Impacts of coastal development on hawksbill hatchling survival and swimming success during the initial offshore migration

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A B S T R A C T

The impacts of coastal development on survival and swimming success were investigated for hatchling hawksbill turtles (*Eretmochelys imbricata*) swimming away from artificially lighted and dark nesting beaches in Barbados. The overall predation rate was 6.9%. Predation rates were not significantly affected by offshore substrate type or beachfront lighting. However, of those hatchlings leaving lighted beaches that successfully escaped predation, a significantly smaller percentage (32.9%) were able to swim the prescribed distance seawards during the observation period. Moonlight significantly improved the swimming success of hatchlings leaving lighted beaches, particularly when the moon was full, but also significantly influenced predation rates, which were highest during the full moon (12.6%). Some hatchlings released from dark beaches were attracted by lights from neighbouring beaches, which only became visible after they were a substantial distance from shore. Artificial light may override the effects of wave cues in the low wave energy conditions characteristic of leeward Caribbean beaches, making swimming hawksbill hatchlings especially vulnerable to the effects of beachfront lighting.

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1.   Introduction

Sea turtle hatchlings are vulnerable, both during the crawl from the nest to the sea and in the initial phase of their swim away from the beach when they cross shallow, predator-rich nearshore waters (Salmon and Wyneken, 1987; Gyuris, 1994; Pilcher et al., 2000). This initial phase lasts for approximately 24 h (Wyneken and Salmon, 1992) and is characterized by frenzied swimming which facilitates the rapid movement of hatchlings away from shallow nearshore areas (Wyneken and Salmon, 1992; Wyneken, 2000). Factors which confound or delay the completion of this phase may significantly increase hatchling mortality (Whelan and Wyneken, 2007).

Barbados is the most easterly of the Caribbean territories (59°35′W and 13°10′N) and supports one of the largest nesting populations of Critically Endangered (IUCN, 2007) hawksbill sea turtles, *Eretmochelys imbricata*, in the wider Caribbean (Beggs et al., 2007). Nesting is a nocturnal activity (Beggs et al., 2007) and typically occurs on sandy beaches in bays between near-shore fringing or patch reefs. Nest density is highest on the leeward coast which is characterized by low wave energy and calm waters (Beggs et al., 2007). Extensive tourism-based development of this coast has reduced the quality of nesting beaches used (Harewood, 2007). Hawksbills nesting on developed beaches often fail to find the native beach vegetation in which they prefer to nest (Horrocks and Scott, 1991), and frequently encounter sea walls, pavements and other anthropogenic obstructions which prevent them from reaching higher elevations on the beach and/or are deterred from nesting by artificial light spilling onto the beach.

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Although offshore substrate is not always a reliable predictor of where females may choose to emerge (Woody et al., 2000), many females show a preference for emerging onto beaches with sandy approaches and rubble-free foreshores (Mortimer, 1982). The alternating areas of sand and live reef/rubble substrate in the near shore of the leeward coast of Barbados provide sandy approaches interspersed by reef/rubble habitat which is sometimes exposed at very low tides. Hotels in Barbados tend to be located centrally in the sandy bays, often at the widest point of the beach. Artificial beachfront lighting associated with these properties typically results in hawksbills avoiding the wide sections of sandy beach and emerging instead on the narrow beaches towards the peripheral fringes of bays. Here light intensity is lower, but nests are made in an area of the beach adjacent to live reef/rubble substrate, rather than sand. The structural complexity of reef and rubble substrates may support higher species diversity and larger fish populations than adjacent sandy habitats (Gyuris, 1994). Therefore, hatchlings crossing complex substrate of these types might suffer higher rates of predation (Gyuris, 1994).

Wyneken et al. (2000) have shown that aquatic predators accumulate near to beach sites where large numbers of hatchlings regularly enter the water, particularly offshore of hatcheries. The concentration of nests into smaller areas of beach due to anthropogenic obstruction and degradation of nesting beaches in Barbados may have a similar effect. Glenn (1998) and Pilcher et al. (2000) have found that loggerhead and green turtle hatchlings, respectively, released from sites where hatchlings tend to be released *en masse*, e.g. from hatcheries, had higher predation rates than those from control sites.

The importance of light as the primary cue used by hatchlings to locate the sea, and wave action as an additional cue for hatchling orientation away from the beach, is well established (e.g. Salmon and Wyneken, 1987; Wyneken et al., 1990). On developed beaches, artificial light sources overwhelm natural light cues and regularly result in hatchling misorientation (Witherington and Bjorndal, 1991; Salmon et al., 1995; Witherington and Martin, 2000; Horrocks, 2002; Bell et al., 2007). Extended periods of misorientation can lead to exhaustion and dehydration of affected hatchlings (Salmon, 2003; Witherington and Martin, 2000) and increased terrestrial predation (particularly by crabs, e.g. *Ocypode* sp., Smith et al., 1998). It has also been shown to impair the subsequent seaward orientation ability of loggerhead hatchlings (Lorne and Salmon, 2007).

Hatchlings that do succeed in reaching the sea after suffering a period of misorientation have been shown to be compromised in their initial swim offshore. Lorne and Salmon (2007) noted that hatchlings that completed seaward crawls were able to orient away from shore in the absences of wave cues, while those placed in the sea after two hours of misorientation were unable to do so. Further, hatchling activity and swim speed are known to decrease with retention time after emergence (Pilcher and Enderby, 2001). Pilcher and Enderby (2001) also noted that green turtle hatchlings adopted a less efficient swimming style after prolonged retention; the dog-paddle instead of the powerstroke.

Several studies have investigated the behaviour of marine turtle hatchlings during their initial offshore swim (e.g. Liew and Chan, 1995; Walker, 1994; Pilcher et al., 2000; Hasbún, 2002), and some have also investigated hatchling survival during this phase. Coastal predation rates have been estimated for green turtles (Gyuris, 1994; Pilcher et al., 2000), loggerhead turtles (Witherington and Salmon, 1992; Glenn, 1998; Stewart, 2001), and leatherbacks (Nellis and Henke, 2000). However, with the exception of Hasbún's (2002) study which followed twelve hatchlings released after sunrise from beaches in Honduras, little is known of hatchling survival in hawksbills.

Despite the increasing development of marine turtle nesting beaches globally, and the widespread occurrence of hatchling misorientation on the beach, few studies to date have investigated the potential for artificial light to affect hatchling orientation during the swim offshore (Salmon and Wyneken, 1987; Witherington, 1990). Witherington (1990) followed loggerhead hatchlings leaving an experimentally lighted beach and observed slower swim speeds and wider dispersion, but did not investigate the effect of this on hatchling predation. Other studies have shown hatchling predation to be higher in shallow nearshore waters than deeper waters (Gyuris, 1994; Pilcher et al., 2000). If disorientation of hatchlings by artificial lights occurred and delayed departure from shallow coastal waters, it can lead to higher levels of hatchling predation. For example, Whelan and Wyneken (2007) observed higher predation rates for loggerhead hatchlings that spent more time in shallow waters due to the influence of skyglow. Finally, since Trullas et al. (2006) have shown that the swimming frenzy is the most energetically expensive phase of dispersal for hatchlings, prolonged detention in coastal waters is likely to result in the wastage of energy reserves needed by hatchlings to reach the safety of the open ocean and hatchlings may adopt slower post-frenzy swimming speeds before they even escape coastal waters (Wyneken, 2000).

Investigation of the impacts of beach lighting on hatchling survival and swimming success during the initial swim away from shore is particularly important in Barbados since hawksbill nesting in Barbados occurs predominately on the highly developed leeward coasts (Beggs et al., 2007) and over 50% of nests are made on lighted beaches (Horrocks, 2002). A summary of hatchling misorientation data collected over several years showed that half of the hatchlings produced from these nests can be misoriented on the beach by lights each year (Horrocks, 2002). The impacts of lights on the survival of the half that do successfully enter the water is unknown. Given the increase in "sun, sand and sea" tourism globally, it may be an issue of significance to long term survival of sea turtle populations. The objectives of this study are to determine predation rates for hawksbill hatchlings during their initial swim away from the beach over sand and over reef/rubble substrate, and to examine the potential impact of coastal development by comparing predation rates and swimming success of hatchlings leaving dark and lighted beaches.

2. Methods

A total of 485 hawksbill hatchlings were used in the experimental releases. They were collected upon emergence and placed in covered containers and transported to the experimental release sites. The release sites were on leeward nesting beaches, where hawksbills nested at high frequencies

(Horrocks and Scott, 1991; Beggs et al., 2007). Due to the proximity of beaches on this coast, travel times from the beaches where hatchlings emerged to release sites were similar for each trial. The sea conditions were similar at all release sites to minimise the possible effects of currents on the swim offshore and to ensure that the hatchlings could be seen and followed as effectively as possible. Release sites differed in terms of whether the nearshore substrate consisted of sand or of hard live reef/rubble complexes, and in whether they were at lighted or dark beaches (Fig. 1). Over one hundred hatchlings were released at each type of site i.e. lighted, sand ($n = 102$), lighted, hard substrate ($n = 110$), dark, sand ($n = 132$), and dark, hard substrate ($n = 141$) (Table 1). Releases ($n = 382$) were conducted both during low light moon phases (i.e. first and last quarters and new moon) and during the full moon ($n = 103$).

The release point for harnessed hatchlings was 3 m offshore. After release, each hatchling was followed offshore for a distance of 100 m or for 20 min. The distance and time period were chosen since they were sufficient to allow hatchlings to reach water depths of 6–9 m and to clear any near-

shore hard substrate areas if they were present at the release site. The 20 min period also ensured that hatchlings to be used for trials were not retained for excessive lengths of time prior to being tested. The 100 m transect extending out to sea perpendicular to the shoreline was defined using marker buoys placed at 50 and 100 m. Although the tidal range is small in Barbados ($\leqslant 1$ m), low tide releases were avoided to minimise the effect of tidal height on predation rates (Gyuris, 1994).

At each site, one trial per night was undertaken, with a trial consisting of the release of ten randomly selected hatchlings from a clutch. Hatchlings were placed on the beach and allowed to walk towards the surf where they were then collected and retained. Each hatchling was then fitted with a lightweight Spandex© vest attached via a 4 m polyfilament nylon line to a float, constructed from matchsticks, bearing a 3 mm × 23 mm cylume light stick (Starlite SL-5 mini-light stick); see Fig. 2. The floats were 40 mm × 16mm in size and weighed 1.5–1.8 g; approximately 10% of hatchling weight. All floats were painted dark brown on the underside to reduce their visibility to predators. Light sticks were
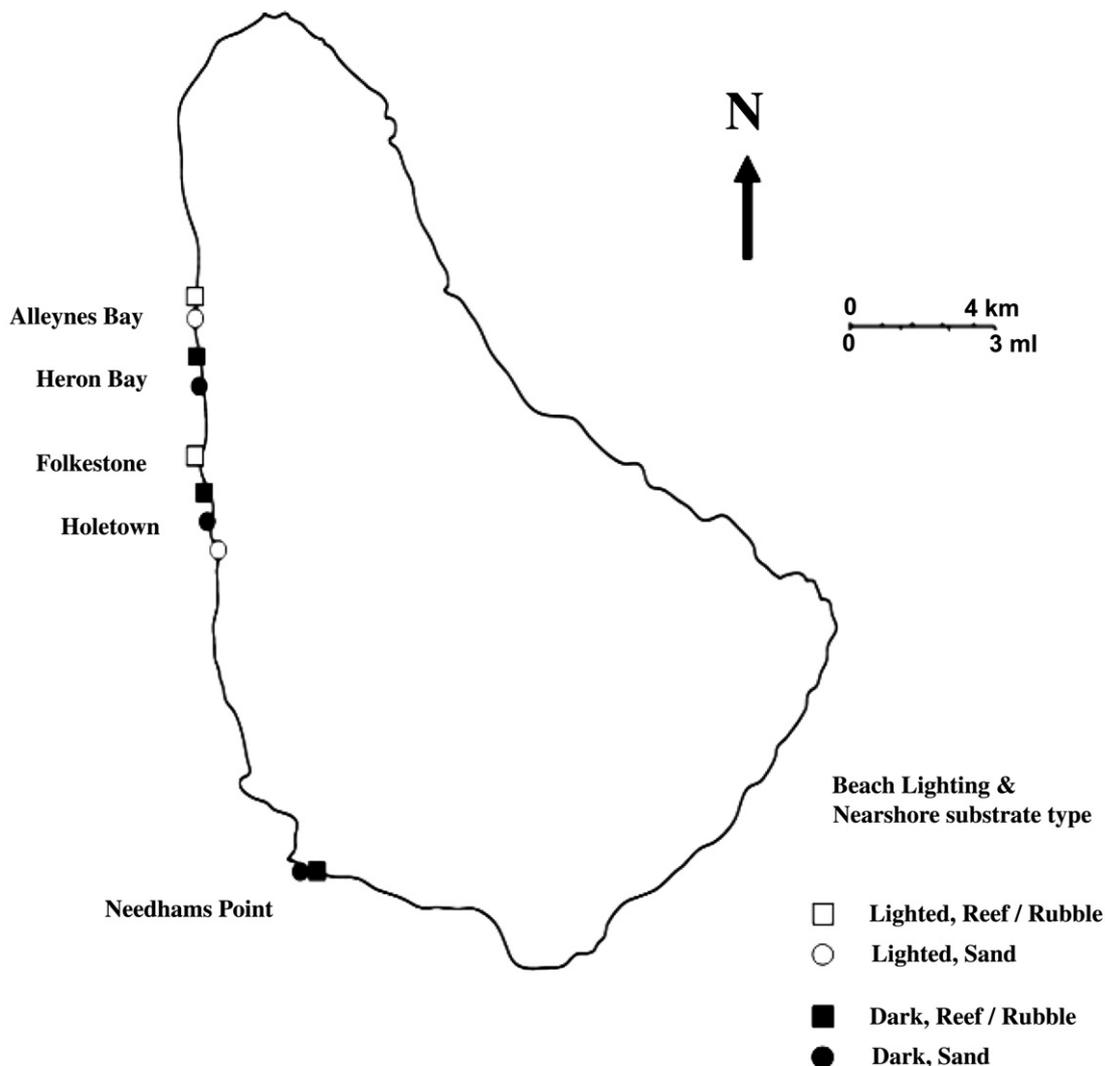

Fig. 1 – Outline map of Barbados indicating the locations of beach sites used in hatchling trials. Trials were conducted on leeward beaches only, as these constitute the main nesting habitat of hawksbill turtles on the island.

Substrate type	Lighted		Dark		Total
	Hard[*]	Sand	Hard[*]	Sand	
# Lost	16	9	6	4	35
# Followed hatchlings with known fate (excludes lost)	94	93	135	128	450
# Unpredated hatchlings	85	91	125	118	419
# Unsuccessful hatchlings	56	62	40	36	194

Table 1 – Fate of hawksbill hatchlings released from lighted and dark beaches on the leeward coast of Barbados; includes the substrate type over which hatchlings were followed

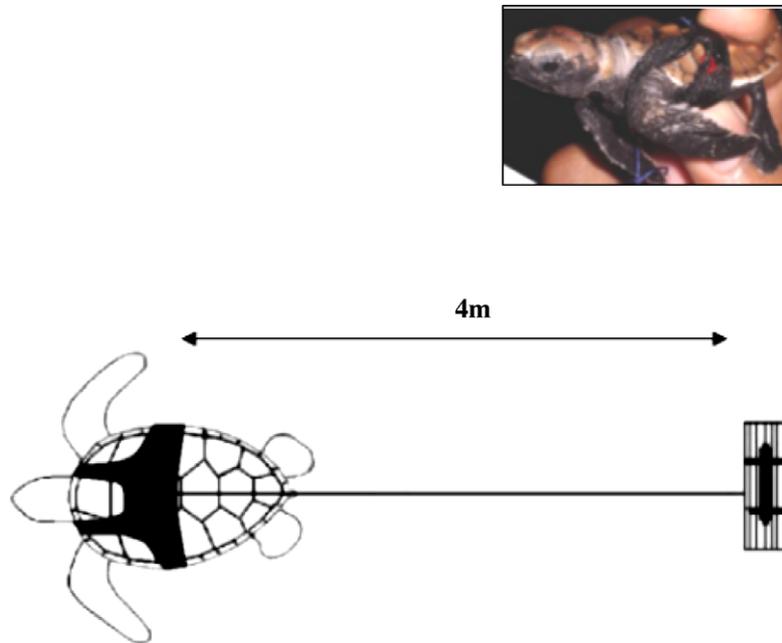Hard[*] substrate = reef/rubble.

Fig. 2 – Hatchling tracking equipment (a black Spandex© vest, monofilament line, matchstick float and a green luminous lightstick). Insert – hawksbill hatchling in Spandex© vest.

secured to the middle of the float and were therefore only visible from above.

In order to minimise influencing either hatchling or predator behaviour, each observer stayed an estimated distance of 4–6 m behind the lighted float and therefore maintained a distance of 8–10 m from the hatchling until the trial was completed. At the end of every release, the fate of the hatchling was determined as Predated (the sudden, temporary or permanent disappearance of the float, with or without an accompanying splash); Successful (the hatchling crossed the 100 m mark within the 20 min period); or Unsuccessful (the hatchling had not crossed the 100 m mark in the 20 min period, but was still visible). The swimming success for each trial was calculated as the percentage of released hatchlings that were Successful during the offshore swim. A portion of the Unsuccessful hatchlings stranded back onto the beach within the 20 min period. The observer lost sight of some hatchlings soon after release, and since their fate could not be determined, they were excluded from the analyses. At the end of each trial, Successful and Unsuccessful hatchlings were recaptured, the vests were removed and they were allowed to continue swimming. Any stranded hatchlings were collected and re-released on a dark beach.

Category data were analysed with Pearson's contingency chi square, with Yates continuity corrections where appropriate, using SPSS 11.5 statistical software.

3. Results

Of the 485 hatchlings that were released, thirty-five (35) were lost from view and could not be followed (Table 1). Substrate type ($\chi_c^2 = 1.46$, $P > 0.05$) did not affect the number of hatchlings that were lost from view, but hatchlings were lost more frequently when released from lighted beaches than dark beaches ($\chi_c^2 = 9.8$, $P < 0.05$). Although, moon phase did not affect the number lost from view ($\chi_c^2 = 0.004$, $P > 0.05$), artificial light cast across the sea surface tended to obscure the visibility of the hatchlings from the observer. Since the fate of these hatchlings could not be determined, they were excluded from further analysis (see Table 1 for final sample sizes).

3.1. Predation

Thirty-one of the remaining 450 hatchlings that were successfully followed were taken by predators, resulting in a confirmed predation rate of 6.9% (Table 1). Predation of
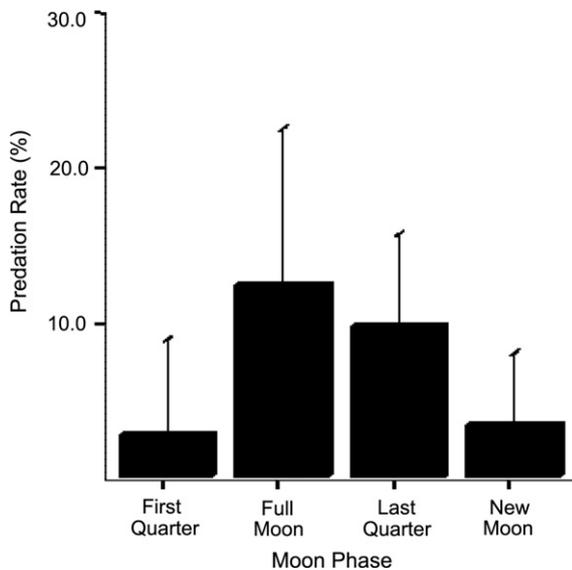
Fig. 3 – Mean predation rates during different phases of the lunar cycle for hatchlings followed over reef/rubble substrates and sandy substrates combined. Number of hatchlings followed: first quarter (102), full moon (96), last quarter (128) and new moon (125).

hatchlings that swam over hard substrate (8.3% of 229 hatchlings), although higher, did not differ significantly from that of hatchlings that swam over sand substrate (5.4% of 221 hatchlings; $\chi_c^2 = 1.03$, P > 0.05). Predation rates were significantly affected by moon phase, with 12.6% of hatchlings followed during the full moon (n = 95) being predated compared to an overall mean of 5.4% for the other moon phases (n = 355) when natural light was lower ($\chi_c^2 = 5.0$, P < 0.05, Fig. 3).

Increased predation could have been due to greater visibility of hatchlings to predators at full moon or due to the behaviour and/or population sizes of predators during this phase of the moon. Therefore, hatchlings followed during the full moon (n = 95) were considered separately from those followed during other moon phases. There were no significant differences in predation rate for these hatchlings as they were followed over hard substrate (10.7%) or over sand substrate (20.0%; ($\chi_c^2 = 0.353$, P > 0.05). Similarly, although predation on hatchlings released during the full moon from lighted beaches was almost twice as much (21.1%) as that for hatchlings released from dark beaches (10.3%) during the full moon, the difference was not significant ($\chi_c^2 = 0.64$, P > 0.05). This result may suggest that natural light emanating on a full moon

night may be sufficient to override the negative effects of artificial light. However, the fact that there was also no difference in predation rates for hatchlings followed from lighted or dark beaches during other moon phases when celestial light is lower ($\chi_c^2 = 0.97$, P > 0.05), suggests that artificial light may not significantly increase nearshore predation, perhaps because artificial light tends to shine from an angle that is lower to the horizon than celestial light, and therefore does not increase the visibility of hatchlings to submarine predators.

3.2. Swimming success

Swimming success away from shore was determined for the 419 hatchlings that were not predated during the 20 min observation period. Of these, 225 (53.7%) hatchlings successfully crossed the designated 100 m mark within the observation period, 178 (42.5%) were still swimming after 20 min but had not yet crossed the 100 m mark, and 16 (3.8%) had stranded back on shore. Swimming success was affected by moon phase, with hatchlings being more successful at travelling the 100 m distance during the full moon period (65.1% successful) than during other moon phases (50.9% successful; $\chi_c^2 = 4.81$, P = 0.03; Table 2). Considering only those unpredated hatchlings that were followed for the full 20 min observation period during the full moon phase (n = 83), those from lighted beaches tended to be less successful (2; n = 15 hatchlings) than those released from dark beaches (52, n = 68 hatchlings; $\chi_c^2 = 18.9$, P < 0.05). Swimming success of hatchlings during other moon phases was even lower, with 56 of 161 hatchlings (34.8%) swimming successfully away from lighted beaches compared to 115 of 175 hatchlings (65.7%) from dark beaches ($\chi_c^2 = 32.1$, P < 0.05). These results suggest that artificial lights emanating from a landward direction, although not increasing predation measurably, may still interfere with hatchlings' escape away from the nearshore and into deeper waters, even when there is also a bright celestial light source.

All 16 hatchlings that stranded back onto the beach within the 20 min observation period had been released from lighted beaches. Unsuccessful hatchlings that did not actually strand on the beach either swam more slowly or alternated between swimming landwards and swimming seawards. Twenty-eight (36.8%) of the 76 unsuccessful hatchlings followed from dark beaches initially swam successfully away from shore, but then appeared to be confused by lights from neighbouring beaches or headlands. Of these, more than half stayed within 10 m of shore and travelled parallel to the shoreline, orienting towards the lighted headlands at the extreme ends of the

Table 2 – Numbers of successful and unsuccessful hawksbill hatchlings followed for 20 min from lighted and dark beaches on the leeward coast of Barbados during the full moon and other moon phases (excludes missing and predated individuals)

Moon phase	No. of hatchlings		Total
	Lighted beaches S(U)	Dark beaches S(U)	
Full moon	2(13)	52(16)	83
Other phases	56(105)	115(60)	336
Total	58(118)	167(76)	419

S – number of successful hatchlings; U – number of unsuccessful hatchlings.

beach. Only six hatchlings reoriented away from land before completion of the trial. Even when harnesses were removed at the end of the 20 min period, some of the unsuccessful hatchlings were observed still swimming in nearshore waters after 30 min and in one case after one hour.

4. Discussion

The overall level of confirmed predation on hatchlings leaving beaches in Barbados was 6.9%. This was higher than predation rates for loggerhead hatchlings followed offshore for 15 min from beaches on the coast of Florida (Palm Beach: 2.5%, Glenn, 1998 and Juno Beach: 5%, Stewart, 2001). Stewart (2001) followed hatchlings over varying substrates, and found, similar to this study, that rates tended to be higher over reef (8.1%) than over intermediate sites (2.7%) or sand (4.2%), but not significantly so. Higher rates of predation have been observed for hatchlings of other species in tropical waters, for example 60–71% for *Dermochelys coriacaea* hatchlings in the tidal zone of beaches in Sandy Point National Wildlife Refuge, St Croix, US Virgin Islands (Nellis and Henke, 2000); 31% (0–85%) for *Chelonia mydas* hatchlings followed for 10 min over reef in eastern Australia (Gyuris, 1994) and 46.7% for hatchlings followed for an hour over, or near to, reefs in Sabah, Malaysia (Pilcher et al., 2000). Substrate type and the longer time followed may have contributed to the much higher predation rate observed in the latter study. Nest density may have also influenced predation rates in the nearshore (Wyneken et al., 2000). For example, Glenn (1998) obtained much higher levels of predation (17%) for hatchlings released from hatchery sites in Hillsboro, Florida. In Barbados, the lack of a significant difference in rates of predation over hard and sand substrates may be due to predator reduction caused by over-fishing of nearshore reefs (Ministry of Physical Development and the Environment, 2001). If there were larger numbers of predators in the protected and/or more pristine habitats of the above studies, then this may also explain the higher predation rates on hatchlings observed.

A full moon may improve sea finding success of hatchlings, especially on lighted beaches (Salmon and Wyneken, 1987), but has also been reported to result in greater nearshore mortality (Gyuris, 1994). In this study too, predation was higher during the full moon phase than other moon phases, but artificial light, even during the low light intensity moon phases, did not have the same effect. This may occur as a result of the acute angle at which artificial light typically strikes the water surface compared to celestial light, resulting in a less obvious silhouette of hatchlings on the water surface compared to that caused by a bright moon shining from a higher angle overhead.

Substratum was expected to have a negative impact on hatchling survival, as a consequence of the greater complexity of reef substrate compared to sand. However, as also observed by Stewart (2001) who followed loggerhead hatchlings away from nesting beaches in Florida, this was not the case. The lateral displacement of nesting females from sites in front of sandy emergence points to sites adjacent to fringing reefs (Harewood, 2007) may not therefore result in a measurable increase in hatchling mortality. Trials within this study were however conducted during intermediate and high tides only. Predation rates have been found to be higher during low tides (Gyuris, 1994) and may be substantially increased if hatchlings are retained in rock pools and crevices in the reef substrate at low tide. The impact of displacement of nests to the periphery of beaches on hatchling predation in Barbados, caused by anthropogenically reduced nest site selection options, may therefore be underestimated in this study.

Hatchling predation has been reported to be highest within the first hour after entering the water (Gyuris, 1994; Pilcher et al., 2000), after which loggerhead, green turtle or hawksbill hatchlings would typically have travelled over 1000 m offshore (Salmon and Wyneken 1987; Pilcher et al., 2000; Hasbún, 2002). Any delay in departure from the nearshore is therefore likely to result in elevated rates of predation for a longer time period. In this study, the major impact of beachfront lighting on hawksbill hatchling survival in nearshore waters appeared to be misorientation of hatchlings leading to delays in escape from the nearshore zone. Although predation rates were not increased by artificial lighting, spending extended periods in the nearshore environment may lead to decreased hatchling survival through exhaustion of energy reserves before they reach a food supply (Pilcher and Enderby, 2001). Even the delays observed in this study (>20 min to >60 min) may impact on subsequent hatchling swim speeds. Pilcher and Enderby (2001) found that the swim speeds of green turtle hatchlings decreased with as little as one hour of retention after emergence.

Background illumination by the moon has been shown to reduce the attractiveness of artificial lights to hatchlings, by decreasing contrasts in light intensity perceived by turtles on artificially lighted beaches (Salmon and Witherington, 1995; Tuxbury and Salmon, 2005). Hatchlings were found to be more successful at swimming offshore during the full moon phase than other moon phases, but even so, they were much less successful at leaving brightly lighted beaches than dark beaches during the full moon. The effect of artificial light was even more pronounced during the lower light intensity phases of the moon. It is somewhat ironic that the favourable influence of the full moon on hatchling orientation and swimming success, particularly in artificially illuminated waters, may be countered by elevated predation rates. In the absence of moonlight however, the combined hatchling mortality on the beach and in the nearshore zone on lighted beaches, would have been even greater.

Once in the water, hatchling sea turtles typically use wave direction as a cue towards the direction of the open ocean (Lohmann and Lohmann 1996). In Barbados, artificial light reduced swimming success, suggesting that light may override wave cues. Since hawksbill nesting beaches are typically on leeward, more sheltered coasts where wave energy is lower, the importance of a wave direction cue in offshore navigation may be less significant for hawksbill orientation than for other sea turtle species, making this species especially vulnerable to misorientation by lights, even after they have successfully found the sea.

In Barbados, there are currently no laws to regulate beachfront lighting, although new developments on nesting beaches are obliged to consider protection of sea turtles and

their habitats in the planning process. The high levels of misorientation observed in this study are indicative that this policy is insufficient to protect hatchlings. Currently, the primary mitigation technique used by the Barbados Sea Turtle Project, when responding to the 5–10 calls received per night in regard to hatchling misorientation, is to collect up the hatchlings and release them on adjacent dark beaches. These hatchlings may have difficulty orienting away from shore if surface waves are absent (Lorne and Salmon, 2007). The observation that hatchlings swimming away from dark beaches may still be attracted shorewards by lights on adjacent beaches makes it essential that potential hatchling release sites be evaluated, not only in terms of the level of beachfront lighting adjacent to the beach, but also on the degree of lighting on neighbouring beaches.

Acknowledgements

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