Artificial night lighting and sea turtles

Courtesy of J Amos, National Geographic

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Natural transitions between light and darkness influence the biology and behaviour of many organisms. What happens when humans introduce light into darkness? Oceanic beaches, where sea turtles nest, provide an example of both the problem and approaches to its solution.

In south-eastern Florida, sandy beaches attract tourists during the day whose principal activities are recreational: basking, building sand castles, swimming and socialising. But, at night, a clientele with more utilitarian objectives frequents the beach. These visitors approach shore from the ocean rather than from land. Their stay (like tourists') is brief and also recorded by tracks on the sand surface. However, these nocturnal visitors leave behind something of substance: clutches of about 100 eggs buried deeply in the sand.

Our nocturnal visitors, marine turtles, are huge reptiles that have a residency of tens of millions of years on this planet. But 'newcomers' – humans – have catastrophically reduced their numbers directly (by egg and adult harvesting) and indirectly (incidental capture by fisheries, and habitat modification and degradation). Here, I describe another kind of habitat modification: how our use of night lighting repels females from nesting beaches and causes the death of many of their hatchlings.

We've recognised the severity of this impact for only about 30 years. Now, there is a growing International effort to restore darkness to coastal and other wildlife habitats. It's a global problem, affecting the survival of many species of nocturnally active wildlife and the integrity of the communities in which they play a role. Solving the lighting problem for sea turtles thus becomes part of the international effort to modify how we design and use artificial lighting, with widespread economic, aesthetic and ecological consequences.

Sea turtles and nesting beaches

To see a marine turtle nest is an inspiring, as well as fascinating, experience (Figure 1). The process is much the same in all seven species of sea turtles. The patient observer first sees a huge head, then a glistening carapace (top shell) emerge from the surf. The turtle then pauses, perhaps gauging the slope and elevation of the beach, perhaps scanning for predators, perhaps stunned by feeling its 200–400 kg body weight without the buoyancy provided by water. If all seems well, she begins to drag her huge mass up the beach. It is a slow, but deliberate, movement punctuated by frequent pauses. Finally, the female reaches a location between the dune vegetation and high tide wrack, and begins to dig a depression ('body pit') using sweeping motions of the fore and hind flippers. Next, and with delicate movements of her rear flippers, she scoops out a flask-shaped egg chamber with dimensions determined entirely by 'feel'. Finally, the turtle will spread her rear flippers to each side of the egg chamber and, every few seconds, drop two to five soft-shelled eggs at a time into the egg chamber until the cavity is almost filled.

The process is completed by 'covering' and 'hiding' the eggs. Covering is also accomplished by feel, using the rear

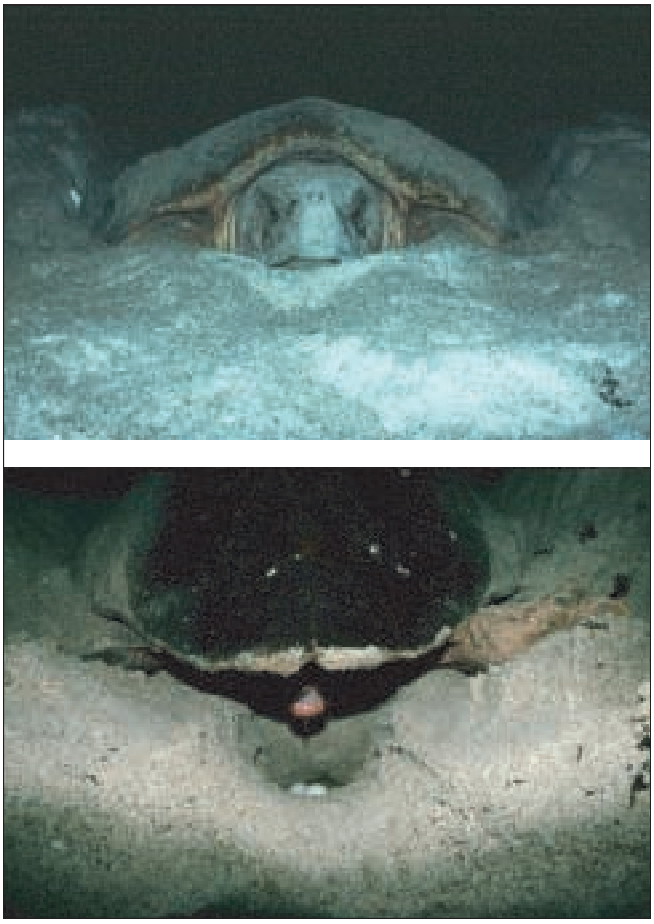

Figure 1. Anterior and posterior views of a nesting loggerhead. Note that her body lies in a shallow pit that she dug earlier (upper). Lower photo shows the egg chamber, with two eggs at the top of the clutch just visible. Photos courtesy of J Wyneken.

flippers to shovel sand over the open egg chamber, then to compress sand over the opening. Hiding that follows is done by scattering surface sand about the whole area with sweeping movements of the foreflippers. Finally, the turtle turns toward the sea and crawls, somewhat less laboriously, down the beach, leaving behind another track that terminates at the surf but leads the eye up the beach toward the wide area of disturbed sand. The whole process takes anywhere between 30 minutes to over an hour.

It's been estimated that depending upon species, a female will reach sexual maturity in 10–50 years. By marking nesting females with external and internal tags, we've learned that nesting will occur from two to eight times in a season, at intervals ranging between nine and 14 days. Using satellite telemetry, we've also learned that females arrive at nesting beaches from feeding grounds that could be either adjacent to the beach or over hundreds of kilometers away. Long journeys are accomplished through the use of a spatial 'map' that enables turtles to travel on precise, and often direct, routes between these locations.

Having completed a seasonal nesting cycle, a female may take from two to five years to accumulate enough energy at the feeding grounds to again support both her migration to the nesting beach (where, typically, there's no food) and the production of hundreds of eggs over a season lasting a few weeks. Long-term records for individual females show they have reproductive life spans that can exceed 40 years. Finally, we know from maternal genetics that females nesting at specific rookery beaches are descendants of one or a few 'founders' – turtles that were the first to initiate nesting in the area many generations ago.

After incubation in the moist, sun-warmed sand for about 50 days, hatchlings break through the eggshell, dig their way almost to the surface and then wait for the sand to cool (a signal that it's night time). Suddenly, the turtles will break through the surface and emerge, then scamper *en masse* (like little wind-up toys) directly from the nest to the ocean (Figure 2). Carried seaward by a retreating wave, they will swim non-stop for 24–36 hours on a migration that takes them to 'nursery' areas located many miles distant in the open sea.

This process of locating the ocean from the nest, or *seafinding*, is accomplished visually. A small hatchling crawling upon an uneven beach surface cannot directly see the ocean from the nest; it must find its way using reliably simple, but indirect, cues. Hatchlings instantaneously scan 180° wide areas close to the horizon, then crawl away from scans that contain elevated, darker locations (the light-absorbing dune and its covering vegetation behind the beach) and toward scans with lower, flatter and, typically, brighter locations (the light-reflecting view, seaward). This response usually depends upon a simultaneous evaluation of light intensity and detection of object detail, using form vision. When turtles nest on continental shorelines, hatchlings probably use both cues; when nests are placed on isolated low, flat islands lacking much vertical detail, intensity cues are probably more important. Equipped with these rudimentary essentials, the outcome is much the same: hatchlings' crawls seldom deviate more than ± 20° from a heading directly toward the sea (Figure 2).

Only one of every few thousand hatchlings will have the unique combination of good genes and good luck to survive the many decades of growth required to reach sexual maturity. Those that do will join the small proportion of individuals in the population that perpetuate the next generation.

Female survivors will choose nesting beaches geographically near to sites where, many years before, they emerged from nests as hatchlings. How such memories are learned and retained is one of many mysteries of marine turtle biology. But what is certain is that this form of rapid learning early in life ('imprinting') makes it possible for a female, nesting for the first time, to avoid a prolonged search for an appropriate nesting location. She places her eggs where her ancestors completed the process successfully. Such an

Figure 2. Loggerhead hatchlings emerge (left). Their tracks, visible the morning after, lead directly from the nest (foreground) to the ocean. Photos, courtesy of J Wyneken and R Ernest.

efficient strategy has probably served marine turtles well during most of their history, but it was never designed to anticipate how rapidly humans could alter habitats. Within one sea turtle generation, a once-ideal nesting beach can become a coastal town, a major port, or even a city. Thus, by the time a hatchling reaches maturity and performs her first nesting migration, she may find a natal site that is no longer 'safe' or 'attractive'.

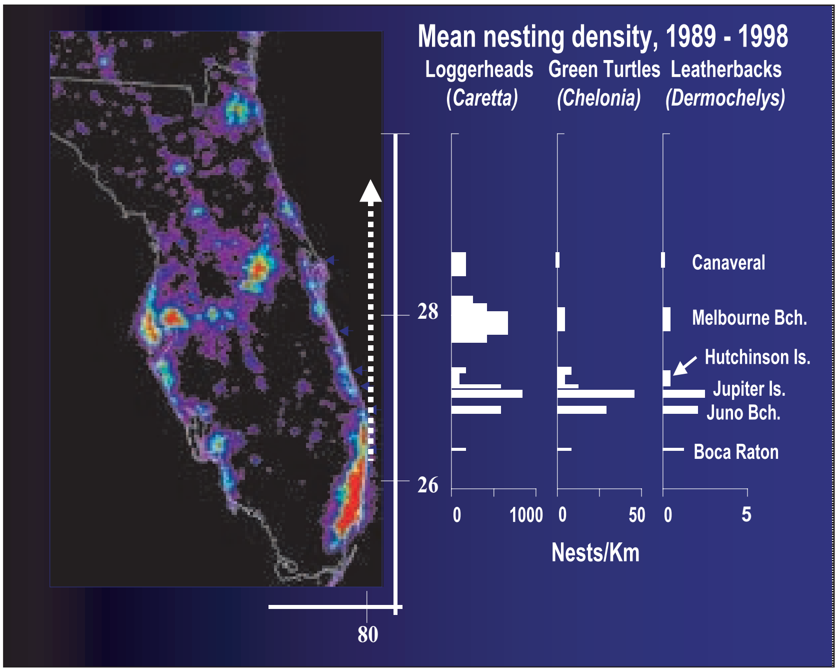

Figure 3. Florida at night, showing areas of brightest irradiance (red). Right plot shows latitude of the major nesting beaches along the southeastern coastline. Dashed arrow indicates the approximate western margin of the Florida Current that carries hatchlings to their nursery areas. All three species nest at the darkest remaining beaches in closest proximity to that current. Satellite photo courtesy of C Elvidge (NOAA).

Artificial lighting and nesting behaviour

Since the 1950s, the State of Florida has been keeping records of nesting 'activity' along its coastline. Three species routinely use the beach: the loggerhead *(Caretta caretta)*, green turtle *(Chelonia mydas)* and leatherback *(Dermochelys coriacea)*, with the loggerhead most common. While nesting is widespread, most of it is confined to the south-eastern coast. Furthermore, all three species nesting in Florida seem to prefer the same beaches within this area, suggesting that common selection pressures determine their choice (Figure 3). These sites have proximity to the Florida Current (western portion of the Gulf Stream) in common, so close to shore that it can be reached within a few days by a hatchling. Since hatchlings are slow but strong swimmers, proximity to favourable oceanic currents is one of many factors influencing the choice of a nesting beach by females.

Currently preferred nesting sites are also locations where coastal development is sparse. Why? There are numerous possibilities. Less development means fewer people on the beach at night to disturb wary females. Alternatively, it could be that the association with human development is accidental, and that at those sites sand quality is better for egg development, or predators take fewer hatchlings. In a simple experiment, one of my colleagues, Blair Witherington, showed that absence of artificial lighting was important. He used portable generators to illuminate a portion of two prime nesting sites every few days: Melbourne Beach in Florida, where loggerheads nested, and Tortuguero in Costa Rica, a location favoured by green turtles. When the lights were on, nesting activity declined nearly to zero; when they were off, the females returned. Light quality was also important. 'White' light (containing both short and long wavelengths) repelled the turtles, while yellow light (composed of a single long wavelength, visible to the turtles) did not.

At locations in Florida where beaches are exposed to lower levels of artificial lighting, nesting still occurs, though in lower numbers. Thus, the repelling effect is 'dose dependent'. We studied the distribution of nests at such a location: a seven-kilometre-long beach located in front of a small Floridian city (Boca Raton). Half of the beach is backed by tree-filled parks while the remainder is backed by high rise condominiums, unoccupied (and dark) during the summer nesting season. To our surprise, records over the years showed that more nesting occurred in front of the condominiums than in front of the parks, though surely the latter more closely resembled a natural shoreline. We looked for reasons, both on land and underwater, to explain why condominium sites were preferred. The only consistent variable was the amount and pattern of city lighting reaching the beach. At the condominium site, the darkened buildings acted as light barriers that shaded the beach, except at the spaces between buildings. The turtles nested selectively in front of the buildings, avoiding the illuminated gaps. Nest counts revealed that numbers in front of each building were positively related to building elevation (Figure 4). At the parks, trees also shadowed the beach from inland urban lighting but less effectively, perhaps because of their lower elevation and uneven density.

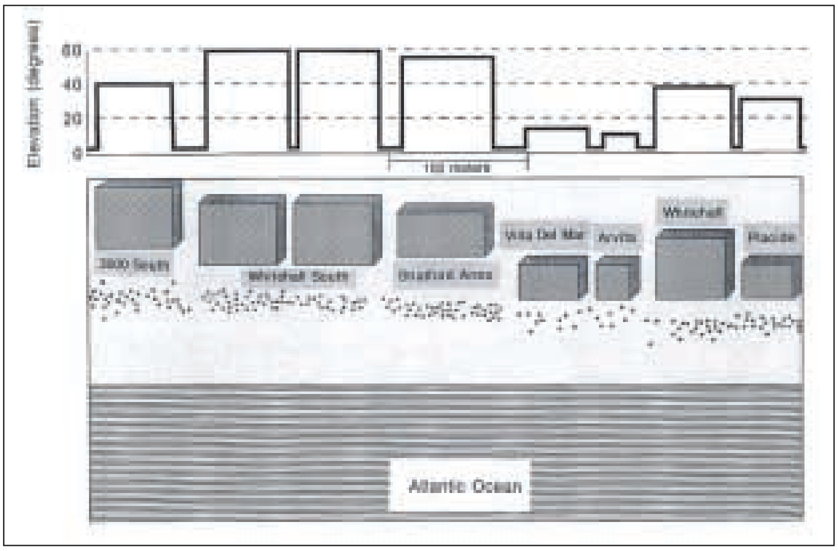

Figure 4. 'Condominium row' at Boca Raton, Florida. Top: Elevation (in degrees above the horizon) of the buildings. Below: Overhead view showing the buildings and distribution of turtle nests (black dots) on the beach. Nests are clustered in front of the buildings, with more nests in front of the tallest structures (from Salmon et al.*, 1995).*

Even so, nest 'densities' per length of city park beach exceeded those at locations adjacent to Boca Raton where the dune had been flattened and cleared, and where beaches were directly exposed to lighting.

What can we conclude from these findings? We know from other studies that many variables are correlated with preferred rookery sites. Typically, sites are remote, exposed to relatively low wave energies (and, therefore, weaker erosion that could destroy nests), located near favourable oceanic currents, and characterised as well by the absence of large terrestrial predators that could take females. Before humans (and their lighting) became a presence, all potential beach sites were dark and so contrasts in 'darkness' probably played no role in the selection process. Now, in what must represent only 'seconds' in a long marine turtle history, coastal lighting has become an important intruding variable that is likely to compromise site selection based upon cues with 'proven' survival value.

At locations like Florida, where the pace of coastal development has been exponential, the consequences of this trend can easily be predicted: more nests will be concentrated in a decreasing area of dark beaches. The spatial concentration of nests is known, elsewhere in the world, to attract both terrestrial and marine hatchling predators, and to increase hatchling mortality rates. Spatial concentration of nests has other negative effects including: destruction of previously deposited nests by females that nest later; microbial blooms in sands with too many left-over dead eggs; and increasing probabilities that chance events (such as local storms or a hurricane landfall) will destroy a large proportion of the annual allotment of nests.

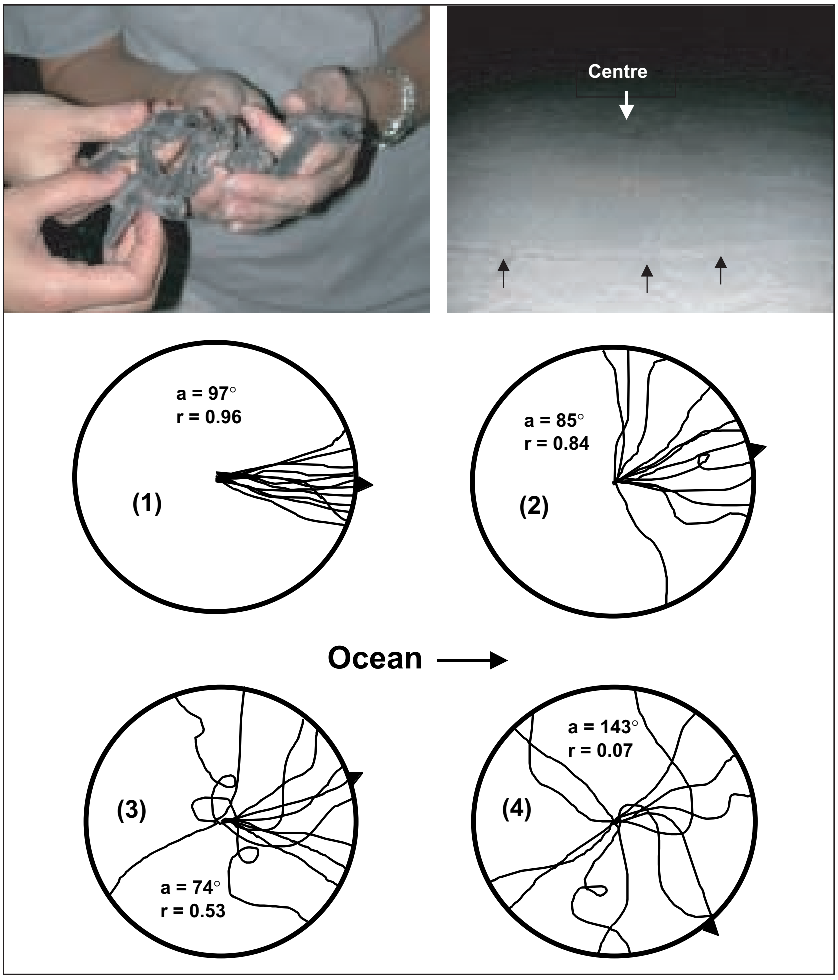

Figure 5. Use of 'arena assays' to document the effect of artificial lighting on hatchling orientation. These assays are staged emergences at locations varying in exposure to artificial lighting. Turtles are collected just prior to a natural emergence (upper left), then transported to another beach. They are released in the centre of a four-metre-diameter circle, drawn on the beach surface at a location where nests are typically deposited. As it crawls away, each turtle leaves a track in the sand. Its orientation is measured by the angle between the arena centre and the arena boundary exit point (arrows, upper right).

Line drawings below show tracks at four Boca Raton sites, ranging from darkest (1) to most lighting-exposed (4). The ocean is East (~ 90°). Circular statistics are used to determine 'a', the mean angle of orientation for all of the turtles in that group, and 'r' (r-vector), a measure of their angular dispersion, which ranges between 0 and 1. Both indicate whether artificial lighting disrupts orientation. At dark beaches, the mean angle is typically ± 20° of the seaward direction, and the r-vector is ≥ 0.9. Note that at sites exposed to more lighting, 'a' and 'r' depart increasingly from those values. In this example, artificial lighting causes disorientation (modified from Salmon et al.*, 1995).*

Artificial lighting and seafinding

Hatchlings that emerge from nests exposed to even a few luminaires often fail to locate the sea. What happens is documented on the beach surface by their flipperprints (Figure 5). Instead of tracks leading directly to the sea, turtles leave evidence that they crawled for hours on circuitous paths ('disorientation'), or on direct paths away from the ocean and toward lighting ('misorientation'). In Florida, thousands of these hatchlings die annually from exhaustion, encounters with terrestrial predators, entanglement in dune vegetation, dehydration after sunrise, or even crushing by cars as turtles traverse coastal roadways.

We don't know what physiological changes are responsible for the breakdown in normal orientation behaviour, either in hatchling sea turtles or in the many other nocturnally active species whose 'orientation systems' are similarly disrupted by exposure to artificial lighting. Disorientation may signal either an inability to perceive natural cues, or a competition between natural cues and artificial lighting that can't be resolved. Misorientation suggests another consequence: directional cues are received but they represent 'misinformation', which directs organisms toward goals that promote death rather than survival.

We do, however, now understand how natural and artificial lighting differ as visual stimuli (Table 1); these differences form the basis for hypotheses that may explain why normal orientation behaviour fails with artificial lighting. The contrasts between natural and artificial light were effectively highlighted in papers published by Verheijen (1985). Verheijen was critical of contemporary attempts to classify visual orientation by animals. His criticisms were prompted, firstly, by the simplified visual environments used and, secondly, because the responses they evoked ('forced movements' either toward or away from lamps) were not representative of those shown by animals in nature, especially those with image-forming eyes.

For example, in many animals, orientation involves choosing a biologically appropriate direction away from

Table 1. Differences between artificial and natural lighting (modified from Verheijen, 1985).

Source	Artificial lighting comes from nearby luminaires; natural lighting comes from distant celestial objects (sun, moon, or stars).
Scattering	Because luminaires are nearby, there is little scattering or reflection before their light is detected; natural light is scattered by the atmosphere before it reaches an observer.
Reflection	Artificial light appears bright because of its proximity, but fades rapidly with distance, where there is little energy left to reflect. Natural light is everywhere and is abundantly reflected by both distant and nearby objects.
Directivity	Artificial sources radiate light from one direction (the source) but not from other directions (high directivity). Brightness toward the source greatly exceeds brightness measured from elsewhere. Natural light illuminates and reflects from many objects. Its brightness differences, as a function of direction, are much less extreme (low directivity).
Direction	Artificial light sources can be positioned anywhere (above, below, to the side) relative to an observer. Natural light sources are above, and reliably indicate downward. Exposed to the former, body orientation of flying or swimming animals may be abnormal, whereas, under natural light, orientation is usually normal.

one habitat and toward another – for reasons that promote either short- or long-term survival. The visual cues used to govern these movements are often located at *some angle* relative to the body, not directly ahead or behind. In solar and lunar orientation, which is commonly used for these purposes, animals choose a constant direction (away from habitat A and towards habitat B) and compensate (using their time sense) for the constantly changing azimuth of the celestial reference. Thus, argued Verheijen, a proper understanding of visual orientation could not be gained by analysis of movements 'toward or away'. Neither could the properties of animal perceptual systems (visual receptors and neural connections to information-analysing brain areas) that control orientation – in this case relative to objects that change in elevation, colour, brightness and even apparent size as they 'travel' across the sky.

Perceptual systems, he insisted, were designed by evolution to process natural distributions of light stimuli. When presented with experimentally simplified distributions (typically, a single luminaire in an otherwise dark surround), the result was *pathological behaviour* such as disorientation and misorientation, observed not only in hatchling sea turtles but many animals under these testing conditions. In 1985, Verheijen proposed the term 'photopollution' to describe '… *degradation of the photic habitat by artificial light*'.

There are several differences between natural and artificial light (Table 1), but most of them lead to a common result: excessive 'directivity' (greater brightness in one direction, toward the luminaire, than in all other, background, directions). If directivity caused abnormal behaviour, then an increase in background illumination should reduce the directivity of luminaries as well as the pathological behaviour that they cause. Verheijen reported that just such an effect was well documented (but previously unexplained) in the wildlife literature. Many night-migrating birds (that fly *en route*, by the thousands, into lighted towers, lighthouses, or other illuminated structures) and countless nocturnal insects (that similarly aggregate at lights) are injured or killed annually. But the incidence of injury or death in birds and insects declines under full moon illumination. Witherington and I found much the same pattern on Florida beaches. Reports of hatchling orientation problems state-wide reached their peak during the days surrounding new moon, but declined to almost zero during the evenings when a full moon was present.

Solving the 'photopollution' problem

Beaches in Florida are exposed to lighting because, until recently, nobody realised that improperly designed or placed lighting fixtures caused a problem. They do. Instead of focusing light where it is intended (generally, downward), it is scattered in all directions including upward, where it serves no useful purpose (except as a tool to demographers who estimate the growth of cities by night-satellite photography!). In the US alone, it's estimated that 30% of all outdoor lighting is wasted by illuminating the atmosphere, at an estimated cost of $1.5 billion in wasted electricity (and six million tons of burned coal used to generate that energy). Reducing or eliminating this waste not only benefits nocturnal wildlife, but human health and treasury.

Strategies required for effective light management almost anywhere are intuitively obvious. (1) Turn off unnecessary lights. (2) Reduce luminaire wattage to the minimum required for function. (3) Redirect and focus lighting so it only reaches the ground, or those areas (*e.g.*, signage, parking lots, streets) where it is intended. Such control is achieved through the use of properly shielded fixtures that redirect lighting, or the addition of appropriate shielding to luminaires that scatter lighting. (4) Eliminate all upward-directed decorative lighting. (5) Use alternative light sources where possible and practical. These include luminaires that emit restricted subsets of (longer) light wavelengths, which are less disruptive to most wildlife, or those that carry out their function not by brightening areas, but rather by directing humans or human traffic in specific directions ('chains' of light-emitting diodes in walkways, along trails, or embedded in roadways). (6) In any new construction, incorporate the latest light management technology so that continued growth and expansion leads to no increase in the impact of artificial lighting. The summed effect of these modifications is not only energy conservation, but also night lighting that is optimally functional for humans. Indeed, the aim is not to eliminate lighting but rather to reduce its unintended impact.

Most coastal counties in Florida have passed lighting ordinances or laws that regulate and restrict lighting practices adjacent to sea turtle nesting beaches. Enforcement is stricter in some counties than in others, but the very passage of these laws indicates a growing public awareness that marine turtles are exceptional creatures whose continued existence has intrinsic value, despite the costs. Many of Florida's beaches are getting darker, and numbers of turtles nesting annually are slowly, but significantly, on the rise. This positive outcome must, however, be tempered by the knowledge that the threat of artificial lighting is not going away in Florida, but simply changing. In a few years, the most important lighting issues affecting turtles may not be from luminaires at the beach, but from those placed inland. Light pollution from those sources (such as shopping centres, open-air sports arenas and car dealerships) produces sky glow, which also disrupts the orientation of hatchlings. But perhaps, by then, we will have adopted a national lighting policy so that not only coastal marine life, but all wildlife, can benefit.

Further Reading

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Witherington B E (1997) The problem of photopollution for sea turtles and other nocturnal animals. In: *Behavioral Approaches to Conservation in the Wild*. Clemmons J R and Buchholz R (Eds). Cambridge University Press.

Websites

www.urbanwildlands.org/nightlightbiblio.html

This private environmental advocacy group recently sponsored a meeting of experts entitled *Ecological Consequences of Artificial Night Lighting*. See their web site for meeting abstracts; these will soon be published in book form.

www.darksky.org.html

The International Dark-Sky Association was formed by a few astronomers concerned about the impact of night lighting on their ability to view the heavens. Its much larger membership now consists both of scientists and citizens who actively promote light management worldwide. It is an excellent source of information about lighting issues that includes packages for public education, bibliographies, meeting announcements, legal issues, lighting technology and legislation.

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