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# The effect of on-shore light pollution on sea-turtle hatchlings commencing their off-shore swim

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**Abstract**

***Context.*** Off-shore recruitment impairment of sea-turtle hatchlings because of light pollution is a growing concern to conservation of sea-turtle population throughout the world. Studies have focussed on sea-turtle hatchling sea-finding behaviour, and ignored the possible effect that on-shore lighting might have on hatchlings after they have entered the sea.

***Aims.*** We experimentally evaluated the effect that on-shore light pollution has on the swimming behaviour of green turtle hatchlings once they have entered the sea and begun swimming off-shore. We also estimated the decrease in off-shore recruitment of hatchlings as a result of light pollution disruption of the off-shore swim.

***Methods.*** Hatchling misorientation rates were quantified by releasing marked hatchlings to the sea from different land-based locations adjacent to light-polluted beach areas under a variety of environmental conditions. The beach in light-polluted regions was then searched for marked hatchlings returning to shore from the sea.

***Key results.*** Misorientation rates were highest in trials conducted during moonless nights (66.7% of trials had some hatchlings return to shore) and lowest during trials conducted during moonlit nights (no trials had hatchlings return to shore). Green turtle hatchling off-shore recruitment for the entire 2014–15 nesting season at Heron Island was estimated to decrease 1.0 –2.4% as a result of on-shore lights disrupting hatchling off-shore swimming behaviour.

***Conclusions.*** On moonless nights, sea-turtle hatchlings after having successfully completed their journey from nest to sea and entered the sea can be lured back to shore again by shore-based light pollution and, this will decrease their off-shore recruitment success.

***Implications.*** To ensure maximum off-shore recruitment of sea-turtle hatchlings, on-shore light pollution adjacent to nesting beaches needs to be minimised so as to minimise misorientation and disorientation of hatchlings while on the beach and in near-shore waters.

**Additional keywords:** *Chelonia mydas*, green turtle, Heron Island, misorientation, recruitment, swimming.

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## Introduction

Sea turtles can be found in temperate, tropical and subtropical waters around the world (Hirth 1997). During all life stages (i.e. eggs to adults), they are susceptible to high mortality rates because of their vulnerability to natural and anthropogenic threats (IUCN 2004). A growing problem facing sea turtle populations is the increasing demand for urban and industrial development on or adjacent to nesting beaches. This results in a subsequent increase in artificial illumination falling on coastlines, termed 'light pollution'. Light pollution frequently disrupts both nesting female turtles and the sea-finding ability of emerging hatchlings (Lorne and Salmon 2007; Bourgeois *et al*. 2009; Berry *et al*. 2013) and near-shore light pollution is increasing (Kamrowski *et al*. 2012, 2014*a*, 2015*a*). When hatchling sea-finding behaviour is disrupted, the prospect for hatchling survival significantly diminishes (Witherington and Martin 2003).

Following nest emergence, sea-turtle hatchlings typically crawl directly towards the shoreline by using environmental cues (Lorne and Salmon 2007). The principle cue used is visual, based on the direction the light is coming from and elevation of the beach relative to the horizon (Limpus and Kamrowski 2013). Hatchlings orientate away from dark, high silhouettes and move towards the light horizon line at the lowest angle of elevation (Lohmann and Lohmann 1996; Limpus and Kamrowski 2013). Night-time artificial illumination pollutes nesting beaches and degrades the environmental visual cues commonly used by hatchlings to assist in the navigation from their nest to the sea (Salmon 2003; Tuxbury and Salmon 2005). Artificial lights have the potential to overwhelm natural light and shape cues, which results in hatchling disorientation or misorientation (Salmon *et al*. 1995; Salmon and Witherington 1995). Hatchlings that are disorientated will crawl in no set direction and can circle aimlessly for hours, using up vital energy reserves necessary for a successful off-shore swim (Salmon and Witherington 1995; Pilcher and Enderby 2001; Hamann *et al.* 2007; Rich and Longcore 2013). Misorientated hatchlings will crawl in a set direction, but away from the appropriate direction, typically crawling towards an inland artificial light source (Salmon and Witherington 1995). Both misorientated and disorientated hatchlings can become physiologically stressed by dehydration, and are frequently preyed on by terrestrial predators or killed after sunrise because of the exposure to high temperatures (Bustard 1972; Witherington and Bjorndal 1991; Rich and Longcore 2013).

Several environmental factors have been found to alter how sea-turtle hatchlings respond to artificial illumination when crawling from the nest to the sea, with lunar cycle being the most significant (Salmon 2003). During nights when the moon is full and the skies are clear, artificial lights have little to no influence over hatchling orientation because the horizon is illuminated and clearly visible (Salmon and Lohmann 1989; Berry *et al*. 2013; Limpus and Kamrowski 2013). In contrast, during nights when no moon is present or when cloud cover is dense, the majority of hatchlings exposed to light pollution exhibit disrupted sea-finding behaviour (Salmon 2003; Berry *et al*. 2013).

Once hatchlings enter the sea and begin swimming, they orientate themselves by swimming perpendicular to wave fronts (Salmon and Lohmann 1989; Lohmann and Lohmann 1992). Hatchlings have the ability to detect the earth's magnetic field and this cue comes into play once they have left the near-shore environment (Lohmann *et al*. 2012). Although wave direction and the earth's magnetic field are the principal cues used to orientate the off-shore swim, artificial light can also affect this process, by attracting hatchlings towards the light source, even after hatchlings have left the shore (Thums *et al.* 2016).

Heron Island (23°26′S, 151°51′E) is a coral cay in the Capricorn Bunker group of the southern Great Barrier Reef. Green turtles nest predominantly on the east- and north-facing beaches of Heron Island, with peak nesting occurring during December and January (Bustard 1972; Limpus 2007). During the 1930s, a tourist resort developed on the Island and became a well established holiday destination (Walker 1991). As consequent of the resort, the nesting area adjacent to the resort has been exposed to significant night-time light pollution (Walker 1991).

Whereas it is unequivocal that light pollution can affect sea-turtle hatchling navigation on land, there is uncertainty as to how land-based artificial lights might affect hatchlings once they have entered the water and commenced their off-shore swim. Recently, it was demonstrated that off-shore lights can influence the off-shore swim of sea-turtle hatchlings (Thums *et al*. 2016). There are also unquantified reports that on moonless and heavily overcast nights, land-based lights can cause hatchlings swimming off-shore to return back to shore (Limpus *et al*. 1981; Limpus and Kamrowski 2013). Conversely, other studies have reported that hatchlings nearly always swim away from land and show no tendency to orient towards land-based lights (Ireland *et al*. 1978; Salmon and Lohmann 1989). However, Harewood and Horrocks (2008) demonstrated that hatchling dispersal in inshore waters was slowed by elevated sky-glow over the nesting beach. On coral cays, such as Heron Island, where near-shore fish predation of hatchlings is high (Gyuris 1994), hatchlings may be distracted by land-based light pollution while swimming off-shore. If this is the case, their chances of successfully crossing the fringing reef may be reduced because a direct and timely off-shore swim is necessary to minimise the chance of predation (Gyuris 1994).

The purpose of the current study was to determine how green turtle hatchlings respond to land-based light pollution while swimming off-shore under a range of environmental conditions. The following questions were addressed: (1) are hatchlings swimming off-shore attracted back to shore by light pollution, and if so, does moon light affect this behaviour; (2) does wave presence/absence influence hatchlings response to light pollution while swimming off-shore; and (3) does current direction influence the likelyhood of hatchlings coming ashore? It was hypothesised that under moonless, low-wave conditions and during an incoming tide (in which the current might sweep hatchlings directly in front of on-shore lights), hatchlings would be most susceptible to being misorientated by the land-based artificial lights.

## Materials and methods

### *Study site*

Heron Island (23°26′S, 151°51′E) is one of 13 vegetated coral cays that make up the Capricorn Bunker group in the southern Great Barrier Reef, Australia. Heron Island provides a nesting habitat for green and loggerhead (*Caretta caretta*) turtles (Limpus 2007). During a peak nesting season, Heron Island can host up to 300 nesting female green turtles per night (Limpus and Nicholls 2000). Shark Bay (to the east) and the northern beach are the two highest-density turtle nesting sites on the island (Bustard 1972); therefore, all of the hatchling release trials were performed at these two locations. Sixty-three numbered posts spaced 25 m apart are located on the edge of vegetation fringing the beach around the island (Fig. 1). Heron Island resort bar and ~15 accommodation buildings overlook the north-western beach. At night-time, these rooms emit artificial illumination that spills directly onto the adjacent beach. Lights from the resort, University of Queensland Research Station on the southerly facing beach of the island and the Marine Parks base contribute to making a sky-glow over the western end of the island. A rock strip runs for ~300 m along the north-western beach from the resort bar to the sector Post 7 (Fig. 1). During high tide, this rock outcrop is covered with water and during low tide the rock outcrop is completely exposed. The tidal range varies between 2 m (spring tides) and 1 m (neap tides; Bureau of Meterology 2015). During the incoming tide, the prevailing current tends to sweep in a westerly direction along northern beach towards the resort, and, during the outgoing tide, the current tends to sweep in an easterly direction away from the resort (Fig. 1).

### *Data collection*

The area between the island's primary dune and the dense vegetation was searched every afternoon between 1500 hours and 1900 hours, so as to locate clutches that were about to emerge, as indicated by a small depression in the sand or hatchling heads or noses partially protruding through the sand surface. Following the identification of a pre-emerged clutch, a square piece of plywood


**Fig. 1.** Map of Heron Island, south-eastern Queensland. Adapted from (Google Earth 2016).

(30 cm × 30 cm) was placed on top of the nest and covered with sand until it was no longer visible. A corral constructed of gutter guard mesh (area of 0.2 $m^2$) was placed around the clutch. Corrals were checked every hour to ensure that any hatchlings emerging before the time when experimental trials begun were not left to crawl around inside the enclosure for extended periods of time and also to limit their exposure to predation by birds.

Between 1900 hours and 2000 hours, the plywood was removed and, shortly after, the clutch would begin to stir. The emerging hatchlings were counted and placed in a bucket, which was then transported by foot to the release site. During this period, the bucket was covered with a damp, heavy cloth to settle the hatchlings down and they became still within 10 min of being placed in the darkened bucket. Hatchlings were collected from their nest site 1–2 h before being used in release trials.

If more than one release was performed at a specific time, the collected hatchlings (often multiple clutches) were placed haphazardly into groups of a known number, the number averaging 80 per group. Each group was allocated to an individual bucket and the group consisted of individuals that emerged from nests within 20 min of each other. Alternatively, if only one release was scheduled for a specific time then the entire clutch was used. Prior to release, all individuals within a group were marked with the same unique group letter–colour combination on the plastron with a permanent marking pen. Marked hatchlings were then returned to the bucket in preparation for release.

Each group was allocated a specific release site and time. The release of each group was timed to include different moon and tidal phases. Hatchlings were released 5 m above the waterline along the northern beach (Posts 2, 7, 12 and 17) and Shark Bay (Posts 22 and 27). At Posts 2 and 7, hatchlings were released on the ocean side of the rocky outcrop to prevent hatchlings from being trapped in rock pools and crevasses. Hatchlings were released under the following eight different conditions: high tide and moon light, low tide and moon light, half way through an incoming tide and moon light, half way through an outgoing tide and moon light, high tide and no moon light, low tide and no moon light, half way through an incoming tide and no moon light, and half way through an outgoing tide and no moon light. During all releases, surface water temperature ranged between 25°C and 27°C.

Before the release of each group, all lights used by researchers, volunteers and tourists were turned off. Hatchlings were released by overturning the bucket onto the sand, and then rapidly lifting the bucket away. The group was then observed crawling to the edge of the water and swimming off-shore. Five minutes after all hatchlings had entered the water, searching of the beach for returning hatchlings began. A 5-min period was chosen because an initial trial indicated that some hatchlings began returning to shore 5 min after entering the water. The shoreline from the release site to the light-polluted area was searched for hatchlings by using torch light (LED flash). To minimise the disturbance to nesting females and naturally emerging hatchlings, the torch was used intermittently; directed towards the ground and held below knee height. This method of searching for hatchlings did not appear to attract hatchlings out of the water, as all hatchlings found returning to shore were already ashore and 3–5 m from the waterline, crawling inland in the direction of shore-based lights and not towards the searcher. The searcher walked continuously and stopped only to collect hatchlings what were wet, indicating that they had recently returned to shore. All searching was undertaken from the beach, the search never entered the water or shone the light at the water. Depending on how far away from the resort the hatchlings were released, the search continued for 45–60 min. Marked hatchlings that were found on the shoreline, on the rocks, swimming in rock pools and being attacked by crabs were classified as 'misorientated' and checked for identifying marks on the plastron. The number of hatchlings that returned to shore was recorded, along with the time. These hatchlings were then transported to Shark Bay where light pollution was not visible, and were released.

### *Assessment of environmental factors*

Immediately before and after each release trial, wave height, cloud cover, moon phase and moon visibility were recorded. Wave height was measured with a metre ruler and float. The height of 20 consecutive waves was recorded at a depth of 20 cm directly off the beach at the release site and, from this, an average wave height was calculated. The wave fronts were parallel to the beach during these measurements. The lunar phase and percentage of moon visible was obtained online through the WillyWeather website (WillyWeather 2015).

### *Data analysis*

A two-tailed, independent-sample Student's *t*-test was used to analyse the means of releases made during the presence (wave height greater than 5 cm) and absence (wave height less than 5 cm) of waves and the presence (moon visible for 80–100% of time) and absence (no moon visible for the duration of trial) of the moon. To investigate whether the outgoing and incoming tides influenced the proportion of returning hatchlings, the hatchling return rate during half-tide during both incoming and outgoing tides was compared. Percentage data were arsin-transformed before statistical analyses were performed. One-way ANOVA was used to compare return rates among the release sites along the northern beach. A significant difference was assumed if $P < 0.05$.

To predict a theoretical total number of misorientated hatchlings during each trial (the sum of hatchlings found returning to shore and hatchlings that were expected to be eaten by fish while returning to shore), the number of hatchlings expected to be eaten by fish while returning to shore was calculated using the observed number of hatchlings that returned to shore, the time elapsed between these hatchlings leaving the shore and returning to shore, and the survival rate per 10 min of swimming under different moon and tide conditions reported for Heron Island (table 3 in Gyuris 1994), as follows:

$$N_{\mathrm{m}} = N_{\mathrm{r}}/S_{\mathrm{d}},$$

where $N_{\mathrm{m}}$ = the total number of misorientated hatchlings (returned to shore + assumed to be eaten by predators), $N_{\mathrm{r}}$ = the number of hatchlings observed returning to shore after entering the water, and $S_{\mathrm{d}}$ = the survival probability of the hatchlings making it to the shore, depending on the period of time spent in the water. For the trial listed in Row 1 of Table 1, 33 of the 69 hatchlings released when the tide was half-way through coming in (10-min specific-survival probability = 0.835 (Gyuris 1994); hence, to extrapolate to a 5-min survival probability = $\sqrt{0.835} = 0.914$) returned to shore within 35 min after they had entered the water, so $S_{\mathrm{d}} = 0.835^3 \times 0.914 = 0.532$, and $N_{\mathrm{m}} = 33/0.532 = 62$. Hence, in this trial, of the 69 hatchlings that were released, 62 were predicted to become misorientated, and the proportion of misorientaed hatchlings would have been 62/69 = 90%. The number of hatchlings unaffected by misorientation was predicted to be 69 – 62 = 7.

Two scenarios were used to predict what might happen to misorientated hatchlings once they had returned to shore. Scenario S1 assumed that all misorientated hatchlings died, because they failed to re-enter the water and died on land. Therefore, the total number of hatchlings expected to make it off-shore in Scenario S1 is equal to the number of non-misorientated hatchings multiplied by the 30-min survival probability because it takes ~30 min for a hatchling to swim across the fringing reef (Gyuris 1994). Hence, for the trial in Row 1 of Table 1, the number of hatchlings predicted to make it off-shore was $7 \times 0.835^3 = 4$.

Scenario S2 assumed that the misorientated hatchlings that came ashore immediately returned to sea and swum directly off-shore. The total number of hatchlings expected to survive the swim off-shore under this scenario was calculated as the sum of hatchlings making it off-shore in Scenario S1 and the number of hatchlings making it off-shore when they entered the water for a second time. For the trial in Row 1 of Table 1 this was $4 + 33 \times 0.835^3 = 23$.

To quantify the effect of light pollution on the number of hatchlings making it off-shore, the proportional reduction in the number of hatchlings making it off-shore as a result of light pollution was calculated. To do this, the predicted number of hatchlings to make if off-shore under no light pollution was calculated, assuming a 30-min swim, and the appropriate 10-min survival probability. Hence, for the trial in Row 1 of Table 1, the predicted number of hatchlings making it off-shore under light pollution-free conditions was estimated to be $0.835^3 \times 69 = 40$, and the proportional reduction (%) in hatchlings making it off-shore in Scenario S1 was: $100 - 4/40 \times 100 = 90.0\%$, whereas for Scenario S2, it was: $100 - 23/40 \times 100 = 42.5\%$.

## Results

In total, 24 release trials (1849 hatchlings) spread over 20 nights were conducted at the western end of the northern beach on Heron Island (released at Posts 2, 7, 12 and 17), in the area where light pollution was visible during January and February 2015. Six trials (504 hatchlings) were conducted under moonlit conditions and 18 trials (1345 hatchlings) were conducted in the absence of moon light. Another two trials were conducted under no moon conditions, at Shark Bay (Posts 22 and 27), which were largely unaffected by light pollution.

### *Misorientation*

Of the 504 hatchlings released during the six moonlit trials (80–100% moon visibility) on the light-polluted section of the northern beach, no marked or unmarked hatchlings returned to shore. Of the 18 trials conducted when no moon was present, 12 trials had some marked hatchlings return to shore, and six trials had no marked hatchlings return to shore (Table 1). The proportion (mean ± s.e.m.) of marked hatchlings found returning to shore on moonless nights in this light-polluted region was 10.7 ± 3.7%. None of the 163 marked hatchlings released during the no-moon trials at Shark Bay returned to shore.

The proportion of marked hatchlings returning to shore in the light-polluted region was similar at the four release sites, as follows: Post 2: 39.3 ± 16.2% ($n$ = 6); Post 7: 11.8 ± 4.4% ($n$ = 4); Post 12: 2.4 ± 3.8 ($n$ = 5); and Post 17: 7.8 ± 7.8 ($n$ = 2; one-way ANOVA, $F_{3,14} = 2.921$, $P = 0.071$). The proportion of hatchlings returning to shore did not differ between wave presence (12.8% ± 6.7%, $n$ = 12) and wave absence (3.6% ± 2.5%, $n$ = 7; independent-sample *t*-test, $P = 0.19$). The proportion of hatchlings returning to shore did not differ between

**Table 1. Details of experimental release trials conducted in the absence of moon light**

Includes release location (post), number of hatchlings released, tidal conditions at time of release (half-tide, incoming tide (1/2 T IN); half-tide, outgoing tide (1/2 T OUT); low tide (LT); high tide (HT)), condition-dependent 10-min survival rate (calculated from Gyuris 1994), number of hatchlings that returned to shore after entering the water, approximate time taken for hatchlings to return, misorientated hatchling survival probability ($S_d$), total number of misorientated hatchlings ($N_d$), number of hatchlings that would make it off-shore if not misorientated ($N$), number of hatchlings that would make it off-shore in Scenario S1, number of hatchlings that would make it off-shore in Scenario S2, the proportional reduction of hatchlings making it off-shore in Scenario S1, and the proportional reduction of hatchlings making it off-shore in Scenario S2. n.a., not applicable

| Release location (post number) | Number of hatchlings released | Environmental conditions | Condition-dependent 10-min survival rate (Gyuris 1994 ) | Number of hatchlings that returned to shore | Time taken to return to shore (min) | Misorientated hatchling survival probability (Sd) | Predicted total number of misorientated hatchlings (Nm) | Predicted number of hatchlings that would make it off-shore if not misorientated | Predicted number of hatchlings that would make it off-shore with misorientation (S1) | Predicted number of hatchlings that would make it off-shore with misorientaion (S2) | Proportional reduction in hatchlings making it off-shore (S1) (%) | Proportion reduction in hatchlings making it off-shore (S2) (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trials with some hatchlings returning to shore | | | | | | | | | | | | |
| 2 | 69 | 1/2 T IN | 0.835 | 33 | 35 | 0.532 | 62 | 40 | 4 | 23 | 90.0 | 42.5 |
| 2 | 77 | 1/2 T IN | 0.835 | 14 | 25 | 0.634 | 22 | 45 | 32 | 40 | 28.7 | 10.5 |
| 2 | 25 | 1/2 T OUT | 0.835 | 5 | 20 | 0.697 | 7 | 15 | 10 | 13 | 28.7 | 8.7 |
| 2 | 90 | 1/2 T OUT | 0.835 | 41 | 35 | 0.532 | 77 | 52 | 7 | 31 | 86.0 | 40.4 |
| 2 | 62 | LT | 0.72 | 1 | 15 | 0.655 | 2 | 23 | 22 | 22 | 2.5 | 2.5 |
| 7 | 98 | 1/2 T IN | 0.835 | 16 | 20 | 0.697 | 23 | 57 | 44 | 53 | 23.4 | 7.1 |
| 7 | 69 | 1/2 T IN | 0.835 | 5 | 35 | 0.532 | 9 | 40 | 31 | 34 | 23.5 | 7.2 |
| 7 | 90 | 1/2 T OUT | 0.835 | 3 | 10 | 0.835 | 4 | 52 | 50 | 51 | 4.0 | 1.2 |
| 7 | 69 | 1/2 T OUT | 0.835 | 3 | 20 | 0.697 | 4 | 40 | 38 | 39 | 6.2 | 1.9 |
| 12 | 84 | 1/2 T IN | 0.835 | 2 | 15 | 0.759 | 3 | 49 | 47 | 48 | 3.1 | 0.8 |
| 12 | 81 | 1/2 T OUT | 0.835 | 5 | 20 | 0.697 | 7 | 47 | 43 | 46 | 8.9 | 2.7 |
| 17 | 73 | 1/2 T IN | 0.835 | 6 | 35 | 0.529 | 11 | 42 | 36 | 39 | 15.5 | 7.3 |
| Average | 73.9 | | | 11.2 | 24 | 0.649 | 19 | 42 | 27 | 29 | 23.7 | 11.1 |
| Trials with no hatchlings returning to shore | | | | | | | | | | | | |
| 2 | 76 | LT | 0.72 | 0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 0 | 0 |
| 12 | 76 | HT | 0.835 | 0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 0 | 0 |
| 12 | 75 | 1/2 T IN | 0.835 | 0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 0 | 0 |
| 12 | 76 | 1/2 T OUT | 0.835 | 0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 0 | 0 |
| 12 | 75 | 1/2 T OUT | 0.835 | 0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 0 | 0 |
| 17 | 80 | 1/2 T OUT | 0.835 | 0 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 0 | 0 |
| Average | 76.3 | | | 0 | | | | | | | 0 | 0 |

incoming tide when the current was running in a westerly direction (12.5% ± 5.6%, $n = 8$) and outgoing tide when the current was running in an easterly direction (9.7% ± 5.6%, $n = 8$; independent-sample *t*-test, $P = 0.76$). In total, 15 marked hatchlings (11%) returning to shore were attacked by crabs. A further four hatchlings were seen in silver gull beaks; however, it was unclear whether those hatchlings were marked or not.

Within trials in which some marked hatchlings returned to shore after entering the water, the mean misorientation rate was 25.9 ± 8.8% (range 3.1–90.3%), and the estimated reduction in hatchling turtles making it off-shore in Ssenario S1 was 25.9 ± 8.8% and, in Senario S2, it was 10.8 ± 4.2% (Table 1).

### *Proportion of nests and hatchlings potentially affected by light pollution on Heron Island*

So as to evaluate the influence of light pollution on off-shore swimming success of green turtle hatchlings for the entire 2014–15 nesting season at Heron Island, data on the time that emerging clutches are exposed to moonless conditions (see Table S1, available as Supplementary material to this paper) and the number and distribution of green turtle nests around Heron Island (see Table S2) were used to estimate the proportion of emerging clutches affected by light pollution. Of the 1266 green turtle nests constructed, 307 (24%) were constructed between Posts 0 and 17 and, therefore, were potentially affected by light pollution (Table S2). Nest emergence was first observed on 25 December 2014 and continued until the end of April 2015, and moonless conditions lasting longer than 3 h (a conservative estimate of the maximum time required for hatchlings to make the crawl from the nest to the water and swim over the fringing reef flat) occurred on 59.8% of nights (76/127, Table S1). Only 66.7% of clutches that emerged on nights without moon light in the light-polluted region had hatchlings return to shore (Table 1). Hence, hatchlings from an estimated $307 \times 0.598 \times 0.667 = 122$ nests were predicted to be affected by light pollution, which corresponds to 9.6% of all nests laid by green turtles on Heron Island during the 2014–15 nesting season.

To estimate the potential influence of light pollution on the number and proportion of green turtle hatchlings recruited off Heron Island during the 2014–15 nesting season, calculations were performed assuming that the average clutch size was 115 (Limpus *et al*. 1984), nest emergence success was 87.9% (Limpus 2007), and that hatchling survival probability was 0.582 for the 30-min swim across the fringing reef (Gyuris 1994). Hence, for a hypothetical situation where there was no light pollution affecting the 1266 nests, the expected hatchling recruitment was $1266 \times 115 \times 0.879 \times 0.582 = 74481$. The survival rates for hatchlings exposed to light pollution under no moon conditions were estimated from the mean reduction in off-shore recruitment rate reported in Table 1. In Scenario S1, when no misorientated hatchlings survived, this was $0.582 \times (100 - 23.7)/100 = 0.44$, and for Scenario S2, where misorienated hatchlings that returned to shore re-entered the sea and swam off-shore, this was $0.582 \times (100 - 11.1)/100 = 0.52$. Hence, for Scenario S1, the expected hatchling recruitment was $122 \times 115 \times 0.879 \times 0.44 + (1266–122) \times 115 \times 0.879 \times 0.582 = 72729$, a reduction of 1752 hatchlings, representing a 2.4% reduction in recruitment. For Scenario S2, the expected recruitment was $122 \times 115 \times 0.879 \times 0.52 + (1266–122) \times 115 \times 0.879 \times 0.582 = 73716$, a reduction of 765 hatchlings, representing a 1.0% reduction in recruitment.

## Discussion

The extent to which artificial lights disrupt the off-shore swimming behaviour of hatchling sea turtles is poorly documented, with a single recent study reporting that off-shore lights can at least temporarily distract swimming hatchlings (Thums *et al*. 2016), and anecdotal comments that hatchlings can be attracted to shipboard flood lights on boats anchored off-shore nesting beaches. However, once they have entered the sea, hatchling sea turtles returning to shore under the attraction of shore-based artificial lights has not been formally documented. The current study is the first to experimentally address this issue and found that hatchlings entering the ocean up to 500 m (Post 17) away from the source of light pollution had the potential to become misorientated on moonless nights and return to shore after they had entered the sea. The majority of hatchlings that became misorientated during their off-shore swim were found returning west of Post 2, in the area where the artificial light pollution spilled directly onto the beach. However, on nights when the moon was present (lunar visibility was between 36% and 100%), no hatchlings were found returning to shore, indicating that the distracting influence of the artificial lights was mitigated by the presence of moonlight. These findings are consistent with those of previous studies, which also concluded that land-based hatchling misorientation and disorientation is mitigated by moonlight (Salmon 2003; Berry *et al*. 2013).

Hatchlings were found returning to shore after they had been swimming at sea both in the presence and absence of waves. Once in water, hatchling sea turtles use wave direction as a guide to assist in directing them off-shore (Lohmann and Lohmann 1996). Previous studies have found that in the absence of waves and in the presence of artificial lights, hatchlings have a reduced off-shore swimming success (Harewood and Horrocks 2008; Limpus and Kamrowski 2013). In the current study, green turtle hatchlings swimming off-shore could be misorientated by the land-based artificial lights regardless of the presence or absence of waves. Because the green turtle hatchlings emerging from Heron Island enter protected in-shore waters where wave energy is generally low, the importance of wave direction as a cue for off-shore navigation may be less important than for hatchlings navigating off surf beaches. The lack of a strong wave cue may make hatchling turtles emerging from low wave-energy beaches especially vulnerable to misorientation by land-based artificial lights after they have successfully found the sea and started their off-shore swim. Harewood and Horrocks (2008) came to a similar conclusion for the population of hawksbill turtles, which they studied in the protected waters of Barbados.

We anticipated that the rate of hatchlings returning to shore would be greatest where the intensity of light pollution was highest (Post 2), and diminish as the release site became more distant from the highest intensity of light pollution, because light intensity decreases as distance from the source increases, and the distractive effect on swimming is expected to be dependent on light intensity. Although this trend was present in the data, it was not statistically significant, because of the large variation in data and a small sample size.

We expected that the rate of hatchlings returning to shore would be greater on the incoming tide because, during this time, the prevailing current runs westward across the fringing reef, which would tend to sweep hatchlings in front of the most intensely light-polluted section of the beach; however, we did not find this. We did not quantify current speed and the possible effects of wind speed and direction on hatchling drift effects, so this might have accounted for the absence of a tide effect on marked hatchling return rates. Also, as mentioned above, the effectiveness of on-shore lights to attract hatchlings ashore probably diminishes the further away from the lights the hatchlings are. Hence, the current direction may have little effect on hatchling return rate because by the time hatchlings are being swept significant distances east or west by the tidal current, they are far enough off-shore so that the on-shore lights have little effect on their swimming behaviour.

Tide height, although not directly related to the effects of night-time artificial light pollution, is known to have a significant effect on the survival rates of hatchlings swimming off-shore at Heron Island (Gyuris 1994). Although a full moon may improve the sea-finding success of hatchlings emerging from nests, especially on artificial light-polluted beaches (Salmon and Wyneken 1987), Gyuris (1994) found that it also results in greater in-water hatchling mortality because of increased fish predation. The study of Gyuris (1994) concluded that predation rates were highest during low tides and full moons and lowest during high tides and new moons. During nights when lunar illumination is high, hatchlings are more visible to predators and, when the tide is low, they swim closer to the substrate where fish reside (Gyuris 1994). If hatchlings spend a prolonged period in the near-shore environment, it is likely to result in elevated rates of predation because they are exposed high predation rates for a longer period of time (Gyuris 1994; Harewood and Horrocks 2008). During the current study, the artificial illumination was seen to misorientate hatchlings swimming off-shore, delaying their escape from the near-shore zone and, thus, increasing their vulnerability to fish predation.

The number of marked hatchlings returning to shore does not give an absolute representation of the entire number of hatchlings that may have been distracted by land-based light pollution, as misorientated hatchlings that have been predated on by fish during their prolonged swim are not counted in this number. To account for this, the survivorship values from the study of Gyuris (1994) were used to estimate the total number of misorientated hatchlings for each trial (Table 1). To further calculate the number of hatchlings expected to make it successfully off-shore, two scenarios were explored. Scenario S1 assumed that all misorientated hatchlings that had come ashore would die on land, as a result of predation, exhaustion or over heating during sunlight exposure the next day, which is a realistic expectation. In this scenario, it was estimated that, on average, there was a 25.9% decrease in hatchlings making it off-shore, compared with when light pollution was absent. Scenario S2 assumed that all hatchlings that came ashore would return to sea and swim directly off-shore again, which is an unlikely expectation. In this scenario, there was, on average, a 10.8% decrease in hatchlings making it off-shore, compared with when light pollution was absent. These scenarios represent the best and worst cases for the fate of distracted hatchlings, and, in real life, the actual reduction in off-shore recruitment is likely to be between these values. Although it is unknown whether the probability of predation increases in the waters adjacent to light-polluted beaches, the prolonged amount of time spent swimming in the near-shore environment will ultimately lead to a decreased hatchling survival rate, because of both reduction of energy reserves (Pilcher and Enderby 2001; Hamann *et al*. 2007) and increased predation (Gyuris 1994).

We estimated that during the 2014–15 nesting season on Heron Island, between 765 and 1752 green turtle hatchlings were likely to have perished because of being misorientated by shore-based light pollution after they had entered the water and commenced their off-shore swim. These numbers correspond to between a 1.0% and 2.4% reduction in off-shore recruitment across the entire nesting season. These values are likely to be an underestimate of the total impact of light pollution on green turtle hatchling recruitment, because they do not account for the on-shore misorientation of hatchlings as they emerge from the nest and crawl down the beach to enter the water before they commence their off-shore swim. It is well documented that light pollution disrupts hatchling sea-turtle sea-finding behaviour (Witherington and Bjorndal 1991; Witherington 1992; Salmon and Witherington 1995; Witherington and Martin 2003; Berry *et al*. 2013; Limpus and Kamrowski 2013; Kamrowski *et al*. 2014*a*) and, during our trials, we encountered two instances of on-shore misorientation. In the first instance, when 73 hatchlings were released at Post 2, 48 of them immediately crawled over the rocks and up the beach towards artificial lights, and, in the second instance, when 73 hatchlings were released at Post 17, 20 of them crawled immediately up the beach in the direction of the resort. These observations confirmed that terrestrial misorientation of green turtle hatchlings occurs at Heron Island, and that this disruption to normal sea-finding behaviour can occur up to 500 m away from the light-pollution source (Salmon 2003; Tuxbury and Salmon 2005).

Although we did not investigate the possible disrupting effect of on-shore light pollution on the off-shore swim of loggerhead turtle hatchlings, it is highly probable that these lights affect them in a way similar to that they affect green turtle hatchlings because, like green turtle hatchlings, loggerhead hatchlings can have their sea-finding behaviour disrupted by artificial lights. Of the 537 loggerhead turtle nests constructed on Heron Island in the 2014–15 nesting season, 161 (30%) were constructed in the light pollution-affected beach area, so this species is also likely to have hatchling recruitment adversely affected by light pollution.

## Conclusions

It is well documented that night-time artificial illumination present on nesting beaches distracts hatchlings emerging from their nests and discourages nesting females from coming ashore (Witherington 1992; Salmon *et al*. 1995; Berry *et al*. 2013; Limpus and Kamrowski 2013), and the current study has now demonstrated that hatchlings that have entered the sea and begun their off-shore swim can be attracted back to shore by land-based artificial lights. Finding effective, publicly acceptable and economically viable solutions to prevent sea-turtle hatchling disorientation and misorientation is problematic (Kamrowski *et al*. 2014*b*, 2015*b*). Management options specific to Heron Island Resort may include the shading of floodlights to prevent light from spilling directly onto the beach and to minimise the sky-glow; switching off floodlights after the last guest leaves the bar area; educating guests and staff to ensure that curtains and blinds of guest rooms are closed after 2000 hours and that veranda and balcony lights are switched off before going to bed. Revegetating areas between the resort and beach with a dense planation of casuarina trees may also help minimise the amount of light spilling on to the beach. Implementing better light-management strategies will not only benefit the sea-turtle hatchling off-shore recruitment rate, but will likely lead to a reduction in energy costs; ultimately saving the resort money.

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