

OBSERVING STRESS OF ARTIFICIAL NIGHT LIGHTING ON MARINE ECOSYSTEMS – A REMOTE SENSING APPLICATION STUDY

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ABSTRACT:

Satellite based observation of nocturnal lighting opens up a variety of research and application fields dealing with impacts of light on the environment. The National Oceanic and Atmospheric Administration's National Geophysical Data Center (NOAA-NGDC) processes and archives nighttime lights data acquired by the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS). Initially designed to detect moonlit clouds this sensor is equipped with a photomultiplier tube intensifying the visible band signal at night and enabling the detection of lights present at the surface of the earth. It thus provides up-to-date information on the location and impact zone of oil and gas producing facilities, heavily lit fishing boats and the artificial night sky brightness that can extend many kilometers out from urban settlements. Artificial night lighting represents a direct threat to marine ecosystems and is an excellent proxy measure for indirect impacts such as human associated chronic water pollution. A growing body of evidence indicates that artificial sky brightness is an important stressor for many marine organisms, including birds and fish. In this paper we present selected 'eco-applications' of nighttime Earth Observation including assessment of light pollution impact on coral reefs and sea turtles. Coral reefs are highly photosensitive, i.e. many species synchronize their spawning through detection of low light intensity from moonlight and reef structure is strongly influenced by illumination. Settlements and other artificial sources of lighting provide illumination brighter than the full moon, especially at shorter wavelengths. Seabirds are intimately linked with the light features of their environments since they are nocturnally active. On the Azores Islands a campaign was initiated reporting light-induced falls of marine birds. Results will be presented of taking these available in situ data as reference for analyzing spatial correlations of altered environmental conditions and actual impact cases.

1. INTRODUCTION

A consequence of the explosive expansion of human civilization has been the global loss of biodiversity and changes to life-sustaining geophysical processes on Earth. The footprint of human occupation is uniquely visible from space in the form of artificial night lighting, ranging from the burning of the rainforest to massive offshore fisheries to omnipresent lights of settlements and connecting road networks. The systematic global mapping of nighttime lights from space opens up a variety of research and application fields dealing with human impacts on the environment. Artificial night lighting represents a direct threat to marine ecosystems and is an excellent proxy measure for indirect impacts such as human associated chronic water pollution. A growing body of evidence indicates that artificial sky brightness is an important stressor for many marine organisms, including birds and fish. Increasing research activities on assessing ecological consequences of artificial night lighting ('*ecological light pollution*') in recent years have attracted the attention of both scientists and journalists (Longcore & Rich, 2004; Rich & Longcore, 2006; Hotz, 2008).

2. NIGHTTIME EARTH OBSERVATION

Satellite based observation of nocturnal lighting opens up a variety of research and application fields dealing with impacts of light on the environment. The National Oceanic and Atmospheric Administration's National Geophysical Data Center (NOAA-NGDC) processes and archives nighttime lights data acquired by the U.S. Air Force *Defense Meteorological Satellite Program* (DMSP) Operational Linescan System (OLS). This sensor was initially designed for cloud monitoring using a pair of visible and thermal spectral bands. With the DMSP satellites flying in sun-synchronous, low altitude polar orbits and with a swath width of 3,000 km each OLS collects a complete set of imagery of the earth twice a day. At night a photomultiplier tube (PMT) intensifies the visible band signal in order to enable the detection of moonlit clouds, whereas the boost in gain allows the observation of lights present at the surface of the Earth. Most lights can be linked to human settlements (Elvidge et al., 1997) and ephemeral fires (Elvidge et al., 2001a), but also gas flares and offshore platforms as well as heavily lit fishing boats can be identified.

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1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	
F-10																		
	F-12																	
		F-14																
			F-15															
				F-16														

Figure 1. DMSP satellites and their respective covered time span used for time series analyses.

Nighttime image data from individual orbits meeting pre-defined quality criteria (i.e. referring to geolocation, sunlight, moonlight, cloudiness conditions) form the basis for the annual global latitude-longitude grids with 30 arc second resolution cells corresponding to approximately 1 km² at the equator (see Aubrecht et al., 2008 for more detailed explanations on data selection criteria and data composition).

NOAA's NGDC stores and maintains the long-term DMSP archive (figure 1), and has built up comprehensive experience in nighttime image processing and algorithm development related to feature identification (e.g. lights and clouds) and data quality assessment (cp. Elvidge et al., 1997; Elvidge et al., 2001b). Dating back to 1992 the data archive enables the production of a time series of inter-comparable single-year data sets for assessing temporal trends in human activity. Considering the entire available digitally preprocessed time series, temporally overlapping data from five DMSP satellites are used for inter-calibration: (1) F-10: 1992-1994, (2) F-12: 1994-1999, (3) F-14: 1997-2002, (4) F-15: 2001-2009, (5) F-16: 2004-2009.

3. SELECTED APPLICATIONS OF MARINE ECOSYSTEM MONITORING USING NIGHTTIME EARTH OBSERVATION

In the following sections we present selected applications of observing exposure of marine ecosystems to artificial night lighting. First, *coral reefs* are examined on a global scale, building up an inventory of stressors (derived from nighttime lights data) in close proximity to reef locations. Second, light pollution was observed on a more regional scale, comparing temporal patterns in *sea turtle* nesting activity with anthropogenic beach lighting development in Florida. Finally, this applications selection is concluded with a new study on mapping light pollution impact on *marine birds* on the Azores Islands where a ground data collection of light-induced bird fall locations serves as actual impact reference information.

3.1 Coral reefs

A growing body of evidence indicates that *artificial sky brightness is an important stressor for coral and other marine organisms* (Jokiel et al., 1985). In addition, satellite observations of lighting can be used as a *proxy for other stressors*, such as water pollution from urban areas, fishing and recreational use of reefs.

Coral reef ecosystems are generally found in shallow waters, between the Tropic of Capricorn and the Tropic of Cancer. Data indicating the spatial distribution of coral reef ecosystems are available on a global scale covering a total area of 255,000 km².

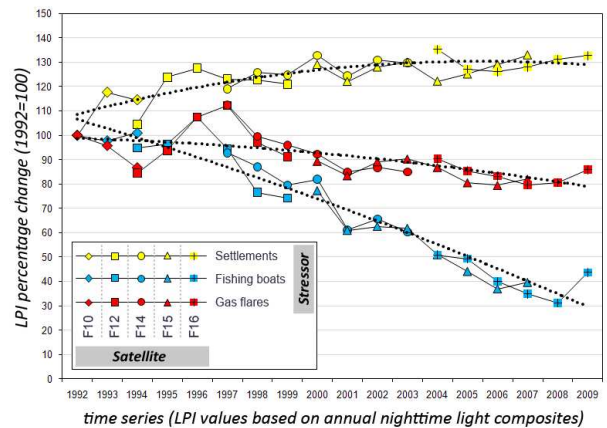


Figure 2. Lights Proximity Index relative change since 1992: (1) settlements, (2) fishing boats, (3) gas flares.

The data was obtained from 'Reefs at Risk' (Bryant et al., 1998) and originates from the United Nations Environment Programme - World Conservation Monitoring Centre (UNEP-WCMC). The initial base data had been converted into raster format at a spatial resolution of 1 km. For further spatial analyses this grid was (re-)converted into a point dataset. In the presented project a list of 330,490 coral reef point locations is used where each record is linked with a region classification table assigning the reef points to around 150 distinct geographic regions worldwide (primarily country-/archipelago-based).

For a globally consistent assessment of coral reef exposure to anthropogenic activities, reef stressors have to be derived from a spatially and temporally inter-comparable data source available on a global scale. Based on DMSP nighttime lights data, we developed an indicator (Lights Proximity Index, LPI), which integrates the brightness and distance of lights near known coral reef sites. Separate LPI values are calculated for the three stressors observable in nighttime lights: (1) human settlements, (2) gas flares, and (3) heavily lit fishing boats. The contribution of lights to the LPI declines as their distance away from the reef site increases. The initial LPI calculation is described in Aubrecht et al. (2008).

Based on the digital nighttime lights data archive a time series has been created which enables monitoring of temporal trends and detecting areas of improvement and degradation on a regional scale. First results of this temporal trend analysis were presented by Aubrecht et al. (2009). The current version of the LPI time series includes annual composites of nighttime lights from DMSP satellites F10 to F16 covering the years 1992 through 2009.

As illustrated by figure 2, results indicate that since 1992 lighting from human settlements in proximity to coral reefs has grown (yellow graph), an indication of the expansion in population and infrastructure in coastal areas in many parts of the world. In contrast, lit fishing boats activity (blue graph) has declined. This may be the result of improved regulation and management of reef areas, changes in fishing practices, or the depletion of fish stocks that are amenable to capture using bright lights. The LPI time series from gas flares (red graph) shows a more complex pattern, with dips in 1994 and 2001, a peak in 1997, and a largely steady pattern from 2002 through 2009.



Figure 3. (1) DMSP nighttime lights and superimposed Core Florida Index Beach locations; (2) warning sign indicating the legal protection status of loggerhead turtle nesting areas (photo, www.maxrharris.com/caretta); (3) baby loggerhead properly oriented towards the ocean (photo, www.dep.state.fl.us).

3.2 Sea turtles

Turtles are reptiles that are tied to the land for oviposition (egg-laying). There are seven species of marine turtles today, six of which are listed as endangered and one as threatened. The reasons for their listings are diverse, but all are human-caused: loss of habitat, habitat alteration, illegal and legal fishing, boat hits, pollution, etc. (Nicholas, 2001). One particularly adverse effect is light pollution, i.e. the presence of detrimental artificial light in the environment. *Anthropogenic beach lighting significantly impacts critical nocturnal behaviors of marine turtles* such as (1) the choosing of nesting sites for laying, incubating, and hatching eggs, (2) the returning to the sea after nesting, and (3) hatchlings finding their way to the sea after emerging from their nests (Witherington & Martin, 2000). The cues for orienting in the proper direction appear to be based upon natural light. Because of their tendency to move in the brightest direction, hatchlings show an immediate and well-directed orientation towards the water in natural conditions. Before anthropogenic lighting, dune silhouettes were typically darker than the surf. Now the reverse is often true. On artificially lighted beaches, hatchlings become misdirected by lighting sources, which leaves them unable to find the water and likely to die from dehydration and predation (Salmon, 2003; Lorne & Salmon, 2007). Furthermore, light pollution literally destroys the natural habitat, as beaches become unsuitable for nesting. Adult females favor dark beaches for their nest sites when emerging from the sea at night, with artificial lighting basically deterring them from doing so (Witherington, 1992).

In the presented study nesting activities of Loggerhead sea turtles (*Caretta caretta*) along the coast of Florida are examined and set in relation to the development of artificial night lighting as observed by DMSP-OLS (Ziskin et al., 2008). Loggerheads live in tropical and temperate oceans and have a generation time of approximately 45 years. Mature females (approximately 30 years old) tend to return to their natal beach to lay their eggs (Heppel et al., 1997). Since 1989, the Fish & Wildlife Research Institute of the Florida Fish & Wildlife Conservation Commission has coordinated the Index Nesting Beach Survey (INBS), a detailed sea turtle nesting-trend monitoring program, in conjunction with the Statewide Nesting Beach Survey (SNBS) program. The INBS program was established with a set of standardized data-collection criteria to measure seasonal nesting, and to allow accurate comparisons between beaches and between years. The INBS program is suited to these trend assessments because of its uniformity in beach-survey effort, spatial and temporal detail, as well as the specialized annual training of beach surveyors.

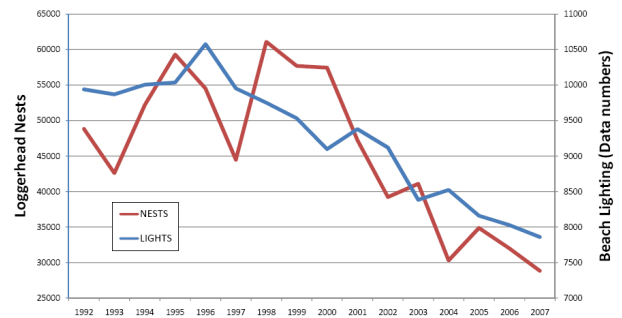


Figure 4. Temporal trends in loggerhead nesting counts and anthropogenic beach lighting.

To measure the temporal trend in artificial beach lighting DMSP-OLS data is used, i.e. the annual mean of persistent lights (1992-2007 time series). Imagery was inter-calibrated to account for changes in platforms and instrument fluctuations. Observations from multiple platforms were averaged. Nighttime lights data is superimposed on the locations of Core Florida Index Beaches, where surveys of Loggerhead nesting occurred (see figure 3). The brightness intensity values are then summed up for each index beach pixel. Referring to the natural nocturnal marine turtle behavior our hypothesis was that an increase in night lights along Florida's coast would result in a decrease in loggerhead sea turtle nesting. Comparing the two time series results, we find that Florida has decreased its night lighting near nesting beaches, yet total loggerhead sea turtle nesting continues to decline (see figure 4).

The observed 25% decrease in beach lighting since 1996 is most likely due to newly introduced legal restrictions. In 1986 Florida passed a law requiring localities to regulate beachfront lighting for the protection of sea turtles (*Florida Law 161.163*). This law was followed by the promulgation of a Model Lighting Ordinance in 1993.

Excerpt from Florida Law 161.163:

“Coastal areas used by sea turtles; rules.

--The [Department of Environmental Protection] shall adopt by rule a designation of coastal areas which are utilized, or are likely to be utilized, by sea turtles for nesting. The department shall also adopt by rule guidelines for local government regulations that control beachfront lighting to protect hatching sea turtles.”

Looking at the continuous decline in nesting activities along Florida's coast and taking into account the loggerhead life cycle, we come to the following conclusions. Total loggerhead nesting has declined for reasons other than contemporary levels of anthropogenic beachfront lighting. There would be approximately a 30-year lag between hatchling mortality and lowered nest counts (female maturity at the age of 30 years). With the digital DMSP data archive dating back to 1992, more than 10 years of data records would still have to be collected, before we might be able to observe direct relations. Anthropogenic lighting is furthermore expected to affect nest site choice on a scale finer than the entire state of Florida. Nesting loggerheads are predicted to favor individual beach segments with the lowest levels of anthropogenic lighting.

3.3 Seabirds

Petrels and shearwaters (Family *Procellariidae*) are known to be very sensitive to artificial lights (Imber, 1975) because they commonly attend breeding colonies at night. *Artificial lights can attract and disorientate birds* (Verheijen, 1981; Longcore & Rich, 2004), particularly fledglings during their first flight to the sea, and many of them thus fall to the ground with fatal injuries, are killed by predators or die to starvation (Le Corre et al., 2002). Oro et al. (2005) reported the increase of predation rates by yellow-legged gulls. There are two main reasons to explain this attraction: (1) The artificial lights can lead to incorrect visual orientation since the first-time navigation to the sea at night depends on visual cues given from moon and star light (Telfer et al., 1987), (2) petrels and shearwaters feed on bioluminescent squids, and inexperienced birds tend to search for lights (i.e. including artificial lights) to improve their chance of getting a meal (Imber, 1975; Klomp & Furness, 1992; Montevecchi, 2006).

Many petrels and shearwaters have undergone a substantial decline in recent times. In accordance to BirdLife International (2000), more than 50% of these species are threatened, mostly due to the presence of introduced predators and the impact of commercial fisheries. Although many of these species breed on islands inhabited by humans, very few studies focus on the impacts of artificial lights on their ecology. In Hawaii, urban lights were responsible for a large mortality of petrels (Telfer et al., 1987; Anley et al., 1997). On Réunion Island, light pollution induced mortality to all breeding species of petrels (Jouanin & Gill, 1967; Jouanin, 1987; Le Corre et al., 1996, 1999). On Canary Island of Tenerife, light-induced mortality rates are reportedly of concern for petrels and small shearwaters (Rodríguez & Rodríguez, 2009).

In the Azores, the attraction of Cory's shearwater to artificial lights has been known for a long time and since 1995 the regional government arranges rescue and awareness campaigns. This protected species is the most abundant seabird species of the Azores and is not in threat. Anyhow, populations are restricted to the Atlantic and Mediterranean Sea and their breeding population suffered a huge effective decrease in recent years (Bolton, 2001). During the last 10 years the Regional Government has carried out an awareness campaign called 'SOS Cagarro', which involves local media asking people to collect fallen birds and follow provided guidelines to release the animals safely (i.e. at the coast during daylight to avoid repeated distraction by artificial lights). Every night during the months of October and November, which is the period coinciding with the departure of juveniles from their nests for the first flight to the sea, the NGO 'Amigos dos Açores' ('Friends of Azores') formed several groups of volunteers that roam the streets and roads of São Miguel island in search of fallen birds, collecting all the Cory's shearwater they found. For each bird (dead or alive) exact place and date were recorded. We finally brought the data into GIS format in order to be able to use it for subsequent spatial analyses.

The aim of the presented study is to report light-induced falls of Cory's Shearwater on São Miguel Island, the biggest island in the Azores archipelago, and relate this data with satellite-observed nighttime lights (Rodrigues et al., 2010). Results will serve as a basis for recommendations and proposed actions to minimize light pollution stress on Cory's Shearwater and marine birds in general.

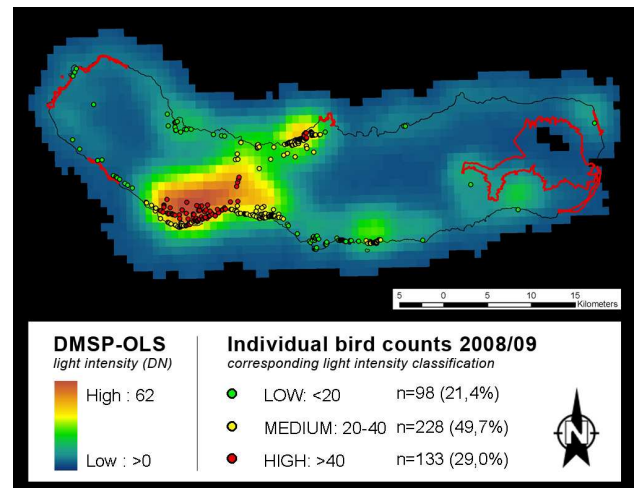


Figure 4. Spatial correlation between fallen bird records and light intensity. Important bird areas are delineated in red.

Figure 4 shows the spatial correlation of Cory's shearwater records from the 'SOS Cagarro' campaign and nighttime light intensity patterns. The bird counts are classified according to the lighting intensity at that corresponding location as derived from DMSP-OLS. Results underline the general light pollution problem in the context of adverse alteration of the natural environmental conditions for marine birds. Nearly 80% of all collected birds were found in areas with medium to high lighting intensity, while just about 20% were recorded in low light intensity regions. It can be assumed that all the fallen birds would have died without the intervention of rescue campaigns (Imber, 1975; Le Corre et al., 2002). Fallen birds, even if not injured, do not fly, but rather try to seek a dark hiding place where they would probably die of hypothermia, starvation, predation or anthropogenic causes (i.e. traffic accidents).

4. CONCLUSION AND OUTLOOK

The DMSP results indicate that it is possible to track the brightness and type of nocturnal lighting using satellite data. Calculated index values (e.g. LPI) can be used as a proxy measure for human stressors that would be difficult to observe in a consistent manner on a global scale. This includes anthropogenic stressors such as polluted urban runoff, sedimentation, and the recreational uses of marine ecosystems, which all tend to be higher in proximity to population centers. Regarding the direct impacts of artificial lighting, further research would be required to quantify the effects of artificial lighting on reef organisms. On the other hand, terrestrial studies have already confirmed direct light pollution impact on both sea turtles and marine birds (e.g. Salmon, 2003). Because of the 30 years time span female sea turtles need to return for nesting there is however no DMSP data available (i.e. archive dating back to 1992), which makes it impossible to explain temporal trends in nesting activity using nighttime earth observation.

It is known that lighting types vary spectrally (Elvidge et al. 2010) and as a result we recommend that the analysis of biological effects take into account the spectral differences in lighting types. While the DMSP nighttime lights are panchromatic, future satellite sensors may provide multispectral observations of nighttime lights (Elvidge et al. 2007), enabling more specific analysis of lighting impacts.

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