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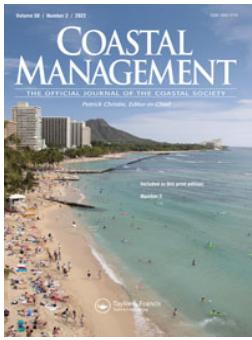


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Balancing Human and Sea Turtle Safety: Evaluating Long-Wavelength Streetlights as a Coastal Roadway Management Tool

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ABSTRACT

Coastal roadways with tall, full-spectrum streetlights along sea turtle nesting beaches present a challenge for managers seeking to balance protection of sea turtles with public safety. Many communities extinguish these lights during nesting season to avoid impacting nesting and hatchling sea turtles. Long-wavelength light emitting diodes (LEDs) offer an alternative for managers in these communities, but additional information on sea turtle response to these lights is warranted prior to installation. We conducted arena assays on Florida's west coast to evaluate hatchling orientation when exposed to a shielded, long-wavelength (624nm) prototype lamp compared to an adjacent beach with the streetlights turned off. We compared orientation in test and control arenas simultaneously over two consecutive nights, recording crawl direction and timing for individual hatchlings. Hatchlings in test and control arenas oriented correctly toward the ocean in all trials, with no differences in hatchling dispersion or circling. Thus, the fully shielded, long-wavelength LED streetlight fixture tested provides an appropriate option to minimize impacts to sea turtles along coastal roadways throughout the United States and elsewhere. As such, this alternative solution to extinguishing necessary streetlights can aid coastal managers in concurrently protecting nesting habitat and providing light for public safety.

KEYWORDS

Behavior;
coastal lighting;
LED;
loggerhead;
nesting beach

Introduction

Light pollution from human development has significant, unintended impacts on many terrestrial and aquatic species (Davies et al. 2014; Longcore and Rich 2004). Sea turtles are particularly vulnerable to the effects of artificial lighting (Dimitriadis et al. 2018; Erb and Wyneken 2019; Lorne and Salmon 2007; Peters and Verhoeven 1994; Tuxbury and Salmon 2005; Witherington 1992). Hatchling sea turtles emerge from their nests at night and immediately crawl toward the ocean, aided primarily by visual cues

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(Daniel and Smith 1947; Mrosovsky 1968; Witherington, Bjorndal, and McCabe 1990). Their sea-finding ability is driven by phototaxis (Celano et al. 2018; Witherington and Bjorndal 1991a), whereby hatchlings crawl toward bright, open horizons and away from tall, dark silhouettes (Ehrenfeld and Carr 1967; Mrosovsky and Shettleworth 1968; Salmon et al. 1992). Loggerhead sea turtles (*Caretta caretta*) exposed to artificial light exhibit spectrally biased phototactic responses, generally orienting toward shorter wavelengths and away from longer wavelengths, e.g., >560 nm (Mrosovsky and Carr 1967; Mrosovsky and Shettleworth 1968; Witherington and Bjorndal 1991a). However, these behaviors can vary according to the brightness of a light source, and even long-wavelength light can elicit an attraction response at high intensities (Robertson, Booth, and Limpus 2016; Witherington and Bjorndal 1991a).

Hatchling survival depends upon correctly orienting seaward to reach the water successfully. On developed coastlines, artificial lighting from sources near the beach often interferes with natural orientation cues, prolonging the amount of time hatchlings spend on the beach. This disruption of sea-finding is expressed in two ways: hatchlings crawl in a straight path parallel to or away from the water, which is known as misorientation, or they wander aimlessly, which is known as disorientation (Peters and Verhoeven 1994; Salmon and Witherington 1995; Tuxbury and Salmon 2005; Witherington and Bjorndal 1991b). Disorientation and misorientation are significant causes of nest-to-surf mortality on urbanized beaches (Erb and Wyneken 2019) and may lead to reduced population recruitment from those areas (Dimitriadis et al. 2018). Disoriented or misoriented hatchlings are susceptible to predation, desiccation, or exhaustion (Pankaew and Milton 2018; Witherington and Bjorndal 1991a) and are often unable to reorient themselves seaward (Lorne and Salmon 2007). Hatchlings eventually reaching the water exhibit slower swimming speeds and altered trajectories in the presence of artificial lighting, which inhibits their offshore migration (Cruz et al. 2018; Thums et al. 2016; Wilson et al. 2018). In severe cases, hatchlings may even crawl back out of the water toward particularly bright lighting (Truscott, Booth, and Limpus 2017).

Pole-mounted streetlights along coastal roadways can be especially problematic. Streetlights fitted with full-spectrum light sources are a well-documented cause of hatchling misorientation and disorientation (Bertolotti and Salmon 2005; Cowan et al. 2002; McFarlane 1963; Nelson Sella, Salmon, and Witherington 2006; Peters and Verhoeven 1994; Salmon, Wyneken, and Foote 2003). In Florida, the most important nesting grounds for loggerheads globally (Ceriani et al. 2019), streetlights contributed to approximately 20% of all lighting-related impacts to sea turtles reported to the Florida Fish and Wildlife Conservation Commission (FWC) between 2011 and 2020 (Florida Fish and Wildlife Conservation Commission 2021a). Unfortunately, previous attempts to mitigate these impacts by fitting existing streetlights with amber and red acrylic filters were ultimately unsuccessful (Cowan et al. 2002; Nelson 2003; Nelson Sella, Salmon, and Witherington 2006; Salmon, Wyneken, and Foote 2003; Tuxbury and Salmon 2005). Although the filters were designed to omit most wavelengths below 530 nm and 570 nm respectively, both filters allowed a partial transmission of light below the intended cutoff wavelengths (Nelson 2003). Consequently, the resultant light still contained wavelengths well within the range known to attract hatchling sea turtles.

Other methods of modifying existing streetlights to prevent visibility of the light source, such as angling fixture heads away from the beach or adding additional external shielding, also failed to prevent hatchlings from being attracted (Bertolotti and Salmon 2005; Salmon, Wyneken, and Foote 2003).

To avoid violating Federal, State, or local laws protecting threatened and endangered sea turtles by causing disorientation or misorientation, many coastal areas extinguish their streetlights during the nesting season. While this solution alleviates the potential for impacts to sea turtles on adjacent nesting beaches, it can create driver and pedestrian safety concerns. To ensure safety for both sea turtles and the public along coastal roadways, managers must identify alternative streetlighting options that will not interfere with hatchling sea-finding. With advancements in lighting technology, light emitting diode (LED) lamps can now produce specific, narrow ranges of long-wavelength light (greater than 560 nm) that are less disruptive to sea turtles without a filter. If these long-wavelength LED lamps are indeed less attractive to hatchling sea turtles, streetlights with this technology could remain illuminated for public safety during sea turtle nesting season.

Light between 590 and 650 nm has been shown to be minimally disruptive to loggerhead hatchlings, although high-intensity lighting may still induce attraction, even with a spectral output within that range (Robertson, Booth, and Limpus 2016; Witherington and Bjørndal 1991a, 1991b). Based on these findings and the previous efforts to reduce hatchling attraction to streetlights, we hypothesized a luminaire (fixture housing with light source) with a dominant spectral output above 600 nm and a light source that is fully shielded to reduce its intensity should not interfere with seaward orientation in loggerhead hatchlings. Therefore, we predicted the sea-finding ability of hatchlings exposed to a streetlight meeting these specifications would be comparable to hatchlings on a dark beach.

To test this, we first identified a streetlight prototype that met all standard streetlight criteria established by Florida Power & Light (FPL), an electric utility company that offers service to many coastal areas, as well as the FWC sea turtle lighting guidelines. We then conducted paired field-arena assays to measure loggerhead hatchling orientation on a beach within sight of the streetlight prototype compared with orientation on an adjacent section of beach where the streetlights were extinguished.

Methods

Streetlight prototype selection

We conducted standard laboratory testing on three different LED luminaires to ensure they would maintain their structural and mechanical integrity when exposed to Florida's harsh environmental conditions including high heat, salt spray, high humidity, rainfall, and severe storms. Such testing included salt fog testing (ASTM G85-19), electrical surge testing (ANSI/IEEE C62.41-1991), voltage sag and swell testing, and cycle testing, wherein we repeatedly turned the luminaires on for three minutes and off for three minutes, to assess durability under various electrical stressors. We then evaluated the luminaires that passed the laboratory tests to determine which met the FWC sea turtle lighting guidelines (Florida Fish and Wildlife Conservation Commission 2021b). To

meet these guidelines, luminaires must not emit any light below 560 nm, they must be completely downward directed, and they must have a fully shielded light source. First, we used a handheld spectroscope (Krüss model 1504) to test the spectral output of the luminaires to ensure only those that emitted long-wavelength light (>560 nm) would be considered. We also evaluated various shielding options, including three and four-sided shields of varying sizes, in order to select one that prevented direct visibility of the light source.

One luminaire met all FPL and FWC criteria and was deemed suitable for field testing: a Cree® LEDway streetlight fitted with a 624-nm-peak-wavelength (614-nm dominant wavelength) LED light source with an opaque three-sided shield that extended approximately 17 cm below the bottom of the fixture. This prototype met the minimum wavelength cutoff, emitting only reddish-amber light above 560 nm (Figure 1). The shielded luminaire was evaluated at a mounting height of approximately 7.5 m above grade, a common mounting height for streetlights, and the light source was not directly visible when standing at a horizontal distance of 6 m or more from the pole.

Study area and existing lighting conditions

Testing the prototype luminaire in a situation where streetlights are being extinguished required locating a site with existing streetlights but little to no other onsite lighting. Turtle Beach, a 0.3-km public beach park at the south end of Siesta Key, Florida, USA

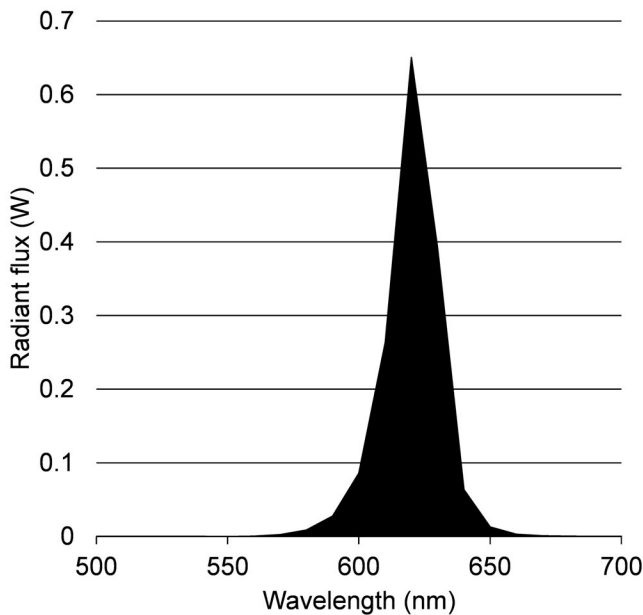


Figure 1. Spectral power distribution for the Cree® LEDway prototype luminaire indicating the energy output (radiant flux in watts) of all wavelengths produced. The light source emits no light below 570 nm and produces a peak at 624 nm. Approximately 98.9% of the light produced by the luminaire is emitted at or above 590 nm. Spectral data were provided by Cree® and were measured using a Gooch & Housego spectroradiometer (model number 770VIS/NIR).

met this requirement (Figure 2 inset). Four streetlights are spaced at 75-m to 85-m intervals along the landward side of the road with the fixture heads directed toward the beach. The existing light poles are equipped with flat-lens full-spectrum cobra-head fixtures mounted at approximately 7.5 m above grade; these fixtures were either extinguished or replaced with the test luminaire during arena trials. The sandy nesting beach was bordered by a low dune vegetated primarily by sea oats (*Uniola paniculata*) and other sporadic low-level vegetation, and all four streetlights along the road were visible from the beach. All streetlights within the park are typically turned off during nesting season, and there are no other light sources within the park. However, ambient light is visible within the park from development outside the study area, particularly to the north.

Test illumination conditions

We conducted trials over two consecutive nights surrounding the new moon period on 28 and 29 August 2014. We delineated paired test and control sites by dividing

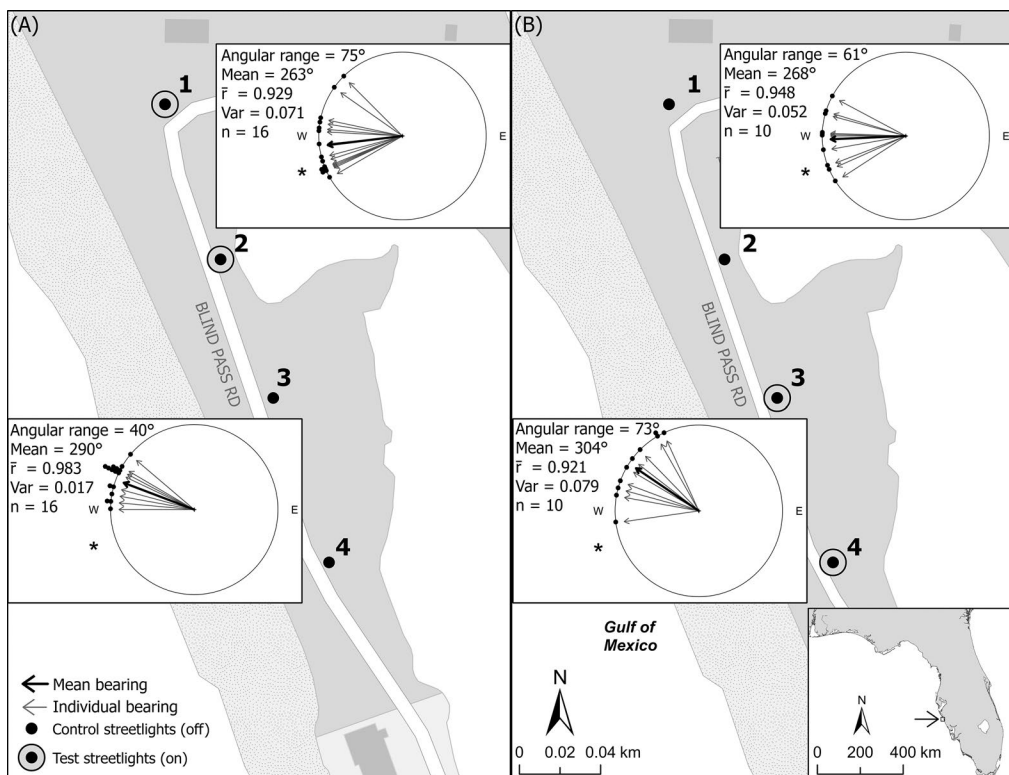


Figure 2. Turtle Beach study site, located in Siesta Key, Florida. The site layout indicates the locations of streetlights used for the trials (1 – 4) and the configuration of test and control luminaries on the first (A) and second (B) nights. The circle plots approximate the locations of the north arena (between streetlights 1 and 2) and the south arena (between streetlights 3 and 4) and indicate the individual and mean hatchling exit bearings within each arena. The variance in exit bearings (Var) is noted for each arena as well as the concentration of bearings ($\bar{r}$, where $\bar{r} = 1 - \text{Var}$). The direct bearing from the center of each arena to the water is approximately 250° (*).

the study area in half with two streetlights visible from the beach in each half. For the first night of testing, the two existing streetlights adjacent to the north site were replaced with the prototype luminaires and illuminated during the trials, creating the test conditions. In all cases, while glow from the prototype streetlights was visible from the site, no light was cast directly onto the beach. The two streetlights adjacent to the south site remained in place but were not turned on, providing a dark control. To control for ambient lighting and beach effects, FPL crews exchanged the prototype luminaire from the north study site to the south for the second night of testing (Figure 2).

Hatchling collection and arena assays

Each night just before sunset, we placed restraining cages covered with black shade cloth over nests where hatchlings were predicted to emerge that night; this allowed them to emerge naturally into the cage while remaining light-naïve. We checked the cages for emergent hatchlings at 60- to 90-minute intervals and transferred any hatchlings under the cover of the shade cloth into lidded Styrofoam containers with a layer of moist sand in the bottom. We then transported the hatchlings to the testing location and held them in the dark until they were released in the test arenas. Once we had collected at least 20 hatchlings from multiple nests – enough to complete at least 10 paired trials for that night – we removed any cages remaining over additional nests. No hatchlings were held overnight for use in later trials, and any additional hatchlings collected but not used for testing were released that night once the trials were concluded.

Before each trial, we created arenas on the north and south sites by drawing a 4-m circle in the sand using two wooden dowels connected by a 2-m piece of twine. We placed the arenas approximately 150 m apart at similar locations on the berm. The width of the beach was relatively consistent throughout the study area, so we placed the arenas roughly halfway between the water and the dune such that they were laterally in line with each other. In both locations, the direct bearing from the center of the arena to the water was approximately 250°. Each arena (one test and one control) was within line-of-sight of the two corresponding streetlights and located roughly halfway between them. We then smoothed the sand inside each arena with a broom to create a flat, even surface, and created a shallow depression (approximately 2 cm deep by 5 cm wide) to mark the center.

We began conducting trials at approximately 0000 h on 28 August and 0030 h on 29 August, releasing one hatchling at a time. To control for any differences in ambient light and cloud cover, we released hatchlings simultaneously in the illuminated (test) and dark (control) arenas (all methods after Salmon and Witherington 1995). Each hatchling was tested only once. We transferred hatchlings individually from the dark container into a black cloth bag with a drawstring closure that was attached to a plastic pole. We laid the cloth bag containing the hatchling at the center depression of the arena with the drawstring loosened. While laying prone landward of the arena boundary, we used the pole to carefully remove the bag, releasing the hatchling. We remained in a motionless prone position until the hatchling exited the arena boundary to reduce any influence of silhouette or movement on hatchling behavior. We then

captured each hatchling after it exited the arena and released it slightly landward of the water line after each trial. We used a hand-bearing compass to determine the exit direction (in degrees); bearings were taken along each hatchling's track from the center of the arena to the point at which it crossed the arena boundary. We also noted the number of times a hatchling crawled in a complete circle inside the arena (if any). After each trial, we swept the tracks from the arena and reestablished the boundary if it had been disturbed.

Data analysis

We performed all analyses using the R language and environment for statistical computing (R Core Team 2014) with $\alpha=0.05$. We grouped together the exit directions of all hatchlings within each test and control arena to calculate a mean exit direction for each arena. We compared mean exit directions using two methods to control for variables that may impact the results but could not be explicitly addressed through the study design. First, we used a randomization version of Moore's nonparametric test for paired circular data to test for differences in exit direction between paired control and test trials (Pewsey, Neuhauser, and Ruxton 2013). This approach compared the mean exit direction of hatchlings released simultaneously in the north and south arenas and controlled for temporal variables, such as cloud cover or ambient lighting that may change throughout the night, but not those associated with the arena location, such as beach slope or dune silhouette. To control for orientation differences associated with the arena locations (e.g., ambient lighting, beach slope, dune vegetation), we swapped the location of the prototype streetlights on the second night of testing; thus, each arena served as both a test and control over the course of the trials. We tested for a location effect using a bootstrap version of Watson's nonparametric test for a common mean direction to compare control and test trials conducted in the same arena on consecutive nights.

We calculated the angular range of exit track dispersion in each arena as the angle between the two most widely separated tracks. We also calculated the variance in exit track bearings and the concentration of tracks in each arena, i.e., how tightly they were grouped together (r , where $r = 1 - \text{variance}$). Using bootstrapping, we determined if the groups of tracks showed reflective symmetry around the mean exit direction, wherein a significant result indicates a lack of symmetry. We then used the nonparametric Wallraff test to check for homogeneity in track concentration between test and control arenas (Pewsey, Neuhauser, and Ruxton 2013). We compared trials conducted simultaneously in adjacent north and south arenas and trials conducted in the same arena over consecutive nights.

Results

Over the two nights of testing, we conducted 26 paired trials ($n=52$ hatchlings). The number of trials completed each night was dependent on weather conditions and the time at which hatchlings emerged from their nests and could be collected. Once hatchlings set an intended path toward the water, they maintained a direct course with only one instance of circling, which occurred in the control arena on the second night of testing.

Regardless of the direction hatchlings were facing when released from the bag, most immediately adjusted their position and then headed in a consistent seaward direction. The mean direction at which hatchlings exited the arena was significantly different between test and control trials conducted simultaneously (mean = 263° and 290° respectively, $n=32$, $p<0.001$ on the first night; mean = 304° and 268° respectively, $n=20$, $p=0.002$ on the second night) but not for trials conducted within the same arena on consecutive nights (mean = 263° and 268° respectively, $n=26$, $p=0.60$ for the north arena; mean = 304° and 290° respectively, $n=26$, $p=0.15$ for the south arena). Bootstrapping indicated the groups of hatchling tracks were symmetrical around the mean for both treatments on both nights ($p>0.05$ for all arenas). Angular ranges in each arena ranged from 40° to 75°, and Wallraff tests found no significant differences in track concentration between test and control arenas on the same night or on the same beach half ($p>0.5$; Figure 2).

Discussion

Hatchling orientation and behavior

Hatchlings in all test and control trials moved quickly and directly toward the water regardless of the illuminated, shielded streetlight. Tracks in all arenas created similar, symmetrical track dispersion patterns with angular ranges that indicate proper seaward orientation (Salmon and Witherington 1995; Witherington, Crady, and Bolen 1996). The significant difference in mean exit bearing between the north and south arenas was consistent across both nights irrespective of the placement of the test luminaires, indicating that arena location affected seaward orientation more than the presence of the adjacent streetlight.

These experiments were specifically designed to test hatchling orientation in the presence of the test luminaire compared to a beach with no streetlighting, assuming coastal areas that currently turn off their streetlights during the nesting season are most likely to be interested in lighting options that can remain illuminated during nesting season. This approach met the goal of identifying a luminaire that would not disrupt sea-finding, thereby providing coastal managers an alternative management strategy. To do this, it was not necessary to include existing streetlights in our comparison. The impacts of full spectrum streetlighting on hatchling orientation are well documented (Bertolotti and Salmon 2005; Cowan et al. 2002; Peters and Verhoeven 1994; Salmon, Wyneken, and Foote 2003) and in fact were the reason the lights at the study site were being extinguished.

Green turtle (*Chelonia mydas*) and leatherback (*Dermochelys coriacea*) hatchlings exhibit behavior analogous to loggerheads when presented with long-wavelength light (Horch et al. 2008; Mrosovsky and Carr 1967; Rivas et al. 2015; Witherington and Bjorndal 1991a). Future studies to evaluate the response of these species to a comparable long-wavelength LED luminaire would be valuable for managers of nesting beaches that host multiple sea turtle species. The use of shielded, long-wavelength streetlights may also offer an additional benefit in maintaining a favorable nesting environment for adult females. While a number of factors influence nest site selection, light plays an important role (Hays et al. 1995; Wood and Bjorndal 2000). Adult female sea turtles

will nest preferentially on dark beaches (Price et al. 2018; Witherington 1992), and the most densely nested beaches are those exposed to the lowest levels of light pollution (Hu, Hu, and Huang 2018; Weishampel, Cheng, and Weishampel 2016). Furthermore, Witherington (1992) demonstrated that nesting female loggerheads and green turtles avoided beaches illuminated with white light but were indifferent to low-pressure sodium light with a peak wavelength of 590 nm. Nesting females should be similarly undeterred in the presence of long-wavelength LED streetlights, though field trials are needed to verify if they would indeed find the conditions suitable for nesting.

Management implications

Coastal managers tasked with balancing roadway lighting requirements with protection of nesting and hatchling sea turtles have historically been faced with a lack of acceptable options. Wildlife and natural resource agencies involved in the protection of sea turtles recommend the use of shielded, low-mounted, long-wavelength lights along sea turtle nesting beaches, and apply these standards for roadway lighting as well (Witherington, Martin, and Trindell 2014). In the United States and abroad, these recommendations are codified in various State and local regulations (e.g., 62B-55 Florida Administrative Code; Code of Ordinances of Jekyll Island-State Park Authority, Georgia Chapter 10 Article IV; Municipal Code of the Town of Hilton Head Island, South Carolina Title 8 Chapter 5) and official guidance documents (Commonwealth of Australia 2020). Additionally, the Florida Department of Transportation recently incorporated them into their roadway design standards (Florida Department of Transportation 2020). Lighting systems designed to satisfy requirements for both human safety and sea turtle protection, such as embedded roadway lights (Ellis and Washburn 2003) or installation of lower-mounted fixtures, may require extensive engineering and roadway reconstruction, making implementation cost prohibitive. Thus, managers fall back on simply extinguishing the lights during nesting season. The fully shielded, long-wavelength streetlights tested here can be mounted on existing poles, thereby reducing part of the need for costly replacements. Our preliminary field trials confirm that these luminaires can provide an appropriate alternative for coastal managers seeking to maintain roadway lighting for public safety while minimizing the potential for impacts to hatchling sea turtles on adjacent beaches.

A challenge unique to streetlighting is that fixtures are often supplied by the power company that owns the utility poles on which they are mounted, further limiting the available options for coastal communities. This pilot project represents an innovative partnership between a state wildlife agency and a major utility provider to collaboratively identify alternative streetlighting for use along sea turtle nesting beaches. Our combination of lab-based fixture durability testing and field-based assays has provided an opportunity to add wildlife-sensitive options to the utility provider's list of available luminaires. For the first time, their coastal customers have access to roadway lighting specifically designed to reduce impacts to sea turtles. Several other options, including additional amber-colored LEDs, have since been evaluated in the lab for appropriate wavelength and shielding and are now available for use by local communities. However, these newer luminaires have not been field-tested. While additional tests are warranted

given the slight variation we saw in hatchling orientation, the logistics and work crews required for a study of this scale make additional field testing impractical. Thus, the placement and shielding of streetlights within line of sight of sea turtle nesting beaches must be carefully reviewed prior to installation.

The goal of the present study was to test a potential alternative streetlight for use in areas where streetlighting is needed for human safety during nesting season. It should be noted that no luminaire is completely “turtle friendly”, as even long-wavelength lamps, such as the one used in this study, are still visible to sea turtles and can elicit a response in some circumstances (Longcore et al. 2018; Robertson, Booth, and Limpus 2016). Therefore, the use of shielded, long-wavelength streetlights should be approached with caution, particularly in areas that traditionally had no streetlighting during nesting season. Although hatchlings in our test and control arenas exhibited a similar ability to successfully locate the water, the cumulative impact on marine turtles of introducing long-wavelength light on a larger scale into a historically dark environment is unknown and may also have impacts on other species within the ecosystem. Our study also does not account for the indirect effects that may result from the installation of new lights, such as increased human presence on the beach that may disturb nesting females or emerging hatchlings. Rather than considering long-wavelength streetlights a “one size fits all” solution, sites should be individually evaluated to determine whether such fixtures would maintain or improve the functionality of both the roadway and the adjacent nesting beach. Nevertheless, the results of this study suggest that fully shielded, long-wavelength streetlights may be a suitable option for supplying streetlighting along some coastal roadways while minimizing impacts to sea turtles.

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