Part III

Reptiles

and

Amphibians

Night, Tortuguero

Because the turtles come out to nest after dark, much of my work was done at night. There was a great deal of waiting between turtles, plenty of time to sit on a driftwood log and think. In the first years of my research I was often the only one on the beach for miles. After ten or twenty minutes of sitting without using my flashlight, my eyes adapted to the dark and I could make out forms against the brown-black sand: the beach plum and coconut palm silhouettes in back, the flicker of the surf in front, sometimes even the shadowy outline of a trailing railroad vine or the scurry of a ghost crab at my feet. The air was heavy and damp with a distinctive primal smell that I can remember but not describe. The rhythmic roar of the surf a few feet away never ceased—my favorite sound. I hear it as I write in my landlocked office in New Jersey. And then, with ponderous, dramatic slowness, a giant turtle would emerge from the sea.

Usually I would see the track first, a vivid black line standing out against the lesser blackness, like the swath of a bulldozer. If I was closer, I could hear the animal’s deep hiss of breath and the sounds of her undershell scraping over logs. If there was a moon, I might see the light glistening off the parabolic curve of the still wet shell. Size at night is hard to determine: even the sprightly 180-pounders, probably nesting for the first time, looked big when nearby, but the 400-pound ancients, with shells nearly four feet long, were colossal in the darkness. Then when the excavations of the body pit and egg cavity were done, if I slowly parted the hind flippers of the now-oblivious turtle, I could watch the perfect white spheres falling and falling into the flask-shaped pit scooped into the soft sand.

Falling as they have fallen for a hundred million years, with the same slow cadence, always shielded from the rain or stars by the same massive bulk with the beaked head and the same large, myopic eyes rimmed with crusts of sand washed out by tears. Minutes and hours, days and months dissolve into eons. I am on an Oligocene beach, an Eocene beach, a Cretaceous beach—the scene is the same. It is night, the turtles are coming back, always back; I hear
a deep hiss of breath and catch a glint of wet shell as the continents slide and crash, the oceans form and grow. The turtles were coming here before here was here. At Tortuguero I learned the meaning of place, and began to understand how it is bound up with time.

David Ehrenfeld
Chapter 7

Protecting Sea Turtles from Artificial Night Lighting at Florida’s Oceanic Beaches

Michael Salmon

Artificial night lighting is a well-documented cause of mortality among migratory birds and hatchling sea turtles. Consequently, the plight of both groups has received significant public attention. For sea turtles, a substantial literature has been produced since McFarlane (1963) first described the effect of lighting on these animals. In response, local and state governments have expended considerable resources on efforts to ameliorate this problem.

In the United States, Florida’s beaches are major rookery sites for loggerheads and northern breeding areas for increasing numbers of leatherback and green turtles. But coastal development in Florida continues unabated, increasing beach exposure directly to the lights themselves and indirectly to sky glow from lights not directly visible. Both influence female choice of nest sites and hatchling orientation. The Florida coast has of necessity become a laboratory for testing methods designed to protect turtles from “photopollution.”
In this chapter I first review how, under natural conditions, females choose nesting sites and hatchlings that emerge from those nests locate the sea. I then describe how behavior of both females and hatchlings is affected by exposure to artificial night lighting. Next, I critically evaluate two approaches to protecting hatchlings at local beaches: those that prevent the turtles from responding to illumination and those that manage lighting. The second approach is preferred because it promotes habitat restoration. Finally, I review the design, philosophy, and implementation of plans to control lighting at the community, county, and state levels. Plans that concentrate efforts to reduce lighting only on beach habitats ignore the deleterious effects of lighting from adjacent and more distant areas. For this reason, conservation of marine turtles ultimately depends on local efforts but also on national and international light management policies.

Sea Turtles in Florida

The coastal waters of Florida serve as important feeding habitats for juvenile and adult marine turtles, and Florida’s sandy beaches serve as important rookery sites for three species: loggerhead (*Caretta caretta*), green turtle (*Chelonia mydas*), and leatherback (*Dermochelys coriacea*). Surveys of the coastline since 1979 have established that most nesting (more than 90%) occurs on Florida’s southeastern shores, that nesting numbers for some species have increased, and that most nesting is by loggerheads: well over 70,000 nests annually produced by at least 17,000 females (Meylan et al. 1995). This contribution represents about 80% of all nesting by loggerheads in western Atlantic waters, the second largest population of this species in the world.

Since the 1920s, Florida’s human population has grown from about 1 million to more than 16 million residents, a rate of increase at least 2.5 times greater than that of the U.S. population (Bouvier and Weller 1992). Immigration has transformed Florida from a largely agricultural to a predominantly metropolitan state, with most of the major cities located on the coast. Once isolated and pristine beaches have become sites for resorts and high-rise condominiums, many adjacent to major ports such as those at Tampa–St. Petersburg, St. Augustine, Miami, Ft. Lauderdale, and West Palm Beach. City and suburban development along the coast has also transformed the lighting environment, although there are few quantitative data to estimate by how much. But it is clear to anyone indulging in a nocturnal beach stroll that almost everywhere in south Florida, lighting
from beach dwellings, roadways, shopping centers, hotels, and office buildings reaches the beach, either directly from sources visible at the horizon or indirectly as the result of sky glow, light reflected from these sources down to the beach from the atmosphere. Put simply, photopollution, defined as the “degradation of the photic habitat by artificial light” (Verheijen 1985:2), has become another threat to sea turtle populations that, worldwide, are already seriously depleted.

Florida is a paradox. Thanks to conservation and management efforts in this country and abroad, the number of female turtles returning to nest in Florida has increased. But at the same time coastal development and artificial night lighting degrade Florida’s nesting beaches as a habitat. Without a comprehensive solution to this problem the gains seen in sea turtle nesting might be offset or even reversed.


Sea Turtle Behavior in the Absence of Artificial Night Lighting

I begin with a brief review of sea turtle behavior at the nesting beach in the absence of artificial night lighting.

**Nest Site Selection by Females**

Sea turtles normally nest on remote beaches, shrouded in darkness. Some sites are more attractive than others, but why? It has proved impractical to do many controlled experiments with gigantic (150- to 400-kg [330- to 880-lb]) females, but we have a general idea of what processes must be involved. These may be conceived as consisting of decisions made at different spatial (geographic) scales. At the largest scale, females show preferences for particular nesting locations, manifested behaviorally by site tenacity. Tenacity is demonstrated by capturing females found near a nesting beach, then displacing them. They typically return within hours or days, depending on distance, to the capture site (Luschi et al. 1996).

Site tenacity is also manifested genetically. Females nesting at partic-
ular sites have similar mitochondrial DNA signatures. These indicate that the females are descendants of one or a few original matrilineages. It follows that each female hatchling learns and remembers the location of its natal site and returns there after many years of growth to sexual maturity. The sensory cues used for habitat imprinting are unknown. Evidence suggests that hatchlings respond to magnetic landmarks and use these cues to gauge their spatial position in the open ocean (Lohmann et al. 2001). Such a capacity may also underlie their ability as adults to return to natal beaches (Lohmann et al. 1999, Lohmann and Lohmann 2003). Experimental evidence demonstrates that juvenile turtles are also capable of navigation and that orientation is based on both visual and geomagnetic cues (Avens and Lohmann 2003, 2004).

Populations within species differ in their specificity for rookery sites. For example, loggerheads nesting in Florida consist of four genetically distinct matrilineages, each nesting in a different part of the state. Within each of these populations, females may deposit eggs in one to seven nests, each at 12- to 14-day intervals, many kilometers apart. Loggerheads in Australia often nest on a single small island but not another that may be only a few hundred meters distant, however.

The selection of a nesting site also involves decisions on a finer spatial scale, that is, the search for an attractive site at a particular location. Attractive sites have certain ecological characteristics. For example, prime nesting beaches usually are adjacent to the nearshore oceanic currents needed for hatchling transport to nursery habitats. Nesting beaches also have a favorable underwater nearshore approach profile and contain few obstructions, such as shallow water rocks or reefs, that might injure a female attempting to reach the surf zone.

Once a female is in shallow water adjacent to the beach, and also during her crawling ascent on the beach itself, she can assess local terrestrial features such as the dune or vegetation profile behind the beach, beach slope, depth, and elevation of the beach “platform” above sea level. Sand characteristics, such as temperature and moisture content, may also be detected. For loggerheads, beach slope is an important cue (Wood and Bjorndal 2000), but other sea turtle species may have different, and currently unknown, requirements.

Females usually nest at night, when temperatures are lower and when nests, and the females digging them, are less likely to be detected by terrestrial predators. Nesting can take an hour or more and involves digging a shallow body pit with all four flippers, then an egg chamber with the rear flippers. The egg chamber can receive a clutch of more than a hun-
dred eggs, which is covered with sand. Extra sand is scattered to mask the location of the egg chamber. The female then returns to the sea, abandoning the unprotected nest to its fate.

If no predators locate the egg chamber, and if the nest is not flooded by storm-generated high tides or wave action, embryological development will be completed in 45–75 days depending on temperature.

**Hatchling Orientation: Locating the Sea from the Nest**

After extricating themselves from their eggs, the hatchlings dig their way upward en masse toward the sand surface. If the surface sand is hot, they stop and become inactive until the sand cools after sunset. This response normally results in a simultaneous nocturnal emergence of most of the hatchlings to the beach surface. Their appearance is immediately followed by a rapid (2 minutes or less) crawl directly to the ocean, an orientation behavior known as seafinding.

Seafinding is mediated visually, using a perceptual filter that confines the visual field to directional cues located in a horizontally wide (180°) and vertically narrow (–10° to +30°) “cone of acceptance” (Lohmann et al. 1997). The visual cues that the hatchlings use are simple. They crawl away from tall or dark objects located against the landward horizon, characterized by the dune or vegetation behind the beach, and toward the lower, uniformly flatter beach-facing horizon. This horizon also typically reflects and emits more light from the stars or moon. In the surf zone, incoming waves lift the turtles off the sand surface and induce vigorous synchronized paddling with the foreflippers. Hatchlings are carried seaward by the retreating waves. Continued orientation offshore is then directed by swimming into wave-induced orbital currents (Lohmann et al. 1995). Because surface waves typically approach the beach parallel to shore, the hatchlings move into deeper water. The turtles swim continuously during a swimming frenzy that lasts 24–36 hours. This migratory activity is the turtle equivalent of migratory restlessness, or zugunruhe, which has been so well studied in birds (Berthold 1993).

**Artificial Night Lighting and Sea Turtles**

Artificial night lighting disrupts the normal behavior of sea turtle females searching for appropriate nest sites and of hatchlings attempting to orient toward the ocean.
Effects of Lighting on Female Nest Site Selection

The number of nests placed on a length of beach can vary locally for reasons that are not always obvious. For example, nest densities typically are lower at beaches exposed to artificial night lighting, but lighting may not be the only or even the primary cause. Lighting is associated with coastal development, and coastal development may be correlated with a host of changes such as dune alteration, deliberate changes in beach profile, or other anthropogenic modifications. These can include increased compaction, shoreline armorng to retard sand loss, accumulated debris, and human traffic that can cause a decline in nesting by disturbing females, either as they begin their crawl ascent or as they begin to dig their nests. Thus to determine whether lighting causes a decline in nesting activity, these other potential variables must be excluded.

Witherington (1992) completed the critical experiments with loggerheads in Florida and green turtles in Costa Rica. Portable generators were used to power lights that illuminated an otherwise dark and, for the females, attractive nesting beach. When the beach was exposed to mercury vapor lighting, the number of nesting attempts, whether or not they resulted in nests, was reduced almost to zero. But when the beach was exposed to near-monochromatic yellow light from low pressure sodium vapor lamps or when the lamps were left in place but turned off, both unsuccessful and successful nesting attempts returned to normal.

Many beaches in south Florida are exposed to less intense and more diffuse lighting than in Witherington’s experiment, and as a consequence lowered levels of nesting occur in these areas. At these locations, the influence of lighting often is revealed by the spatial distribution of the nests. In Boca Raton, Florida, we found that most loggerhead nests were clustered in front of tall condominiums, largely dark and unoccupied during the summer nesting season (Salmon et al. 1995a). Further study showed that clustering was unrelated to beach physical attributes such as width, elevation, or slope or differences in nearshore, underwater profile. But clustering was significantly and positively correlated with building elevation. The buildings apparently acted as light barriers, shadowing the beach from city lighting in the interior. That observation led to the hypothesis that at urban locations exposed to lighting, nesting females found shadowed patches of beach most attractive. Apparently the more that shadow extended above the horizon, the more attractive the location was as a nest site.

The correlation between relative darkness and nesting density is also evident on a larger geographic scale. Most loggerhead nesting in the
United States occurs in south Florida, but within that area the distribution of the major nesting sites is not uniform. Three species—loggerheads, green turtles, and leatherbacks—favor the same, darkest beaches (Salmon et al. 2000; Figure 7.1). This association suggests that female choice of nesting site is strongly biased by coastal development and its associated lighting.

We cannot determine whether choosing nest sites to avoid lighting affects reproductive success. Choice of nest site seems to have no effect on nest success, defined as the proportion of eggs that ultimately result in hatchlings that leave the nest. We lack information to compare the proportion of hatchlings that reach their offshore goals from the few and darkest available beaches today with that proportion before human settlement in Florida without the influence of lighting on nest site choice. We can draw two conclusions, however. The first is that if nesting sites are currently selected by the absence of lighting, then selection based on factors that in the past did not include lighting must be weakened. The second conclu-

![Figure 7.1](image_url)

**Figure 7.1.** Artificial light radiating from ground level in Florida, as measured by satellite photographs. Gray areas surrounded by white patches radiate the most light; white patches are intermediate; black regions are dark. Nesting on Florida’s east coast is clustered at five beaches where levels of development and lighting are low. Boca Raton (a sixth site) has high nesting densities for a metropolitan area. It is located in a small patch of intermediate light radiance, surrounded to the north and south by brighter regions. Redrawn from Salmon et al. (2000).
sion is that if current trends continue, more nests are likely to be concentrated in an ever-declining area of remaining dark sites. We already know that when nests are concentrated in space, under natural (Gyuris 1994) or artificial conditions, rates of hatchling mortality increase.

**Effects of Lighting on Hatchling Orientation**

Artificial lighting disrupts the normally accurate seaward orientation of hatchlings. Disruption typically is discovered through inspections conducted in daylight, when the tracks, or flipper prints, of the turtles can be seen on the sand surface. *Disoriented* hatchlings crawl in circuitous paths, as if unable to detect directional cues. *Misoriented* hatchlings crawl on straight paths, but they often lead directly toward light sources visible from the beach at night (Salmon et al. 1995b). When their orientation is disrupted, the prospects for hatchling survival diminish (Witherington and Martin 1996). Disoriented hatchlings may crawl on the beach for hours, wasting time and limited stores of yolk energy that should be used for offshore migration during the dark period. Some of the disoriented turtles may eventually locate the sea, but the fate of misoriented turtles is far worse. Those not trapped in dune vegetation may exit the beach, traverse coastal roadways where they are crushed by passing vehicles, or gather at the base of light poles. Misoriented hatchlings are also weakened by exhaustion, physiologically stressed by dehydration, taken by terrestrial predators, or killed after sunrise by exposure to lethally high temperatures. Florida hatchlings lost annually as a consequence of disrupted orientation are estimated to number in the hundreds of thousands (Witherington 1997).

Why is hatchling orientation so seriously affected by artificial lighting, whereas the orientation of their mothers is rarely affected? One possibility is that hatchlings are simply more sensitive to lighting than adults. Another is that the two life history stages respond to different visual features even though both stages show orientation. Females nesting at illuminated beaches are attracted to dark patches of beach or some correlate thereof, such as a tall, dark object behind the beach. After nesting is completed, females need only to reverse the sign of this preference (i.e., crawl away from dark patches) to locate the sea. Hatchlings scan a broader (180°) length of horizon, however, and are naturally attracted to areas reflecting more light, which is usually the seaward horizon. By virtue of their brightness in comparison with the remainder of the visual environment, luminaires may simply be supernormal substitutes for naturally directing stimuli (Witherington 1997).
The lights themselves do not have to be directly visible to hatchlings. At many developed sites, lighting from sky glow, or from gaps between buildings, dunes, or vegetation behind the beach, compromises hatchling orientation (Figure 7.2).

Figure 7.2. The orientation shown by loggerhead hatchlings in a laboratory arena. The turtles are presented with natural (crescent-shaped and unbroken) or artificial (odd-shaped, broken, or both) “landward” silhouettes. Solid dots within circle diagrams show the mean angle of orientation for each hatchling; arrow outside circle is the mean angle for the three groups that show statistically significant orientation. (a) Hatchlings crawl away from “land” when presented with a natural silhouette, but (c) show less accurate orientation when the silhouette is broken and allows light into the arena. (b) Orientation is more variable when hatchlings are exposed to a solid, unnaturally shaped silhouette. (d) Turtles show no significant orientation when the silhouette is broken. Thus, hatchlings depend on both horizon shape and continuity for accurate seafinding. Redrawn from Salmon et al. (1995b).
Mitigating Effects of Artificial Lighting by Manipulating Nests or Hatchlings

How can managers best protect turtles from lighting? What are the common management strategies, and what have we learned about their efficacy?

For very practical reasons, managers of nesting beaches have concentrated on protecting hatchlings from artificial lighting, ignoring any effects on nesting female turtles. In Florida, most nesting beaches are surveyed by volunteer groups, private educational and research organizations that showcase marine turtles, park and wildlife personnel, and biologists hired by local governments. The primary concern of monitoring personnel is to document nest success in terms of hatchling production and to minimize any loss of hatchlings associated with exposure to artificial lighting. When such losses occur, the signs are evident: abnormal hatching tracks, turtles reported crossing coastal roadways, and hatchlings collected under light poles. Although most efforts are concentrated on hatchlings, artificial lighting affects both hatchlings and nesting females. It is much more difficult to document effects on the females, however; doing so takes years of data to establish that there has been a nesting decline. Even if such a trend is documented, it is difficult to determine a causal relationship between more lighting and less nesting.

Protecting both females and their hatchlings ultimately entails a coordinated effort that involves monitoring, local code enforcement personnel, and state and federal agencies responsible for resolving lighting problems. In the last 10–15 years the need for such cooperation has increased, and successful collaborations have become more common. As a result, management practices have shifted in emphasis from protecting hatchlings to habitat restoration through large-scale planning. Such an approach obviously benefits both hatchlings and females. I return to discuss this more holistic approach to sea turtle management and recovery at the end of this chapter, after discussing methods of hatching protection. This discussion begins with nest relocation and nest caging, two procedures intended to prevent hatchlings from being affected by artificial lighting.

Nest Relocation

In Florida some beaches are exposed to so much lighting that emerging hatchlings cannot locate the sea. Nests deposited at these beaches are relocated to hatcheries, sites where the eggs from each nest are reburied in sand cavities that mimic, in size and proportion, the egg chambers excavated by females. Some hatcheries are fenced to exclude predators and confine the
turtles. Hatchlings that emerge in fenced locations are collected twice during the dark period, in late evening and early morning, then released at a dark beach. Self-releasing hatcheries are located at dark beaches and have no fences. After emergence, the turtles crawl to the sea unassisted.

Managers recognize that hatcheries are costly to operate, that relocation not done properly (e.g., within 12 hours of deposition by the female) can damage embryonic membranes and cause egg death, and that spatially concentrating nests can result in low hatching success and poor hatchling quality. Hatcheries therefore are considered a method of last resort (Mortimer 1999), to be used only when conditions virtually guarantee that nests left in place will not survive.

Despite the drawbacks, managers until recently considered hatcheries successful if sufficient care was taken to minimize egg mortality and if hatchling tracks led to the sea. These criteria have been shown to be inadequate, however (Wyneken and Salmon 1996). For more than a decade Broward County has managed a large self-releasing hatchery where more than 1,500 nests annually were routinely placed chronologically in neat rows by deposition date (Figure 7.3). From late May through September, hatchlings from several nests deposited on the same day or within 1–2 days of each other emerged each night, crawled to the surf zone, and entered the sea. But waiting for them, often within just a few meters of

Figure 7.3. A self-releasing hatchery at Hillsborough Beach, Broward County, Florida. Each stake marks the position of a nest.
shore, were predatory fishes (e.g., tarpon, mangrove snapper, and sea catfishes) and squid that had learned where to find a reliable source of prey. To quantify predation rates, observers in kayaks followed hatchlings at a distance as they swam offshore. Predators took about 29% of the turtles within 15 minutes after they entered the sea.

After this discovery, an alternative hatchery system was explored for the next two seasons. Instead of a single large hatchery, three hatcheries separated by several hundred meters were used. Second, nests were transferred to a single hatchery for no more than 2 weeks; thereafter, they were transferred to another hatchery. As a result, hatchlings entered the ocean at any one site for only brief (2-week) periods. Presumably, this schedule reduced the time that predators had to learn where prey were available. Predation rates were assayed again by observers following hatchlings offshore. Rates averaged 2.5% at control sites between the three hatcheries and 17% in front of the hatcheries. Thus spreading hatchling risk, both spatially and temporally, resulted in lower turtle mortality levels than those at a single large hatchery. But even smaller, separate hatchery sites resulted in an average predation rate seven times higher than those at the control, nonhatchery sites.

**Nest Caging**

At some rookery sites, sea turtle nests are covered with wire mesh cages, open at the bottom and anchored in the sand. Cages are the analogs of hatcheries, reduced in size to protect single nests. Self-release cages are constructed so that the mesh on the ocean-facing panel permits the hatchlings to escape from the cage, then crawl unassisted to the sea. These cages typically are used to protect nests from natural predators such as raccoons, foxes, armadillos, and skunks. Restraining cages are used to protect hatchlings from artificial lighting (Florida Fish and Wildlife Conservation Commission 2002). They do not permit hatchling escape. Beach monitoring personnel must inspect these cages twice each night for turtles, then release them at a dark site.

At our study site in Boca Raton, Florida, self-releasing cages commonly were used at locations where raccoon predators were a serious threat or where light levels were believed to be too low to seriously affect hatchling orientation. At sites where light levels were low, cages were supposed to prevent the turtles from immediately crawling toward the lights until the hatchlings could adapt to local conditions. But was this protection effective? Because some of the turtles left tracks that led from the cage directly to the ocean, the initial assumption was that the method was
successful. But observations and experiments led to different conclusions (Adamany et al. 1997).

Hatchling emergences were staged inside cages placed on dark beaches and inside cages at sites where they were exposed to low lighting. Caging did not alter hatchling orientation at dark sites, but at illuminated sites many turtles crawled against the landward-facing wall. They remained there for part and sometimes all of the dark period.

At most of the illuminated sites, artificial lighting diminished after midnight, and many turtles eventually escaped from the cage. But some escapees crawled only a short distance before their orientation was again disrupted. At other sites where lighting levels were higher, the hatchlings remained trapped inside the cage until dawn and only then crawled to the ocean. They left behind a record of tracks that were spatially normal but temporally inappropriate because in the absence of darkness the turtles were vulnerable to visual predators on land and in the sea. Finally, all caged hatchlings, whether they escaped from the cages before dawn or at dawn, spent time and energy crawling within a cage. That energy should have been used for offshore migration.

At Boca Raton, caging also provided inadequate protection against predators. Raccoons learned to use the cages to locate nests (Mroziak et al. 2000).

**Mitigating Effects of Artificial Lighting by Controlling Light Emissions**

Adverse effects of lights on sea turtles can be reduced at the source through the design of lighting systems used in coastal environments. Such approaches include the use of streetlight filters on existing or new lamps and nontraditional lights embedded in roadways instead of mounted on light poles.

**Streetlight Filters**

Hatchlings vary in their response to light of different pure wavelengths. Turtles are strongly attracted to the shorter, violet to green wavelengths but are either indifferent to or, uniquely in the case of loggerheads, repelled by longer amber wavelengths (Lohmann et al. 1997). These results led to the development of dyed acrylic filters designed for streetlights and other luminaires that permit the transmission of only the longer wavelengths. The assumption underlying filter development was that the responses elicited by a range of single light wavelengths could be
used to predict the responses elicited by a spectrum that included the same light wavelengths.

Two filters were designed by General Electric Lighting Systems, Inc. (GELS) to exclude transmission of wavelengths less than 530 nm (#2422 filter) or 570 nm (NLW filter; Figure 7.4). The Florida Power and Light Company installed #2422 filters in poled streetlights along coastal roadways throughout south Florida. These streetlights were equipped with high pressure sodium vapor (HPS) luminaires that transmitted wavelengths known to attract hatchlings. If completely effective, the filters would render these lights unattractive to the turtles; if partly effective, they might substantially reduce orientation disruption. Unfortunately, GELS produced fliers advertising the filters as “turtle friendly” before they were adequately field tested.

Such filters have several potential advantages. First, they immediately modify the spectral output of HPS streetlights at a modest cost. Second, they reduce the amount of light energy transmitted to the environment and therefore make the luminaires less likely to affect hatchling orientation. Third, they can be removed after turtle nesting season, if desired. The critical question, then, is whether filtered lighting is effective, either by not attracting hatchlings or by being less attractive than unfiltered HPS lighting.
Response of Females to Filtered Lighting

Pennell (2000) monitored loggerhead nesting attempts over an entire summer at a dark beach in Palm Beach County, Florida. Highway A1A, which is illuminated by numerous streetlights, runs parallel to and just behind the beach. The site was divided into three 440-m (quarter-mile) sections: north and south control sites, where the streetlights were turned off, and a central experimental zone where three filtered streetlights on poles were alternately turned on and off for 1-week periods.

When the lights were on there was no evidence that nesting attempts, both successful and unsuccessful, or their ratios were affected because there were no statistical differences in nesting density between the control and experimental sections. There were also no differences in nesting attempts in the experimental section when the streetlights were turned on or off (Figure 7.5). Nest densities recorded during that summer fell within

![Graph showing nesting attempts by loggerheads at Carlin Park, Florida. The beach was divided into north and south control sections, where streetlights were turned off, and a central experimental section exposed to filtered (#2422) street lighting. There were no statistical differences in nesting attempts between the control and experimental sections. Nesting attempts in the experimental section did not differ when the streetlights were on or off. n = the total number of nesting attempts. Modified from Pennell (2000).](image-url)
the range of those recorded in the previous 12 years, when all of the streetlights were turned off. But because females often nest where lighting can affect their offspring, these studies were followed by experiments with hatchlings. Unfortunately, those results were less encouraging.

**Response of Hatchlings to Filtered Lighting**

Tuxbury (2001) performed laboratory experiments in a circular arena, located inside a windowless room. Hatchlings were tethered by a short line to the center of the arena but could crawl in any direction. Half of the arena presented the turtles with a flat, unobstructed “seaward” horizon. The opposite “landward” half had two book lights placed upright against the arena wall, 90° apart (Figure 7.6). These lights simulated in position two streetlight poles about 33 m (108 ft) apart, which is a typical spacing of these luminaires along some coastal roadways. The lamp bulbs used in the book lights emitted a broader spectrum of wavelengths than HPS luminaires. When fitted with filters, however, emissions were confined to the expected amber wavelengths.

*Figure 7.6.* Arena used by Tuxbury (2001) to investigate hatchling orientation during exposure to filtered street lighting and silhouettes. Hatchlings are tethered inside the arena but are free to move in any direction. Their average orientation direction is noted. Two surrogate streetlights (miniature book lamps whose openings are covered with a General Electric Lighting Systems filter) are placed against the “landward” half of the visual field. A dark, crescent-shaped silhouette mimics the presence of a vegetated dune behind the beach. The “seaward” half of the visual field is dark and flat. Responses of the turtles to light transmitted through each of two filters (#2422, NLW) were measured in the presence or absence of the silhouette.
Orientation was examined under four treatment conditions: when light passed through a #2422 or NLW filter, in the presence or absence of a silhouette, 15° high, measured at center. Green turtle and loggerhead hatchlings, about to emerge from their nests, were collected during the afternoon and served as the experimental subjects that evening.

In the absence of silhouettes, hatchlings of both species crawled toward the lamps, regardless of which filter was used. In the presence of a silhouette, however, some of the turtles crawled “seaward,” or away from the lamps. The response of each species to the “light with silhouette” treatment differed. Loggerheads, but not green turtles, crawled away from #2422 filtered lighting, whereas green turtle hatchlings, but not loggerheads, crawled away from NLW filtered lighting.

The results led to three conclusions. First, filtered lighting was not “turtle friendly,” because it attracted the turtles. Second, attraction could be reversed by a stronger natural cue, a high silhouette, resulting in seaward orientation even when the turtles were exposed to filtered lighting. Third, the two species differed in their response to lighting in the presence of identical silhouettes, depending on small differences in the transmitted light spectra. Thus, species-typical differences in light perception must be considered in management decisions. At many rookery sites, nesting by two or more marine turtle species is common; a single kind of filtered light may reduce orientation disruption in one hatchling species, but not in others.

Is Filtered Lighting Less Attractive to Hatchlings Than Unfiltered HPS Lighting?

Although filtered lighting attracted loggerhead and green turtle hatchlings, it might be less attractive than unfiltered lighting. If so, then filtering might be an effective management tool under certain conditions. For example, if filtered lighting were only weakly attractive to hatchlings, normal orientation might be restored by coupling the use of filters with lower-wattage luminaires, by moving lights farther away from nesting sites, or by making the silhouette behind the beach taller or more complete.

Nelson (2002) conducted experiments in the laboratory in which loggerhead hatchlings were exposed to filtered and unfiltered HPS lighting. A T-maze apparatus was used to determine how the hatchlings responded. Turtles initially crawled down a runway and then, at the T-intersection where lighting was visible, turned either to the left or right. In one set of tests a single light (HPS or filtered HPS) was presented for
turtles to choose between an illuminated and dark side of the maze. In a second set of experiments, two different lights (filtered and unfiltered) were viewed simultaneously, one light from each side. Intensities of the lights were matched to those measured at a beach when light poles were 60 m (about 200 ft) distant.

Almost all (more than 96%) of the turtles turned toward the HPS light when it was presented alone. When filtered light was presented alone, attraction was weaker; 68% of the hatchlings turned toward the #2422, whereas 85% turned toward the NLW. When filtered and unfiltered lights were presented simultaneously, the HPS light attracted more than 90% of the turtles. Reducing HPS brightness by 1 or 2 log units, thereby rendering it dimmer than the filtered light with which it was paired, made the two lights equally attractive; that is, about half of the hatchlings turned toward each luminaire. A significant attraction to the filtered light occurred only when the HPS light was reduced in intensity by 3 log units. These results indicate that filtering an HPS luminaire does make its light less attractive to the turtles. They also show that attraction depends on both the intensity and the spectral composition of these lights.

**Embedded Lighting on Coastal Roadways**

If street lighting on poles is visible at the beach, filtering may reduce orientation disruption, but it does not eliminate the light stimulus. A better alternative is to confine roadway lighting to the street surface. The Florida Department of Transportation sponsored an embedded lighting project in Boca Raton. Light-emitting diodes were installed along a 1-km (0.6-mile) section of coastal roadway (Highway A1A; Figure 7.7). Streetlights with filters, which were already present along the roadway, were left in place.

The project site was located at a park bordering the nesting beach. Because few other lights were present, this location was ideal for experiments designed to compare hatchling orientation under three conditions: when only the filtered streetlights were on, when only the embedded lights were on, and when both lighting systems were switched off. Bertolotti and Salmon (in press) used beach arena assays to measure turtle orientation under each of these conditions. Hatchlings were captured in the afternoon of the day they would naturally emerge and then taken to the beach that evening. They were released in the center of a 4-m (13-ft) diameter circle drawn on the beach surface. Hatchlings showing normal orientation all crawled east, toward the ocean. Hatchlings whose ori-
Orientation was disturbed by lighting either crawled toward the lights or failed to show any significant orientation preference as a group.

At a control site, vegetation between the beach and the roadway acted as a light barrier, and the hatchlings under all treatment conditions crawled toward the sea. At two experimental sites the streetlights were

**Figure 7.7.** The coastal roadway used for the embedded lighting project in Boca Raton, Florida. The nesting beach is located to the right (not visible). Above, view at night with the traditional poled streetlights turned on; below, view with the streetlights turned off and the embedded lights turned on. The streetlights, but not the embedded lights, were visible from the beach.
visible; orientation was disrupted when the streetlights were turned on but not when the embedded lights were on or when both the streetlights and embedded lights were switched off.

Embedded lighting was also an effective lighting alternative for people. Pedestrians, cyclists, and motorists all responded favorably to the lighting modification.

**Comprehensive Plans to Reduce Artificial Light at Sea Turtle Nesting Beaches**

Restoration of natural levels of darkness on sea turtle nesting beaches will require large-scale plans. When implemented fully, such plans can dramatically reduce artificial light experienced at beaches. Following are three examples of comprehensive light management plans from Florida.

**A Light Management Plan for Broward County**

The beaches of Broward County in southeastern Florida receive about 2,500 sea turtle nests each year. Most (about 70%) are deposited on beaches exposed to so much lighting that they must be relocated. The cost of this effort to the county is substantial (e.g., $95,000 in 2001). As discussed earlier in this chapter, concentrating nests in hatcheries increases predation rates on hatchlings, but that is not the only problem. Relocated eggs may be damaged in transport, increasing probabilities of egg death or sublethal effects during development that could reduce hatchling vigor. Additionally, concentrating nests in one location year after year increases the risk that local perturbations, such as a storm, a raid by terrestrial predators, or accumulating sand pathogens, may destroy large numbers of eggs.

An alternative approach is light management, eliminating the need to cage or relocate nests. Although also initially expensive, the benefits of habitat restoration are long term and obvious. Restoration is encouraged by both the state (Florida Fish and Wildlife Conservation Commission) and federal (U.S. Fish and Wildlife Service) agencies responsible for coordinating sea turtle recovery efforts. The issue then becomes one of devising a plan that promotes habitat restoration most efficiently and on the largest scale possible. Such a plan (Ernest and Martin 1997), developed for Broward County by an environmental consulting firm, is being implemented.
The county spans about 23 miles (37 km) of coastline that includes eight jurisdictional boundaries. Some beaches in the county are dark and undeveloped, such as in front of single-family residences or parks, whereas others are brightly illuminated by buildings constructed just behind the beach (e.g., Fort Lauderdale and Hollywood). Nest density was inversely correlated with beachfront development. Given this variation, and considering that resources to implement management plans are always limited, the challenge of the plan is to restore the natural light regime of the habitat, thereby reducing the need to relocate nests.

The plan consisted of an initial assessment phase followed by an implementation phase. The assessment phase began with a lighting inspection and a review of the most recent (1994–1995) nest density data. This information was used to rank the beaches into management areas. Ranks were based on the sum of scores for nest densities, number of nests needing relocation, extent of coastal development, and proximity to other management areas, specifically the potential for lighting in one area to cause problems in an adjacent, darker area. Sites with low scores were those that were least developed and contained many nests. A second element of the plan was public awareness. Coastal property owners were informed about the plan’s objectives and its benefits for sea turtles, the environment, and coastal residents. Residents were also provided with guidelines for voluntary compliance. Finally, a single simplified lighting ordinance stating the rules and regulations for protecting nesting turtles and their hatchlings was created for the county, designed to establish uniform criteria to identify lighting problems and to enforce compliance.

The implementation phase began in 2001; more time will be needed to evaluate the plan’s strengths and weaknesses. But its basic elements seem appropriate and workable. Initial light management efforts will be directed to the sites with low scores, that is, sites where the largest numbers of nests are located and where light control can be most easily achieved. To ensure that plan goals are continuously achieved, lighting inspections will be continued, and property owners will be notified of any lighting infractions. They will also be provided with assistance in the effort to resolve them. Finally, once changes are made they will be evaluated to ensure that they are effective.

Overall, the plan represents an approach toward, and provides a framework for, the management of problem lighting at any coastal habitat. What is essential for its success is a firm commitment by the community and its regulators to achieve those goals.
**Patrick Air Force Base and Cape Canaveral**

Brevard County receives more than 40% of Florida’s sea turtle nests and, for this reason, is an area of special concern. It is also home to the 45th Space Wing of the U.S. Air Force, which maintains two facilities on the coast: the Patrick Air Force Base (PAFB) and the Cape Canaveral Air Force Station (CCAFS). On average, about 1,800 loggerhead nests are deposited annually on the 7-km (4.3-mile) beach in front of the PAFB, and an average of 3,500 nests of the same species are placed on the 23-km (14.3-mile) beach in front of the CCAFS.

In 1988, meetings were initiated between the U.S. Fish and Wildlife Service and the U.S. Air Force to resolve lighting issues that had caused serious hatchling misorientation and disorientation problems at both sites. A lighting plan was developed for the CCAFS in 1988 and for the PAFB in 1995. Light reduction was complicated by the necessity at both sites to maintain lighting essential for human safety and national security. Nevertheless, both sites are now impressively dark, thanks to changes that collectively involved more than 1,000 luminaires. Modifications included replacing high pressure sodium with low pressure sodium luminaires, reducing wattage, shielding and recessing lights, installing motion detector controls to turn on lights only when they were needed, and eliminating unnecessary lights at both facilities. The affected areas included roadways on the facility and between the facility and the beach, parking lots, family housing units, hangars, runways, launch pads, and sport fields. Lighting curfews were imposed during turtle nesting season for all outdoor sporting and social activities. Once the project was completed, the transformation was remarkable. The coastal roadway between the beach and the base is extremely dark.

The Air Force took responsibility for ensuring compliance at existing facilities and for reviewing lighting plans for all new construction. The Air Force also agreed to annually monitor and record sea turtle nesting activity and hatchling behavior, to support beach dune enhancement by planting native dune vegetation, and to add light screens at sites where hatchling orientation problems persisted. Finally, the Air Force agreed to support monitoring efforts, to report the annual take of turtles (primarily losses of hatchlings caused by lighting problems) to the Fish and Wildlife Service, and to limit take to 2% or less of all hatchlings from all nests.

This example illustrates the successful enforcement of the Endangered Species Act, where the military in cooperation with the Fish and Wildlife Service achieved conservation goals without sacrificing readiness. It also
shows that a structurally complex coastal community consisting of residential, specialized industrial, service, and recreational components can function effectively while having a minimal adverse effect on sea turtles.

**Lighting Plans for Coastal Roadways**

Disruption of hatchling orientation is especially common at coastal roadway sites in Florida. In recognition of this problem, a technical working group met to formulate a *Coastal Roadway Lighting Manual*. The working group consisted of representatives from industry, state and federal government, and technical experts. The manual (Ernest and Martin 1998) presents a step-by-step approach to the diagnosis of roadway lighting problems at sea turtle nesting beaches and their resolution through effective light management. It is intended for a wide audience of regulators, traffic planners and engineers, utility company personnel, conservationists, and environmental planners. Tables in the manual list the efficacy of lighting alternatives as a function of local conditions. An appendix provides technical specifications, costs, and sources of standard roadway luminaires.

Lighting problems are identified by nighttime surveys, by hatchling disorientation reports submitted by permit holders to the Florida Wildlife Commission, or by beach arena assays. Specific solutions appropriate to each site vary, but a standard approach is advocated that applies to any location. It involves three elements: keep lighting off the beach by repositioning or shielding the light; reduce luminance by turning lights off, installing fewer lights, or lowering wattage; and minimize the disruptive wavelengths by using light filters or low pressure sodium luminaires. Finally, the manual stresses the importance of incorporating new technology as it becomes available.

**Conclusion**

Forty years have passed since McFarlane (1963) published the first report of sea turtle hatchling disorientation by artificial roadway lights in Florida. Since then, other studies have stressed the effects of artificial lighting on all wildlife (Verheijen 1985, Outen 1998, Longcore and Rich 2004) and on sea turtle nesting beaches. Some (Raymond 1984, Witherington and Martin 1996) have also described methods that work best to achieve light control. Thanks to the efforts of permit holders, concerned citizens, municipal and county environmental regulators, the federal gov-
ernment, and private environmental organizations (especially the Center for Marine Conservation), many historically dark beaches remain dark, and others previously exposed to stray lighting have been partially, and in a few cases completely, restored. There has also been an increase in public awareness of the sea turtle lighting problem. That awareness has resulted in the adoption of strict local lighting regulations. For example, it is now impossible to obtain a building permit for a coastal structure without having an approved lighting plan.

But as this review indicates, some strategies to manage and protect marine turtles have been more successful than others. Those least successful have sought to remove the turtles from areas of problem lighting or prevent the turtles from responding to the lights by caging. These strategies fail for two reasons. First, they create new problems for the turtles. Second, they fail to deal with causes, in this case habitat degradation by lighting, and for this reason have been criticized as “half-way technology” (Frazer 1992). The alternative approach advocates habitat restoration through light management to reduce the need to manipulate either sea turtle nests or hatchlings. The scale of light management has varied from small patches of beach to entire communities or municipalities. Obviously, small-scale modification will be effective where there are few, easily modified sources of artificial lighting. But large-scale plans are needed at locations where development is more extensive and where there are many kinds and sources of artificial lighting.

In the last few years there has been a gradual increase in the number of green turtle and leatherback nests at Florida’s beaches, whereas loggerhead nesting has slightly declined, for reasons that remain unknown. For green turtles and leatherbacks, these changes may be a consequence of a widespread international effort to protect marine turtles at their nesting beaches, feeding grounds, and nursery habitats and along their migratory routes. But despite that positive trend, continued vigilance will be needed; this is particularly true when it comes to the artificial lighting problem.

In Florida, there are two elements of continued concern. The first is the absence of a plan to limit population growth in the state. The current population is dangerously near the state’s carrying capacity (Bouvier and Weller 1992). Continued development places an excessive burden on infrastructure such as roads, schools, water, sewage, police and fire protection, and family and other social services. It also portends dire consequences for the preservation of natural areas and wildlife, including sea turtles.

The second concern is that current efforts to manage artificial lighting at nesting beaches stress a highly regional near-coastal approach. A
regional approach will reduce lighting directly visible from the beach but will not reduce inland sources that produce ever-increasing sky glow. In fact, one might predict that if regional approaches succeed and beach habitats become darker, the problem of sky glow from interior locations will become even more serious. This prediction arises because the influence of artificial lighting depends on its contrast with adjacent, interior location environments.

What is needed in Florida is a statewide (or, one could argue, national) policy for artificial light management. Organizations around the world have recognized this need and are actively proposing change through public education, stressing the energy-saving, ecological, and aesthetic benefits of light management. But the task will take time, hard work, and patience. For the moment, the best we can do as conservation scientists is to act locally to protect wildlife in critical habitats. But we must also promote through our conversations with public officials, our writings, and our lectures a message that artificial lighting must be managed everywhere.

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