

Article

Assessing Light Pollution Exposure for the Most Important Sea Turtle Nesting Area in the Mediterranean Region

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Abstract

Artificial light at night (ALAN) is impacting sea turtle nesting around the globe by decreasing the nesting attempts, disorienting the sea turtle hatchlings while trying to find the sea, and disrupting hatchlings' offshore migration. In the Mediterranean Sea, the shoreline of Kyparissia Bay is considered the most important nesting site for loggerhead sea turtles (*Caretta caretta*), with several thousand nests on an annual basis. The current study reports for the first time the exposure of the core 10 km of nesting area to ALAN pollution, evaluates the potential impact on sea turtle conservation, and discusses mitigation measures as coastal urbanization and touristic activity increase rapidly in the region. Our findings demonstrate that most of the core area was not impacted by ALAN pollution, although a specific region (Kalo Nero) was subjected to high illumination at night, leading to reduced sea turtle nests and potential threats to hatchlings.

Keywords: artificial light at night (ALAN); sea turtles; drone; GIS; Mediterranean Sea



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1. Introduction

Artificial light at night (ALAN), the change in nocturnal light levels due to anthropogenic infrastructure, is considered a major threat to humans and several types of marine and terrestrial organisms [1–3]. More than 20% of our planet is exposed to this form of pollution, with an annual increase ranging from 2 to 10% [4].

In the coastal environment, more than 20% of our planet's marine protected areas (MPAs) and general coastal areas are subject to ALAN pollution, a number that continues to increase due to increased coastal development [5–7]. This affects the organisms that use the coastal and marine habitat for foraging, nesting, resting, and reproduction (such as marine mammals, seabirds, fish, and sea turtles) [8]. Several studies have shown the impacts of ALAN on the behavior of organisms that use coastal habitats (e.g., [2,9–13]). The impacts for both marine and terrestrial organisms that inhabit the coastal environment discussed in these studies are most commonly fitness reduction, population dynamics, disorientation, behavior, increased risk of predation, and disruption of foraging and reproduction [14–16].

Sea turtles exhibit a complex life history, with distinct stages occurring in separate habitats and geographic regions on broad spatial scales [17]. In the weeks preceding the nesting season, adult males and females gather near breeding grounds to mate [18], after which males leave the area [19]. During the nesting season, females remain in near-shore waters and return to beaches near their natal sites to deposit eggs, often decades after hatching. Incubation typically lasts around two months, after which hatchlings emerge from the nest and engage in a brief “swimming frenzy” to reach deeper offshore waters [20]. The sea-finding process in hatchlings relies on visual cues, guiding them toward the brightest and lowest point on the horizon [21]. The overlap of the nesting season (May–September) with peak tourist activity in the Mediterranean poses considerable conservation challenges for sea turtles.

Sea turtles around the globe are subjected to several impacts by natural and/or indirect anthropogenic causes, such as the loss of nesting grounds from sea level rise and beach erosion, decreased hatchling success, storm severity, nest feminization due to higher temperatures, reduced food availability, and the expansion of diseases due to climate change [22–29]. Considering the anthropogenic impact, sea turtles are facing bycatch, habitat loss due to touristic development, boat collisions, touristic pressure, and plastic and microplastic pollution, among other threats [26,30–37]. Several studies have shown the negative impact of light pollution on hatchlings’ sea-finding orientation and the unwillingness of sea turtles to choose a highly illuminated nesting beach [10,38,39]. The most important negative effects of ALAN on sea turtles include the influence on nesting site selection, the decrease in nesting attempts, the increased predation risk for sea turtle hatchlings, the disruption of the sea-finding orientation of the hatchlings, the disturbance of hatchlings’ swimming behavior and offshore migration capacity, as well as the decreased reproductive success [21,39–43]. Moreover, as nighttime darkness becomes less common on nesting beaches, this could lead to increased nesting density, causing the destruction of other nests and an increase in hatchling predation and reduced fitness [44,45]. Changing the nesting location due to ALAN impacts may lead hatchlings to be born away from favourable oceanographic features and currents that assist their oceanic dispersal and conservation [46,47]. Thus, ALAN may critically undermine the successful recruitment of sea turtle populations [48].

In the current study, we investigated the exposure of sea turtle nests to ALAN in Kyparissia Bay, the most important nesting area in the Mediterranean for loggerhead sea turtles (*Caretta caretta*), based on the high number of nests recorded annually [49]. To achieve this, we analyzed the spatial distribution of sea turtle nests and their exposure to varying levels of light pollution within the 10 km area of the core nesting activity. The goal of our study was to achieve a deeper understanding of light pollution, its evolving trends, and potential future impacts during growing coastal development and tourism activities. Potential conservation measures aimed at safeguarding population recruitment under the influence of ALAN are discussed.

2. Methods

2.1. Study Site

Kyparissia Bay is an EU Natura 2000 site located on the western coast of central Peloponnese (Ionian Sea). Kyparissia Bay falls within the boundaries of three NATURA 2000 sites—one marine (GR2330008) and two terrestrial (GR2330005 and GR2550005)—managed under the authority of the Natural Environment and Climate Change Agency (NECCA) and the relevant Management Unit of the Strofylia Wetlands National Park and Protected Areas of Western Peloponnese (<https://necca.gov.gr/en/protected-areas-management-units/>, (accessed on 10 September 2025)) [50]. This area currently hosts the

largest reproductive population across the Mediterranean for loggerhead sea turtles, with more than 7500 nests during 2024 [49]. The sandy coastline consists of about 44 km of almost continuous beach. Although sea turtles nest along the entire coast, the core nesting area is concentrated in the southernmost 10 km, which accounts for over 70% of all laid nests [49] (Figure 1).

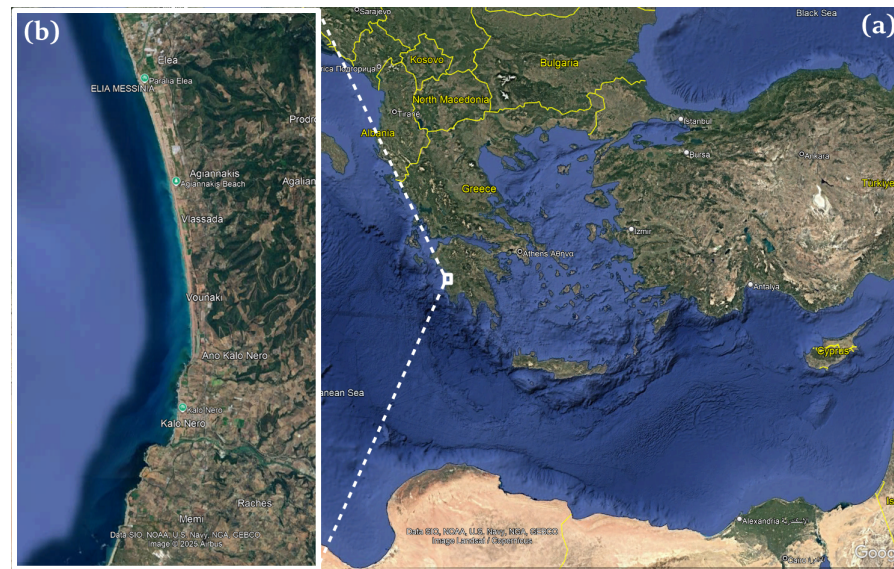


Figure 1. (a) A map of the Eastern Mediterranean region with (b) the location of the study area.

2.2. UAV Survey

The authors performed a detailed Unmanned Aerial Vehicle (UAV) survey and mapping of the entire core nesting area of 10 km coastline to identify and record sea turtle nests (based on ARCHELON's signs (the sea turtle protection society of Greece), cages, and poles on the beach). The survey occurred with the use of DJI's Air2S drone, DJI, 2018, Shenzhen, China with 5.4 K photo capability (5472×3648 pixels) with GPS location embedded in each photo. The flight time was approximately 2.5 h from 09:30 a.m. to 12:00 p.m. on the 23 July 2025. A total of 178 photos were taken along the entire area at an altitude of 60 m with the camera at nadir (direct downward direction), which gave an approximate width of 120 m, a few meters of overlap so that we were able to put the images in the correct order, and allowed for the detection of sea turtle nests and other features in each photo. During the selected survey period, all human infrastructure and tourism activities were fully operational and at their peak. This approach aimed to capture an indication of the beach's maximum potential illumination.

2.3. Light Pollution Measurements

The light meter survey was carried out to assess the level of the different lights at night. The measurements included the intensity of light coverage from artificial lights, using a portable digital light meter (iNGCO HETLU01, INGCO, 2006, Suzhou, China 0–200,000 Lux), with a sensitivity of 0.1 Lux (luminous flux per unit area), and a Garmin eTrex GPS, 2015, Olathe, KS, USA. Measurements below 0.1 Lux were recorded as 0 Lux owing to the sensitivity limitations of the light meter. Consequently, very low illumination levels may be present but remain undetectable with the instrumentation used. Given that hatchlings are oriented by using a visual 'cone of acceptance' from 0 to 30 degrees in the vertical level, light intensity at each sampling station was measured at an elevation of 15 degrees from the beach surface [21]. The light meter survey was conducted in the absence of cloud cover on a moonless night (24 July 2025) between 23:00 and 00:00 to

eliminate interference from natural light sources and cloud albedo [51]. Light intensity was measured at stations placed at 10–40 m intervals near areas of intense illumination and at 100–400 m intervals in undeveloped coastal zones across the study area, based on the presence of light sources. Three replicate readings were obtained per station, and the average value was retained for analysis [8]. A total of 87 measurements were recorded at 29 stations, accompanied by the documentation of other beach characteristics such as backshore vegetation, presence of buildings, beach furniture, and light emission sources visible from the beach.

Furthermore, the authors collected and analyzed VIIRS/DMSP data (data from sensors onboard the satellites from the Defense Meteorology Satellite Program (DMSP) and the Visible Infrared Imaging Radiometer Suite (VIIRS)) from the study area over the past decade, to identify trends in time for the entire region and for selected areas, and to establish the reasoning for the sampling effort (source: <https://www.lightpollutionmap.info>, accessed on 9 September 2025) [52].

2.4. Data Analysis

The drone images were analyzed using MATLAB 2021a to detect and extract the location of sea turtle nests based on the signs of ARCHELON and other features [53]. It is important to acknowledge that this method offers only an approximation, rather than an exact count, of nest numbers and their spatial distribution. Thematic maps were created by integrating geospatial data on luminance, topography, and nest locations to depict high-exposure areas. Geographic information systems (GIS) software was used to analyze and visualize both sea turtle nesting patterns and artificial light pollution within the core 10 km nesting area of Kyparissia Bay. The spatial data layers generated during field surveys, including UAV-derived nest locations and ground-based measurements of light pollution, were processed and visualized using ArcGIS (Esri, ArcGIS Desktop: Release 10.4.1; Environmental Systems Research Institute: Redlands, CA, USA, 2015).

For the mapping of sea turtle nests, the GPS coordinates extracted from the UAV aerial images were georeferenced and overlaid on high-resolution satellite imagery (Figure 2). Kernel Density Estimation (KDE) was applied to visualize areas of high and low nesting density, facilitating the identification of critical nesting hotspots along the coastline (Figure 3) [54]. The Kernel Density tool in ArcMap 10.4.1 (Esri, Redlands, CA, USA) was used to calculate nest density. A default cell size of 10 m and a search radius of 100 m were applied to visualize spatial clustering patterns along the 10 km coastline.

Regarding light pollution, field measurements in lumens were georeferenced and interpolated using the Inverse Distance Weighting (IDW) method to visualize the spatial extent and intensity of artificial illumination across the study area [54]. The IDW method was selected for the interpolation of light pollution data because it provides a straightforward and reliable way to estimate illumination intensity across areas where direct measurements were not possible [55]. The default power parameter ($p = 2$) and a cell size of 10 m were applied, and the search radius was set to the 12 nearest points. IDW assumes that values measured closer to a given location exert a stronger influence than those farther away, making it particularly suitable for environmental studies with spatially clustered field data, such as light intensity measurements along a coastline. This approach ensures that the resulting spatial distribution map reflects the gradual decay of artificial light with distance from its sources, thereby producing a realistic visualization of illumination patterns [56,57]. Particular focus was given to the Kalo Nero settlement, where elevated levels of light pollution were recorded. An inset map was developed for this area to present the detailed spatial distribution of luminance values. Measurements for the rest of the coastline confirmed near-zero illumination. Additionally, spatial correlation analysis enabled the

understanding of the relationship between light pollution and nesting patterns, supporting targeted management measures. The core nesting area was divided into five segments, each measuring 2000 m (Kalo Nero, Vounaki, Agiannakis, Elea, and the area between Kalo Nero and Vounaki), to evaluate whether the Lux intensity and the number of nests vary significantly in space. Then we performed a non-parametric Kruskal–Wallis test (followed by a pair-wise comparison) to check if the number of nests and light intensity levels differed significantly among different segments.



Figure 2. Reconstruction of the coast of Kalo Nero, Greece, using images from the drone survey.

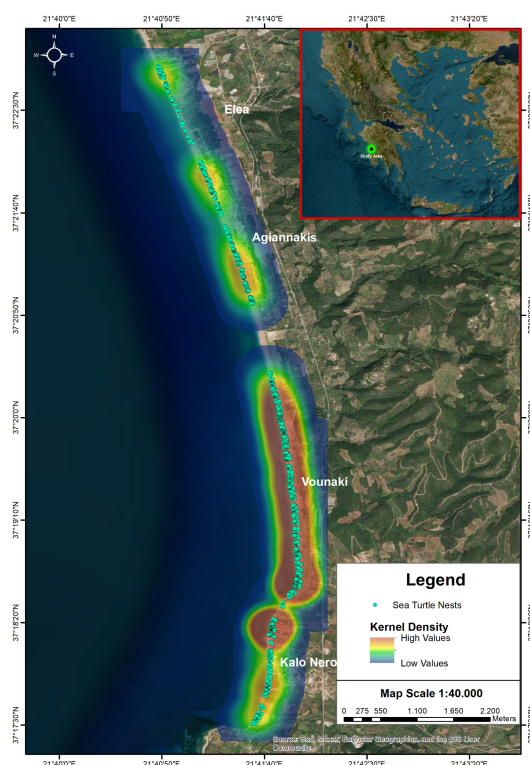


Figure 3. Sea turtle nest distribution and kernel density in Kyparissia Bay, Greece. The map displays the spatial distribution of sea turtle nest approximations recorded during the study in the Kyparissia Bay. Kernel Density Estimation (KDE) is applied to visualize areas with high (red) and low (green) nest densities along the coastline. Key coastal locations such as Elea, Agiannakis, Vounaki, and Kalo Nero are indicated for reference.

3. Results

The drone survey allowed the authors to analyze the entire coast between Kalo Nero and Elea in the Kyparissia Bay and evaluate the sea turtle nests and the location of lights that may pollute the nesting beach (Figure 2). Image analysis showed at least 2000 nests along the study area. The highest nest density was recorded on the beach sections adjacent to Kalo Nero and around Vounaki, along a stretch of approximately 2.5 km (Figure 3). Additional areas of moderate nest density were identified south of Agiannakis and Elea. According to the findings of the IDW method, light substantially affecting the nesting area was detected only on the coastline of the Kalo Nero village near the local restaurants and bars located above the nesting beach (Figure 4, Table 1). The nesting area most exposed to light pollution was located between sampling stations M2 and M15, with an average illumination level of 2 Lux (± 0.8 SE, ranging between 0.1 and 11.1 Lux (Figure 5). The highest levels of light pollution were recorded at stations M13 and M3, in front of taverns, where the light sources were directly visible from the beach (Figure 4). In contrast, street lighting was not directly visible from the beach, as the road running parallel to the shore is elevated approximately 2–3 m above beach level, preventing direct line-of-sight exposure. Light intensity exhibited very low values for the rest of the study area (Table 1). There were significantly lower numbers of sea turtle nests in beach segments with higher light intensity (SS = 62.5, dF = 1, MS = 62.5, $\chi^2 = 7.26$, $p = 0.0071$ in the reported cases).

Radiance data from 2014 to 2024 demonstrated that the Kalo Nero region has experienced levels of light pollution several times higher than those recorded in the Vounaki, Elea, and Agiannaki areas combined, throughout the year (Figure 6). Considering the average radiance measurements for the summer months over the past decade, the region has experienced a negligible decline in the light pollution trend, which is most probably associated with the low values observed between 2019 and 2021 (the COVID-19 pandemic epicenter). Comparing the summer months (June, July, and August), it was determined that July was the month of higher radiance levels for 2022–2024, justifying using this month in the current sampling efforts (Figure 7).

Table 1. Light intensity measurements per sampling station along the coast of Kyparissia Bay, Greece. See Figure 5 for sampling station locations.

Sampling Station	Lux	Sampling Station	Lux	Sampling Station	Lux
M1	≤ 0.1	M11	≤ 0.1	M21	≤ 0.1
M2	0.3	M12	≤ 0.1	M22	≤ 0.1
M3	4.5	M13	11.1	M23	≤ 0.1
M4	2.7	M14	1.1	M24	≤ 0.1
M5	3.8	M15	≤ 0.1	M25	≤ 0.1
M6	0.7	M16	≤ 0.1	M26	≤ 0.1
M7	≤ 0.1	M17	≤ 0.1	M27	≤ 0.1
M8	≤ 0.1	M18	≤ 0.1	M28	≤ 0.1
M9	≤ 0.1	M19	≤ 0.1	M29	≤ 0.1
M10	4.1	M20	≤ 0.1	-	-

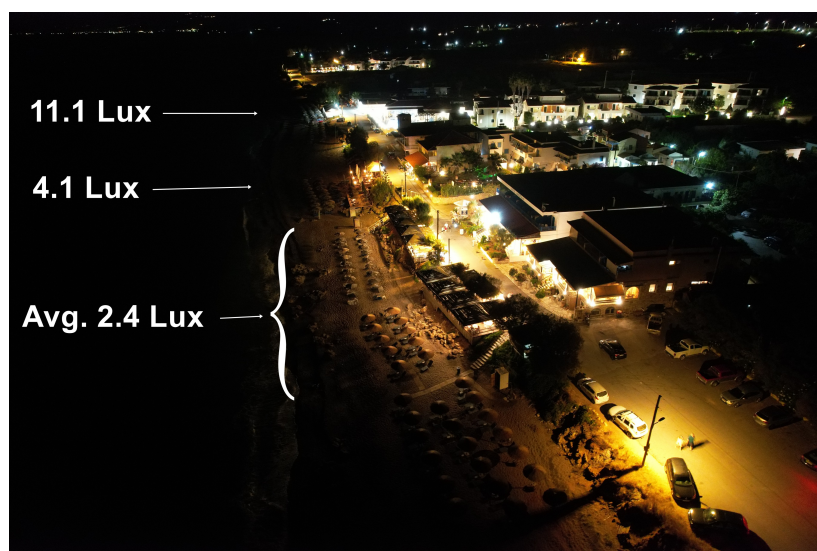


Figure 4. A photo above the village of Kalo Nero at 23.00 as taken by the drone at an altitude of 50 m. The location and intensity of the light pollution measurements are shown on the left side of the image.

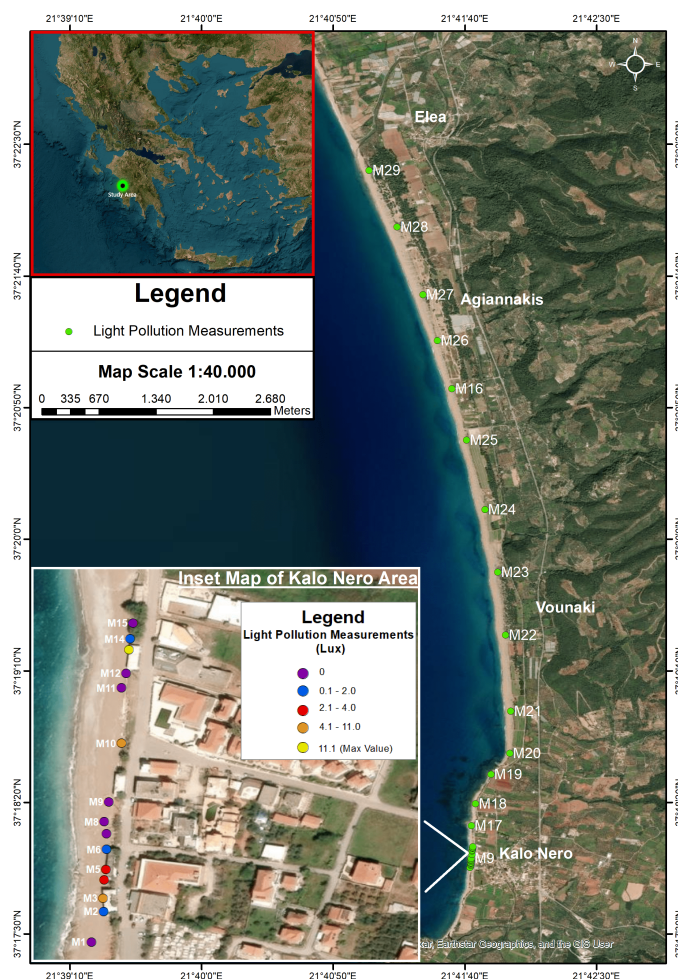


Figure 5. Measurements of light pollution along Kyparissia Bay. The map displays light pollution measurements (in Lux) along the coastline. The inset map focuses on the Kalo Nero area, where elevated light pollution values were recorded, whereas the remaining beach areas exhibit near-zero values (see Table 1).

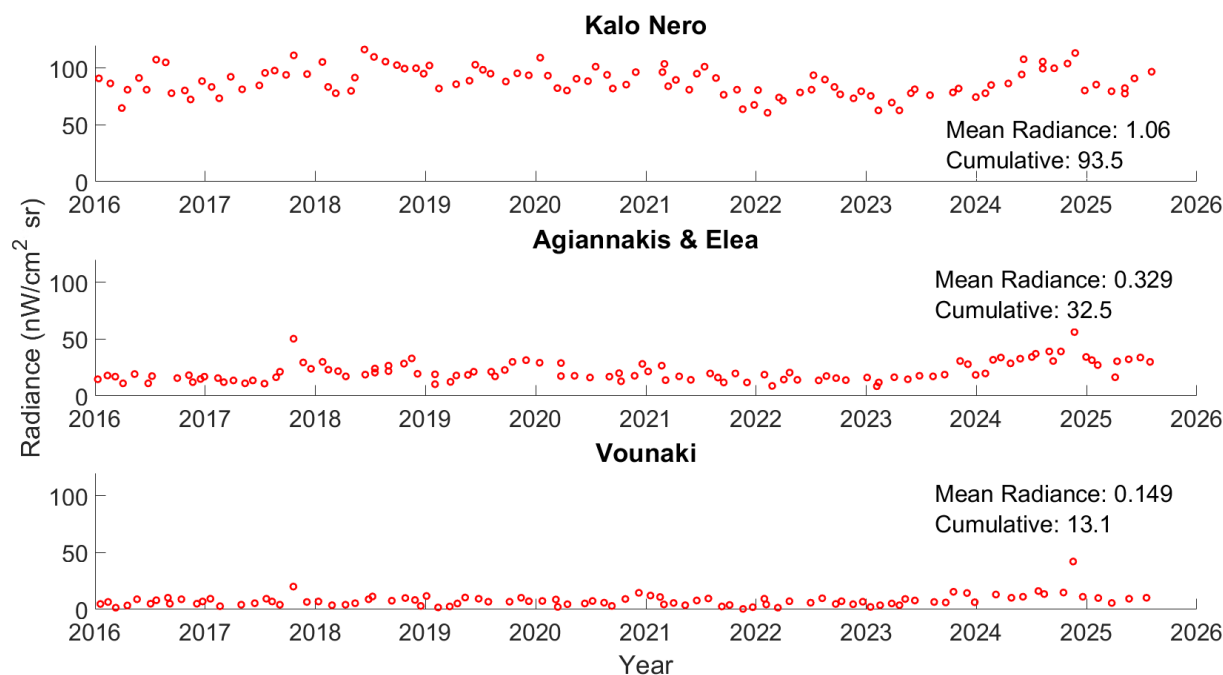


Figure 6. The last decade's monthly radiance measurements from the VIIRS/DMSP dataset for the three different subsections within the study area. Data were extracted from <https://www.lightpollutionmap.info>, (accessed on 10 September 2025).

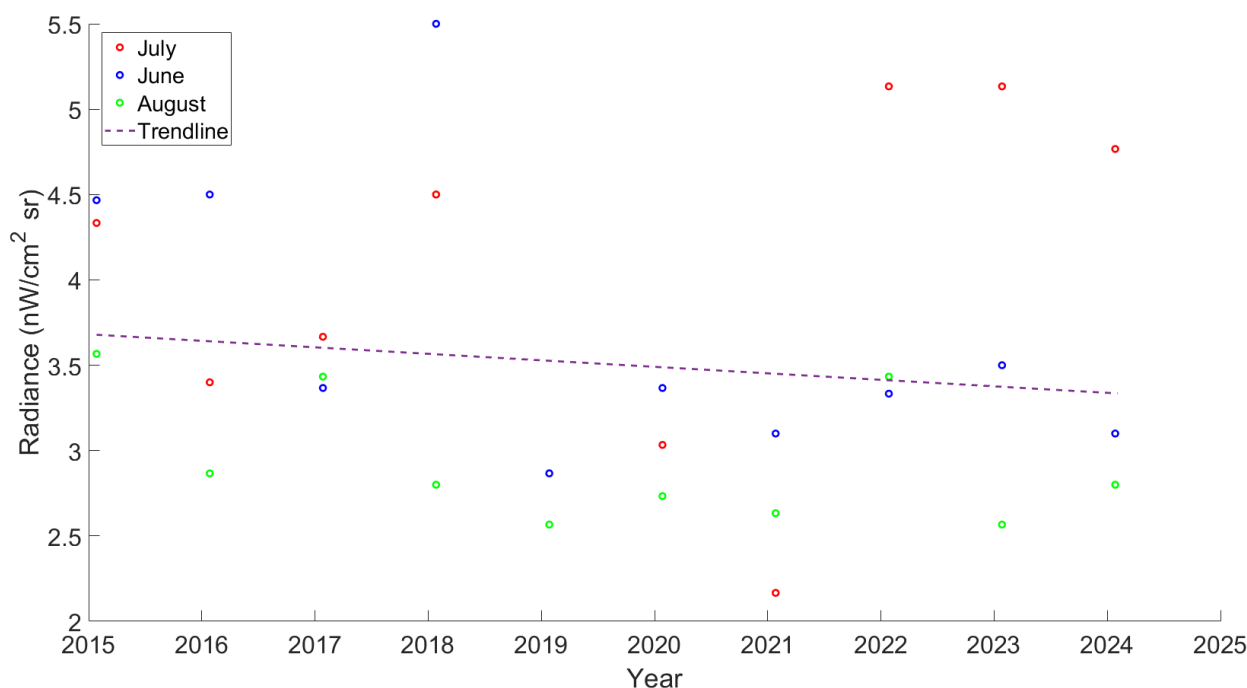


Figure 7. Average measurements of radiance for the study area during the summer months from the VIIRS/DMSP dataset. Data were acquired from <https://lighttrends.lightpollutionmap.info/>, (accessed on 10 September 2025).

4. Discussion

The shoreline of Kyparissia Bay exhibits a high illumination only at a specific part of the nesting area, specifically the Kalo Nero (Figure 4). As shown in comparable studies (Table 2), the measured light intensity in Kyparissia (ranging from 0.01 to 11 Lux, with an average of 3.5 Lux) can be deemed as moderate locally in the Kalo Nero area and very

low throughout the remainder of the study area. This level of illumination may have contributed to the reduced nesting density of sea turtles observed in Kalo Nero compared with that in adjacent beach segments. However, studies have shown that light intensity levels similar to those measured at Kalo Nero can cause hatchling disorientation and deter female adults from attempting to nest [8,10,58]. Besides light pollution, female adults may be driven away due to tourist activity, the occurrence of humans at the beach, and the presence of sunbeds and umbrellas [50].

Table 2. ALAN measurements in sea turtle studies around the globe.

Region	Species	Light Intensity (Lux)	Reference
Kyparissia (Greece)	<i>Caretta caretta</i>	3.5	Current study
Zakynthos (Greece)	<i>Caretta caretta</i>	0.08	[8]
St. George Island, FL (USA)	<i>Caretta caretta</i>	1.5	[40]
Heron Island (Australia)	<i>Caretta caretta</i>	2	[58]
Castiglione della Pescaia (Italy)	<i>Caretta caretta</i>	10	[10]
Boa Vista (Cape Verde)	<i>Caretta caretta</i>	7	[42]
Lanyu Island (Taiwan)	<i>Chelonia mydas</i>	15	[59]
Playa Grande (Costa Rica)	<i>Lepidochelys olivacea</i>	69	[60]
Indian River, FL (USA)	<i>Caretta caretta</i>	1.9	[61]
Xcacel (Mexico)	<i>Caretta caretta</i>	21.5	[62]
Santa Rosa (Guatemala)	<i>Lepidochelys olivacea</i>	4.5	[63]

Apart from Kalo Nero, the rest of the 10 km nesting beach exhibited no measurable evidence of light pollution, thereby supporting suitable nesting conditions and facilitating an undisturbed sea-finding process for hatchlings. However, as noticed in the past 20 years, coastal development is increasing, and the areas near Vounaki, Agiannaki, and Elea are experiencing rapid urbanization. According to the local NGOs that protect and conserve the area, several houses and other infrastructure have been built over the past 2–3 years, which causes concerns regarding the possibility of experiencing higher levels of light pollution at night. Hence, there is an extremely important need to define the best practices for managing light pollution along the coast of Kyparissia Bay.

There are a number of methods used to prevent, manage, and mitigate ALAN pollution [64–67]. The most prominent ones are (i) keeping light sources at an appropriate distance from the beach to be practical but also not overilluminating the area with all lights consistently directed downward, (ii) removing unnecessary light sources, (iii) adjusting the light sources' intensities to the necessary levels, (iv) using automated switches based on the movement of vehicles/people on the road at night, (v) replacing older types of light-emitting sources with newer and environmentally friendly ones (long wavelength lights), (vi) adjusting the direction of the beam at each one of the light sources near the nesting area to face away from the beach, (vii) designing the lighting of roads near the nesting beach to be targeted and not illuminating the nesting beach, (viii) finding ways to shield the nesting beach from the light sources (e.g., vegetation fence), (ix) the protection and establishment of sand dune systems and beach vegetation to reduce the impact of lights, and (x) raising awareness and informing the local owners of beach houses and tourism infrastructure about the best practices to mitigate ALAN impacts [10,52,66,68–72].

In the case of the Kyparissia Bay, most of the aforementioned management methods are urgently needed near the Kalo Nero where the higher intensity of light pollution was recorded, while the increasing urbanization of the surrounding areas of Vounaki and Agiannakis shows that a management plan is needed for the protection and conservation of sea turtle nesting in the most important nesting area of the entire Mediterranean region. Continuous monitoring efforts for the occurrence of and increase in ALAN in this area are

necessary, and local authorities should urgently take further measures to protect sea turtles in Kalo Nero.

Considering the limitations of the present study, the short sampling time frame (one summer) does not reflect variations in nesting behavior or how it was affected by light pollution over time. However, it does provide a reference for the exposure of sea turtles to ALAN pollution and can be used as a preliminary dataset for assessing its impact in the future. Additionally, the drone survey implemented in this study cannot detect all nests due to obstacles such as vegetation or human artifacts on the beaches. Nevertheless, this shortcoming applies to the entire coastline and does not affect the comparison between the different locations. It is also important to state that the nesting behavior is also affected by other factors, such as erosion, anthropogenic activities, and climate change, among others, and light pollution is one important parameter, but it does not solely affect sea turtle nesting in the region. Future research on the effects of ALAN in this critical rookery for the Mediterranean population of *Caretta caretta* should take into account changes in beach erosion, climate, and exploitation, and encompass additional aspects, including mapping and identifying visible light sources along the horizon, assessing night-glow sources, and quantifying hatchling mis-disorientation levels [8,41,70]. Further studies on the number of non-nesting emergences (i.e., false crawls) at the study area are necessary to assess the specific impact of these factors on nesting females. Furthermore, the Kalo Nero area's hatchling disorientation should be evaluated in future studies, in order to evaluate the direct impact of light pollution.

5. Conclusions

In the current study, we assessed ALAN pollution along the coast of Kyparissia Bay, the most important sea turtle nesting area in the entire Mediterranean region. Our findings demonstrated that most nests are located away from the highly polluted area of Kalo Nero, a village with high anthropogenic pressure due to the presence of restaurants and bars above the nesting beach. The Kalo Nero nesting beach is subjected to severe illumination at night that reaches up to 11.1 Lux, which may disrupt the sea-finding orientation of sea turtle hatchlings and discourage nesting attempts for female adults. Concerning other locations, the increasing urbanization of the region has the potential to cause ALAN impacts in the entire nesting area, which holds several thousand nests each year and is essential to the species' conservation and sustainability. Preserving the natural coastal environment of the Kyparissia Bay and ensuring the mitigation of ALAN pollution should be considered as a priority for local authorities and the management agency of the nesting beaches. In the future, monitoring the level of ALAN pollution and its impact on sea turtles is crucial for the protection of the species and the entire marine ecosystem.

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