-134.

Twaddle, H., Limpus, J., Pople, L., Wildermann N., and Limpus, C. J. (2014). Marine Turtle Nesting Population: Peak Island Flatback Turtles, 2013-2014 Breeding Season. Brisbane: Department of Environment and Heritage Protection, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation’s Ecosystem Research and Monitoring Program. 14 pp.

Twaddle, H., French, K., Howe, M., Limpus, G., McLaren, M., Pople, L., Sim, E., and Limpus, C. J. (2015). Marine Turtle Nesting Population: Peak Island Flatback Turtles, 2014-2015 Breeding Season. Brisbane: Department of Environment and Heritage Protection, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of

Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. 19 pp.

Yntema, C. L. and Mrosovsky, N. (1982). Critical periods and pivotal temperatures for sexual differentiation in loggerhead sea turtles . *Canadian Journal of Zoology* **60**: 1012-1016.

Zar, J. H, (1984) Biostatistical Analysis, 2nd ed. (Prentice-Hall : Englewood Cliffs).

Tables

Chapter 3- Curtis Island Tables

Table 3.1. Curtis Island data from 2013/14 – 2019/20 of nesting Flatback turtles, *Natator depressus*, including total values or average values with ± standard deviation (SD) and sample size (n).

Parameter	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020
# nesters census	58	39	43	35	31	25	31
% new recruits census	27.6	25.6	16.3	14.3	19.4	16.0	32.3
remigration (yr)	3.2 ± 1.4 n = 50	3.1 ± 1.7 n = 31	2.8 ± 2.1 n = 35	3.7 ± 1.6 n = 35	3.4 ± 2.2 n = 33	3.3 ± 1.1 n = 20	3.5 ± 1.1 n = 24
remigration range (yr)	2 - 10	1 - 9	2 - 12	2 - 8	1 - 10	2 - 6	2 - 7
CCL (cm) experienced	95.7 ± 2.3 n = 50	95.0 ± 2.9 n = 28	94.6 ± 2.9 n = 32	94.2 ± 2.5 n = 35	94.7 ± 2.2 n = 30	95.0 ± 2.2 n = 20	93.8 ± 2.3 n = 24
CCL (cm) new recruits	93.6 ± 1.9 n = 16	92.2 ± 2.5 n = 11	92.2 ± 2.2 n = 7	92.6 ± 2.3 n = 10	91.0 ± 3.6 n = 8	90.6 ± 1.6 n = 4	92.8 ± 2.0 n = 13
tracks/night	5.1 ± 2.8 n = 14	4.6 ± 3.8 n = 14	4.4 ± 2.0 n = 14	4.5 ± 4.1 n = 14	3.4 ± 2.2 n = 14	2.6 ± 2.1 n = 14	3.4 ± 2.2 n = 14
return interval (d) unsuccessful	0.60 ± 0.72 n = 30	0.64 ± 0.57 n = 25	0.70 ± 0.77 n = 17	0.60 ± 0.51 n = 19	0.92 ± 1.2 n = 13	0.80 ± 1.3 n = 5	1.6 ± 1.3 n = 7
Inter-nesting interval	14.2 ± 3.6 n = 18	14.2 ± 2.2 n = 13	13.8 ± 1.6 n = 15	14.7 ± 1.7 n = 71	15.5 ± 1.9 n = 11	14.1 ± 1.5 n = 9	13.0 ± 0.43 n = 12
1st nesting	na	23 Oct	22 Oct	14 Oct	8 Oct	17 Oct	10 Oct
last nesting	na	na	13 Jan	2 Feb	13 Jan	17 Jan	11 Jan
1st emergence	5 Dec	20 Dec	15 Dec	17 Dec	5 Dec	8 Dec	8 Dec
% nesting success	66.7	59.7	73.4	73.1	82.1	75.0	70.8
total clutches	58	40	45	39	34	30	34
clutches/ night	4.1 ± 2.3 n = 14	2.9 ± 2.4 n = 14	3.2 ± 1.5 n = 14	2.8 ± 2.8 n = 14	2.4 ± 1.6 n = 14	2.1 ± 1.8 n = 14	2.4 ± 2.0 n = 14
clutches/ female	na	na	na	2.7 ± 0.92 n = 46	na	na	na

Table 3.1. Continued

Parameter	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**
eggs/clutch	55.2 ± 7.5 n = 48	56.0 ± 11.7 n = 34	56.8 ± 9.8 n = 44	52.6 ± 8.4 n =40	51.6 ± 10.0 n = 31	52.1 ± 8.1 n = 31	62.8 ± 5.9 n = 4
egg diameter (cm) n = clutches	5.32 ± 0.54 n = 40	5.24 ± 0.22 n = 22	5.21 ± 0.16 n = 29	5.20 ± 0.13 n = 3	5.11 ± 0.14 n = 14	5.18 ± 0.14 n = 28	5.04 ± 0.12 n = 2
egg wt (g) n = clutches	76.3 ± 5.4 n = 16	76.7 ± 3.6 n = 22	77.7 ± 4.5 n = 29	76.3 ± 4.7 n = 3	75.2 ± 5.0 n = 14	77.0 ± 5.6 n = 28	71.7 ± 3.7 n = 2
nest depth-top (cm)	34.9 ± 9.7 n = 47	42.2 ± 9.7 n =31	42.5 ± 7.1 n = 38	40.1 ± 8.1 n = 8	47.2 ± 8.8 n = 16	42.8 ± 8.7 n = 25	44.8 ± 8.2 n = 7
nest depth-base (cm)	55.5 ± 8.4 n = 47	60.2 ± 8.4 n = 29	61.8 ± 7.4 n = 40	56.8 ± 5.9 n = 36	55.4 ± 7.6 n = 28	57.0 ± 6.0 n = 33	62.0 ± 4.9 n = 4
period to emergence (d)	52.0 ± 3.0 n = 6	48.0 ± 3.2 n = 23	48.3 ± 2.8 n = 96	47.4 ± 2.2 n = 29	47.5 ± 1.7 n = 32	48.4 ± 1.8 n = 14	47.0 ± 3.0 n = 72
period to emergence range (d)	49 - 57 n = 6	42 - 57 n = 23	43 - 58 n = 96	44 - 53 n = 29	44 - 52 n = 32	46 - 53 n = 14	44 - 51 n = 72
% incubation success	77.4 ± 23.3 n = 47	79.1 ± 24.2 n = 40	87.7 ± 10.4 n = 47	89.0 ± 15.8 n = 37	74.7 ± 19.0 n = 33	86.7 ± 14.9 n = 31	86.2 ± 21.1 n = 31
% emergence success	77.4 ± 23.3 n = 47	78.6 ± 24.3 n = 40	86.4 ± 10.6 n = 47	85.7 ± 15.9 n = 37	64.2 ± 26.1 n = 33	81.8 ± 20.2 n = 31	82.4 ± 20.8 n = 31

Chapter 4- Peak Island Tables

Table 4.1. Peak Island data from 2013/14 – 2019/20 of nesting Flatback turtles, *Natator depressus*, including total values or average values with ± standard deviation (SD) and sample size (n).

Parameter	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**
# nesters census	218	171	207	214	158	121	155
% new recruits census	17.9	19.3	12.1	12.6	10.8	10.7	16.1
remigration (yr)	2.8 ± 1.3 n = 173	2.7 ± 1.15 n = 134	2.7 ± 1.16 n = 180	3.0 ± 1.4 n = 184	2.8 ± 1.23 n = 137	3.3 ± 1.7 n = 108	3.6 ± 3.1 n = 124
remigration range (yr)	1 - 5	1 - 6	2 - 7	1 - 8	2 - 8	1 - 10	1 - 30
CCL (cm) experienced	94.6 ± 2.7 n = 163	94.1 ± 2.6 n = 124	94.5 ± 2.8 n = 176	94.2 ± 2.6 n = 178	94.1 ± 2.9 n = 135	93.6 ± 2.7 n = 102	93.7 ± 2.7 n = 120
CCL (cm) new recruits	92.6 ± 2.6 n = 37	92.4 ± 1.6 n = 29	92.8 ± 2.7 n = 24	91.9 ± 2.9 n = 25	92.5 ± 2.3 n = 12	92.6 ± 2.6 n = 12	91 .1 ± 2.9 n = 25
tracks/night	21.6 ± 15.3 n = 14	19.7 ± 10.5 n = 14	25.7 ± 16.6 n = 14	25.6 ± 18.8 n = 14	16.6 ± 10.8 n = 14	17.6 ± 9.5 n = 14	16.5 ± 8.3 n = 14
return interval (d) unsuccessful	0.96 ± 1.0 n = 26	1.1 ± 0.7 n = 69	0.84 ± 0.84 n = 85	0.83 ± 0.86 n = 82	1.3 ± 1.1 n = 28	1.1 ± 0.86 n = 53	1.1 ± 1.0 n = 44
Inter-nesting interval	na	na	12.5 ± 0.81 n = 15	na	na	13.3 ± 1.5 n = 16	12.2 ± 0.70 n = 6
1st emergence	28 Nov	na	na	30 Nov	6 Dec	na	na
% nest success	71.7	67.3	59.3	53.1	67.7	48.3	58.0
total clutches	211	168	211	209	157	114	134
clutches/ night	15.07 ± 11.8 n = 14	12.0 ± 7.8 n = 14	15.1 ± 10.0 n = 14	14.9 ± 10.9 n = 14	11.2 ± 7.0 n = 14	8.0 ± 4.6 n = 14	9.6 ± 6.1 n = 14
clutches/ female	na	na	na	na	na	na	na
eggs/clutch	52.6 ± 7.4 n = 11	55.4 ± 7.8 n = 38	51.4 ± 8.2 n = 38	50.4 ± 6.2 n =17	52.0 ± 8.7 n = 17	51.6 ± 8.1 n = 29	51.4 ± 5.9 n = 27

Table 4.1. Continued

Parameter	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**
egg diameter (cm) n = clutches	5.24 ± 0.15 n = 10	5.22 ± 0.13 n = 35	5.20 ± 0.11 n = 27	5.20 ± 0.14 n = 14	5.14 ± 0.16 n = 17	5.21 ± 0.11 n = 25	5.18 ± 0.14 n = 14
egg wt (g) n = clutches	78.5 ± 6.7 n = 10	77.5 ± 5.7 n = 35	76.5 ± 4.7 n = 26	76.0 ± 5.5 n = 14	75.1 ± 6.2 n = 17	76.8 ± 7.2 n = 21	76.8 ± 5.3 n = 20
nest depth-top (cm)	34.4 ± 6.6 n = 5	32.1 ± 7.7 n =31	30.6 ± 7.2 n = 38	31.5 ± 5.0 n = 8	34.5 ± 6.5 n = 16	35.3 ± 9.6 n = 25	31.0 ± 7.9 n = 7
nest depth-base (cm)	45.5 ± 6.4 n = 11	53.3 ± 6.4 n = 44	48.0 ± 6.5 n = 83	47.6 ± 7.2 n = 10	53.8 ± 5.8 n = 48	56.4 ± 9.4 n = 15	48.9 ± 5.7 n = 77
period to emergence (d)	na	50.5 ± 2.2 n = 37	na	52.7 ± 3.8 n = 21	47.8 ± 2.7 n = 32	51.1 ± 3.0 n = 11	44.0 ± 3.5 n = 33
period to emergence range (d)	na	46 - 56 n = 37	na	48 - 61 n = 21	45 - 59 n = 32	48 - 57 n = 11	44 - 58 n = 33
% incubation success	76.8 ± 11.1 n = 12	81.2 ± 17.2 n = 132	70.0 ± 20.5 n = 56	88.8 ± 8.8 n = 36	55.9 ± 23.3 n = 61	82.8 ± 12.5 n = 16	69.5 ± 23.1 n = 50
% emergence success	69.4 ± 14.5 n = 12	72.6 ± 21.1 n = 132	62.4 ± 23.1 n = 56	88.7 ± 11.5 n = 36	39.1 ± 26.6 n = 61	73.3 ± 19.8 n = 16	62.4 ± 26.5 n = 50

Chapter 5- Avoid Island Tables

Table 5.1. Avoid Island data from 2013/14 – 2019/20 of nesting Flatback turtles, *Natator depressus*, including total values or average values with ± standard deviation (SD) and sample size (n).

Parameter	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**
# nesters census	78	68	76	88	46	29	52
% new recruits census	66.7	50.0	26.3	18.4	23.9	17.2	15.4
remigration (yr)	2.4 ± 2.3 n = 25	2.8 ± 2.0 n = 34	2.1 ± 0.56 n = 54	2.4 ± 0.91 n = 63	2.6 ± 0.96 n = 53	3.0 ± 1.3 n = 27	3.0 ± 0.83 n = 46
remigration range (yr)	1 - 6	1 - 7	1 - 8	1 - 4	1 - 5	1 - 6	2 - 12
CCL (cm) experienced	93.5 ± 2.5 n = 25	94.2 ± 2.3 n = 35	93.3 ± 2.4 n = 57	93.6 ± 2.6 n = 62	93.3 ± 2.9 n = 61	94.0 ± 2.1 n = 26	93.3 ± 2.8 n = 44
CCL (cm) new recruits	92.5 ± 2.6 n = 52	92.1 ± 3.0 n = 34	93.0 ± 2.4 n = 21	93.3 ± 1.7 n = 14	91.4 ± 2.1 n = 13	90.2 ± 1.7 n = 6	91 .0 ± 3.2 n = 6
tracks/night	8.4 ± 7.5 n = 14	6.8 ± 3.8 n = 14	10.2 ± 7.0 n = 14	8.0 ± 4.0 n = 14	6.1 ± 5.4 n = 14	3.5 ± 4.5 n = 14	5.9 ± 4.4 n = 14
return interval (d) unsuccessful	1.2 ± 1.3 n = 5	1.4 ± 0.8 n = 9	1.1 ± 0.76 n = 12	0.72 ± 0.74 n = 36	1.1 ± 1.0 n = 15	0.33 ± 0.47 n = 3	2.8 ± 2.5 n = 8
Inter-nesting interval	na	12.9 ± 0.30 n = 10	12.8 ± 0.86 n = 27	13.9 ± 1.2 n = 112	13.8 ± 0.83 n = 12	12.7 ± 0.47 n = 3	13.3 ± 0.47 n = 3
1st emergence	28 Nov	6 Dec	8 Dec	27 Nov	5 Dec	> 7 Dec	5 Dec
% nest success	59.8	75.8	62.9	72.1	69.0	63.3	59.0
total clutches	70	72	70	79	61	32	49
clutches/ night	5.0 ± 4.2 n = 14	5.1 ± 2.7 n = 14	6.4 ± 3.9 n = 14	5.6 ± 2.2 n = 14	4.1 ± 3.7 n = 14	2.2 ± 2.6 n = 14	3.5 ± 3.0 n = 14
clutches/ female	na	na	na	2.7 ± 1.1 n = 92	na	na	na
eggs/clutch	34.9 ± 17.1 n = 11	50.8 ± 10.9 n = 44	51.9 ± 6.1 n = 29	42.0 ± 6.1 n = 8	48.5 ± 8.2 n = 48	51.1 ± 5.9 n = 15	51.4 ± 9.3 n = 77

Table 5.1. Continued

Parameter	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**2017-2018**	**2018-2019**	**2019-2020**
egg diameter (cm) n = clutches	na	na	5.17 ± 0.66 n = 290	4.77 ± 0.71 n = 10	5.2 ± 0.08 n = 3	5.2 ± 0.14 n = 28	na
egg wt (g)	na	na	76.8 ± 5.2 n = 290	72.0 ± 5.1 n = 10	78.8 ± 2.1 n = 3	77.0 ± 5.6 n = 28	na
nest depth-top (cm)	na	na	na	48.5 ± 3.9 n = 4	na	na	na
nest depth-base (cm)	33.5 ± 16.0 n = 11	61.5 ± 10.1 n = 44	56.3 ± 6.4 n = 83	59.8 ± 7.8 n = 10	59.6 ± 9.0 n = 48	61.1 ± 12.5 n = 15	59.7 ± 9.9 n = 77
period to emergence (d)	na	na	na	50.2 ± 2.7 n = 60	46.7 ± 1.3 n = 7	49.8 ± 3.2 n = 18	47.7 ± 2.1 n = 14
period to emrgence range (d)	na	na	na	45 - 57 n = 60	45 - 48 n = 7	45 - 60 n = 18	46 - 53 n = 14
% incubation success	85.4 ± 24.6 n = 11	86.4 ± 22.6 n = 44	80.7 ± 21.9 n = 85	73.7 ± 31.2 n = 80	62.0 ± 36.2 n = 49	64.0 ± 38.0 n = 21	80.3 ± 25.2 n = 48
% emergence success	85.1 ± 24.1 n = 11	86.4 ± 22.6 n = 44	80.4 ± 22.0 n = 85	71.4 ± 32.2 n = 80	56.9 ± 36.7 n = 49	61.0 ± 36.4 n = 21	71.7 ± 32.3 n = 48

Chapter 6- Rookery Comparison Tables

Table 6.1. Comparison of reproductive parameters (including ± standard deviation and range) recorded for Flatback turtles, *Natator depressus*, nesting at the three central Queensland index rookeries during the mid-season census period 2013/14 – 2019/20. Parameters shown represent the means of the yearly mean values.

Data Collected	Curtis Island	Peak Island	Avoid Island
Tagged turtles (n)	37.4 ± 10.0 25 - 58	177.7 ± 33.7 121 - 218	60.7 ± 17.4 29 - 78
New recruits (%)	21.6 ± 6.4 14.3 - 32.3	14.2 ± 3.3 10.7 - 19.3	31.1 ± 18.1 15.4 - 66.7
Remigration (yr)	3.3 ± 0.28 2.8 - 3.5	3.0 ± 0.31 2.7 - 3.6	2.6 ± 0.31 2.1 - 3.0
Female experienced CCL (cm)	94.7 ± 0.57 94.2 - 95.7	94.1 ± 0.35 93.6 - 94.6	93.6 ± 0.34 93.3 - 94.2
Female new recruit CCL (cm)	92.1 ± 0.95 90.6 - 93.6	92.3 ± 0.54 91.1 - 92.6	91.9 ± 1.0 90.2 - 93.3
Mean tracks/night (n)	4.0 ± 0.81 2.6 - 5.1	20.5 ± 3.7 16.5 - 25.7	7.0 ± 2.0 3.5 - 10.2
Return interval (d) unsuccessful	0.84 ± 0.33 0.6 - 1.6	1.0 ± 0.15 0.83 - 1.25	1.2 ± 0.70 0.33 - 2.8
Inter-nesting interval (d)	14.2 ± 0.70 13.0 - 15.5	12.7 ± 0.44 12.2 - 13.3	13.2 ± 0.47 12.7 - 13.9
Nesting success (%)	71.5 ± 6.5 59.7 - 82.1	60.8 ± 7.9 48.3 - 71.7	66.0 ± 5.9 .59.0 - 75.8
Total clutches (n)	39.9 ± 8.7 30 - 58	172.0 ± 36.8 114 - 211	61.9 ± 15.1 32 - 79
Mean clutches/night (n)	2.8 ± 0.62 2.1 - 4.1	12.3 ± 2.7 8 - 15.1	4.6 ± 1.3 2.2 - 6.4
Clutches/female (n)	2.65 ± 0.92 n = 46	na	2.73 ± 1.1 n = 92
Mean eggs/clutch	55.3 ± 3.6 51.6 - 62.8	52.1 ± 1.5 50.4 - 55.4	47.2 ± 6.0 34.9 - 51.9
Mean egg diameter (cm)	5.19 ± 0.08 5.04 - 5.32	5.20 ± 0.03 5.14 - 5.24	5.08 ± 0.18 4.77 - 5.20
Mean egg weight (g)	75.8 ± 1.8 71.7 - 77.0	76.7 ± 0.98 75.1 - 78.5	76.1 ± 2.5 72.0 - 78.8
Nest depth-top (cm)	42.1 ± 3.6 34.9 - 47.2	32.8 ± 1.8 30.6 - 35.3	na
Nest depth-bottom (cm))	58.4 ± 2.7 55.4 - 62.0	50.5 ± 3.7 45.5 - 56.4	59.7 ± 1.7 56.3 - 61.5
Period to emergence (d)	48.4 ± 1.6 47.0 - 52.0	50.2 ± 1.7 47.8 - 52.7	48.6 ± 1.5 46.7 - 50.2
Incubation success (%)	83.0 ± 5.3 74.7 - 87.7	75.0 ± 10.1 55.9 - 88.8	76.1 ± 9.11 62.0 - 86.4
Emergence success (%)	79.5 ± 7.0 64.2 - 86.4	66.8± 14.0 39.1 - 88.7	73.3 ± 10.6 56.9 - 86.4

FIGURES

Chapter 1- Introduction

Figure 1.1. Primary nesting study sites for Flatback turtles, *Natator depressus*, within the eAust genetic stock (orange type).

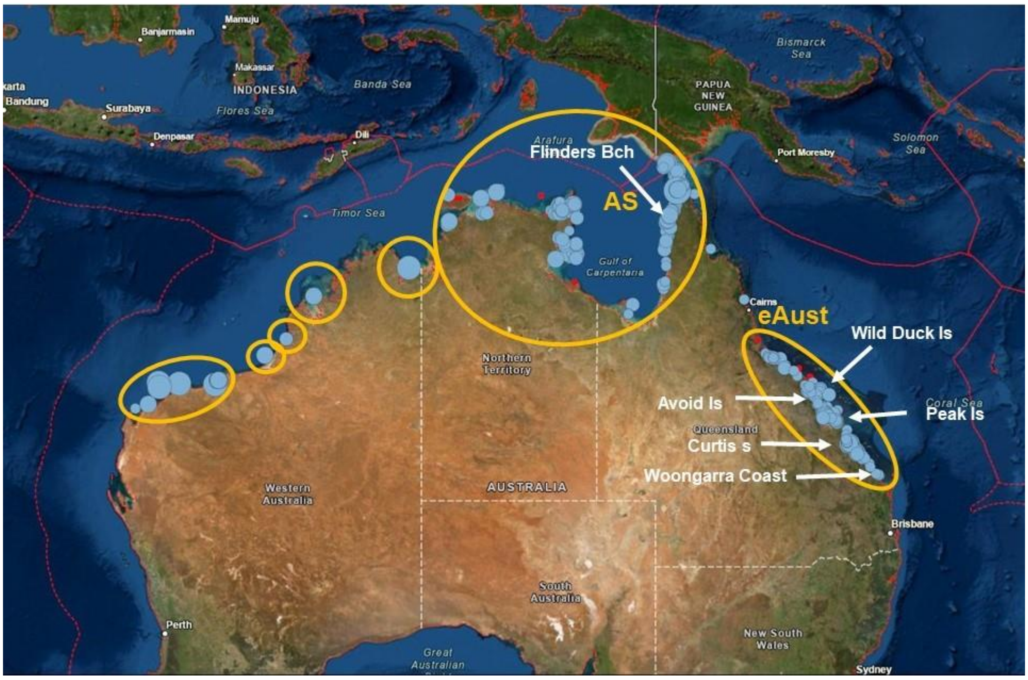

Figure 1.2. Flatback turtle genetic stocks identified by FitzSimmons *et al*. 2019.

Chapter 2- Methods Figures

a. Measuring curved carpace length

b. Nest identification tag

c Fox exclusion device.

d. Weighing and measuring eggs

e. Excavating nest

f. hatchling data collection

Figure 2.1. Examples of methods used in this study.

a. K81015, Curtis Island 2016

b. QA37854 Curtis Island 2016

c. QA35855 Avoid Island 2017/18

d. QA37477 Avoid Island 2017/18

Figure 2.2. Examples of injuries to Flatback turtles, *Natator depressus*: (a). K81015, Curtis Island 2016: recent carapace damage presumed to have occurred when the turtle was dropped from a net onto the deck of a vessel; (b) QA37854 Curtis Island 2016: propeller cuts to the carapace that occurred since nesting in December 2013; (c) QA35855 Avoid Island 2017/18: recently healed fracture to the right side of the carapace, 26 November 2017, which had occurred after the 2013-2014 season, (d) QA37477 Avoid Island 2017/18, with old healed damage.

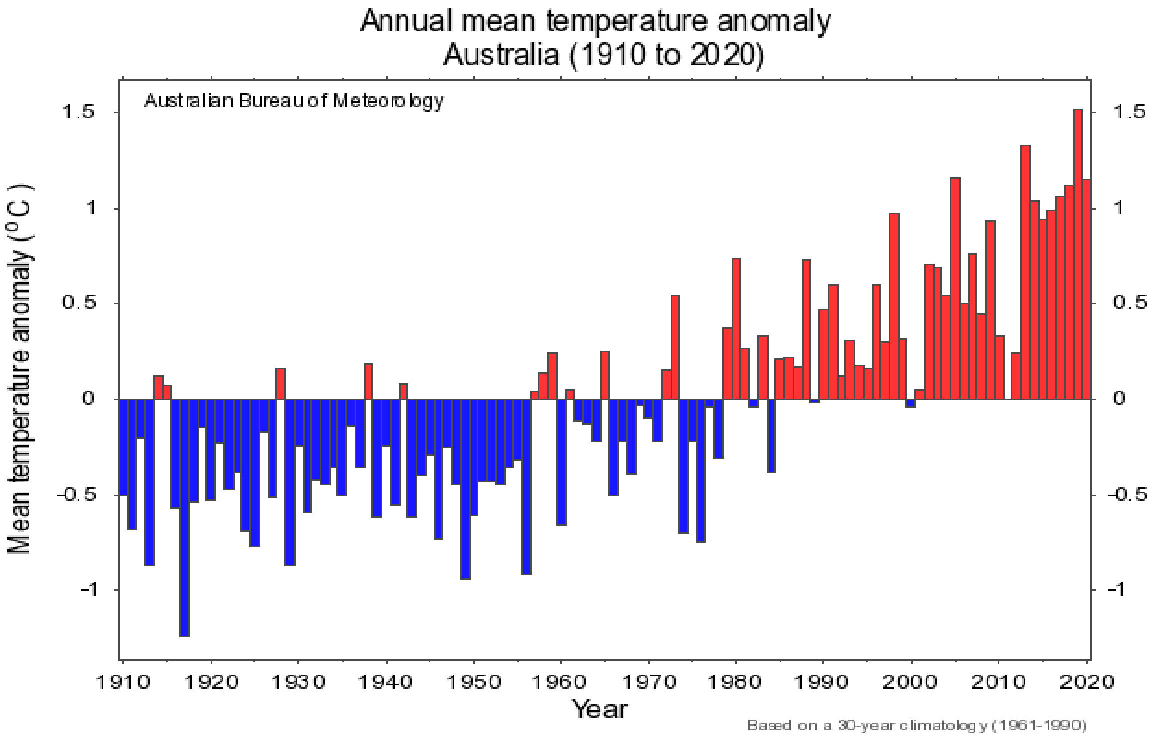

Figure 2.3. BOM (2021) data showing that annual mean temperature anomalies for the duration of the study ranged from +0.94 – 1.52°C and included 8 of the 10 highest anomalies since records commenced in 1910.

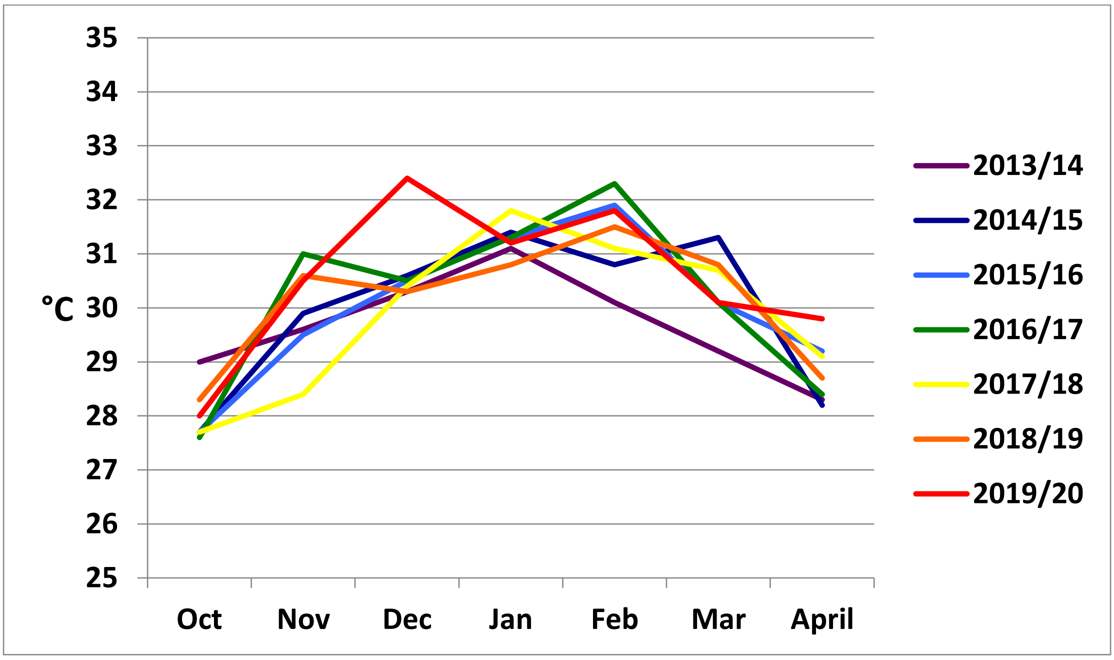

Figure 2.4a. Mean monthly maximum temperatures BOM station Gladstone Airport #39326.

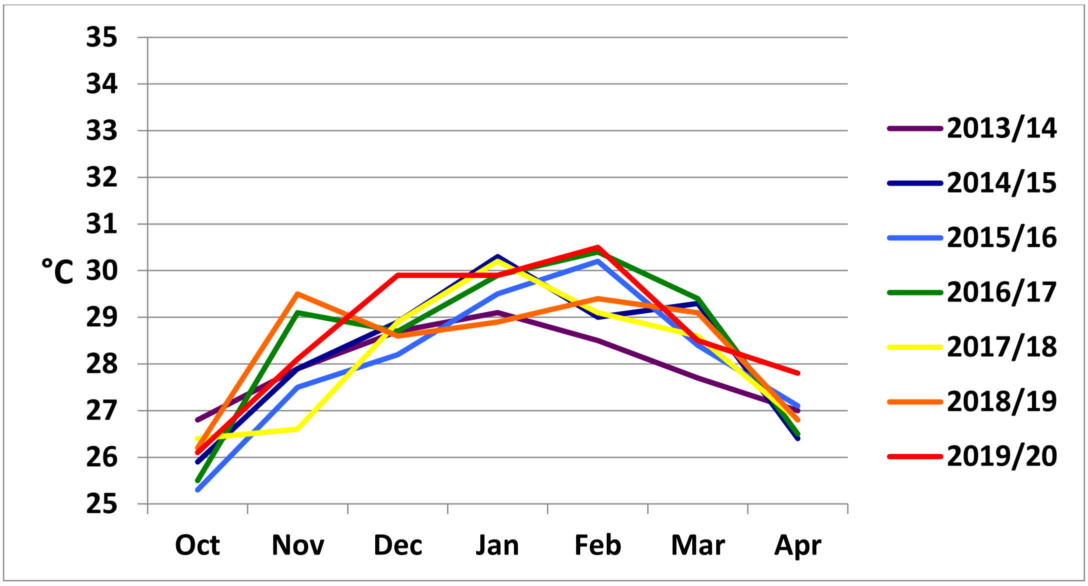

Figure 2.4b. Mean monthly maximum temperatures for BOM station at Yeppoon #33204.

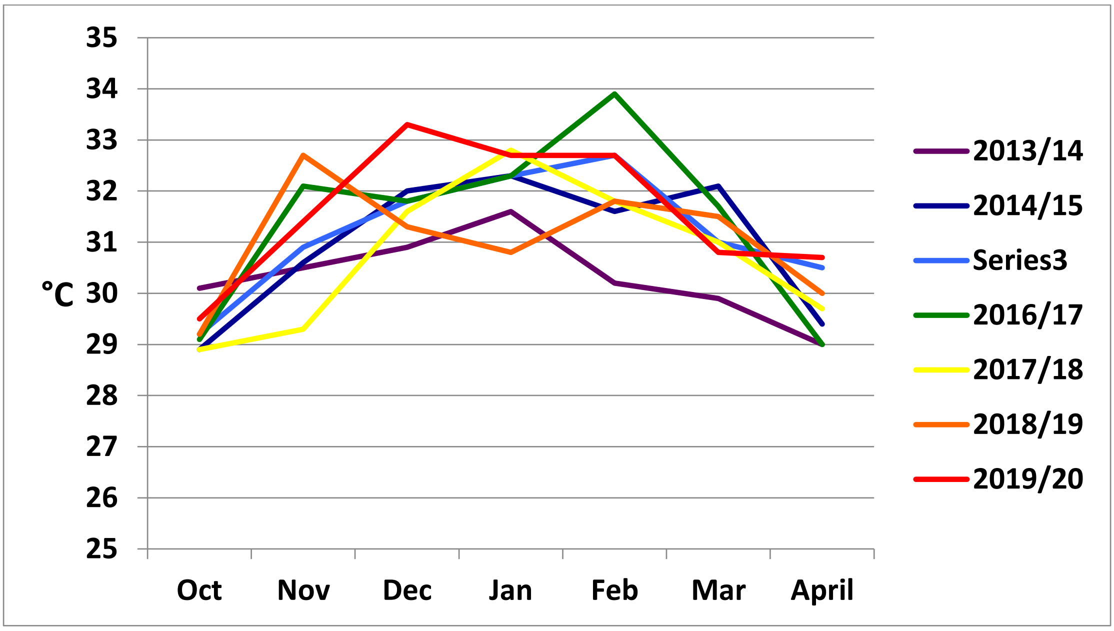

Figure 2.4c. Mean monthly maximum temperatures for BOM station at St Lawrence #33210.

Figure 2.4. BOM data showing that mean monthly maximum temperatures for the duration of the study.

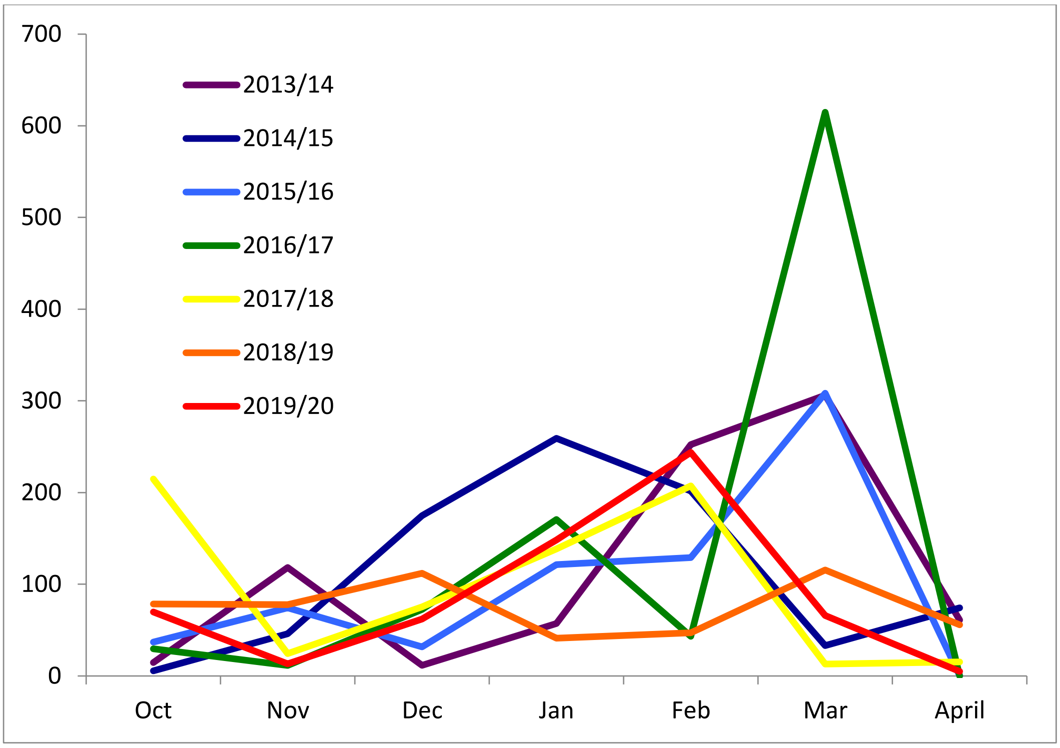

Figure 2.5a. Monthly rainfall totals BOM station Gladstone Airport #39326.

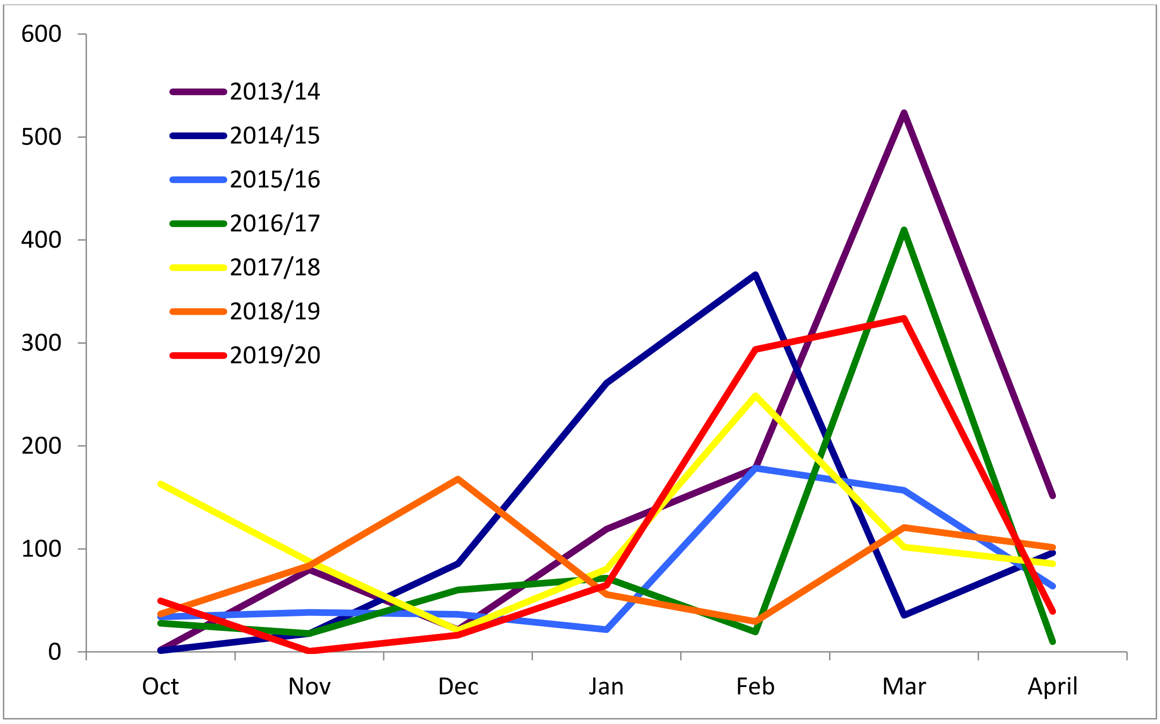

Figure 2.5b. Monthly rainfall totals for BOM stations at Yeppoon #33204, and Great Keppel Island #33260.

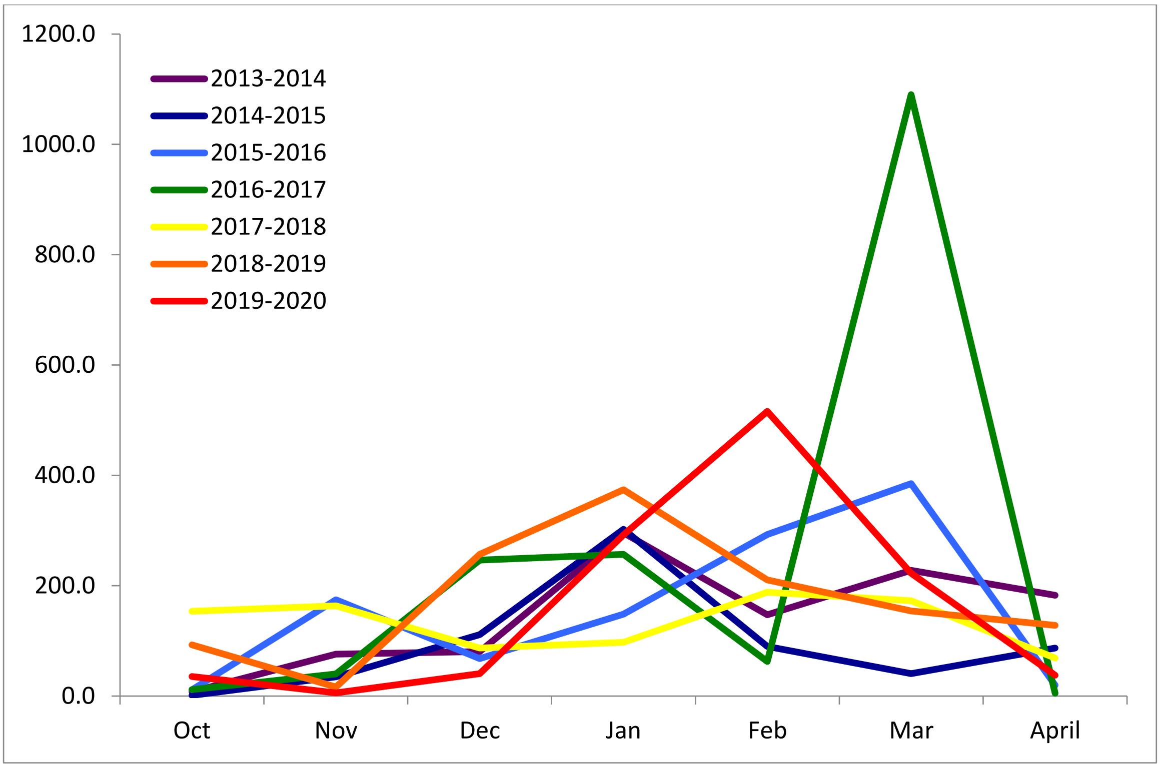

Figure 2.5c. Averaged monthly rainfall totals for BOM stations near Carmila #33071, #033186, #33095, and St Lawrence #33210.

Figure 2.5 Monthly rainfall totals for BOM weather stations nearest to the Avoid Island, Peak Island and Curtis Island rookeries, showing latitudinal variation from south to north. If the nearest station did not have complete records, then the next nearest stations were included to derive a complete data set with averaged values.

3- Curtis Island Figures

a. Curtis Island.

b. South End Beach, looking south from Connor's Bluff.

Figure 3.1. Location of the flatback turtle *Natator depressus* rookery at South End Beach, Curtis Island, in relation to Gladstone, Port Curtis and Port Alma.

a: Curtis Island 2016/17 Sixteen dead, fox predated hatchlings, dug from CI 047 nest prior to emergence.

Figure 3.2. Images from Curtis Island showing fox predation of Flatback turtle nests.

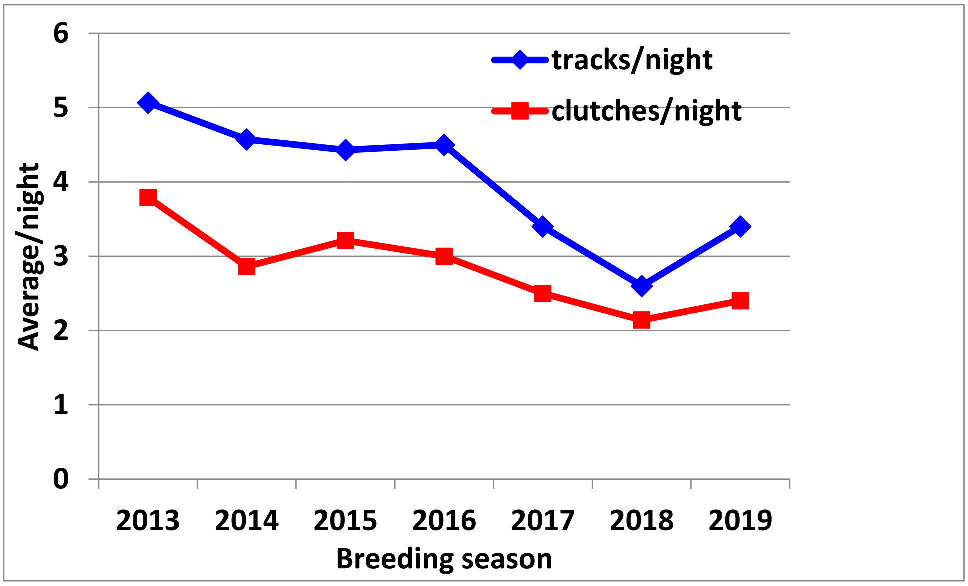

Figure 3.3. Yearly comparison of mean nightly track counts and the number of clutches laid at the Curtis Island Flatback turtle rookery.

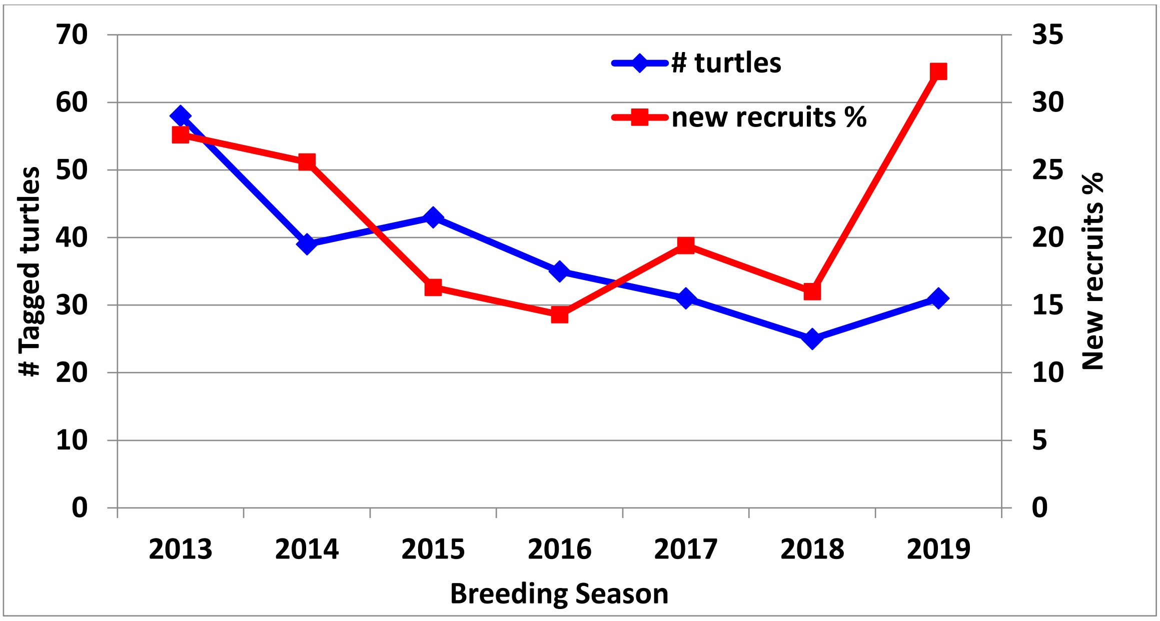

Figure 3.4. Yearly comparison of the number of tagged turtles encountered and the proportion of untagged turtles considered as new recruits at the Curtis Island Flatback turtle rookery.

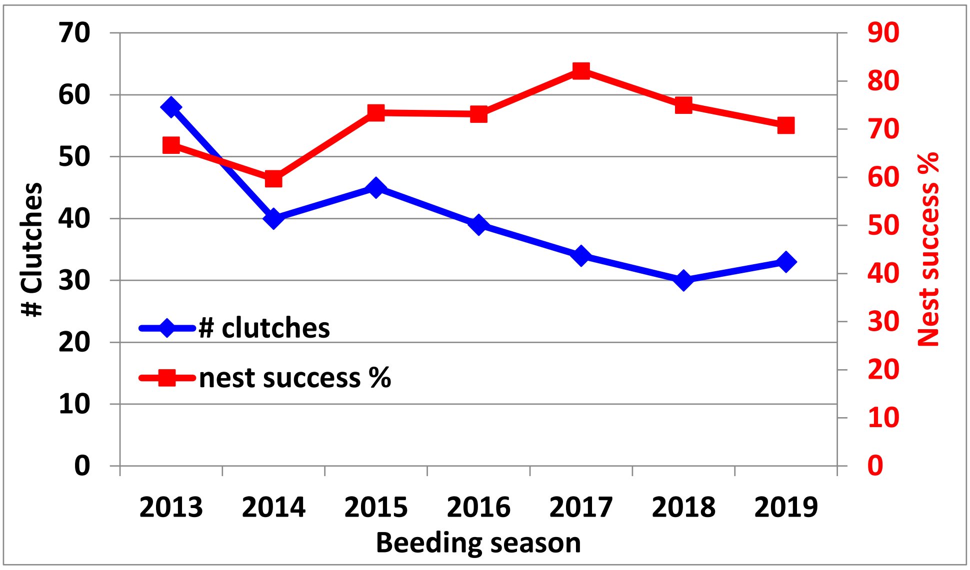

Figure 3.5. Yearly comparison at the Curtis Island Flatback turtle rookery of the number of clutches laid and nest success, which is the proportion of nesting crawls that results in laying a clutch of eggs.

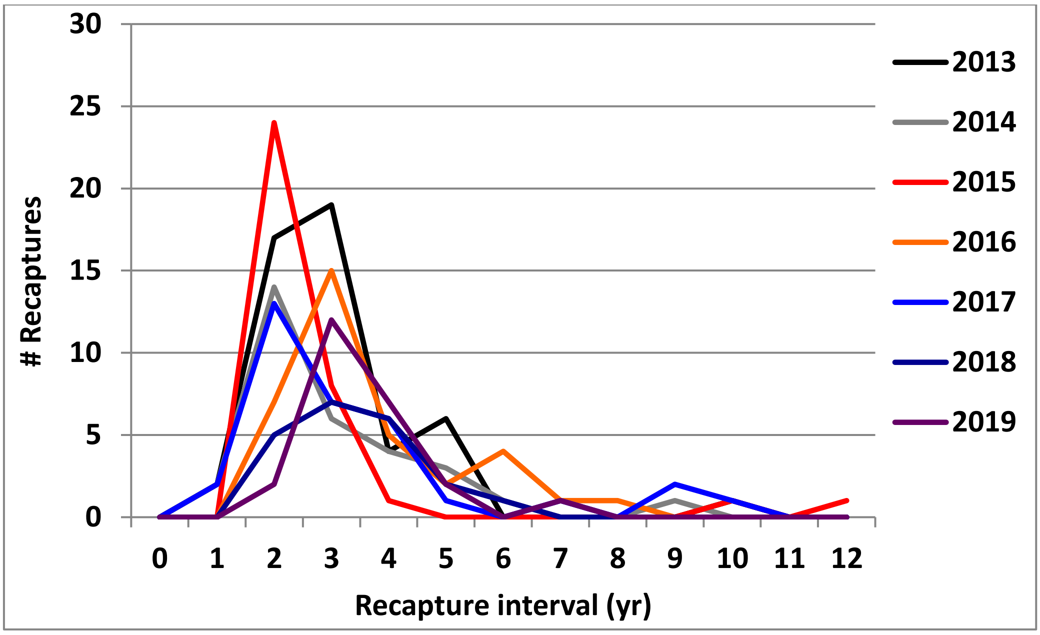

Figure 3.6. Recapture intervals of previously tagged turtles at the Curtis Island Flatback turtle rookery.

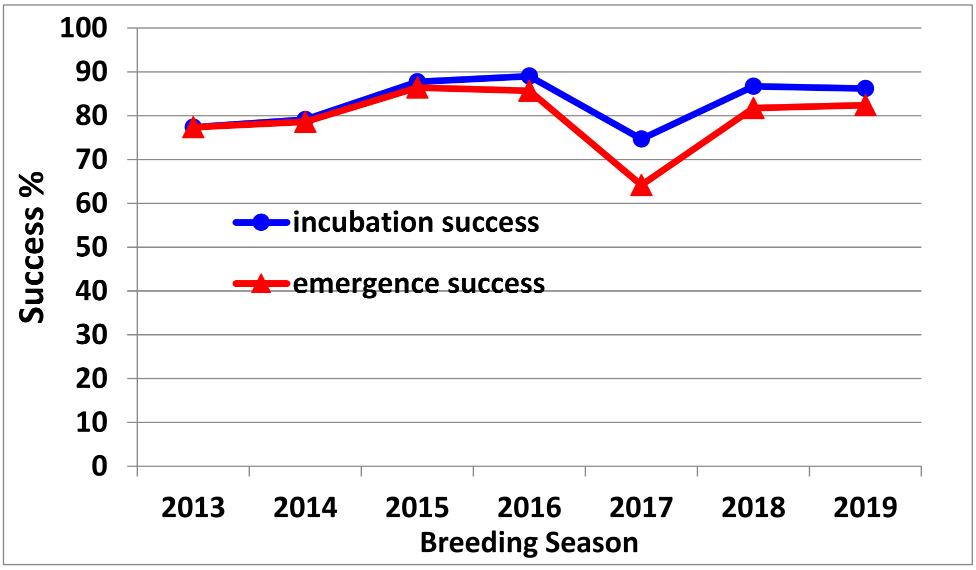

Figure 3.7. Yearly comparison of incubation success and hatchling emergence success at the Curtis Island Flatback turtle rookery.

Chapter 4- Peak Island Figures

a. Peak Island, image from Google Earth, 7 May 2021, nesting beach is along the western shore.

b. Peak Island National Park sign

c. Nesting beach viewed from the north

d. Monitoring camp, January 2015

e. Tracks, 2015/16

Figure 4.1 Images of Peak Island

a. Far southern end of beach b. Aerial view

Figure 4.2 Beach erosion on Peak Island after Tropical Cyclone Marcia

a. Heath stress hatchling death b. Root entrapment hatchling death

Figure 4.3 Heat stress mortality at the Peak Island Flatback turtle rookery (a) of hatchlings that emerged at daylight 25 January 2018 and root entrapment deaths (b) of hatchlings seen in an excavated nest, January 2018.

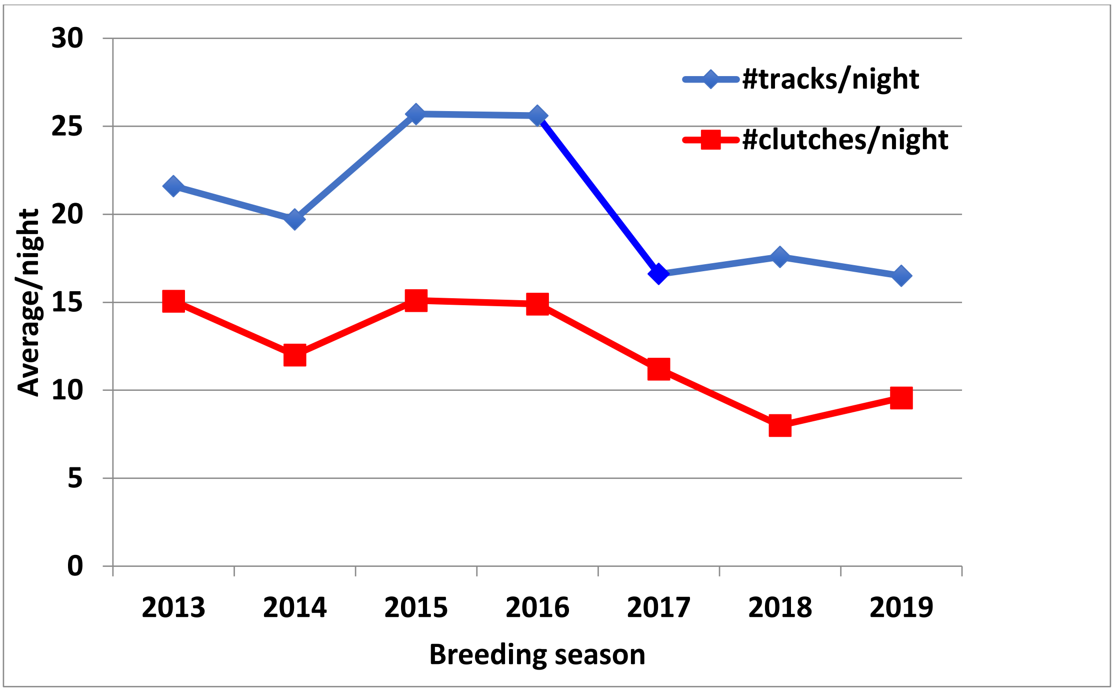

Figure 4.4 Yearly comparison of mean nightly track counts and the number of clutches laid at the Peak Island Flatback turtle rookery.

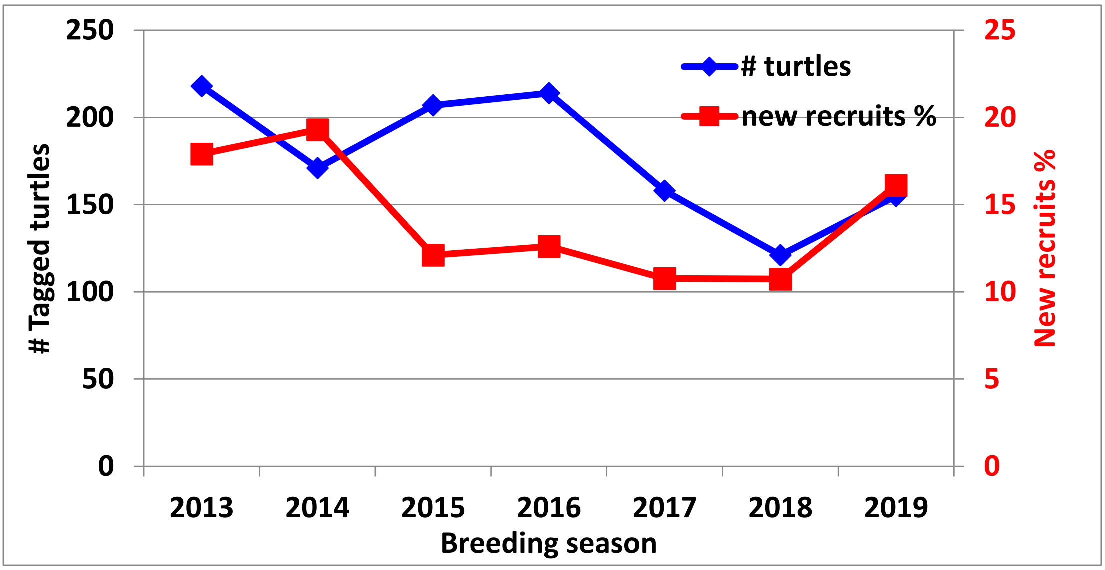

Figure 4.5 Yearly comparison of the number of tagged turtles encountered and the proportion of untagged turtles considered as new recruits at the Peak Island Flatback turtle rookery.

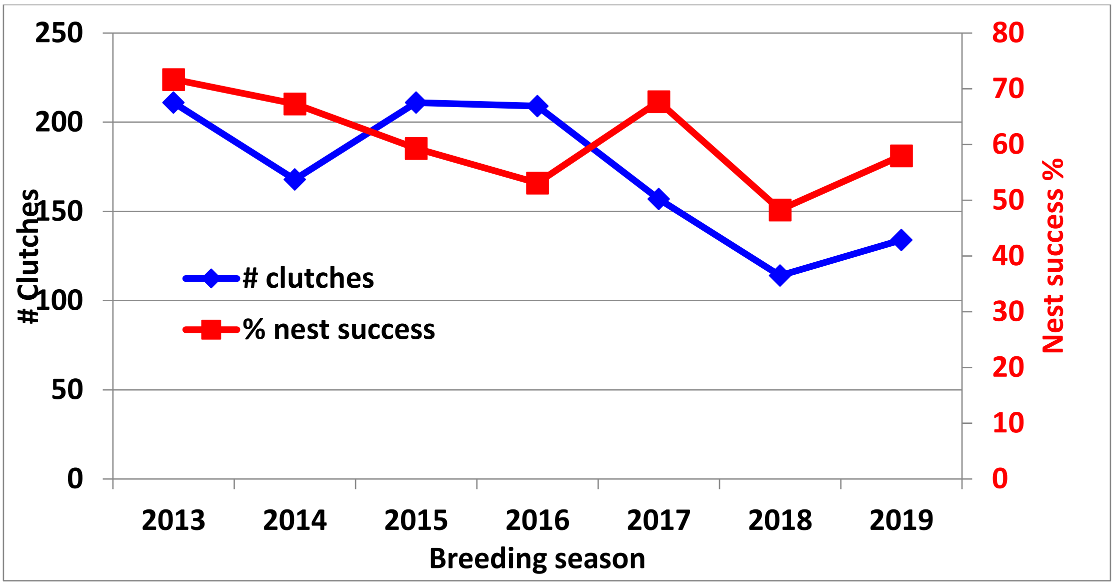

Figure 4.6 Yearly comparison at the Peak Island Flatback turtle rookery of the number of clutches laid and nest success, which is the proportion of nesting crawls that results in laying a clutch of eggs.

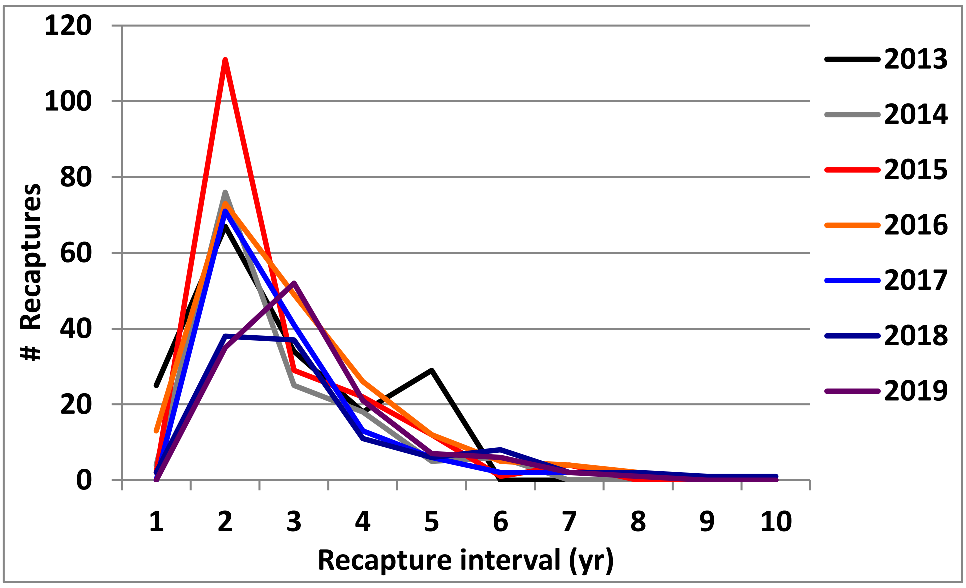

Figure 4.7 Recapture intervals of previously tagged turtles at the Peak Island Flatback turtle rookery.

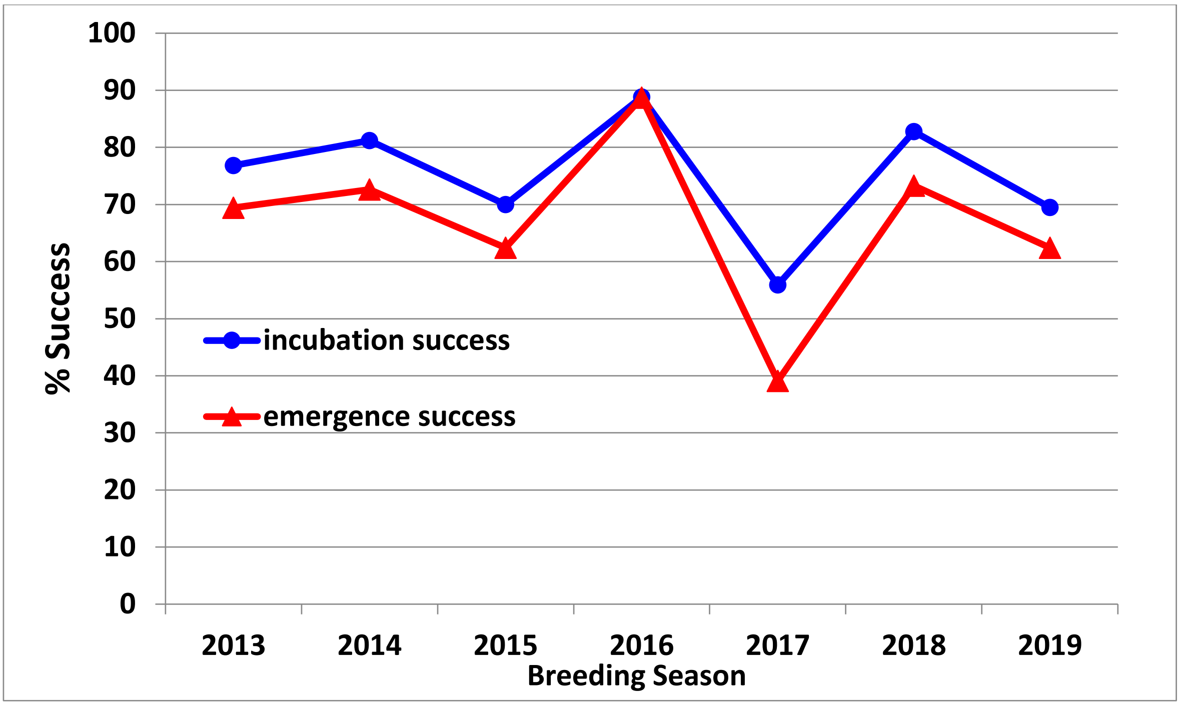

Figure 4.8 Yearly comparison of incubation success and hatchling emergence success at the Peak Island Flatback turtle rookery.

Chapter 5- Avoid Island Figures

a. Turtle nesting beaches and infrastructure locations at Avoid Island.

b. South Beach 2016/17 looking north

c. South Beach

c. North Beach

d. West Beach

Figure 5.1. Aerial map and images of Avoid Island illustrating beach habitats at South Beach and North Beach. The North Beach location was the site of the temporary temperature data logger and West Beach had two nesting tracks.

a. Erosion South Beach 2014

b. Inundation of nests North Beach 2014

c. South Beach prior to Cyclone Dylan

d. South Beach after Cyclone Dylan

e. Trees that fell over in 2014, preventing nesting 2017/18

f. Formation of swale where nests get inundated 2017/18

Figure 5.2 Examples of beach erosion and reformation at Avoid Island due to Tropical Cyclone Dylan on 31 January 2014.

a. Dune, sunny b. Beach slope, sunny

c. Beach slope, shaded d. Beach, sunny

Figure 5.3. Locations of multi-year temperature data loggers at Avoid Island on South Beach (a) sunny first dune (sector 41), (b) sunny beach slope (b) (sector 13), (c) shaded beach slope (sector 27) and (d) a temporary placement on North Beach (sector 53).

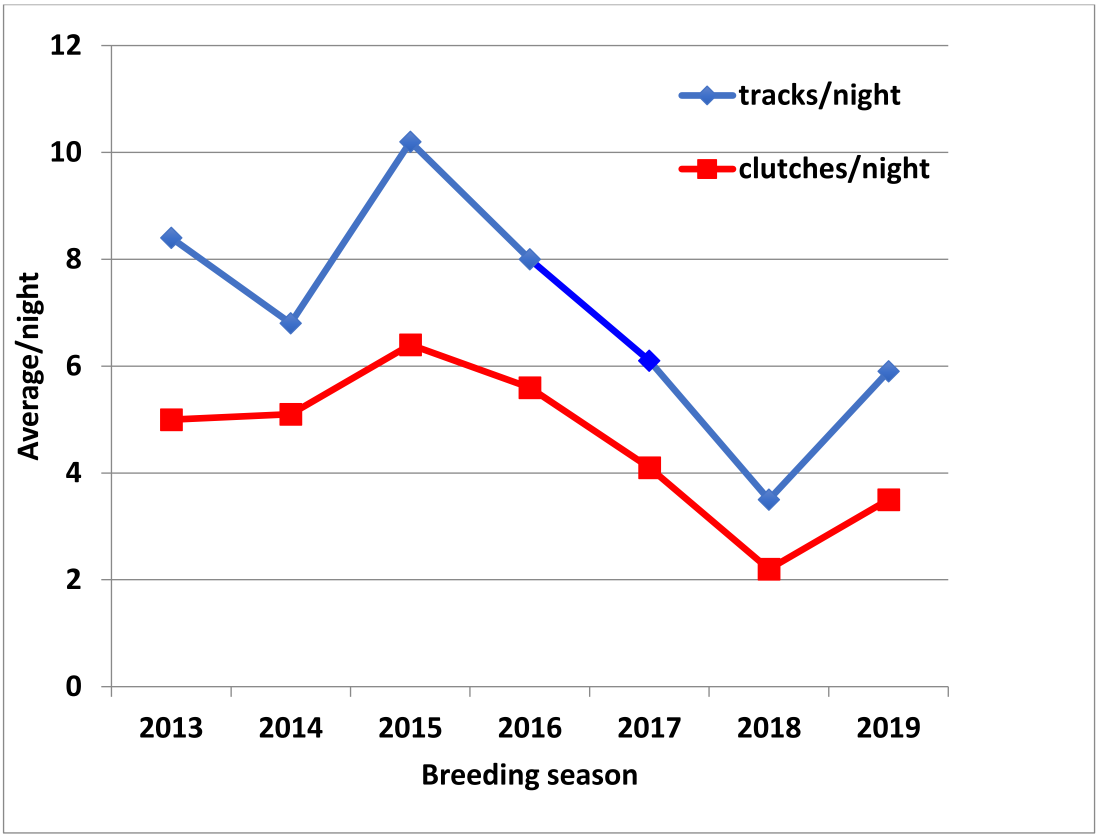

Figure 5.5 Yearly comparison of mean nightly track counts and the number of clutches laid at the Avoid Island Flatback turtle rookery.

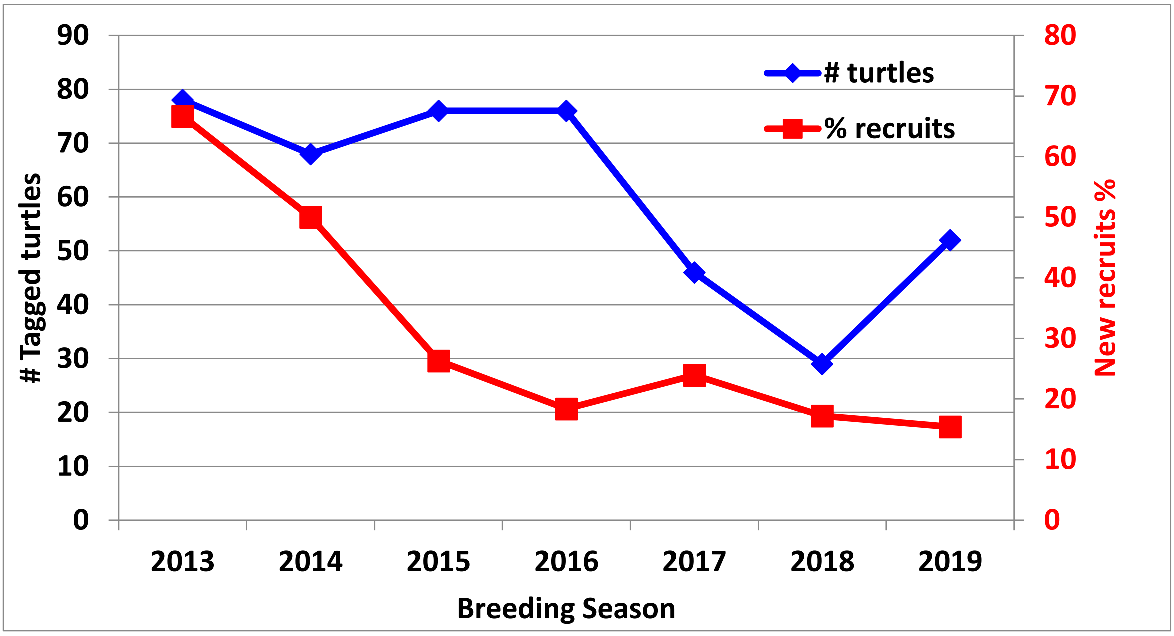

Figure 5.6 Yearly comparison of the number of tagged turtles encountered and the proportion of untagged turtles considered as new recruits at the Avoid Island Flatback turtle rookery.

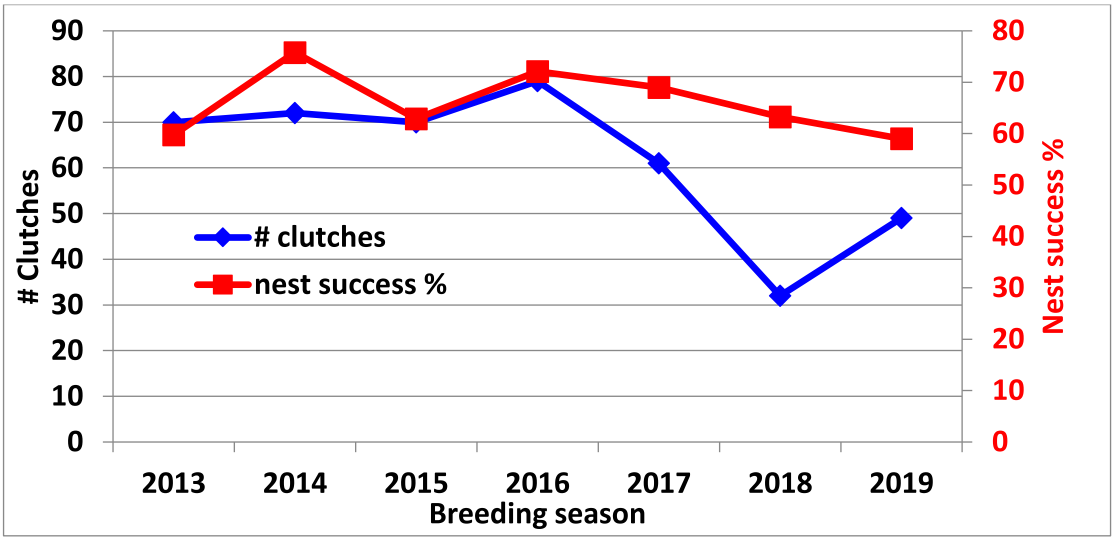

Figure 5.7 Yearly comparison at the Avoid Island Flatback turtle rookery of the number of clutches laid and nest success, which is the proportion of nesting crawls that results in laying a clutch of eggs.

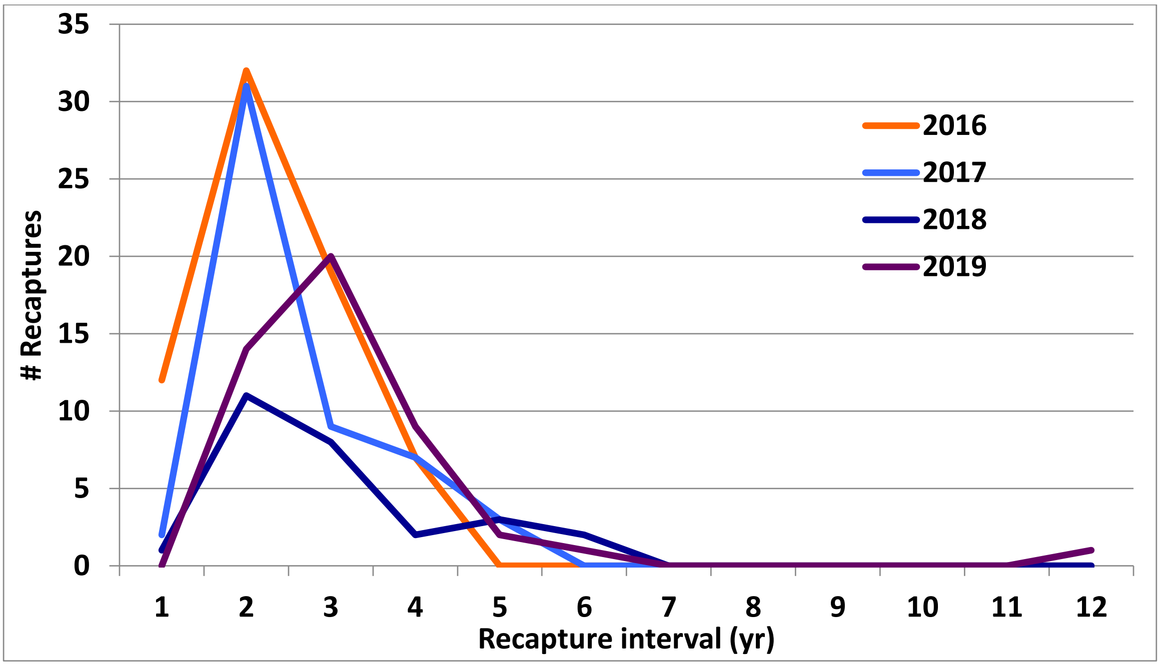

Figure 5.8 Recapture intervals of previously tagged turtles at the Avoid Island Flatback turtle rookery.

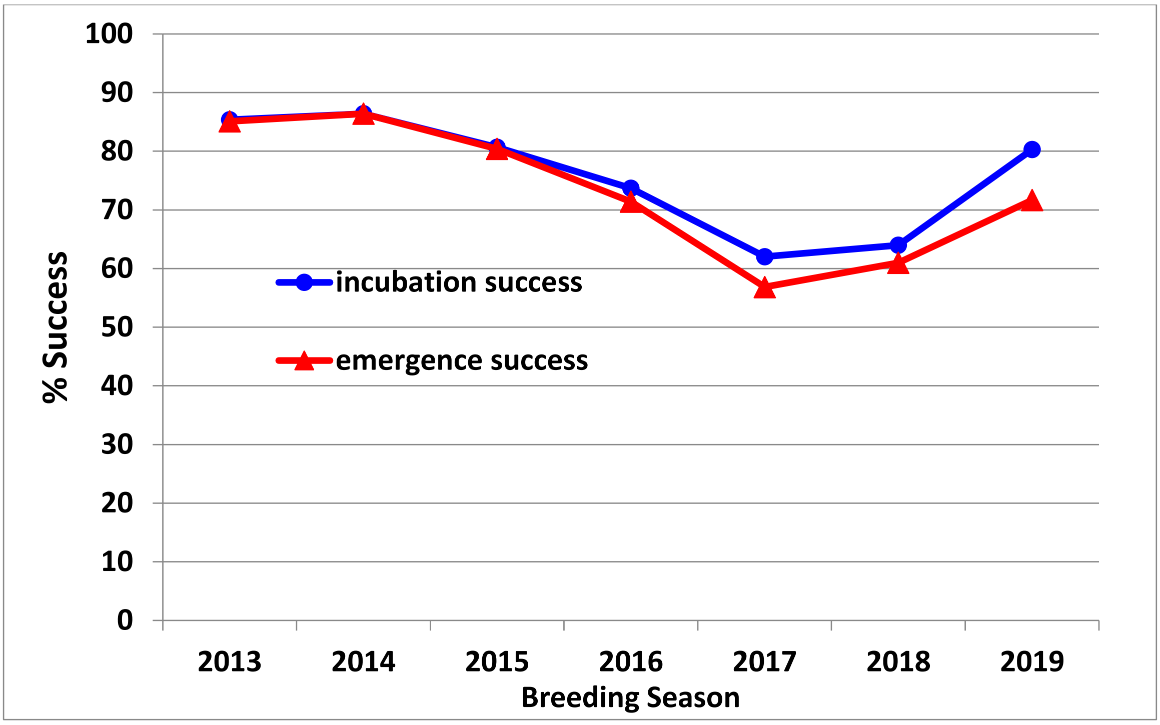

Figure 5.9 Yearly comparison of incubation success and hatchling emergence success at the Avoid Island Flatback turtle rookery.