Protecting nests of the Critically Endangered South Pacific loggerhead turtle *Caretta caretta* from goanna *Varanus* spp. predation

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Abstract The South Pacific subpopulation of the loggerhead turtle *Caretta caretta* is categorized as Critically Endangered on the IUCN Red List because of significant population declines. Five Queensland beaches support high-density nesting of this subpopulation, but egg and hatchling survival are low at some beaches because of feral and native terrestrial predators. We quantified predation of loggerhead turtle eggs by two species of goanna, *Varanus panoptes* and *Varanus varius*, at Wreck Rock beach, one of the turtle's major nesting beaches. In addition, we conducted an experiment to determine the efficacy of a nest protection device. Predation rates at Wreck Rock beach were 15.2% for treatment and 45.8% for non-treatment clutches during the 2013–2014 nesting season. A higher probability of predation (64%) was predicted for the northern beach. Although nests were only partially predated (16.4% of the total number of eggs), nest loss to predators and beach erosion (caused by a cyclone) was 91.7%. If left unmanaged, the cumulative impact of predation and other threats, including those exacerbated by climate change, can cause unsustainable loss of loggerhead turtle nests. This study provides one of the first quantitative data sets on rates of loggerhead turtle clutch predation in the South Pacific. It enhances our understanding of goanna predation impacts and identifies an efficient predator exclusion device for mitigating the effects of terrestrial predators at Wreck Rock beach, and for protecting marine turtle nests across northern Australia and globally.

Keywords Automated cameras, *Caretta caretta*, eastern Australia, feasibility study, goanna predation, loggerhead turtle, predator exclusion device, *Varanus*

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Introduction

There is one genetic subpopulation for the loggerhead turtle *Caretta caretta* in the South Pacific Ocean (Bowen et al., 1994; Limpus et al., 2006; Boyle et al., 2009) and most breeding females from this subpopulation nest on beaches in eastern Australia and New Caledonia (Limpus & Limpus, 2003; Limpus, 2008). Post-hatchlings emerging at these beaches undertake trans-Pacific migrations to the west coast of South America, reaching the coastal waters of Peru and Chile (Kelez et al., 2005; Boyle et al., 2009; Donoso & Dutton, 2010; Alfaro-Shigueto et al., 2011). Along the east coast of Australia, sandy beaches in Queensland support the majority of nesting, with c. 80% occurring at five beaches: Wreck Island, Woongarra Coast, Tryon Island, Erskine Island and Wreck Rock (Limpus, 2008; Limpus & Casale, 2015).

Despite its protected status and several decades of conservation effort, particularly in Queensland, the South Pacific subpopulation of the loggerhead turtle continues to decline (Limpus et al., 2013; Limpus & Casale, 2015) and was categorized as Critically Endangered on the IUCN Red List in 2015 (Limpus & Casale, 2015). In recent years, although the number of nesting loggerhead turtles has been increasing (Limpus et al., 2013), the escalated mortality of post-hatchlings from synthetic debris ingestion in the first few months after leaving the nesting beaches (Boyle & Limpus, 2008) and bycatch mortality of large post-hatchlings caught in long-line fisheries in Peru and Chile (Donoso & Dutton, 2010; Alfaro-Shigueto et al., 2011) have hampered population recovery.

In this context, reducing mortality from other causes at nesting beaches could support population growth. Such causes include the predation of eggs and hatchlings by introduced and native predators, the hatchling loss associated with light pollution, and beach degradation caused by anthropogenic and natural events (Limpus, 2008; Berry et al., 2013; Limpus & Casale, 2015).

Increasing hatchling production by reducing clutch predation is a recommended and common practice for marine turtles (Mroziak et al., 2000; Engeman et al., 2003, 2006;

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O'Connor et al., 2017). Native and feral predators include the red fox *Vulpes vulpes*, raccoon *Procyon lotor* and pig *Sus scrofa*. Strategies to reduce depredation of marine turtle eggs have been used with varying levels of success; e.g. predator control through shooting or baiting, deployment of exclusion devices (fencing, cages) and scent deterrents, and clutch relocation (Stancyk et al., 1980; Addison & Henricy, 1994; Addison, 1997; Ratnaswamy et al., 1997; Yerli et al., 1997; Blamires & Guinea, 2003; Baskale & Kaska, 2005; Norris et al., 2005; Kurz et al., 2011; Engeman et al., 2012; Lamarre-DeJesus & Griffin, 2013). However, there are few in situ studies examining the effectiveness of these strategies for loggerhead turtles (Schroeder, 1981; Macdonald et al., 1994; Yerli et al., 1997; O'Connor et al., 2017).

Wreck Rock beach supports the second largest number of loggerhead turtles nesting on the eastern Australian mainland, with c. 400 nests per season (Limpus, 2008). Clutch loss on Wreck Rock beach results from two primary sources: storm surge erosion and flooding of nests, which varies widely between years (C.J. Limpus, 2017, pers. comm.), and depredation by goannas *Varanus* spp., which may now have the greatest impact on hatchling production at this beach (McLachlan et al., 2015). Historically, predation by feral foxes was a major threat, with predation levels reaching c. 90–95% of clutches laid prior to the mid 1980s (Limpus, 2008). A baiting programme was introduced in 1987 and led to the near-complete elimination of clutch predation by foxes. Although clutch loss to native goannas was considered negligible historically, anecdotal evidence now suggests reduced fox numbers have shifted the balance of predator–prey interactions, resulting in increased goanna predation of turtle nests at Wreck Rock beach. Although goannas have long been known to consume marine turtle eggs (Marquez, 1990, p. 51), their predation rates on loggerhead turtle clutches at Wreck Rock beach remained unquantified (Lei & Booth, 2017a). In addition, there is a dearth of information on varanid ecology, behaviour and predation cues to develop effective goanna management strategies for this region.

Here we report on the outcome of experiments that successfully reduced goanna predation on loggerhead turtle clutches at Wreck Rock beach. We quantify goanna predation rates, provide an effective method to decrease predation and present alternative management interventions to reduce the threat of goanna predation on clutches, which can be applied widely at nesting beaches in northern Australia and globally.

Study area

The study site at Wreck Rock (Fig. 1) comprises 22 km of east-facing beaches from Broadwater Creek to Red Rock. The site lies at the southern end of the Great Barrier Reef Coast Marine Park (Queensland State Government) and Great Barrier Reef Marine Park (Commonwealth), situated within and adjacent to various land tenure (Fig. 1). With a coastline exposed to onshore winds and largely unprotected by the reef, the coastal dunes are a naturally dynamic ecosystem characterized by coastal scrubs, eucalypt woodlands, wet heaths and sedge lands. Delineated by camp and beach access points, Wreck Rock beach is divided into north and south beach sectors and marked every 100 m with timber pegs. Pegs on the north beach sector are numbered 0–65 and on the south beach sector 66–210. The north beach is located adjacent to Deepwater National Park. There are two public access campsites (Middle Rock and Wreck Rock) within the Park (Fig. 1).

Methods

Data collection

The Wreck Rock Turtle Research Team, under the guidance of the Queensland Government's Queensland Turtle Research Programme, has monitored the Wreck Rock beach study site for loggerhead turtle nesting activity for more than 40 years, since 1977. During the 2013–2014 nesting season (1 December 2013–12 March 2014), in addition to carrying out the standard nesting and hatchling emergence census for all turtle species (loggerhead, green *Chelonia mydas* and flatback *Natator depressus* turtles), we monitored predator activity at 57 experimental loggerhead turtle clutches (33 treatment and 24 control) daily. Following oviposition, we marked each nest with flagging tape during the night patrol, and designated them for control or treatment plots (with an exclusion device installed at the latter) the following day. Treatment and control nests were spread throughout the study area to ensure sufficient representation of both on the north (control = 14, treatment = 22) and south beaches (control = 10, treatment = 11; Fig. 1). It was not possible to place control and treatment plots randomly in space and time.

We constructed predator exclusion devices, modelled after those developed and deployed successfully on the Sunshine Coast (O'Connor et al., 2017), from interlocking aluminium mesh panels. We chose aluminium mesh because it has been used successfully in previous studies and is unlikely to disrupt the hatchlings' magnetic imprinting (Irwin & Lohmann, 2003). Each exclusion device (cage) consisted of a 1 m^2 top panel and four side flaps of 20–25 cm width (Supplementary Plate 1). The mesh size of 70 mm was sufficiently large to allow hatchlings to emerge, but small enough to prevent access by varanid and mammalian predators. We placed predator exclusion devices at a depth of c. 20 cm below the sand surface over 33 treatment nests and left 24 control nests unprotected.

We conducted predator activity surveys of the treatment and control plots during daylight hours at low tide using a pro-forma datasheet. For reasons of practicality, data were

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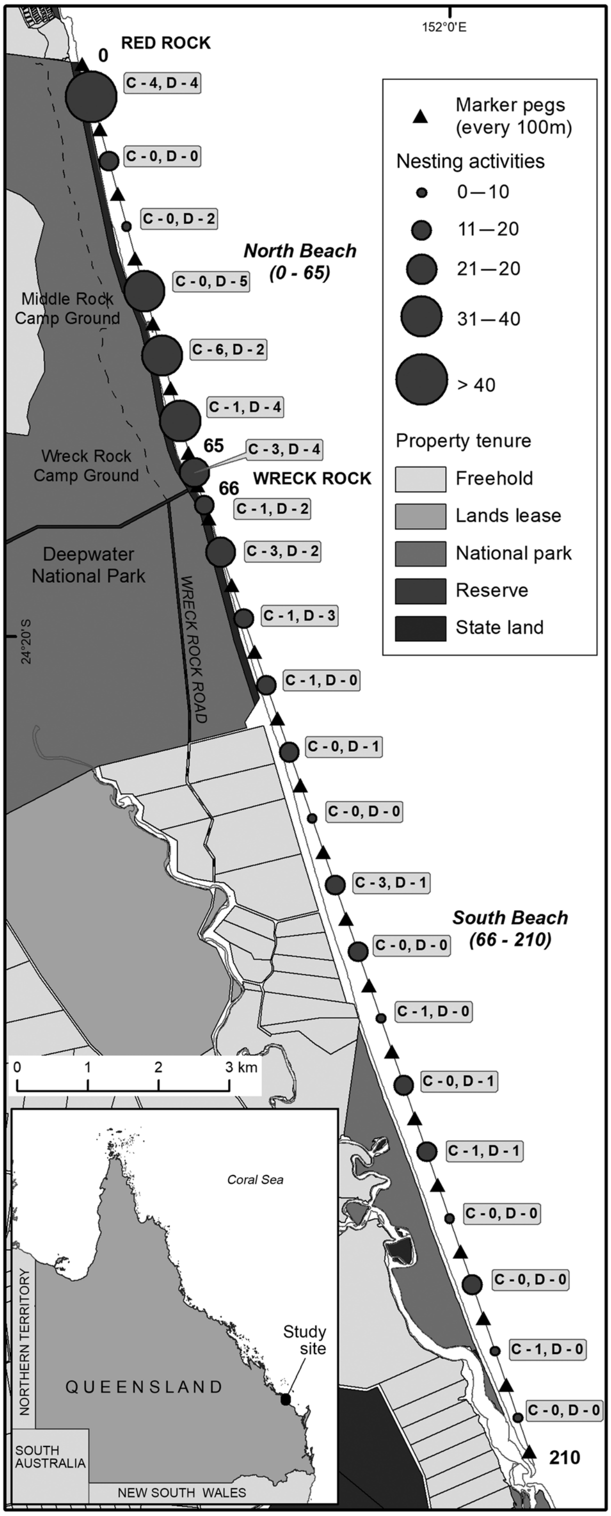

FIG. 1 Study site at Wreck Rock beach, land tenure and location of camp sites. Markers pegs 0–65 are on the north beach and 66–210 on the south beach. C and D indicate the numbers of control and treatment (deployment of a predator exclusion device) loggerhead turtle *Caretta caretta* clutches, respectively, on a stretch of beach between the marker pegs shown. The size of the circles represents the total nesting activity, including failed nesting attempts, per year on the respective beach stretches.

recorded within a 152.4 cm (total length of the measuring tape used) radius from each marked nest centre as a standard measure and distance of likely plot predation. We collected the following data: sand disturbance or predator tracks (species identified as goanna, fox, dog, ghost crab); attempted predation (holes had been dug but no empty egg shells were found); predation: holes dug, number of empty egg shells (if greater than half a shell) and number of undeveloped or unhatched eggs on sand surface; and the distance between the nest centre and the egg remains farthest away from it. After recording the data, we manually removed signs of predator activity using footwear, so as to minimize human scent at the nest site.

In addition, we monitored 12 nests (10 treatment and two control nests) for predator activity throughout the incubation period, using infrared wildlife motion-sensor cameras (Reconyx Hyperfire HC600, Reconyx, Holmen, USA). Cameras were secured onto timber marker posts using bungee cords and positioned to aim at the centre of each nest. The cameras recorded ambient air temperatures and still images whenever movement was detected. If a camera-monitored nest was destroyed by predators, we moved the camera to another nest. We identified species that visited the clutches from the recorded camera images. Goannas were not individually identified and we assumed a new visitation event after 60 s of no recording.

We excavated the clutches when the hatchlings emerged, or after 60 days of incubation, to determine hatching success. We calculated hatching success using data from the unpredated clutches and the following equation:

Hatching success = (no. of empty shells)/(no. of unhatched eggs + no. of undeveloped eggs + no. of empty shells). We then used the median hatching success to estimate the total hatchling production of the beach throughout the nesting season.

Statistical analysis

We calculated clutch loss as the proportion of clutches lost to all causes (predation and erosion) out of the total number of control clutches. Predation rates were computed as the proportion of clutches lost to predation out of the total number of control clutches. Nest monitoring was interrupted during 26 January–7 February 2014 because a cyclone made landfall nearby. Therefore, we calculated loss of nests in two distinct periods: before (quantified predation rate) and after (quantified predation + cyclone-caused nest loss) the cyclone event.

To determine the effectiveness of the exclusion devices on loggerhead turtle clutches, we considered five logistic regression models, using three predictor variables: days since the beginning of the experiment (Days), location of the nests measured by the peg numbers (Location), and treatment

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with a predator exclusion device (Treatment; Table 1). We compared models using the Akaike information criterion (AIC; Akaike, 1974). Using the best model from the analysis on the effectiveness of the treatment, we predicted the probability of predation at all observed nest locations along the entire beach.

To determine whether the exclusion device delayed predation, we compared the mean number of days from laying to predation between control and treatment plots using a Bayesian *t* test. We hypothesized that the mean number of days between laying and predation would be greater for the treatment plots than for the control plots.

To estimate the total number of hatchlings on the entire beach, we used a parametric bootstrap procedure. For all observed clutches at the nesting beach, we estimated the probability of predation using the logistic regression models. The median nest size and median hatching success rate were used to compute the total number of hatchlings for the unpredated nests. We repeated this process 7,000 times to obtain the uncertainty in the estimate from the predation probability.

We conducted all statistical analyses in *R 3.1.2* (R Core Team, 2015) with packages *ggplot2* (Wickham, 2009) and *gamm4* (Wood & Scheipl, 2014). Bayesian computations were conducted using *jags 3.3.0* (Plummer, 2015) through *rjags* (Plummer, 2015) in *R*.

Results

During the 2013–2014 nesting season (1 December 2013–12 March 2014) we recorded 78 loggerhead, 30 green and 20 flatback turtles laying one or more clutches at Wreck Rock beach (Supplementary Table 1). Of the loggerhead turtles, 16 were new recruits and 62 were recaptures from previous nesting seasons. During the nesting season, we recorded 218 loggerhead nesting activities, with 195 successful nests and 23 failed attempts. Of the 195 successful nesting events, 148 clutches were laid on the north and 47 on the south beach. We used 57 of the 195 successfully laid nests in our study, deployed exclusion devices on 33 treatment clutches and used 24 as control. During the study, 19 plots (eight treatment and 11 controls) were lost to erosion when cyclone Dylan made landfall near Wreck Rock beach on 31 January 2014.

Clutch loss

During the 2013–2014 season, 11 of 24 control clutches were depredated (mean = 45.8%, 95% CI = 26.2–66.8%), an additional 11 were lost to erosion. In total, clutch loss to predators and erosion events (exacerbated by a cyclone) was 91.7% (95% CI = 71.5–98.5%). The predation rate was greater prior to the cyclone (41.67%, 10 of 24 control plots depredated; 95% CI = 22.8–63.1%) than after the cyclone (7.7%, 1 of 13 control plots depredated; 95% CI = 0.4–37.9%). The majority of predation of control nests occurred on the northern beach (9/14 = 64%; 95% CI = 35.6–86.0%).

Exclusion devices appeared to be effective in reducing clutch predation. With exclusion devices deployed at 33 nests, only one hatchling became entrapped during emergence. Compared with the control plots (11 of 24 control nests; 45.8%; 95% CI = 26.2–66.8%), fewer treatment plots were depredated during the nesting season (5 of 33 treatment nests; 15.2%; 95% CI = 5.7–32.7%). The point estimate of predation with exclusion devices was 6% (2/33; 95% CI = 0.7–20.2%) prior to the cyclone, and 12% (3/25; 95% CI = 3.2–32.3%) after the cyclone. Although the point estimate was greater for the treatment plots than control (12.0% vs 7.7%), the binomial 95% CI overlapped (3.2–32.3% vs 0.3–37.9%). Because of the large uncertainties associated with small sample sizes, they were not statistically different.

Amongst the models used to determine the effects of the exclusion device on the predation of loggerhead turtle clutches, Model 4 had the smallest AIC value, although differences in AIC values between the top 3 models were < 3, indicating that these models were not substantially different (Table 1). In the following analyses, we use the best model, which included treatment, location, and their interactions.

The interaction term was significant at $\alpha = 0.10$ (Table 2), indicating that the effectiveness of the treatment varied significantly along the beach. This can be seen in Fig. 2, where the predicted probability of predation decreases with increasing peg number (i.e. from north to south along the beach) for the control plots, but increases for the treatment clutches. However, because of the small sample sizes in the area farthest from the field station, on the south beach, confidence intervals are wide in this area. For the area with larger sample sizes, on the north beach, the predicted probability of predation was smaller for the treatment than for the control plots.

The main effect of the exclusion device was also significant at $\alpha = 0.10$ (Table 2), indicating that the devices significantly reduced the predation of loggerhead turtle clutches. This is supported by the percentage of predated clutches in control vs treatment plots (47.8 vs 15.2%, respectively).

Hatching success

The mean clutch size was 113.6 ± SE 7.7 (n = 31; median 118) and the mean hatching success was 0.779 ± SE 0.056 (n = 42; median 0.894). Using the most parsimonious logistic regression model (Model 4) from the previous analysis, we predicted the probability of predation at all observed nest locations; i.e. extrapolated to the entire beach (Fig. 3). Using the probability of predation, median hatching success, median clutch size, and a parametric bootstrap analysis,

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TABLE 1 Logistic regression models used to determine the effectiveness of predator exclusion devices on loggerhead turtle *Caretta caretta* clutches, showing predictor variables and difference in Akaike information criterion values from best-performing model (ΔAIC).

Model	Variables[1]	ΔAIC
Model 4	Treatment × Location	0.00
Model 3	Treatment	0.57
Model 2	Treatment + Location	1.22
Model 1	Treatment + Location + Days	3.12
Model 5	Treatment × Days	4.45

[1]Days, days since the beginning of the experiment; Location, location of the nests measured by the peg numbers along the beach; Treatment, clutch treatment with a predator exclusion device.

TABLE 2 Estimated linear model coefficients of the best-performing model (Model 4), with standard deviations and P values. The model was Predation ∼ Intercept + Treatment + Location + Treatment × Location.

Parameter	Estimate	P
(Intercept)	−1.40 ± SE 0.38	0.00
Treatment	−0.64 ± SE 0.37	0.08
Location	−0.16 ± SE 0.41	0.70
Treatment:Location	0.71 ± SE 0.40	0.08

we estimated the total number of hatchlings produced at Wreck Rock beach during the nesting season to be 11,599 with a 95% CI of 10,439–12,865 (Supplementary Fig. 1). Some loggerhead turtle clutches were only partially predated. Although sample sizes were small, the mean number of predated eggs per nest was c. 16 ± SE 4.5 (16.4%, n = 18). Undeveloped eggs (unhatched eggs with no obvious embryo) also accounted for 16% of the total eggs in nests.

The Bayesian equivalent of a two-sampled *t* test indicated there was no significant difference in the timing of predation between treatment and control nests (Supplementary Fig. 2). Further, the 95% posterior interval (Gelman et al., 2014) of the contrast coefficient (control vs treatment effects) included zero (−1.973, 0.724). For both control and treatments, however, predation seemed to occur either in the early or late stages of incubation (Supplementary Fig. 2).

Predation

With individual cameras operating for 51–62 days, the total camera-trapping time was 13,800 hours over a period of 79 days. Species recorded by automatic cameras included hares *Lepus* sp., kites *Milvus* sp., cats *Felis* sp., foxes *Vulpes* sp., emus *Dromaius* sp., pied butcherbirds *Cracticus nigrogularis* and wallabies *Macropus* sp. The two species of goannas recorded near turtle nests were the yellow spotted or Argus monitor *Varanus panoptes* and the lace monitor *Varanus varius* (A. Amey, 2014, pers. comm.). A third goanna *Varanus gouldii* may be present, but the species identification could not be confirmed. As expected, goanna activity tended to occur during daylight hours (6.00–18.00).

Based on tracks, predation at both treatment and control plots was carried out by goannas, with only one incidence of fox predation recorded, at a treatment plot. On one occasion, more than six goannas were observed predating on loggerhead turtle hatchlings as they emerged from a nest. This was the first recorded observation of goanna predation on emerging hatchlings at Wreck Rock beach. On several occasions we observed predation on nests adjacent to control plots (i.e. on nests not included in this study).

We recorded 177 goanna visitation events to 12 loggerhead turtle nests monitored by automated cameras. The yellow spotted monitor was found most frequently (53 recorded visits) followed by the lace monitor (37 visits). Of the 12 monitored clutches, 8 were visited multiple times by the same species on 74 occasions (46 times by yellow spotted monitors and 28 times by lace monitors). The remaining four nests were visited once by one goanna species, and at two of these nests the second species continued to visit multiple times after the first species had visited.

Ambient air temperature during goanna visits to the clutches was 20–47 °C. We found differences between the mean temperatures at visits by the two goanna species and other species (birds and mammals; Supplementary Fig. 4) Lace monitors visited turtle nests at a lower ambient temperature (mean = 32.7 ± SE 0.44 °C, n = 46) than yellow spotted monitors (36.8 ± SE 0.55 °C, n = 53).

Discussion

As the South Pacific loggerhead turtle subpopulation continues to decline, it requires renewed attention to decrease mortality at all life history stages. Nest predation by terrestrial predators may significantly reduce recruitment and could lead to additional declines in the already depleted population (CMS, 2014). This study provides new information about goanna depredation and demonstrates that exclusion devices effectively reduce predation. We also provide a recent estimate of the predation rate on loggerhead turtle clutches at a major nesting beach in the South Pacific.

The predation rate of loggerhead turtle clutches (45.8%) at Wreck Rock beach was lower than that reported at other nesting beaches. For example, 52% of flatback turtle clutches were predated at Fog Bay (Blamires, 1999; Blamires & Guinea, 2003), 65–70% of flatback turtle clutches at Pennefather beach (J. Doherty and Cape York Peninsula Development Association, unpubl. data in Whytlaw et al., 2013), 64–89% of green and loggerhead turtle clutches in

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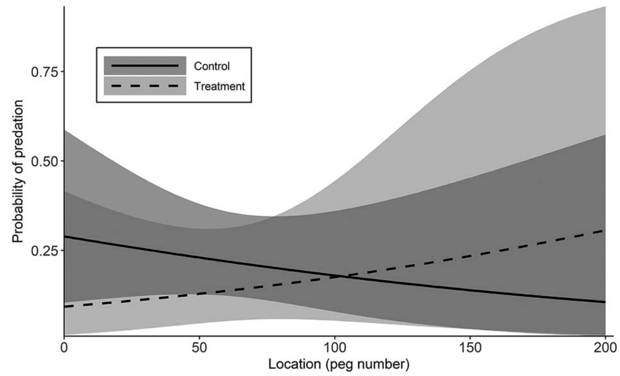

FIG. 2 Predicted probability of loggerhead turtle nest predation as a function of location on the beach and control vs predator exclusion device treatment. Shaded areas correspond to 95% confidence intervals.

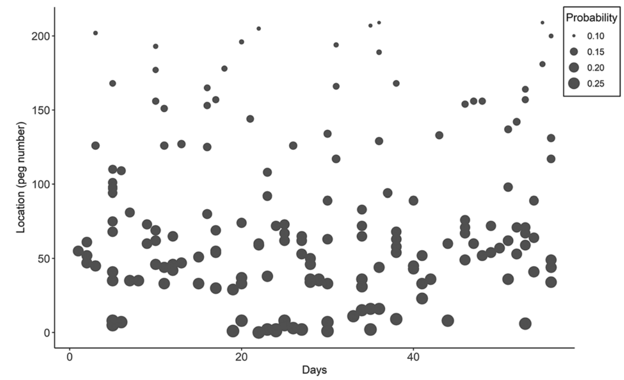

FIG. 3 Predicted predation probabilities with respect to beach marker pegs (location) and time since the beginning of the experiment (days). The size of the points corresponds to the probabilities.

Turkey (Macdonald et al., 1994), and 67–95% of loggerhead turtle clutches in North America (Stancyk et al., 1980; Engeman et al., 2003). During the 2014–2015 and 2015–2016 nesting seasons at Wreck Rock beach, Lei & Booth (2017a) reported 57.7% and 17.4% of clutches predated by goannas, respectively. However, their study was confined to a 6-km stretch of beach, whereas we monitored the entire 22-km stretch. The difference in results may be a result of this spatial difference in sampling effort and the heterogeneity of predation across a rookery (Blamires, 1999). It is also possible that predation is temporally variable because of fluctuations in predator and prey density.

In recent years, as also evidenced in Lei & Booth (2017a), goannas have been the primary predators of turtle eggs and hatchlings at Wreck Rock beach. For the first time, we observed predation of hatchlings by multiple goannas. Foxes are now minor predators of loggerhead turtle clutches, presumably the result of the long-term fox baiting programme. Yellow spotted and lace monitors were the most prominent visitors to turtle nests at the study site. A third species, *Varanus gouldii*, is frequently found in close proximity to yellow spotted monitors (Shine, 1986; A. Amey, 2014, pers. comm.) but further studies are needed to confirm its presence.

In this study, the aluminium cage predator exclusion devices were effective in reducing predation of loggerhead turtle nests at Wreck Rock beach. With only one entrapped hatchling amongst 33 cage deployments, the devices were deemed successful for reducing predation and letting hatchlings pass through. The same conclusion was also reached by Lei & Booth (2017b) in subsequent years. Given Wreck Rock beach is predicted to produce c. 12,000 hatchlings per season, the use of these anti-predator devices should result in increased hatchling production.

The loss of clutches observed in this study (from predation and other causes combined) was 91.7%, which is a cause for concern. Historically only quantified for beaches at Mon Repos (mean 13% loss of entire clutches from natural causes, range 8.4–83.0%; Limpus, 2008), clutches are regularly lost to natural erosion and flooding at Wreck Rock beach (N. McLachlan, unpubl. data). These events will continue to be exacerbated with severe cyclones, floods and storms predicted to increase in frequency with climate change (IPCC, 2007). During the study, a natural tide storm surge and wind additionally exposed turtle nests to predation and increased the total number of clutches lost. This loss was greater for the treatment nests, probably because the exclusion devices provided visual cues for the predators. In addition, hatchlings are affected by light pollution associated with coastal development. Overall, Wreck Rock beach grossly exceeds a sustainable level of annual clutch loss of c. 30% (CMS, 2014). Consequently, it is important to develop ongoing predator management (cognizant of the threat posed by extreme weather events) as this may be the only threat that can be addressed effectively in a timeframe that allows the population to recover.

The deployment of exclusion devices, although effective, may not be feasible for nesting beaches with moderate to high turtle numbers (e.g. > 20 turtles per night). Devices may impede nesting attempts (Kurz et al., 2011), and resources are often limited (Lei & Booth, 2017b; Lei et al., 2017). A suite of alternative predator control methods (some of which are already being applied at Wreck Rock beach) should be included in future studies to develop a conservation strategy considerate of the main predator species, habitat and climatic conditions, and budgetary and logistical constraints. Additional types of predator exclusion devices that could be deployed include plastic mesh nest protectors (Lei & Booth, 2017b) and flat chain link screening or less rigid wire mesh cages, if not disruptive to hatchlings magnetic imprinting (Addison & Henricy, 1994; Addison, 1997). The application of scent deterrents such as habanero powder (see Ratnaswamy et al., 1997; Lamarre-DeJesus & Griffin, 2013; Lei et al., 2017), human scent (see Burke

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et al., 2005), visual disturbance (such as flags, see Burke et al., 2005), or the use of pheromones (goanna's own or other species such as cane toads) may be effective in deterring goannas. Nest relocation (including into hatcheries) should only be trialled as a last resort because it could reduce hatchling imprinting and success (see Kornaraki et al., 2006).

Culling of goannas to protect turtle nests is not viable as they are protected in Australia. Coastal populations of the yellow spotted monitor may be the species' last stronghold, as many inland populations have declined as a result of a toxic diet of cane toads (Ujvari & Madsen, 2009; Shine, 2010). Because the species is not categorized as threatened on the IUCN Red List, Lei & Booth (2017b; Lei et al., 2017) suggest the temporary removal of male yellow spotted monitors (the primary predators of turtle eggs) during the turtle nesting season. However, given the monitor's ecological role as a mesopredator, resource managers must first understand the local predator–prey interactions and the ecosystem-level effects of any predator control method selected (Prugh et al., 2009; Welicky et al., 2012). Studies on the raccoon *Procyon lotor*, another mesopredator that targets marine turtle clutches, showed its removal had no effect on mainland clutch depredation (Ratnaswamy et al., 1997; Barton & Roth, 2007). Tsellarius et al. (2011) suggested goannas scent-mark territorial boundaries to keep strangers out and control local population sizes, so the removal of individual goannas from a local populations could potentially lead to an increase in goanna numbers.

Goanna predation and nest selectivity is probably driven by olfactory and visual cues and influenced by spatial and temporal nest deposition (Blamires & Guinea, 2003; Blamires, 2004; Welicky et al., 2012), proximity to urbanized areas (Smith & Engeman, 2002; Blamires & Guinea, 2003; Prange et al., 2004) and human and goanna conspecific activity (Ferreira, 2012). In contrast to Welicky et al. (2012), predation risk in this study was more probable on the north beach in areas heavily utilized by humans, with campsites and food waste. This raises the question of why goannas have become more abundant at Wreck Rock beach (they were considered uncommon in the 1970s; C. Limpus, 2017, pers. comm.) and what drives their behaviour. It is possible that the control of apex predators (dingoes and foxes) has altered predator–prey relationships and reduced competition for goannas. This, together with increased human activity and camp site waste (particularly on the north beach), could have increased food availability for goannas, supporting them in greater numbers (Prugh et al., 2009).

Research with a focus on goanna ecology and loggerhead turtle clutch predation could improve management interventions for Wreck Rock beach. Such studies should include research into the biology and behaviour of goannas, examination of long-term predation effects and human impacts on predator behaviour. An examination of clutch predation could uncover vital information regarding the timing of predation (Ferreira, 2012; Welicky et al., 2012), repeated visitation by predators, and complete (Limpus, 1971) vs partial clutch loss (Chatto & Baker, 2008). For example, further research could provide insights into why control clutches were predated less than anticipated, and why nests not included in this study but directly adjacent to control plots were also predated (as per the simulation in Blamires & Guinea, 2003). Although the lace monitor was not previously considered a predator of turtle eggs, this species accounted for more than one-third of total predation and visited turtle nests at a lower temperature than the yellow spotted monitor (33 vs 37 °C, respectively).

Until further studies are undertaken, interim management is recommended particularly for the north beach. Camp site usage and waste management should be reviewed as a priority to reduce goanna activity in this area. This could be achieved with relatively little effort through education and enforcement. Future site-specific management is necessary to maximize hatchling success. The exclusion devices deployed in this study are effective in reducing depredation on marine turtle nesting beaches, but are not cost-effective for Wreck Rock beach because of high nesting numbers and limited resources. An alternative predator control programme should be explored, to provide the most efficient allocation of resources and management. This will be the most robust strategy to maximize hatchling production and thus contribute to future recruitment of the declining and Critically Endangered South Pacific subpopulation of the loggerhead turtle.

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Conflicts of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards. Research protocols for this study were approved by an authorised ethics committee (SA 2015/11/531) and authority under the Nature Conservation Act 1994.

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