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Association between nighttime artificial light pollution and sea turtle nest density along Florida coast: A geospatial study using VIIRS remote sensing data☆

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ABSTRACT

Artificial lighting at night has becoming a new type of pollution posing an important anthropogenic environmental pressure on organisms. The objective of this research was to examine the potential association between nighttime artificial light pollution and nest densities of the three main sea turtle species along Florida beaches, including green turtles, loggerheads, and leatherbacks. Sea turtle survey data was obtained from the "Florida Statewide Nesting Beach Survey program". We used the new generation of satellite sensor "Visible Infrared Imaging Radiometer Suite (VIIRS)" (version 1 D/N Band) nighttime annual average radiance composite image data. We defined light pollution as artificial light brightness greater than 10% of the natural sky brightness above 45° of elevation ($>1.14 \times 10^{-11}$ $Wm^{-2}sr^{-1}$). We fitted a generalized linear model (GLM), a GLM with eigenvectors spatial filtering (GLM-ESF), and a generalized estimating equations (GEE) approach for each species to examine the potential correlation of nest density with light pollution. Our models are robust and reliable in terms of the ability to deal with data distribution and spatial autocorrelation (SA) issues violating model assumptions. All three models found that nest density is significantly negatively correlated with light pollution for each sea turtle species: the higher light pollution, the lower nest density. The two spatially extended models (GLM-ESF and GEE) show that light pollution influences nest density in a descending order from green turtles, to loggerheads, and then to leatherbacks. The research findings have an implication for sea turtle conservation policy and ordinance making. Near-coastal lights-out ordinances and other approaches to shield lights can protect sea turtles and their nests. The VIIRS DNB light data, having significant improvements over comparable data by its predecessor, the DMSP-OLS, shows promise for continued and improved research about ecological effects of artificial light pollution.

1. Introduction

1.1. Background

Artificial lighting at night is a new type of pollution. The topic of light pollution is gaining more and more importance and an increasing interest. With the fast industrialization and urbanization over the past decades, the widespread use of artificial light has drastically changed nightscapes, but the negative effects of artificial lighting are often ignored. Excess artificial light affects plants and animals by disrupting their long-evolved diurnal and nocturnal circadian rhythm clock which plays a key role in the body's biological, physical and chemical activities, including feeding, sleeping, reproduction, growth and other behaviors (Dunlap, 1999), and thus affects orientation, communication, forage, food consumption, locomotion, migration, reproduction, and growth (Rich and Longcore, 2006).

Nocturnal light affects wildlife, including marine turtles, in areas near human settlements and other ecosystems (Longcore and Rich, 2004; Luarte et al., 2016; Outen, 1998; Raap et al., 2016; Verheijen,

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1985). Sea turtles have been living on the planet Earth since the time of the dinosaurs - back more than 110 million years (Gaillard et al., 2003). In the past century, sea turtle numbers have greatly declined and are in danger of extinction. A main threat is from artificial light pollution. The gap in knowledge concerning nest density and light pollution correlation at a broader regional scale prevents a complete understanding of the spatial distribution of sea turtles in relation to light pollution. Understanding the factors that affect the distribution and vulnerability of sea turtles is important to effective global conservation (Mazor et al., 2013).

1.2. Existing research using remote sensing and statistical models

Studies of light pollution effects on organisms often experimentally manipulate the light environment, which is limited in spatiotemporal coverage (e.g., Longcore and Rich, 2004; Luarte et al., 2016; Outen, 1998; Raap et al., 2016; Verheijen, 1985). Remote sensing has provided a broad and synoptic view of how humans have shaped the planet and lit up the darkness. Satellite mapping of nighttime light has broadened research about the ecological effects of artificial lights by providing unique data with extensive spatial and temporal coverages. Existing studies of light pollution effects on organisms, including sea turtles, have often used the "Defense Meteorological Satellite Program Operational Linescan System" (DMSP-OLS) imageries (e.g., Aubrecht et al., 2008, 2009; 2010; Aubrecht and Elvidge, 2008; Kamrowski et al., 2012; Mazor et al., 2013; Weishampel et al., 2016). The DMSP-OLS light data, however has several disadvantages: a limited dynamic range due to a low radiometric resolution of 6-bits only (DNs are 0–63), low pixel resolution of 30 arc-seconds, no in-flight calibration, and data saturation on bright urban cores (where the pixel value range does not have the capacity to represent brighter nighttime light) under normal operating conditions (Elvidge et al., 2017).

In 2011, the NASA/NOAA Suomi-NPP satellite was launched carrying the "Visible Infrared Imaging Radiometer Suite (VIIRS)". The sensor VIIRS has a radiometric resolution of 14 bit (a very wide DN range from 0 to 16,383), a pixel footprint of 742×742 m at nadir (vs. $5 \text{ km} \times 5$ km for DMSP-OLS), and an improved spatial resolution of 15 arc-seconds vs. 30 arc-seconds of DMSP-OLS (Elvidge et al., 2013). An important feature that makes VIIRS's DNB data advantageous over its predecessor, the DMPS-OLS, is its ability to screen out light unrelated to artificial lighting including sunlit, moonlit, and cloudy pixel light sources. VIIRS collects source data including larger numbers of multi-angle and multi-season observations which cancel out scan angle and seasonal effects on the brightness of lights to produce monthly and yearly averaged science-quality global nighttime artificial light radiance images (Elvidge et al., 2017; Ziskin et al., 2010).

The VIIRS Day/Night panchromatic band (DNB) is sensitive to visible and near-infrared wavelength range from 500 to 900 nm centered around 700 nm. The spectral wavelength range covered by the VIIRS sensor coincides largely with the visual capacities of sea turtles. Thus, using the VIIRS night radiance data shows great potential for assessing potential correlation of light pollution with sea turtle nesting. Experimental field investigations have shown that both adult and hatchling turtles are sensitive to the visible light with a wavelength range of 440–700 nm, with ~580 nm stimulating maximum response for adults (Levenson et al., 2004) and 540 nm for hatchlings (Horch et al., 2008; Witherington, 1992; Witherington and Martin, 2000). However, few studies have used VIIRS light data to investigate the potential association between sea turtle nest density and light pollution.

Existing studies often use statistical models to examine sea turtle nesting in relation to light pollution. Data used in statistical models often violate essential model assumptions: normal distribution of the dependent variable and residuals, as well as independent observations. Environmental and ecological data are often skewed rather than normally distributed. Observations made at different locations are seldom independent. Data values at nearby locations may be closer than those at locations farther apart - spatial autocorrelation (SA) might exist in the observations and residuals of model-fitted values. SA may give rise to biased correlation coefficient values (higher than what really are) and exaggerated precision (lower standard errors of the coefficients, and thus false statistical significance). SA is often ignored in statistical models, e.g., in Mazor et al. (2013)'s generalized linear model (GLM) about sea turtle nest patterns and night lights. Weishampel et al. (2016) log-transformed sea turtle density and DMSP-OLS artificial light values to obtain a normal distribution required for a simultaneous autoregressive (SAR) model. There might be problems with the classic log-transformation approach. Applying the log-transformation could make the distribution more skewed than the original data. For right-skewed data, the log-transformation could make it either right-or left-skewed. Log transformation can often increase, rather than reduce, the variability of data.

1.3. Florida sea turtle species and conservation status

Five of the seven worldwide species of marine turtles exist within Florida's ecosystems (FWC, 2015). Our research focuses on the three main species: leatherbacks, green turtles, and loggerheads, in the order of increasing nest numbers, with scientific names being *dermochelys coriacea* (DC), *chelonia mydas* (CM), and *caretta caretta* (CC) respectively. The loggerhead is named for its large, wide, block-like head with powerful jaws. An adult loggerhead has an average weight of 125 kg and is about 0.9-m-long. Its carapace is reddish-brown with a yellowish-brown plastron. There are as many as 68,000 loggerheads nests on Florida beaches each year. The green turtle has green body fat. It weighs an average of 160 kg. The head is small relative to its body size. Its olive-brown upper shell is oval-shaped and 1-m-long on average. It has yellow lower shell. As many as 2000 green turtle nests can be found on Florida beaches each year. The leatherback is the largest of the sea turtles. Leatherbacks are 1.8-m-long on average and with weights from 227 to 680 kg. They can grow up to 2.4 m in length and over 900 kg in weight. The leatherback has a firm, leathery skin and a rubbery dark shell with seven ridges running the length of its back. Leatherback can dive more than 900 m deep. They can travel about 5000 km from their nesting beaches. They tolerate cold water. About 200 leatherback nests are found in Florida every year (FWC, 2015).

Florida beaches are most important in the United States for nesting sea turtles. Over 90 percent of sea turtle nests in the conterminous USA are along Florida Atlanta and Gulf of Mexico coasts (FWC, 2015). Florida has the largest number of nests of loggerhead in the western hemisphere. Florida is one of the largest hosts of nesting green turtles in the greater Caribbean and Gulf of Mexico region. Florida has also seen significantly increasing leatherback nests (Dermochelys coriacea) (Stewart et al., 2011).

Protecting sea turtles on Florida beaches is significant in the global biodiversity conservation context. Sea turtles in Florida are endangered by natural predators and anthropogenic disturbances, such as hunting for their eggs, meats, or shells, coastal construction, beach re-nourishment, recreation, solid waste pollutants, fisheries, and artificial light pollution. In the "*Red List of Threatened Species*" by the "International Union for Conservation of Nature", loggerhead and green turtles are listed as "Endangered" and leatherback as "Vulnerable" (IUCN, 2017). The "U.S. Endangered Species Act" lists all the three species as either "Threatened" or "Endangered".