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Can satellite-based night lights be used for conservation? The case of nesting sea turtles in the Mediterranean

Tessa Mazor [a,b,*], Noam Levin [c], Hugh P. Possingham [a], Yaniv Levy [d], Duccio Rocchini [e], Anthony J. Richardson [f], Salit Kark [a,b]

[a] ARC Centre of Excellence for Environmental Decisions, School of Biological Sciences, The University of Queensland, Brisbane, Queensland 4072, Australia
[b] The Biodiversity Research Group, Department of Evolution, Ecology and Behaviour, The Silberman Institute of Life Sciences, Hebrew University of Jerusalem, Jerusalem 91904, Israel
[c] Department of Geography, The Hebrew University of Jerusalem, Mount Scopus, Jerusalem 91905, Israel
[d] Israel's Sea Turtle Rescue Centre, Nature & Parks Authority. Mevoot Yam, P.O.B. 1174, Mikhmoret 40297, Israel
[e] Edmund Mach Foundation, Research and Innovation Centre, Department of Biodiversity and Molecular Ecology, GIS and Remote Sensing Unit, Via Mach 1, 38010, San Michele all'Adige (TN), Italy
[f] School of Mathematics and Physics, The University of Queensland, Brisbane, Queensland 4072, Australia

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A B S T R A C T

Artificial night lights pose a major threat to multiple species. However, this threat is often disregarded in conservation management and action because it is difficult to quantify its effect. Increasing availability of high spatial-resolution satellite images may enable us to better incorporate this threat into future work, particularly in highly modified ecosystems such as the coastal zone. In this study we examine the potential of satellite night light imagery to predict the distribution of the endangered loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) sea turtle nests in the eastern Mediterranean coastline. Using remote sensing tools and high resolution data derived from the SAC-C satellite and the International Space Station, we examined the relationship between the long term spatial patterns of sea turtle nests and the intensity of night lights along Israel's entire Mediterranean coastline. We found that sea turtles nests are negatively related to night light intensity and are concentrated in darker sections along the coast. Our resulting GLMs showed that night lights were a significant factor for explaining the distribution of sea turtle nests. Other significant variables included: cliff presence, human population density and infrastructure. This study is one of the first to show that night lights estimated with satellite-based imagery can be used to help explain sea turtle nesting activity at a detailed resolution over large areas. This approach can facilitate the management of species affected by night lights, and will be particularly useful in areas that are inaccessible or where broad-scale prioritization of conservation action is required.

1. Introduction

Coastal zones are experiencing rapid population growth around the world (Turner et al., 1996) and attract increasing levels of tourism, trade and development (Shi and Singh, 2003; Stancheva, 2010). These anthropogenic pressures threaten biodiversity in the coastal environment, affecting the dynamics of flora and fauna populations and ecosystem processes (Chapin et al., 2000; Crain et al., 2009). While the effects of some human-caused threats have been examined in detail, our understanding of the consequences of artificial night lights on biodiversity in coastal areas, which have rapidly increased in both spatial extent and intensity in recent decades, remains limited (Longcore and Rich, 2004).

Researchers have studied the effect of night lights on species for many years (Longcore and Rich, 2004). Previous studies exploring the impact of artificial lights on organisms were mainly conducted by ecologists studying species of birds (e.g. Longcore, 2010), sea turtles (e.g. Lorne and Salmon, 2007), bats (e.g. Jung and Kalko, 2010) and freshwater fish (e.g. McConnell et al., 2010). Results from these studies demonstrate that night lights can attract, repel, and disorientate organisms in their natural settings. These reactions can further alter behavioral patterns such as reproduction, foraging, migration, communication and predator–prey relationships (Longcore and Rich, 2004). Such studies provide evidence that artificial lights often have adverse effects on organisms (Salmon 2003; Bird et al., 2004; Longcore and Rich, 2004; Bourgeois et al., 2009; Kempenaers et al., 2010; Longcore, 2010).

* Corresponding author at: ARC Centre of Excellence for Environmental Decisions, School of Biological Sciences, The University of Queensland, Brisbane, Queensland 4072, Australia. Tel.: +61 972 2 6585714.

E-mail addresses: tessa.mazor@uqconnect.edu.au (T. Mazor), noamlevin@mscc.huji.ac.il (N. Levin), h.possingham@uq.edu.au (H.P. Possingham), yaniv@npa.org.il (Y. Levy), ducciorocchini@gmail.com (D. Rocchini), Anthony.Richardson@csiro.au (A.J. Richardson), salit.kark@gmail.com (S. Kark).

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The threats of artificial night lights to biodiversity are rarely explored at a broad spatial scale. Previous studies were predominantly conducted at a local scale in field or laboratory settings (Witherington and Bjorndal, 1991; Salmon et al., 1995b; Grigione and Mrykalo, 2004). However, broader, regional spatial patterns of activities and processes that threaten the existence of species are important to examine, especially when management practices are applied at larger spatial scales, as is often the case in regional conservation planning for large marine and terrestrial mammals and reptiles (Watzold et al., 2006). Today, with our improved ability to estimate anthropogenic pressures and activities from advanced sources such as satellite imagery and remote sensing, we are able explore the impact of human-threats on species at various scales (Kerr and Ostrovsky, 2003).

Few studies have used satellite night light data for the assessment of threats and impacts on species, biological or environmental factors. Of the limited studies, night light imagery has been used in conservation to derive an index for environmental sustainability (Sutton, 2003), has been used to explore the temporal impact of light pollution on marine ecosystems (Aubrecht et al., 2010a) and has been incorporated into the management of protected areas (Aubrecht et al., 2010b). However, the effect of artificial light sources and the night environment has largely been neglected in reserve system or corridor designs (Bird et al., 2004; Longcore and Rich, 2004). No studies, as far as we are aware, have explicitly examined the potential of using satellite night light imagery as a tool for examining the distribution of sea turtle nests and its further conservation application.

1.1. Sea turtles – threats and factors affecting nesting patterns

Sea turtle species *Caretta caretta* (Linneaus, 1758, loggerhead turtle) and *Chelonia mydas* (Linneaus, 1758, green turtle) are globally endangered (Calase and Margaritoulis, 2010). Their worldwide conservation status underlines the importance of understanding factors that influence their distribution and vulnerability. Sea turtles display philopatry, where nesting turtles return to their original place of birth (Carr, 1975; Bowen et al., 1994). This behavior is known to operate at a relatively coarse regional scale ~10 km–50 km (Miller et al., 2003) and factors that drive nesting sea turtles within this coarse spatial-scale are poorly understood (Weishampel et al., 2003; Garcon et al., 2009).

One important factor that is known to affect sea turtle behavior is the presence of night lights. Ecologists have found artificial lights disrupt sea turtle behavior in two ways. First, night lights reduce the ability of sea turtle hatchlings to find the sea. Hatchlings are either attracted to the artificial light source or are disorientated (Salmon, 2003; Tuxbury and Salmon, 2005; Lorne and Salmon, 2007; Kawamura et al., 2009). Disoriented turtle hatchlings may fail to find the sea, thereby reducing population viability (Lorne and Salmon, 2007; McConnell et al., 2010).

Second, there is the poorly understood phenomenon of artificial beach-front lighting preventing turtles from nesting. Nesting females of *C. caretta* and *C. mydas* are deterred by artificial lighting (Witherington, 1992; Salmon et al., 1995b; Witherington and Martin, 2000; Bourgeois et al., 2009). The repellent effect could be dose dependent so that highly lit areas deter all nesting and poorly lit areas have a minor impact (Margaritoulis, 1985; Witherington, 1992). Most of these studies are on beach sites along the coast of Florida (Salmon et al., 1995b; Witherington and Martin, 2000; Salmon, 2003; Weishampel et al., 2006; Aubrecht et al., 2010a). Sea turtle researchers along the coast of the Mediterranean Sea seldom investigate this relationship (Kaska et al., 2003; Aureggi et al., 2005) and very few studies have explored this issue at a regional or broad spatial scale. Overall, the relationship between night lights and its effect on sea turtle nesting is poorly understood.

Previous studies found that sea turtles nest in non-random patterns and their selection of nest site is influenced by specific factors (Mellanby et al., 1998; Weishampel et al., 2003). Besides night lights, variables that are considered to influence sea turtle nesting include: beach dimensions (Kikukawa et al., 1996; Mazaris et al., 2006), beach slope (Wood and Bjorndal, 2000) sand characteristics (Le Vin et al., 1998; Kikukawa et al., 1999), beach nourishment (Brock et al., 2009), climate change (Van Houtan and Halley, 2011), predation (Leighton et al., 2011), human settlements (Kikukawa et al., 1996) and coastal development such as seawalls (Rizkalla and Savage, 2011). Understanding the impact of these variables on sea turtle nesting is important for setting spatial conservation priorities (Moilanen et al., 2009).

In this paper we investigate whether night lights, as quantified using space-borne images, can be used to help predict the distribution of sea turtle nests and we discuss the potential application of this tool in future conservation applications. The major questions we test in this study are:

(1) Can night lights derived from satellite imagery help us explain the distribution of sea turtle nests?
(2) Do night lights remain important at predicting sea turtle nest activity when considering additional anthropogenic and environmental variables?

2. Materials and methods

2.1. Study area

The Mediterranean Sea coastline of Israel is ~190 km long and has a north–south orientation (with the exception of the Carmel and Haifa Bay; Schattner, 1967; Fig. 1). The overall width of beaches in Israel is between 20 and 100 m, with wider areas at river mouths. Israel's southern beaches (south of Tel Aviv) are characterized by relatively wider, sandy beaches (compared with northern beaches) with transverse sand dune fields, which have formed behind the shore in the past 1000 years (Schattner, 1967; Tsoar, 2000). In comparison, northern beaches are generally narrower and bordered by aeolionite (kurkar) cliffs. There are 32 rivers and ephemeral streams that flow through this coastal stretch into the sea (Lichter et al., 2010) and tidal movements in Israel are limited to a range of 15–40 cm (Lichter et al., 2010).

Rectangular spatial units along the Israeli coastline were designed to examine the relationship between turtle nesting sites, night lights and associated anthropogenic and environmental factors. A buffer of 500 m to the east and west of the coastline was constructed and 336 spatial units of 1×0.5 km were positioned in this space. The buffer was chosen to allow for longitudinal location errors, as sea turtle nest surveyors sometimes reported only the latitudes. The dimensions of the spatial unit were based on the resolution of available night light imagery and expert advice regarding nesting turtle behavior.

2.2. Sea turtle data

Sea turtle data for this study were provided by Israel's National Parks Authority (NPA). We used nesting data of the two sea turtle species, *C. caretta* and *C. mydas*, which nest on the Mediterranean beaches of Israel (Kuller, 1999; Levy, 2003). The annual number of sea turtle nests have been increasing exponential within the past two decades, however specific reasons for their increase are unknown (Levy, 2011; see Appendix Fig. A1). Sea turtle surveys along the entire coast of Israel were performed by Israel's Nature and Parks Authority since 1993, during the turtle nesting season from May to August. At the start of the nesting season (May), surveys were conducted two or three times a week. During peak season

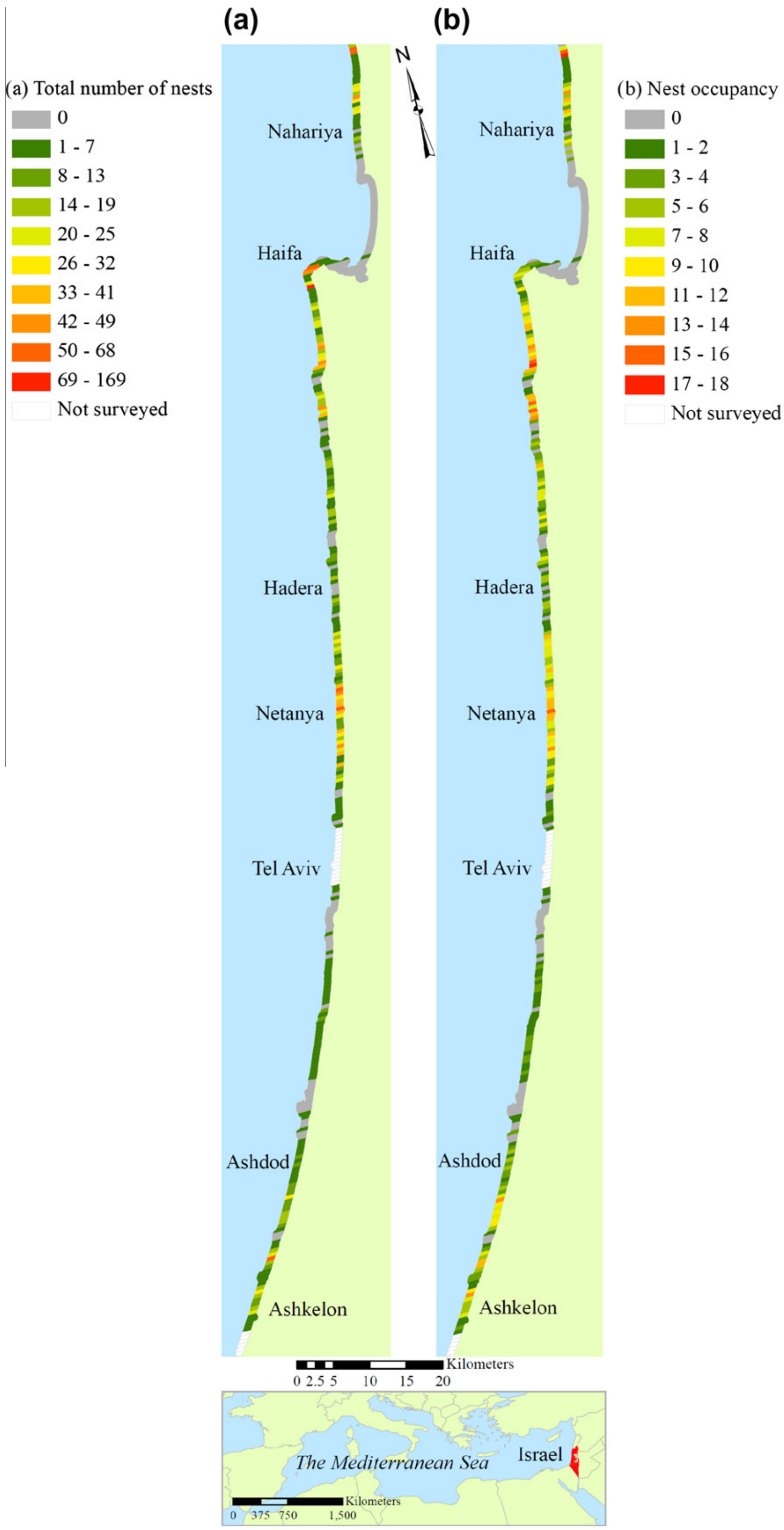

Fig. 1. Map showing the study area along the Mediterranean coast of Israel, using the Israel Transverse Mercator Grid. (a) Total number of sea turtle nests summed from 1993 to 2011 within each spatial unit (1 × 0.5 km) along the coast of Israel; (b) sea turtle nest occupancy (presence/absence) was summed from 1993 to 2011 within each spatial unit. Israel's location within the Mediterranean basin is displayed at the bottom. The map was created with ESRI (2011) ArcGIS, Coastline: Survey of Israel, Turtle data: Israel Nature and Parks Authority.

(June–July), beaches were surveyed daily. Towards the end of the season (August), surveys were performed twice a week. For survey purposes, the Mediterranean coast of Israel was divided equally into seven survey sections. Beach sections from Herzliya to Tel Aviv (∼8 km) were not surveyed due to high human population density and development.

The beach sections were scanned at sunrise by Israel's Nature and Parks Authority rangers along with trained volunteers. Surveys were conducted with 4WD vehicles driven close to the water edge, with a minimum of two people searching from the windows. Turtle nests were identified by the sand tracks that the female turtle leaves behind after laying her eggs. The two turtle species can easily be identified via their large and unique imprints, nest depth and position on the sand. The nest position was recorded via Garmin GPS units. Turtle tracks that did not result in a nest (false crawl), but seem to clearly be a nesting attempt were also recorded. Hatchling emergence or success was not systematically recorded over the years.

We examined and mapped the turtle nest data using ArcGIS (ESRI, 2011). We combined the two sea turtle species together due to their related choice of nesting beaches (Broderick and Godley, 1996; Weishampel et al., 2003) and the low number of *C. mydas* turtle nests in our study (0.8% of all nests). We used two variables derived from the turtle nest surveys: (1) the total number of nests found in each spatial unit summed over 19 years (1993–2011; Fig. 1a); (2) the occupancy (presence/absence) status of each spatial unit for turtle nests in each year and then summed over a 19 year period (1993–2011) – this will be referred to as turtle nest persistence (Fig. 1b). This was performed to limit influences from individual years (Fig. A1). When the total number of turtle nests was summed per spatial unit for this time frame, there was a mean of 9.63 ± 15.5, a median of 3.5 and a range from 0 to 169 individual turtle nests. Twenty-six percent of the surveyed spatial units in our study had no turtle nests (absences).

2.3. Night light data

Two satellite images of the Israel coastline were used for this study, SAC-C (2007; 300 m) and ISS (2003; 60 m). We used a 2007 satellite image from Argentine's Space Agency (CONAE, 2007) acquired by the High Sensitivity Technological Camera (HSTC) onboard the SAC-C satellite launched in 2000 (Fig. 2a). This image showed night lights at a spatial resolution of 300 m (Colomb et al., 2003) for the entire Israeli coastline. The SAC-C image underwent an inverse Fourier transformation to remove striping effects, using Idrisi Taiga (Clark Labs, 2010; Levin and Duke, 2012). Our second image, ISS, was from astronaut photography onboard the International Space Station (ISS mission 6). Imagery was obtained via Kodad DSC 760 camera at a resolution of 60 m in 2003 (Image Science and Analysis Laboratory, 2003). The spatial extent of this image did not cover the entire Israeli coastline (missing data beyond Haifa) but was included due to the difficulty of obtaining high spatial resolution satellite images which covers the entire coastline of Israel. Night light data for 286 of the 336 spatial units were covered by the ISS image (Fig. 2b). For both satellite images we determined an average pixel brightness value for each spatial unit with ArcGIS tools (ESRI, 2011).

2.4. Other explanatory variables

In addition to testing the importance of night lights at predicting turtle nesting patterns, we examined the effect of 21 additional variables that were hypothesized to affect sea turtle nesting and which were available for the full study region. These variables were divided into two groups; anthropogenic and environmental (see Table 1 for the full list of variables tested).

2.5. Statistical analysis

Our statistical analysis was designed to address our two major research questions;

2.5.1. Satellite night lights and sea turtle nests

We tested the ability of the two night light images to explain turtle nest distribution along the coast of Israel. Spearman's rank correlation coefficients were used to test for associations between turtle nest distribution and the average pixel values derived from the two night light images. To test our hypothesis that turtles prefer nesting in darker areas, we split our data into three night light intensity groups based on pixel values (high, moderate and low – each group with an equal number of spatial units) from both satellite images. The three groups were compared via the non-parametric Kruskal–Wallis one-way analysis of variance conducted in R software (R Development Core Team, 2011). Quantile regression was used to further explore the relationship between sea turtle nests and night lights along the entire Israel coastline using the SAC-C image. Quantile regression was performed using the R quantreg package (Koenker, 2007) with an exponential fit and bootstrapping for residuals.

2.5.2. The importance of satellite night lights

Here we examined the importance of night lights when considering other variables which may influence sea turtle nest distribution. We also aimed to construct models that predict: (1) the total number of nests per spatial unit and (2) turtle nest persistence, for the entire Israeli coastline with night lights (using the SAC-C image) and 21 broad scale explanatory variables (Table 1). We used generalized linear modeling (GLM) in R. GLMs simultaneously explore which variables and/or their interactions explain the highest amount of variability in turtle nest distribution. Prior to beginning the modeling procedure we tested for collinearity among the explanatory variables using Spearman rank correlations coefficient and Variance Inflation Factors (VIFs). We used a cut-off value of 3 for removing collinearity from the resulting VIFs (Zuur et al., 2007), and ±0.5 for Spearman's rank correlations coefficients between pairs of variables (Booth et al., 1994). For this analysis we used GLMs with a Poisson distribution, detected overdispersion and corrected the standard errors using quasi-GLMs (Zuur et al., 2009). Due to deviations in the coastline, the area of each spatial unit was not constant and therefore we performed our models with an offset variable for area (Zuur et al., 2009). Model simplification was conducted by dropping each explanatory variable in turn and removing the term that led to the smallest non-significant change in deviance according to *F*-tests (using the drop1 command in R; Zuur et al., 2009). Model validation was conducted using the deviance residuals plotted against the fitted residuals, explanatory variables and spatial coordinates. We also tested our raw data and models residuals for spatial auto-correlation using spline correlograms with 95% pointwise bootstrap confidence intervals and a maximum lag distance of 10 km (Bjørnstad and Falck, 2001; Zuur et al., 2009).

3. Results

3.1. Satellite night lights and sea turtle nests

Night lights from the SAC-C image were negatively correlated with the total number of sea turtle nests (Spearman's rho = −0.31, p = 4.07e−09; Fig. 3a) and nest persistence (Spearman's rho = −0.34, p = 8.12e−11; Fig. 3b) across the Israel coastline. Comparison of the two satellite images when related to sea turtle nests indicated that the ISS image with the higher resolution gave only slightly more significant results compared to the SAC-C image

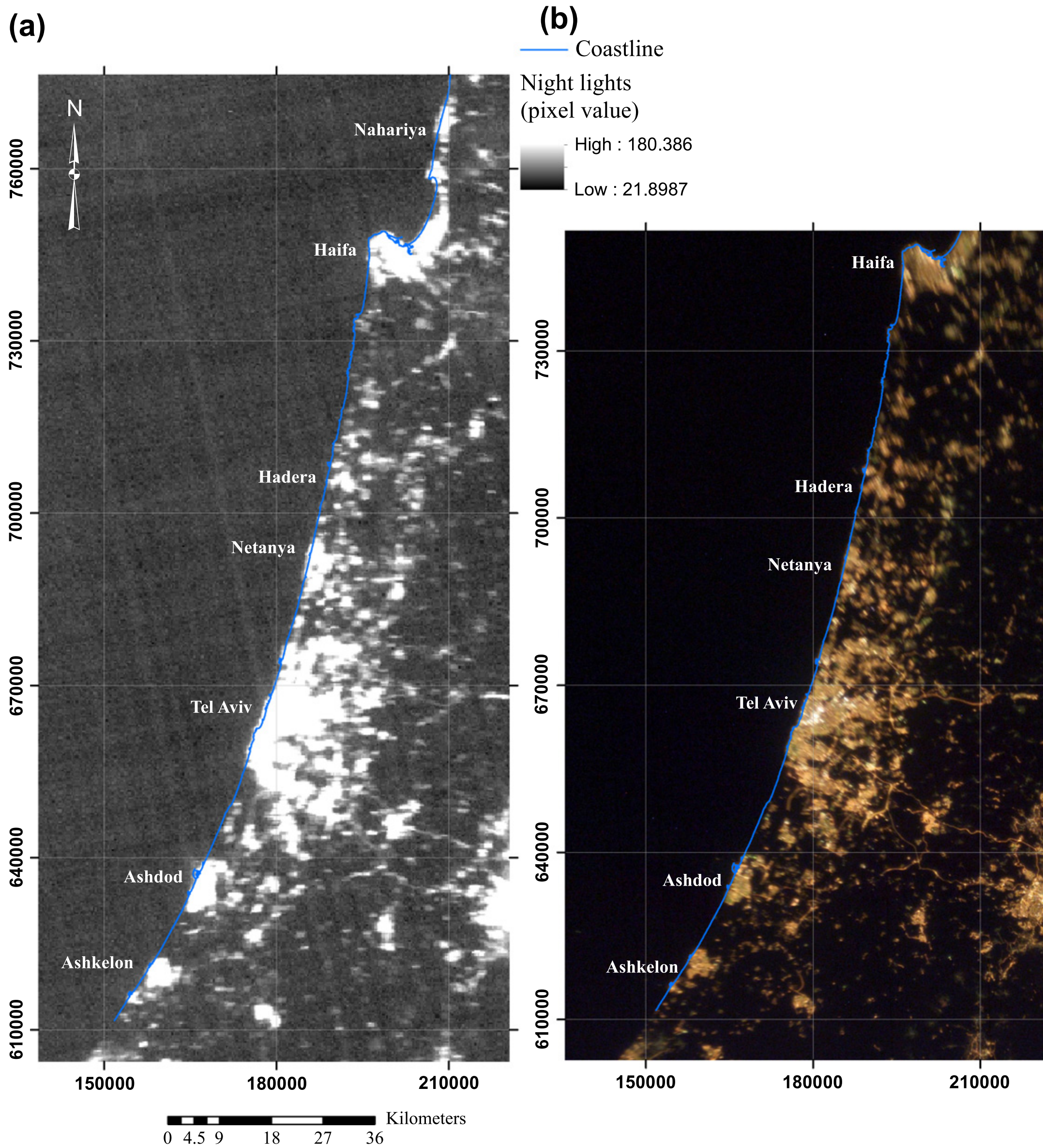

Fig. 2. The satellite images used in this study for calculating night lights along the coast of Israel. Major cities are displayed. (a) SAC-C satellite from Argentine's Space Agency (CONAE, 2007), pixel resolution is 300 m. (b) Image from International Space Station astronaut photography, pixel resolution is 60 m (Image Science and Analysis Laboratory, 2003). The map was created with ESRI (2011) ArcGIS.

(Table 2). We found that the total number of sea turtle nests (Kruskal–Wallis test, SAC-C $p = 4.7e{-}0$, ISS $p = 1.01e{-}06$; Fig. 4) and nest persistence (Kruskal–Wallis test, SAC-C $p = 3.24e{-}08$, ISS $p = 1.28e{-}07$; Fig. 5) within our spatial units were significantly different for the three groups of night light intensity. The mean rank of turtle nest numbers was highest in the low pixel group (mean SAC-C = 202.46; ISS = 173.82), which refers to darker sites, compared to the mean of the moderate (mean SAC-C = 169.91; ISS = 147.08) and high (mean SAC-C = 133.13; ISS = 111.42) groups for both satellite images. Similarly, for both satellite images the mean rank of turtle nest persistence was highest in the low pixel group (mean SAC-C = 206.50; ISS = 175.28), compared to moderate (mean SAC-C = 167.87; ISS = 148.40) and high (mean SAC-C = 131.13; ISS = 108.65) groups. Quantile regression showed that the 0.5 (median) and 0.75 quantiles were statistically significant for the relationship between night lights and sea turtle nests along the entire coastline of Israel (see Appendix Table A1).

3.2. The importance of satellite night lights

Night lights were found to be a significant explanatory variable for explaining the sea turtle nesting activity in both of our resulting GLMs (Table 3). Our resulting models were able to predict 18% (pseudo r^2) of the total number of sea turtle nests and 32% of sea turtle nest persistence within the spatial units along the entire coast of Israel. Of the 22 (including night lights) explanatory variable used in the modeling process, five variables were considered important for explaining the total number of sea turtle nests within our spatial units: night lights ($F = 7.60$, $p = 0.01$), cliffs ($F = 26.22$, $p = 5.19e{-}07$), the interaction between human population density and infrastructure ($F = 10.22$, $p = 1.53e{-}03$) and red sandy clay loam ($F = 5.63$, $p = 0.02$). Similar variables were considered significant for explaining sea turtle nest persistence, three two-way interactions made up our final model: the interaction between beach area and human population density ($F = 4.91$, $p = 0.03$), night

Table 1
Table displaying 21 variables used in this study (in GLM). Four anthropogenic based and 17 environmental variables were used that were suspected to be related to turtle nesting patterns (∗ = categorical variable).

Variables	Data origin
Anthropogenic based	
Human population density	Population density data was obtained as of 2007 for statistical units as defined by Israel Central Bureau of Statistics (CBS, 2007). As a proxy for estimating the population residing near the beach, each spatial unit was given the population density of the closest municipality division alongside the coast
Built-up areas (m)	Data for built up areas was available from the Israeli Ministry for Environmental Protection (Kaplan et al., 2006), within each spatial unit (CBS, 2007). Built-up areas were calculated by the distance from the coastline (middle of spatial unit) to the closest built up area (m)
Infrastructure (m)	To determine the land-use type of the beach we used GIS data supplied by the Society for the Protection of Nature in Israel (SPNI) Open Landscape Institute (OLI). The distance (m) from the center of each spatial unit to beaches clear of national infrastructure (e.g. ports, roads, electrical grids, and military areas) was measured
Reserves	The current areas protected within nature reserves and national parks of Israel were provided by Israel's Nature and Parks Authority. The percentage of each rectangular unit that is protected by a reserve which is either officially declared or approved was calculated using ArcGIS (ESRI, 2011). Reserves that are currently awaiting approval or recently proposed were not taken into consideration
Environmental variables	
Beach area	We digitized the area of beach (sand area) from Google Earth (2011) satellite imagery, performed at the rectangular unit scale (500 m) in ArcGIS (ESRI, 2011). We calculated the percentage of the spatial unit's area which was covered by beach
Cliffs*	We included the presence and absence of cliffs bordering the shoreline of beaches as a categorical variable (1 = cliffs, 0 = no cliff). This data was provided by the Society for the Protection of Nature in Israel (SPNI) Open Landscape Institute (OLI)
Geomorphologic features	We used GIS data from a Geological Survey of Israel for the Ministry of Environment (Zilberman et al., 2006). Fifteen geomorphologic classes (Table A3) were considered in our analysis. We calculated the percentage of each geomorphologic feature within every rectangular unit

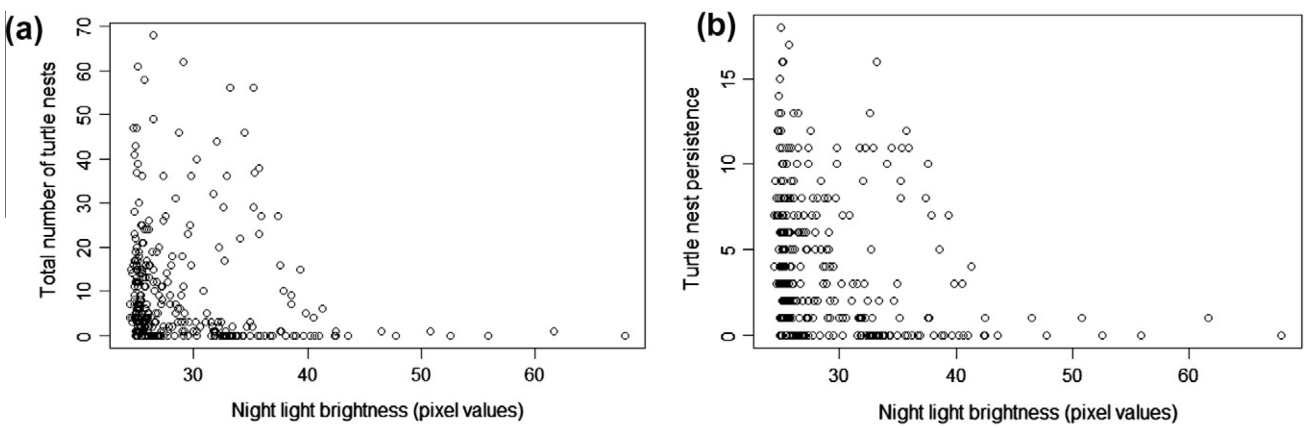

Fig. 3. Scatter plot using spatial units (1 × 0.5 km) along the coast of Israel to show relationships between sea turtle nesting activity over a 19 years period (1993–2011) and night light intensity derived from a satellite image (SAC-C; CONAE, 2007). One outlier was removed from the plot for visualization purposes. (a) Total number of sea turtle nests summed per spatial unit (1 × 0.5 km). (b) Sea turtle nesting persistence (presence/absences) summed over time period for each spatial unit.

Table 2
Spearman rank correlation coefficient of night lights (pixel values) from two satellite images with sea turtle nest persistence and the total number of sea turtle nests (summed over 19 years period within 336 spatial units) along the coast of Israel.

Satellite night light image	Total number of sea turtle nests		Sea turtle nest persistence	
	Spearman's rank correlation coefficient	*p*	Spearman's rank correlation coefficient	*p*
SAC-C (entire Israel Mediterranean coast)	−0.31	4.07e−09	−0.34	8.12e−11
ISS (partial coast)	−0.37	7.71e−11	−0.39	6.44e−12
SAC-C (partial coast as used in ISS image)	−0.35	1.11e−09	−0.38	3.20e−11

lights and cliffs ($F = 4.62$, $p = 0.03$) and human population density and infrastructure ($F = 5.57$, $p = 0.02$; Table 3).

The only explanatory variable showing signs of collinearity with night lights was built up areas along the coast (Spearman's rho = −0.61) however this variable was not significant in our models. We also found that the only interaction with night lights was the presence of cliffs in our model that explains sea turtle nest persistence. No spatial autocorrelation or collinearity (VIFs all below 3; Table A2) among our explanatory variables was found and our models met the validation requirements (Fig. A2; Fig. A3).

4. Discussion

This study demonstrates a novel application of satellite night light imagery to help predict nesting activity of endangered sea turtles. While the impact of artificial night lights on biodiversity is often overlooked, we found that the intensity of coastal night lights derived from satellite-imagery is a significant determinant of sea turtle nest distribution. Results from our GLMs indicated that night light intensity remained an important predictor of sea turtle nest distribution when other anthropogenic and environmental factors were considered. For endangered species with large scale spatial movement such as sea turtles, where factors that influence their selection of nesting sites are largely unknown, improving our ability to determine their nesting patterns can enable us to better direct and target our conservation efforts.

This is one of the first studies to explore the relationship between nesting sea turtles and night lights at a regional spatial scale. Our results indicate that the intensity of artificial night lights along the Mediterranean coastline of Israel affects sea turtle nest-

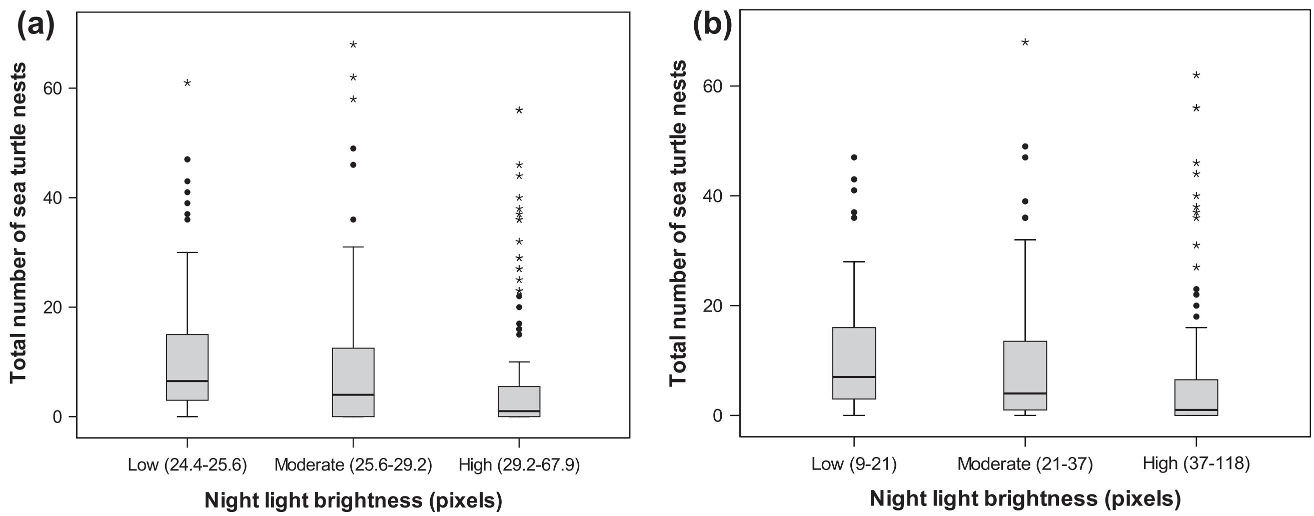

Fig. 4. Box plots of Kruskal–Wallis one-way analysis of variance of three groups of night light intensity; high (well lit areas), moderate, and low (dark areas) related to the total number of sea turtle nests occupancy (summed for years 1993–2011) along the coast of Israel. Pixel values of the three groups are in bracket. One outlier was removed from the plot for visualization purposes. (a) SAC-C satellite image (CONAE, 2007), (b) ISS satellite image (Image Science and Analysis Laboratory, 2003).

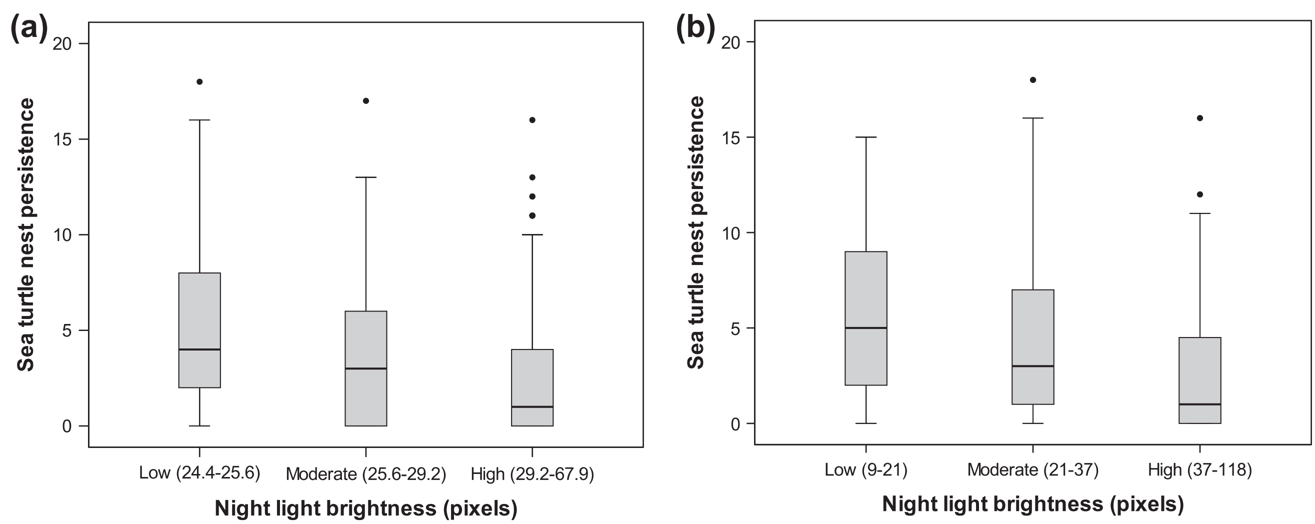

Fig. 5. Box plots of Kruskal–Wallis one-way analysis of variance of three groups of night light intensity; high (well lit areas), moderate, and low (dark areas) related to sea turtle nest occupancy (presences/absence) frequency (summed for the years 1993–2011) along the coast of Israel. Pixel values of the three groups are in brackets. One outlier was removed from the plot for visualization purposes. (a) SAC-C satellite image (CONAE, 2007), (b) ISS satellite image (Image Science and Analysis Laboratory, 2003).

ing patterns, where well lit beaches have lower occurrences of nesting turtles. These large scale findings are supported by local-scale studies that show nesting is influenced by night light intensity (Margaritoulis, 1985; Witherington, 1992). Thus, our broad scale study provides support for the hypothesis that sea turtles prefer darker beach sites for nesting. By utilizing information derived from satellite night light imagery we can explore broader spatial patterns between species and the night environment which were previously spatially restrictive. Our results suggest that night lights derived from satellite-based images provide a useful tool for assessing broad-scale spatial patterns of sea turtle nest sites.

In addition to artificial night lights, we identified other new and significant variables and their interactions that help predict sea turtle nesting activity at a broad spatial scale. The significant predictors found in both our GLMs, besides night lights, were the presence of cliffs (positive effect), human population density (negative effect) and infrastructure (negative effect). Although we were limited with the inclusion of explanatory variables due to data availability at this broad scale, we found new and unexplored explanatory variables that influence sea turtle nesting. This is the first study to find that the presence of coastal cliffs have an important positive influence on sea turtle nests. Findings by Kikukawa et al. (1999) indicated that beach height is an important variable, and Salmon et al. (1995a) found a positive correlation with tall objects along the shoreline, however to our knowledge, no studies have explicitly explored the effect of cliffs. While cliffs were a positive effect on sea turtle nests in our study, we suggest that there may be negative effects in some countries with large tidal ranges or areas where sea levels are beginning to rise (Fish et al., 2005). In such areas the presences of cliffs may cause a barrier for nesting turtles, where the landward movements of nesting turtles are restricted, thus a potential cause of nest destruction by sea water inundation (Fish et al., 2005). We recommend further investigation of other beaches with cliffs around the Mediterranean to better understand the effect that coastal cliffs have on sea turtle nests and its further application for conservation. Hence, at this broad scale we were able to identify variables that influence sea turtle nesting, which is particularly important to consider in conserva-

Table 3
Minimum adequate quasi-Poisson GLM to explain sea turtle nest persistence and the total number of sea turtle nests (between 1993 and 2011) within spatial units along the entire coastline of Israel. See Table 1 for details regarding explanatory variables. Interactions between explanatory variables are marked with a cross. Rows with no values signify explanatory variables that were eliminated within the modeling process and did not contribute to the final model.

Explanatory variable	Total number of nests							Nest persistence						
	Coefficient	SE	*t*	*p*	*df*	*F*	*p*	Coefficient	SE	*t*	*p*	*df*	*F*	*p*
Night lights (SAC-C image) – negative exponential	3.34e+10	1.79e+10	1.87	0.06	1	7.60	0.01**	6.39e+10	9.60e+09	6.66	1.18e−10***			
Cliffs	8.16e−01	2.30e−01	3.54	4.56e−04***	1	26.22	5.19e−07***	1.09e+00	1.67e−01	6.52	2.64e−10***			
Infrastructure	−2.44e−04	1.31e−04	−1.87	0.06				−3.88e−04	9.03e−05	−4.30	2.30e−05***			
Human population density	−4.06e−05	3.63e−05	−1.12	0.26				−9.10e−05	3.70e−05	−2.46	0.01*			
Beach area								1.70e−02	7.81e−03	2.17	0.03*			
Beach area × human population density								1.62e−05	7.57e−06	2.14	0.03*	1	4.91	0.03*
Night lights (neg exp) × cliffs								−5.73e+10	2.85e+10	−2.01	0.04*	1	4.62	0.03*
Human population density × infrastructure	−5.47e−07	4.96e−07	−1.10	0.27	1	10.22	1.53e−03**	−2.80e−07	1.81e−07	−1.54	0.12	1	5.57	0.02*
Red sandy clay loam (Geo_2)	−1.8e−02	1.28e−02	−1.46	0.15	1	5.63	0.02*							

* Statistical significance – 0.05.
** Statistical significance – 0.01.
*** Statistical significance – 0.001.

tion management when very little is known about their spatial distribution.

Night lights and cliffs as individual components have an important effect on sea turtle nests and combined have an important positive interaction effect (Table 3). This is exemplified by the case of Netanya (Fig. 2), a coastal city in Israel where beaches have a high number of sea turtle nests, shoreline cliffs and bright night lights. This interaction should be further explored in small-scale field studies to understand the nature of this relationship and the impact that cliffs near coastal cities exhibit on nesting sea turtles. Beach areas with bright night lights and beach cliffs may be prime areas to focus conservation efforts for the recovery of nesting sea turtle populations.

Anthropogenic based variables may be useful for predicting species distribution and activity within highly modified environments such as the coastal zone. In previous studies at local scales, environmental variables have been predominantly used for determining sea turtle nesting activity (Wood and Bjorndal, 2000; Karavas et al., 2005; Mazaris et al., 2006). However, findings from our study suggest that human based variables were important. Other studies which have included human based variables have also found that sea turtle nests were negatively influenced by such factors. For example, Weishampel et al. (2003) found that nests of green and loggerhead sea turtles increased as the density of human development was lower along beaches in east Florida. A multiple regression approach by Kikukawa et al. (1999) also found that loggerhead sea turtle nests in Okinawajima, Japan, significantly increased with distance from human settlements. We suggest that today with the increasing number of anthropogenic threats on the coastal environment that inclusion of human based factors may serve as helpful predictors of sea turtle nesting patterns or other coastal species.

Artificial night lights may pose a greater threat to sea turtle nests compared with other anthropogenic threats. Our GLM results showed that night lights were more significant at explaining sea turtle nests distribution then other anthropogenic threats such as the human population density, infrastructure and built up areas. Unlike these other variables, night lights account for the presence of most human night time activity, including beach side restaurants, shopping districts, ports and residential areas. Interestingly, we also found that higher resolution satellite night light imagery, comparison between the ISS and SCC-C images, was better related to sea turtle nesting patterns (Table 2). Thus, the threat of night lights on sea turtle nesting, while evident from laboratory and small-scale field experiments (Witherington, 1992; Salmon et al., 1995b) can also be explored with the use of high resolution satellite imagery.

To date, very few explanatory variables and models have been identified which can aid our understanding of nesting patterns of endangered sea turtle species (Garcon et al., 2009). Clearly there are additional unknown factors which affect sea turtle nest distribution. Our resulting models were able to explain 18% and 32% of turtle nest variance. These values suggest that there are other factors which contribute to predicting sea turtle nest distribution. Other contributing factors could be related to the hypothesis that sea turtles use multiple environmental factors/cues with thresholds to reach before choosing a nesting site (Wood and Bjorndal, 2000; Mazaris et al., 2006). Alternatively, these factors could be due to recently explored climatic factors, predation, other anthropogenic threats, interactions among variables (Leighton et al., 2011; Rizkalla and Savage, 2011; Van Houtan and Halley, 2011) or small scale environmental conditions that are not found at this large scale (Wood and Bjorndal, 2000). Thus, with the little knowledge we have on sea turtle nesting patterns, combined with their endangered status, we propose that satellite night light imagery may be a useful tool for the prediction of sea turtle nest distribution at a broad spatial scale and recommend its incorporation into future studies.

4.1. Conservation implications

The advancements in spatial analysis and applications (Sen et al., 2006) continually allow us to consider new techniques and methods to explore and predict species assemblages and patterns at broader spatial scales with higher resolution (Kerr and Ostrovsky, 2003; Turner et al., 2003). In recent years studies have been quantifying biodiversity with remote sensing tools and satellite imagery (Levin et al., 2007; Lahoz-Monfort et al., 2010; Rocchini et al., 2010; Bradter et al., 2011). While such tools and methods cannot replace field work at smaller scales, they can serve as useful tools for exploring larger spatial-scales. In particular circumstances where field work locations are inaccessible or spatial extents are too large, remote sensing can provide us with the best knowledge at hand. Further research therefore, should be conducted with these tools at broader spatial scales and regional levels in order to advance our understanding of species habitat selection, movement and threats.

Predicting species habitats, movements and identifying their threats can greatly aid conservation decisions, which are often made with relatively sparse information (Pressey, 2004). While this study examines nesting sea turtles, the same methodology can be applied to other species that are disturbed by artificial night lights. For such species, we propose that satellite night light imagery can be incorporated into conservation planning in order to mitigate the threat of night lights when selecting priority conservation areas or reserves. This approach is especially relevant for rare and endangered species such as sea turtles, for which there is a limited time to act in the face of increasing human-pressures and where action is needed at broad scales.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2012.11.004.

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