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Exploring The Role of Artificial Lighting in Loggerhead Turtle (*Caretta caretta*) Nest-Site Selection and Hatchling Disorientation

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***Abstract*.—Beachfront artificial lighting can deter nesting sea turtles and disrupt the seaward orientation of hatchlings following their emergence from the nest. We investigated the effects of variable artificial lighting along the 17.5-km beachfront of St. George Island, Florida, USA on both nesting and hatchling Loggerhead Turtles (*Caretta caretta*). We hypothesized that illumination affects nest-site selection and hatchling orientation of Loggerhead Turtles. We predicted that zones with higher artificial luminance levels would have a reduced number of nests laid by Loggerhead Turtles, as well as an increased hatchling disorientation rate. We divided the beachfront into zones 500 m in length and recorded nighttime luminance measurements with a photometer throughout the 2015 nesting season. The 2015 luminance values were analyzed together with Loggerhead Turtle nesting data from the 2015 season, as well as related to a longer-term dataset from 2011–2015. We found a negative relationship between nest-site selection and the intensity of artificial luminance, such that the brighter zones along the beachfront had fewer nests. Within this relationship, we found that nest density was significantly lower above a beachfront luminance value of ~800 µcd/m^2. Finally, we found that hatchling disorientations occurred more frequently in zones with greater luminance. While many factors can affect nesting and hatchling Loggerhead behavior, our results suggest that variable intensities of artificial lighting at a nesting site may lead to a spatially clumped arrangement of nests and hatchling disorientations. These results can help improve the conservation and protection of nesting habitat as they further our understanding of the effects of artificial beachfront lighting on Loggerhead Turtles.**

Key Words.—beachfront lighting; coastal development; false crawl; Florida; light pollution; luminance

Introduction

Increases in coastal development and associated artificial beachfront lighting can have disruptive effects on the behavior and survival of sea turtles (McFarlane 1963; Salmon et al. 1992; Witherington 1992a; Lorne and Salmon 2007). Sea turtles emerge from the ocean to lay their eggs on coastal sandy beaches and are primarily affected by artificial lighting in two ways: first, artificial lighting can act as a repellent to nesting female turtles, affecting the density and arrangement of nests across developed beaches (Witherington 1992a; Salmon et al. 1995a; Silva et al. 2017). Second, light pollution can disrupt the seaward orientation of hatchling turtles after they emerge and begin to move away from the nest, often resulting in fewer individuals reaching the ocean and lowering hatchling survival (e.g., McFarlane 1963; Witherington and Bjorndal 1991; Salmon and Witherington 1995; Robertson et al. 2016). Therefore, artificial beachfront lighting can have important consequences for the management of local turtle populations, particularly because light levels at a nesting site can directly influence the number of hatchlings that successfully reach the water.

Sea turtles rely predominantly on visual and environmental cues during the nesting process and hatchling movement toward the ocean, but these cues can be overwhelmed by artificial lighting (e.g., Witherington 1992a; Salmon et al. 1995b; Kamrowski et al. 2012; Silva et al. 2017). For instance, while adult nesting turtles often return to their natal beaches or regions to lay their eggs, they will select against heavily illuminated and developed coastal areas in favor of darker beaches (e.g., Witherington 1992a; Salmon 2003; Mazor et al. 2013; Weishampel et al. 2016). Hatchlings use dark and elevated landward silhouettes and naturally brighter light from the seaward horizon to orient themselves toward the ocean, but these cues are less apparent when artificial nighttime lighting is present (Witherington and Bjorndal 1991; Salmon et al. 1992). The loss of distinct orientation cues can cause hatchlings to waste energy crawling longer distances to reach the ocean (Triessnig et al. 2012). This energy loss can limit their ability to avoid predation (Pankaew and Milton

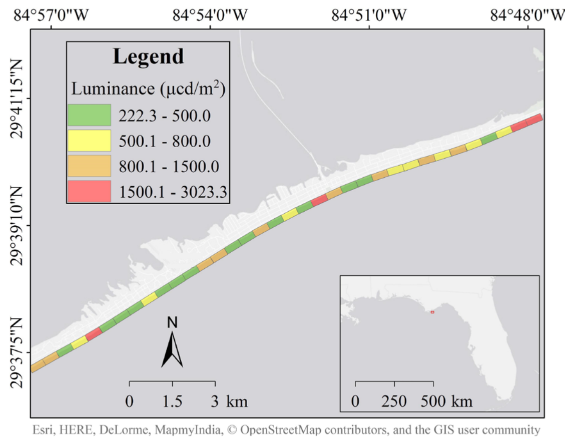

Figure 1. Spatial distribution of mean landward luminance values from moonless nighttime surveys during the 2015 Loggerhead Turtle (*Caretta caretta*) nesting season on St. George Island Florida, USA. Each zone is 500 m in length. Landward luminance was classified to differentiate the zones above and below the 800 μcd/m² threshold where Loggerhead Turtle nest density was found to be significantly reduced on SGI.

2018) and correctly orient themselves when swimming offshore (Rich and Longcore 2006; Truscott et al. 2017). While other variables can affect the behavior of nesting and hatchling sea turtles, such as beach elevation or dune height, artificial light and the associated development is often a principal factor (e.g., Salmon et al. 1995a,b).

Many studies of artificial lighting have used experimental setups or included beaches with dense nesting and consistent commercial development (e.g., Salmon et al. 1995a). However, beaches with fewer nests (< 15 nests/km per season) and inconsistent lighting from small-scale developments have generally been understudied. The latter is the case for St. George Island (SGI), Florida, USA, which is an important rookery among the few beaches that host a genetically distinct population of nesting Loggerhead Turtles (*Caretta caretta*) in the northern Gulf of Mexico (Encalada et al. 1998; Shamblin et al. 2011; Shamblin et al. 2012). Nesting activities on SGI are often clustered at different areas along the beach, but there has been no assessment to provide an explanation for the distribution (Florida Fish and Wildlife Conservation Commission, unpubl. data). Thus, we used beachfront luminance values to test two hypotheses that might explain the arrangement of nests and hatchling disorientations on SGI. We hypothesize that nest-site selection by Loggerhead Turtles and hatchling orientation is affected by artificial lighting. We predict that nest-site selection is negatively correlated with beachfront luminance along SGI, such that more nests occur in relatively dark areas of the beach (Witherington 1992a; Salmon et al. 1995a). Second, we predict that hatchling disorientations are positively correlated with beachfront luminance along SGI, occurring more often in areas illuminated by artificial light (Witherington and Bjorndal 1991; Salmon et al. 1992).

Materials and Methods

Study site.—SGI is a barrier island in the northern Gulf of Mexico and hosts one of the largest aggregations of nesting Loggerhead Turtles in Northwestern Florida, USA (Shamblin et al. 2012). The island has 35 km of beachfront nesting habitat; however, the study area spans approximately 17.5 km of residential and commercial land west of the Dr. Julian G. Bruce St. George Island State Park. This inhabited portion of SGI has restrictions on building height and lighting, which allows the beach to remain relatively protected from large housing developments and commercial operations (http://www.franklincountyflorida.com). Nonetheless, enforcement of nighttime light use across the entirety of SGI is challenging (Bruce Drye, pers. obs.), and the beachfront is regularly exposed to variable levels and types of artificial lighting (Fig. 1).

Sea turtle activity and luminance.—Throughout the 2011–2015 nesting seasons (May-August) of Loggerhead Turtles, we logged GPS coordinates for all nesting emergences and designated each activity as either a nest or a false crawl (i.e., a non-nesting emergence). Similarly, we documented hatchling emergences (July-October) when encountered. From 2011–2015, we documented hatchling disorientations as defined in the Marine Turtle Disorientation Report of the Florida Fish and Wildlife Conservation Commission: five or more hatchling tracks directed parallel or away from the ocean (Florida Fish and Wildlife Conservation Commission, unpubl. report). We increased the consistency of our criteria for designating disorientations during the 2015 season by using a hatchling orientation index (Pendoley 2005; Blair Witherington et al., unpubl data). Briefly, if the modal direction of hatchling tracks at a 10-m radius from the emergence point was greater than 90° from the direction toward the ocean, we considered the tracks to represent a disorientation.

We conducted nighttime luminance surveys (n = 9) throughout the 2015 season using the Unihedron Sky Quality Meter (SQM; Unihedron, Grimsby, Ontario, Canada). The SQM records light intensity of a wide angle, measuring 1.5 steradian with a half width half maximum angular sensitivity of 42°. The SQM measures luminance in units of magnitudes per arcsecond² (mag/arcsec²), where each whole number is comparable to approximately a 2.5-fold change in brightness (e.g., an increase of 5 mag/arcsec² is the same as a 100-fold change in brightness). To improve the clarity of our luminance data and make it comparable with past artificial lighting studies, we converted the measurements to microcandelas per square meter (μcd/m²). The formula for conversion is as follows:

$$\mu cd/m^2 = 10.8 \times 10^4 \times 10^{(-0.4*[\text{value in mag/arcsec}^2])} \times 10^6$$

The SQM responds to wavelengths of visible light between 320–700 nm, which includes the wavelengths of visible light that Loggerhead Turtles are known to detect (340–700 nm; Horch et al. 2008; Kamrowski et al. 2012). This range of spectral responsivity by the SQM does include the near-ultraviolet (UV) wavelengths known to attract Loggerhead hatchlings (340-380 nm; Horch et al. 2008). However, the SQM does not measure these shorter wavelengths as precisely as between 400 and 650 nm (Pierantonio Cinzano, unpubl. report). Although we only collected luminance data in 2015, we used nesting and hatching data from 2011–2015 to briefly evaluate relationships with beachfront luminance on a longer timescale (as in Bonner 2015).

We offset the starting time of luminance surveys to account for variation in lighting use throughout the night. They began at either 2200 (n = 4) or 0200 (n = 5), and the timing of consecutive surveys was not repeated more than once. We measured luminance for each survey over two consecutive nights with similar cloud cover and weather conditions, such that we patrolled one-half of the beachfront each night. The starting point and direction for successive luminance surveys alternated between the eastern and western ends of the beachfront. Surveys only occurred when cloud cover was minimal (i.e., the zenith was less than about 10% covered). We report luminance measurements from surveys during the new moon or when the moon was not visible above the horizon. We used moonless measurements because they were primarily representative of variation in beachfront artificial lighting, rather than the luminance of the moon. The timing of these surveys varied depending on weather conditions, cloud cover, and moon phase, but each month (May-August) had either two or three nighttime surveys. We completed no surveys during the month of September; however, hatchlings had emerged from greater than 70% of nests by this time.

We divided the beachfront into 35 500-m zones with reflective posts placed at the center of each zone for a consistent measurement location at the spring high tide line. The observer measured luminance from behind the SQM on a level tripod stand at a height of 1.0 m above the sand (Rivas et al. 2015). Four different measurements were recorded within each zone: (1) the zenith of the sky (+90° from the horizon) to measure variation in local sky glow; (2) landward, perpendicular to the dunes to represent an inbound nesting turtle; (3) landward, but with a black cover directly above the sensor on the SQM to reduce the vertical perception to + 30°, a value calculated for the visual forward field of hatchling Loggerhead Turtles (Witherington 1992b); and (4) seaward, also restricted to + 30° vertical perception, which we subtracted from measurement #3 to obtain the relative landward luminance for assessing relationships between luminance and hatchling disorientations.

Statistical analysis.—We tested all data for parametric assumptions using the Shapiro-Wilk normality test and Breusch-Pagan-Godfrey heteroscedasticity test for regressions. When necessary, we transformed the data to reduce skewness and allow the use of parametric analyses. We assessed relationships between luminance and turtle nest-site selection using linear regressions. Specifically, we performed a square root transformation on the nest-site selection data, which we then regressed against the luminance values documented on SGI. To find a luminance threshold where nesting density was significantly different, we used a Student's *t*-test on nesting data in zones above and below 800 μcd/m². False crawl and hatchling disorientation datasets did not fit the assumptions of the parametric linear regression, so we tested relationships within these data using a local linear nonparametric method (Li and Racine 2004). Statistical significance of the datasets was determined at $\alpha = 0.05$ and error was reported as standard deviation. We conducted all statistical analyses with R, v3.2.3 (R Core Development Team 2015).

Results

Mean luminance measurements of the zenith during the beachfront surveys (n = 9) had a range of 240.4–387.4 μcd/m² across the 35 zones on SGI, with a grand mean of 282.7 ± 37.4 μcd/m². Mean landward luminance measurements on SGI for each zone were between 222.3 and 3,023.3 μcd/m² (Fig. 1), with a grand mean of 836.6 ± 623.1 μcd/m². Mean seaward luminance was between 116.0–209.4 μcd/m² across the zones on SGI, with a grand mean of 141.2 ± 20.6 μcd/m².

The number of nests laid by Loggerhead Turtles decreased significantly with higher mean landward luminance ($F_{1,33} = 10.18$, $P = 0.003$) in each zone on SGI during the 2015 nesting season (n = 212, Fig. 2A). In the 500-m zones with a mean landward luminance value < 800 μcd/m² (n = 22), there was an average of 7.19 ± 3.5 nests during the 2015 season, which was significantly greater than an average of only 4.08 ± 1.71 nests (n = 13) in zones with a luminance value above that threshold ($t = 3.023$, df = 33, $P = 0.005$; Fig. 2A). Although other luminance thresholds had similar significant differences in nest density, the 800 μcd/m² threshold had the highest *t*-score, suggesting it was the most robust threshold for a decrease in nest density on SGI. We also found that total nesting activities (n = 392) by adult Loggerhead

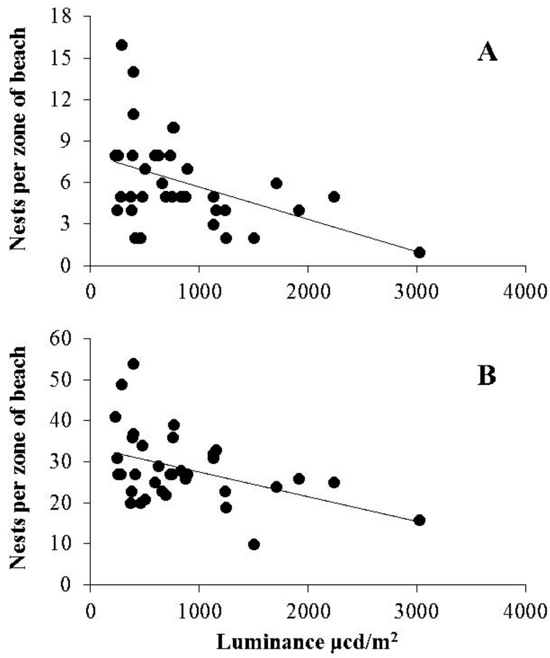

Figure 2. Relationship between the number of successful nesting attempts during the (A) 2015 (n = 212, r^2 = 0.20, P = 0.003) and (B) 2011–2015 (n = 995, r^2 = 0.18, P = 0.011) Loggerhead Turtle (*Caretta caretta*) nesting seasons with mean landward luminance values for each of the 35 500-m zones measured during the 2015 season on St. George Island Florida, USA. Each zone is represented by a black circle.

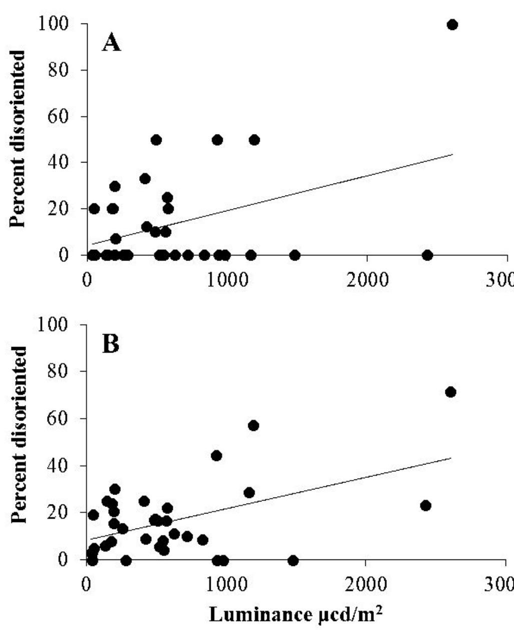

Figure 3. Relationship between the percentage of hatchling emergences recorded as disorientation events from the (A) 2015 (n = 21, r^2 = 0.10, P = 0.025) and (B) 2011–2015 (n = 98, r^2 = 0.28. P = 0.055) Loggerhead Turtle (*Caretta caretta*) nesting seasons with mean relative landward luminance for each of the 35 500-m zones measured during the 2015 season on St. George Island, Florida, USA. Each zone is represented by a black circle.

Turtles during 2015 significantly decreased as mean landward luminance increased across SGI ($F_{1,33}$ = 5.856, P = 0.021). However, the proportion of false crawls (n = 180) to the total number of nesting activities in 2015 was not significantly related to luminance (P = 0.546). Using the landward luminance values across SGI from 2015, we also found that the number of nests laid by Loggerhead Turtles during 2011–2015 significantly decreased with higher mean landward luminance (n = 995, $F_{1,33}$ = 7.336, P = 0.011, Fig. 2B).

Throughout the 2015 season, 21 of 202 nests that produced hatchlings had hatchling disorientations (10.4%). We found that the rate of hatchling disorientations following their emergence from the nest during 2015 was significantly positively related to relative landward luminance values (r^2 = 0.10, P = 0.025, Fig. 3A). However, we found no threshold of relative landward luminance where significantly more disorientations occurred. Finally, although hatchling emergences throughout 2011–2015 included disorientations in 98 of 672 nests (14.5%), the relationship to relative landward luminance was not significant (P = 0.055, Fig. 3B).

Discussion

In this study, we found that luminance from artificial beachfront lighting on SGI may be related to clustered patterns of nest-site selection and increased incidences of hatchling disorientation by Loggerhead Turtles. While the potential for adverse effects from artificial lighting on nesting and hatchling sea turtles is well-established for Loggerhead Turtles (McFarlane 1963; Witherington and Bjorndal 1991; Salmon and Witherington 1995), few published studies have monitored the effects that small-scale variations in beachfront luminance can have on the spatial arrangement of sea turtle nests (Salmon et al. 1995a; Constant 2015; Kelly et al. 2017; Silva et al. 2017). On SGI, the zenith of the sky on moonless nights was below the threshold for nighttime light pollution of approximately 400 µcd/m², as established by Crawford (1997). However, landward luminance along the beachfront of SGI varied widely, suggesting that artificial light from beachfront development was the principal contributor to light pollution throughout the nesting site. The isolation from urban sky glow on SGI preserved a relatively dark nesting site when compared to nesting beaches in other areas of Florida (Weishampel et al. 2016), but also amplified the influence of irregular artificial light usage between individual homes and buildings.

Beachfront lighting had a significant negative relationship with the location of nests laid by the turtles during the 2015 season. The variable luminance across the 17.5 km beachfront created multiple disconnected relatively dark regions that may have produced isolated areas of preferred nesting habitat for the female turtles. The negative relationship supports results from Witherington (1992a), which showed that broad-spectrum white light could inhibit nesting. The relationship between nest site-selection and luminance on SGI also supports findings from a similar study performed by Constant (2015), which assessed luminance at a higher resolution.

Interestingly, we also found that mean nest density was significantly lower on SGI in zones where landward luminance was greater than 800 µcd/m^2. Above a landward luminance of 800 µcd/m^2, mean nesting density was nearly halved. This suggests that a luminance threshold may exist where artificial lighting may become a principal driver of nest-site selection. However, numerous zones above and below this threshold had similarly low nest densities, meaning additional factors are likely affecting Loggerhead Turtle nest-site selection on SGI.

We also found that total nesting attempts in 2015 had a negative relationship with luminance, while the proportion of false crawls had no significant relationship with luminance. This supports the hypothesis that turtles assess the quality of a nest site before their emergence onto the beach (Witherington 1992a). Artificial lighting may not be a deterrent by itself, but it can reduce the ability of a nesting turtle to use visual cues, such as landward silhouettes, while still in the water (Witherington 1992a).

Nesting data on SGI from the years 2011–2015 provide temporal support for the results found using only 2015 nesting data, as successful nesting attempts by turtles from 2011–2015 were negatively correlated with 2015 luminance values. Although these nesting data from 2011–2015 should be considered cautiously because luminance values before 2015 are not defined, the data demonstrate that nest density and the relationship with luminance appear consistent over a multi-year timeframe. While beachfront development may not have considerably changed between 2011–2015, awareness and enforcement of local lighting ordinances over that time may have affected the overall landward luminance values along SGI's beachfront. Indeed, local efforts have been underway through a grant process that gives beachfront homeowners FWC-approved turtle-friendly light fixtures (University of Florida's Institute of Food and Agricultural Sciences Extension. 2016. Comings and Goings. Available from http://sfyl.ifas.ufl.edu/ [Accessed 10 February 2018]). However, it is a slow process to replace fixtures and bulbs to comply with the lighting ordinance.

The pattern of Loggerhead Turtle nest arrangement on SGI may also be an artifact of human development, in general, with artificial lighting being just one of the many contributing factors. Salmon et al. (1995a) found that tall condominiums and trees on an urban beach produced large silhouettes, creating preferential nesting habitat for sea turtles. While SGI lacks large residential or commercial buildings (http://www.franklincountyflorida.com), zones of relatively high development on the island (e.g., concentrated commercial areas or dense housing developments) can affect dune structure and reduce the presence of tall stands of beachfront vegetation in those areas. However, zones on SGI with reduced development often retain the large dune structure that may serve as a cue for nest site selection (Camhi 1993; Roe et al. 2013).

There was a large amount of unexplained variation in the relationships between nest-site selection and luminance. While numerous luminance surveys occurred throughout the season to account for variation in individual home occupancy and light usage, this study does not account for all the factors that could affect the number of nests in each zone. For instance, artificial lighting on SGI includes a combination of the previously mentioned broad-spectrum white lights and amber colored luminaires (James Price and Bruce Drye, pers. obs.), the latter of which is supposed to have less effect on turtle activity (e.g., Witherington and Bjorndal 1991). While the SQM accurately detected the small variations in luminance between zones, the luminance from white and amber light fixtures were not able to be isolated. Additionally, numerous variables affected the amount of light reaching the beach, such as tinted windows, fixture coverings, and the location of buildings, among others.

In addition to differences in the choice and use of different light fixtures, multiple other variables were unable to be accounted for in this study. For instance, zones with a higher luminance often had higher concentrations of homes, and therefore may experience increased nighttime pedestrian traffic. Similarly, obstructions such as chairs, canopies, and stowed boats may have affected the emergence or false crawl rate of nesting Loggerhead Turtles. Beach width and slope also vary across SGI, which likely cause additional variation in nest site selection that is independent from luminance values (Kelly et al. 2017).

It is important to consider the possibility that the relationship between landward luminance and Loggerhead Turtle nest-site selection is spurious. Without measuring physical beach characteristics (e.g., beach slope and dune elevation) and the previously mentioned development associated with artificial lighting, luminance cannot be confidently isolated as a driver of nest-site selection with only the data collected for this study. Loggerhead Turtle nest-site selection across the state of Florida is generally consistent through time (Witherington et al. 2009; Putman et al. 2010), and the stability of the negative relationship between nest-site selection and luminance on SGI may be an artifact of that consistency. However, Weishampel et al. (2016) suggests that this consistency is partially a result of large-scale light pollution on coastlines of Florida, and our results are consistent with previous studies of sea turtle nesting and disorientation behavior (e.g., Salmon et al. 1995a; Constant 2015; Silva et al. 2017).

Unlike nesting females, Loggerhead hatchlings can become severely disoriented by broad-spectrum (Witherington and Bjorndal 1991) or even amber colored lights in some cases (Fritsches 2012; Robertson et al. 2016). Artificial light disrupts the ability of hatchlings to discern visual cues, such as dune profiles and seaward direction, which decreases the output of hatchlings from the nest site (Dimitriadis et al. 2018). We found that the frequency of disorientations in hatchling emergences during the 2015 season increased significantly with luminance. While the association between artificial light and hatchling disorientation has been comprehensively documented across many beaches and sea turtle species (McFarlane 1963; Witherington and Bjorndal 1991; Salmon et al. 1995b; Rivas et al. 2015), the use of the Unihedron SQM allowed us to quantify the difference in luminance between the seaward and landward horizons.

Our hatchling disorientation sample size was small relative to other studies, with just 21 disorientations from 202 successful emergences in 2015 (about 10.4%), but it was representative of annual disorientation rates on SGI. Within this small sample, there was a positive trend between hatchling disorientations between 2011–2015 and relative landward luminance from 2015, but this relationship was not significant. As with factors that could affect nest-site selection, both artificial lighting and pedestrian traffic can vary on a daily scale, going undetected in this study. Hatchling disorientations may be more precisely examined on a smaller scale than 500 m, as hatchlings often disorient due to artificial light in a closer proximity (Robertson et al. 2016). Indeed, we found no luminance threshold at our 500-m resolution on SGI where significantly more disorientations began to occur. Nonetheless, the significant relationship between relative landward luminance and disorientations in 2015 supports numerous other studies in emphasizing the importance of natural darkness for turtles during their movement away from the nest toward the ocean (e.g., Salmon et al. 1992; Tuxbury and Salmon 2005; Robertson et al. 2016).

Artificial beachfront lighting on SGI had significant relationships with nest-site selection and hatchling disorientations by Loggerhead Turtles in 2015, supporting both of our original hypotheses. SGI is largely isolated from large commercial developments and urban sky glow, allowing the variation in beachfront lighting to be amplified as the principal source of artificial luminance on the nesting beach. Although more effort is required to increase the confidence of our conclusions, the variable beachfront development on SGI did create disconnected areas of natural darkness where successful nesting attempts were more prevalent. By linking beachfront luminance with nest-site selection and hatchling disorientation by Loggerhead Turtles, these results provide support for the continued monitoring of sea turtles on SGI accompanied by an effort to reduce artificial beachfront lighting.

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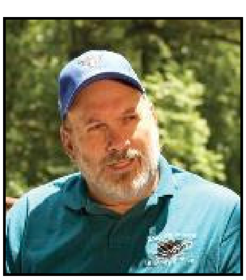

Frank V. Paladino has had over 114 reviewed scientific research publications in top international journals with seven publications in *Nature* as well as numerous publications in journals such as *Proceedings of the Royal Society* and *PLoS One*, among others. Frank was elected as President of the International Sea Turtle Society (ISTS), elected as a Fellow of the American Association for the Advancement of Science (AAAS), elected as a Fellow of the American Physiological Society, and an ISTS Lifetime Achievement Award recipient. He has served as Biology Department Chair at Indiana University-Purdue University Fort Wayne, USA, since 2010, and previously held the position from 1992 to 2003. (Photographed by Turtle Island Restoration Network).