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Assessment of Artificial Light at Night Across Geographical Features in the Sicilian Coastal Zone

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Abstract: This study investigates the impact of artificial light at night (ALAN) along the Sicilian coasts, using satellite data from 2016 to 2023, focusing on three distinct spatial domains: terrestrial areas within 1 km from the coastline, marine areas extending up to 1 km offshore, and marine areas up to 1 nautical mile from the coast. In coastal zones, ALAN is a significant anthropogenic pressure with potentially detrimental effects on ecosystems. By integrating satellite data with geographic datasets such as Corine Land Cover (CLC), Natura 2000 protected areas, and *Posidonia oceanica* meadows, this study aims to characterize and analyse the temporal and spatial variations in ALAN across these domains. The findings reveal substantial differences in light pollution between domains and over time, with coastal terrestrial areas exhibiting the highest levels of ALAN. In contrast, marine areas further offshore experience reduced light pollution, particularly within the 1-nautical-mile domain. This study also indicates that protected areas, especially those within the Natura 2000 network, show significantly lower ALAN levels than non-protected areas, highlighting the effectiveness of conservation efforts. Statistical analyses, including ANOVAs, demonstrate that factors such as geographic domain, year, province, and CLC classes significantly influence ALAN distribution. This study advocates for considering ALAN as a critical factor in environmental impact assessments, such as those under the Maritime Spatial Planning Directive (MSP) and Marine Strategy Framework Directive (MSFD), providing valuable insights to support policies aimed at mitigating the environmental impact of light pollution on coastal and marine ecosystems.

Keywords: artificial light at night; coastal zone management; Corine Land Cover; habitat directive; *Posidonia oceanica*; geographical information systems; Marine Strategy Directive; Maritime Spatial Planning Directive

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1. Introduction

The growing issue of nighttime light pollution, also known as artificial light at night (ALAN), is of increasing concern, particularly in coastal areas where intensified human activities exert significant pressure on both terrestrial and marine ecosystems [1].

This is especially problematic in areas like Sicily, with its extensive coastal zones and rich biodiversity, making it particularly vulnerable to these impacts [2].

Despite the global recognition of ALAN's effects, detailed studies that assess its spatial variability in Mediterranean regions, like Sicily, are still limited. This study aims to address this gap by characterizing ALAN levels along the Sicilian coasts from 2016 to 2023, examining three distinct spatial domains: terrestrial areas within 1 km from the coastline, marine areas extending up to 1 km offshore, and marine areas up to 1 nautical mile from the coast.

Previous studies [3,4] have provided valuable insights into the global and ecological consequences of ALAN. However, few investigations have focused on the Mediterranean, a region characterized by high biodiversity and by complex interactions between natural and human systems [5]. In this context, understanding ALAN's specific local impacts is critical, particularly in areas hosting sensitive ecosystems, such as *Posidonia oceanica* meadows or habitat directives protected areas.

Effective resource assessment and management and environmental protection necessitate balanced exploitation and conservation through a complex set of policies and regulations, both locally and across larger marine basins. The European Union has a well-established legislative framework for maritime protection, consisting of over 200 directives and regulations pertinent to the marine–maritime domain [6,7]. Key policies, such as the Marine Strategy Framework Directive (MSFD) and the Maritime Spatial Planning Directive (MSP), aim to enhance environmental sustainability and support the growth of the marine sector. These directives seek to focus on achieving good environmental status (GES) [8,9] and promoting a coordinated decision process within the framework of the Integrated Maritime Policy (IMP) [10]. The IMP advocates harmonizing the use of marine spaces to support endangered habitats and species, reflecting the broader scientific consensus that high environmental quality in coastal and marine areas positively impacts human well-being [11,12].

Despite these efforts, challenges such as chemical pollution, coastal erosion, habitat loss, eutrophication, and overfishing continue to exert significant pressures on marine life and human health [13,14]. In this context, the study of Land–Sea Interactions (LSIs) is increasingly important for the conservation of marine protected areas, where anthropogenic pressures should be minimized compared to non-protected areas.

Light pollution caused by artificial light at night (ALAN) represents a growing threat to marine and coastal ecosystems as documented by Ferretti [15]. Recent studies have highlighted ALAN's effects on biodiversity and the behavior of many species, contributing to significant ecological disturbances. For instance, Grillo et al. [16] documented how ALAN alters the composition of infralittoral communities along the Maltese coast, while Sanna et al. [17] demonstrated changes in the locomotor behavior of sea urchins in the Mediterranean. Furthermore, Weschke et al. [18] observed an increased prevalence of nocturnal predators on coral reefs, with repercussions on marine community structure. The synergistic effects of ALAN and other factors, such as global warming, have also been studied, with Caley et al. [19] highlighting antagonistic impacts on habitat-forming species like marine algae. These studies underscore the urgency of deepening the understanding of the mechanisms underlying ALAN's impacts and developing strategies to mitigate its effects on marine ecosystems.

To assess ALAN in these varied environments, satellite data from the Visible and Infrared Imaging Suite (VIIRS) were used, offering detailed nighttime brightness measurements at a resolution of approximately 500 m [20,21]. These data were integrated with geographic datasets, such as the Corine Land Cover (CLC) for land use classification, Natura 2000 protected areas, and *Posidonia oceanica* meadows. Data analysis was conducted using ArcGIS for spatial management and R for statistical analysis, following the methodologies established by Gaston and Davies [22] and Falchi et al. [3] to evaluate ALAN in both natural and anthropogenic contexts.

This study is innovative due to its integrated approach, which combines an eight-year temporal analysis with a detailed spatial evaluation of different coastal domains, aiming to analyse the spatio-temporal variability of ALAN along the Sicilian coasts. This research tests the hypothesis that terrestrial and marine areas located near high-density anthropogenic zones exhibit significantly higher levels of ALAN compared to protected areas or those subjected to lower human pressure. This methodology not only enhances the characterization of ALAN trends over time but also identifies critical areas most impacted by light pollution. The results can contribute to maritime spatial planning and environmental management, ensuring more effective conservation strategies. Additionally, the integration of diverse geographic datasets into a single spatial model represents a significant advancement over previous studies, which often focused on a single domain or shorter time periods. By providing a more comprehensive understanding of ALAN at finer spatial scales, this research offers valuable insights into the local impact of light pollution and supports the development of targeted conservation strategies in coastal areas.

2. Materials and Methods

This study was conducted in the coastal and maritime area of the eight coastal Sicilian provinces (CSPs), as detailed in Figure 1. Within the study area, three specific domains were identified: Land (from 1 km inland to the coastline); Sea 1 km (from the coastline to 1 km on the sea); Sea 1 nm (from 1 km to 1 nm offshore).

The assessment of ALAN in Sicilian coastal zones was based on three geographic datasets (GDs), rearranged in spatial domains (SDs) for the analysis (Table 1). The methods proposed by Gaston and Davies [23,24] were used to measure nighttime light pollution. Data processing was performed using ArcGIS 10.3 for data handling and R Core Team for the statistical analysis [25]. The three datasets, downloaded and rearranged for the next analysis processes, are listed below.

1. GD1—Coastal Zone Land Cover/Land Use (CZ-CLC). This dataset provides detailed land cover and land use information for 71 thematic classes for areas along the European coastline for the 2018 reference year. It was downloaded in May 2024 from Copernicus Land Monitoring Service (http://land.copernicus.eu (accessed on 1 September 2024)) and has a Minimum Mapping Unit (MMU) of 0.5 ha and a Minimum Mapping Width (MMW) of 10 m. It is available as vector data.
2. GD2—Natura 2000. This dataset represents the borders of the European ecological network of protected areas, set up to safeguard Europe's most valuable species and habitats. The dataset, updated in 2022, was downloaded in May 2024 from Natura 2000 (https://natura2000.eea.europa.eu/ (accessed on 1 September 2024)).
3. GD3—*Posidonia oceanica*. This dataset shows the current known extent and distribution of seagrass meadows in European waters, collated by EMODnet Seabed Habitats. The dataset, downloaded from EMODnet (https://emodnet.ec.europa.eu/ (accessed on 1 September 2024)) in May 2024, was updated in 2023.
4. SAT—artificial light at night (ALAN).

The annual satellite dataset from 2016 to 2023 was downloaded from the Earth Observation Group (https://eogdata.mines.edu/products/vnl (accessed on 1 September 2024)) using the Visible and Infrared Imaging Suite (VIIRS) "vnl" version, which excludes any data affected by stray light. The dataset provides data at a resolution of approximately 15 arc second (~500 m at the Equator) and the measure unit is nW/cm^2/sr [20,26]. It should be noted that the VIIRS instrument has a spectral response that is insensitive to wavelengths below 500 nm, rendering it less effective at detecting light sources, such as LEDs, with peak emissions near 450 nm.

Table 1. This table summarizes the three spatial domains (SDs) individuated and geodatabases (GDs) used for ALAN assessment. Grey highlights the domains analyzed.

Geographical Dataset		Spatial Domains (SD)		
		Land	Sea 1 km	Sea 1 nm
GD1	Coastal Zone Corine Land Cover level I III			
GD2	Natura 2000 vs. No Natura 2000			
GD3	*Posidonia oceanica* vs. No Posidonia			
SAT	Artificial Light at Night			

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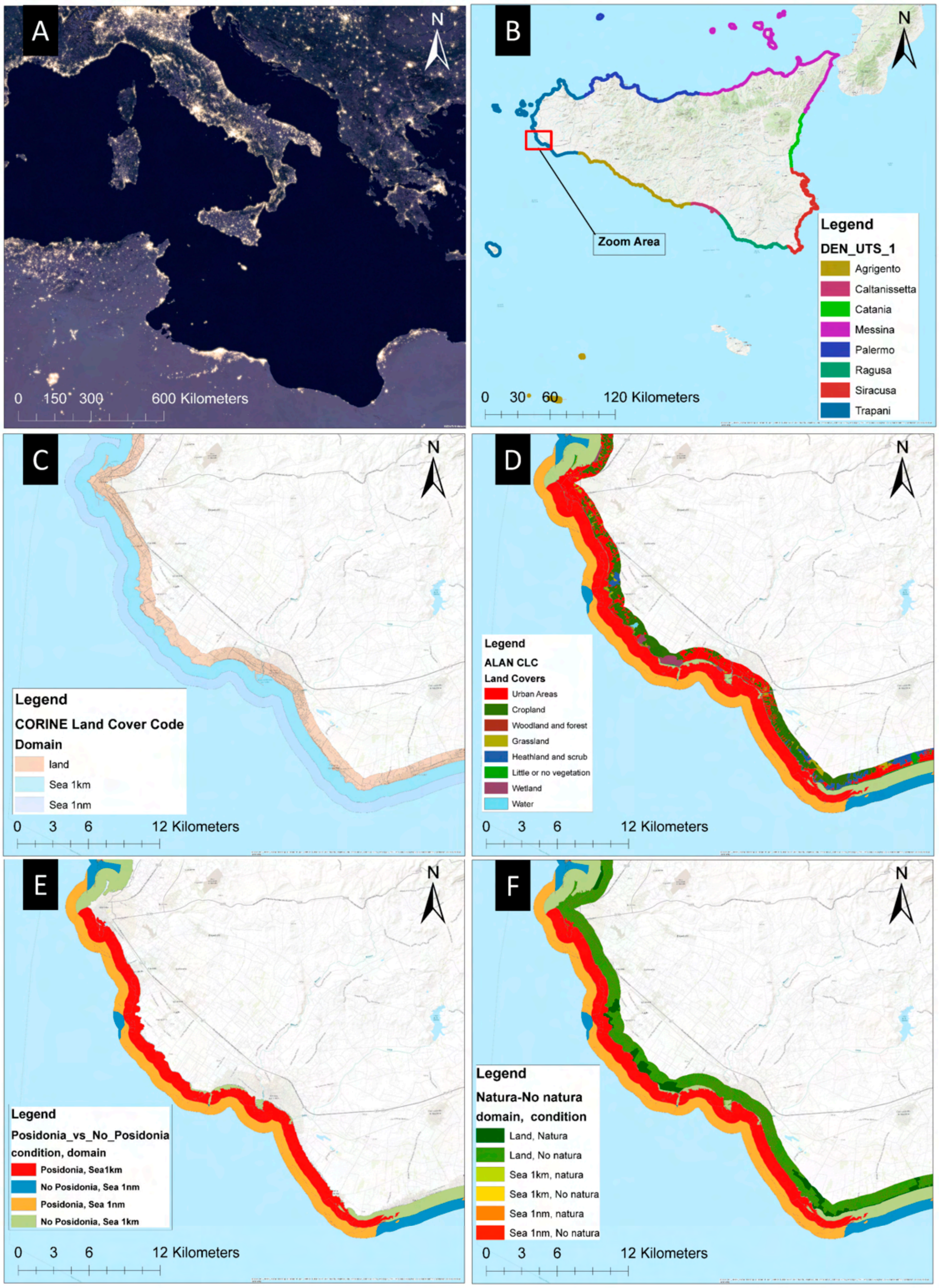

Figure 1. The figure shows: **(A)** ALAN diffusion along the coast of Sicily. **(B)** Study area and analysed Sicilian coastal provinces, with the zoomed-in area highlighted in red, shown in panels C to F to illustrate the datasets and domains analysed. **(C)** Representation of the analysed coastal domains (Land in brown, Sea 1 km in blue, Sea 1 nm in light blue). **(D)** Zoom on the Corine Land Cover dataset, with different colours representing the eight different land-cover types assessed in this study. **(E)** Zoom on the Posidonia dataset with different colours representing domains and conditions. **(F)** Zoom on the Natura 2000 dataset, with different colours highlighting the analysed conditions and domains.

3. Results

3.1. Data Processing and Analysis

Before processing, all datasets were projected using the ETRS-LAEA coordinate reference system (CRS). The data were analysed for eight Sicilian coastal provinces [23,24,27,28] and organized into spatial domains (SDs) to examine how the ALAN conditions spread across the three datasets.

The satellite ALAN data, provided in raster format, were associated with the GD1, GD2, and GD3 datasets, using the Zonal Statistics tool in ArcGIS 10.7. Specifically, the tool was used to calculate the average ALAN values for all the pixels falling within the polygons defined in the GD1, GD2, and GD3 datasets. The Zonal Statistics tool works by identifying which polygon each ALAN raster cell belongs to and then calculating the average ALAN value for all cells within the same polygon.

The Corine Land Cover (GD1) analysis was performed to characterize and compare the annual ALAN effect on several uses of soils, both in coastal zone areas and terrestrial coastal areas (SD/GD1). This data collection allowed for quantitative and qualitative measurement and comparison of the levels of nighttime light pollution in all SDs in GD1, GD2, and GD3 (Table 1). The measures of nighttime light pollution were correlated to the CLC map to identify the main light soils sources. The brightness was measured in nanowatts per square centimeter per steradian (nW/cm^2/sr) for each Level I of the CLC (Figure 1) to obtain a nighttime light pollution profile for Sicilian provinces and domains.

The GD2 dataset (Natura 2000 vs. non-Natura 2000) was created to compare the average ALAN values among areas and provinces within Natura 2000 boundaries and those outside, across the three considered domains.

Using data from EMODnet on *Posidonia oceanica* meadows, the dataset GD3 was created to study the effect of ALAN on these ecosystems. This dataset allows for comparison and assessment of ALAN differences between *Posidonia oceanica* meadows and areas not covered by meadows over the study period.

The ANOVA model was performed to explore statistical differences of ALAN among several factors (years, spatial domains, provinces, CLC classes, and conditions). The factor "condition" relates to the comparison between the protected natural areas (Natura 2000) and those not classified as Natura 2000 in the GD2 and between areas with the presence or absence of Posidonia in the GD3. The model also investigated interaction effects, which assessed whether the combination of two or more factors affects ALAN differently than each factor alone.

Moreover, the coefficient eta squared was calculated when significant results with the ANOVA test were found, to assess how impactful the group factor is on the variance in ALAN. It indicates how much of the total variance in the dependent variable can be attributed to the group factor.

Density plots of ALAN were generated using Kernel density estimation to visually interpret the distribution among different factors and their interactions, complementing the results from the ANOVA model.

ANOVA analysis showed significant statistical differences in ALAN spread for the analysed factors: years, domains, provinces, and conditions (Table 2). The significant differences found could suggest that light pollution impacts or spreads differently in protected areas and specific environmental habitats. Significant differences were also observed when analysing the interaction effects between different factors, as shown in Table 2.

Table 2. Results of ANOVA test for each analysed dataset. Highly significant ***; very significant **; not significant, no star.

Analysed Factors	Corine Land Cover		Natura vs. No Natura		Posidonia vs. No Posidonia	
	F Value	**Pr (>F)**	**F Value**	**Pr (>F)**	**F Value**	**Pr (>F)**
Year	11.513	1.05×10^{-14} **	34.706	$<2 \times 10^{-16}$ ***	3.255	0.00186 **
Domain	97.238	$<2 \times 10^{-16}$ ***	1231.205	$<2 \times 10^{-16}$ ***	1781.537	$<2 \times 10^{-16}$ ***
Provinces	1263.550	$<2 \times 10^{-16}$ ***	2212.51	$<2 \times 10^{-16}$ ***	200.924	$<2 \times 10^{-16}$ ***
CLC Level I	2244.943	$<2 \times 10^{-16}$ ***	No CLC Level I Data		No CLC Level I Data	
Condition	No condition Data		88,019.652	$< 2 \times 10^{-16}$ ***	1272.787	$<2 \times 10^{-16}$ ***
Years * Domain	0.006	1.00000	0.106	0.999987	1.156	0.99323
Years * Condition	No Condition Data		4.058	0.000186 ***	0.455	0.86731
Years * Provinces	1.813	0.000434 ***	4.058	$<2 \times 10^{-16}$ ***	1.659	0.00257 **
Years * CLC LEVEL I	0.118	1.00000	No CLC Level I Data		No CLC Level I Data	
Years * Domain * Provinces	0.003	1.00000	0.067	1.00000	0.427	0.99985
Years * Provincie * Code CLC	0.109	1.00000	No CLC Level I Data		No CLC Level I Data	
Years * Condition * Domain * Provinces	no Condition Data		0.191	1.00000	0.053	1.00000
Condition * Domain	no Condition Data		1867.2810	$<2 \times 10^{-16}$ ***	193.886	$<2 \times 10^{-16}$ ***
Condition * Provinces	no Condition Data		376.832	$<2 \times 10^{-16}$ ***	63.759	$<2 \times 10^{-16}$ ***
Condition * Provinces * Years	no Condition Data		0.9980	0.476587	0.240	1.00000
Condition * Domains * Provinces	no Condition Data		36.1740	$<2 \times 10^{-16}$ ***	12.524	3.57×10^{-12} ***
Condition * Year * Domain	no Condition Data		0.249	0.997861	0.075	0.99934

3.2. ALAN on Corine Land Cover

The ANOVA results indicated significant differences between years (F= 11.513, $p < 0.01$), domains (F = 97.238, $p < 0.01$), and provinces (F = 1.263.55, $p < 0.01$). However, the eta squared coefficient, calculated for the model with the year factor, was about 0.00045, suggesting that 0.045% of the total variance in ALAN was explained by the group factor. Therefore, the independent factor accounts for only a very small portion of the variance in the dependent variable. This implies that changes in ALAN levels over time can be negligible.

The eta squared coefficient, calculated for the model with the domain factor and province factor indicated that 1.1% and 5% of the total variance in ALAN was explained by the two factors, respectively. While the first result is still relatively small in effect size, it is larger than that of the year factor, with the province factor already having a more meaningful impact on the variance in ALAN.

The density plots of ALAN by CLC, shown in Figure 2, describe how the light pollution varies across different land-cover types.

In the three different SDs for GD1, the results revealed that the Land SD had 12.54% of the surface analysed by the zonal statistic tool and had a mean brightness level of 12.46 nW/cm^2/sr, while Sea 1 km and Sea 1 nm with 48.44% and 39.31% of surfaces analysed showed a mean brightness level of 3.32 and 0.58 nW/cm^2/sr, respectively.

Conversely, the analysis revealed different ALAN values for distinct CLC classes. The highest ALAN levels were observed in the urban areas in all years with an 18.56 nW/cm^2/sr mean and an 11.52 nW/cm^2/sr median (50th percentile) and a very wide distribution range. In the croplands, moderate ALAN levels were observed, but levels were significantly lower than urban centres (mean 7.91 nW/cm^2/sr and median 5.06 nW/cm^2/sr), followed by grassland and heathland and scrub, with mean ALAN levels of 10.33 nW/cm^2/sr and 14.27 nW/cm^2/sr (median of 3.93 and 11.52 nW/cm^2/sr), respectively. The water areas also exhibited notable ALAN levels, with a mean value of light pollution of 10.50 nW/cm^2/sr and a median of 5.10 nW/cm^2/sr.

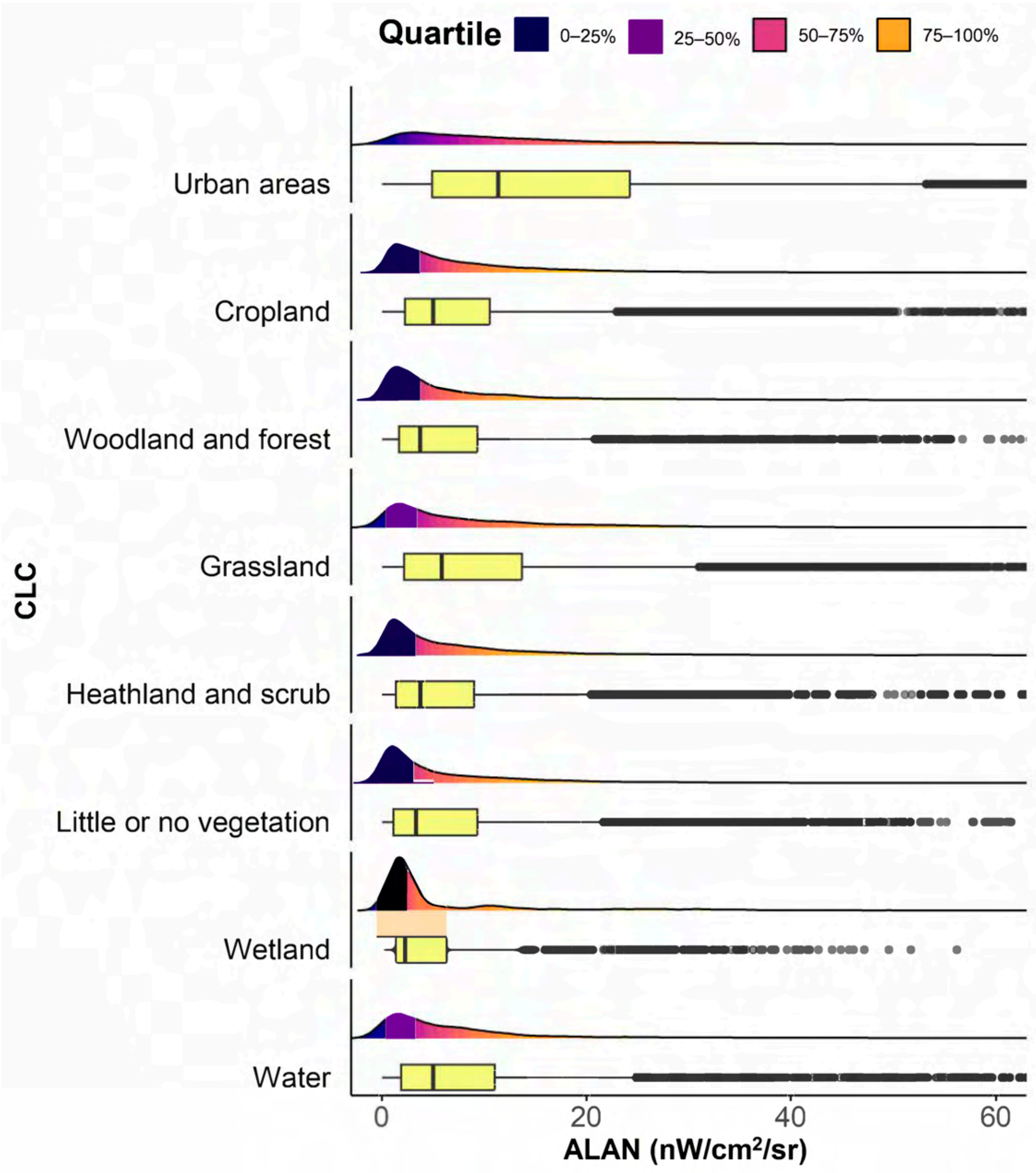

Figure 2. The figure summarizes the density plots of ALAN in the eight Level I Corine Land Cover types in spatial domain (SD Land) and geodatabases (GD1).

3.3. CLC ALAN Interaction Effect Results

The density plot in Figure 3 shows variations in the distributions of ALAN across different land use types and provinces. Urban areas consistently exhibit higher ALAN values in all provinces, with a wide range of distribution. In certain provinces artificial lighting extends beyond urban centres. Indeed, high ALAN levels are also observed in grasslands, croplands, woodlands, and forests in the provinces of Caltanissetta, Catania, Palermo, Ragusa, and Siracusa. Moreover, some provinces, notably Caltanissetta, Catania, and Ragusa, show significant light pollution in areas with minimal vegetation, such as beaches and rocky areas.

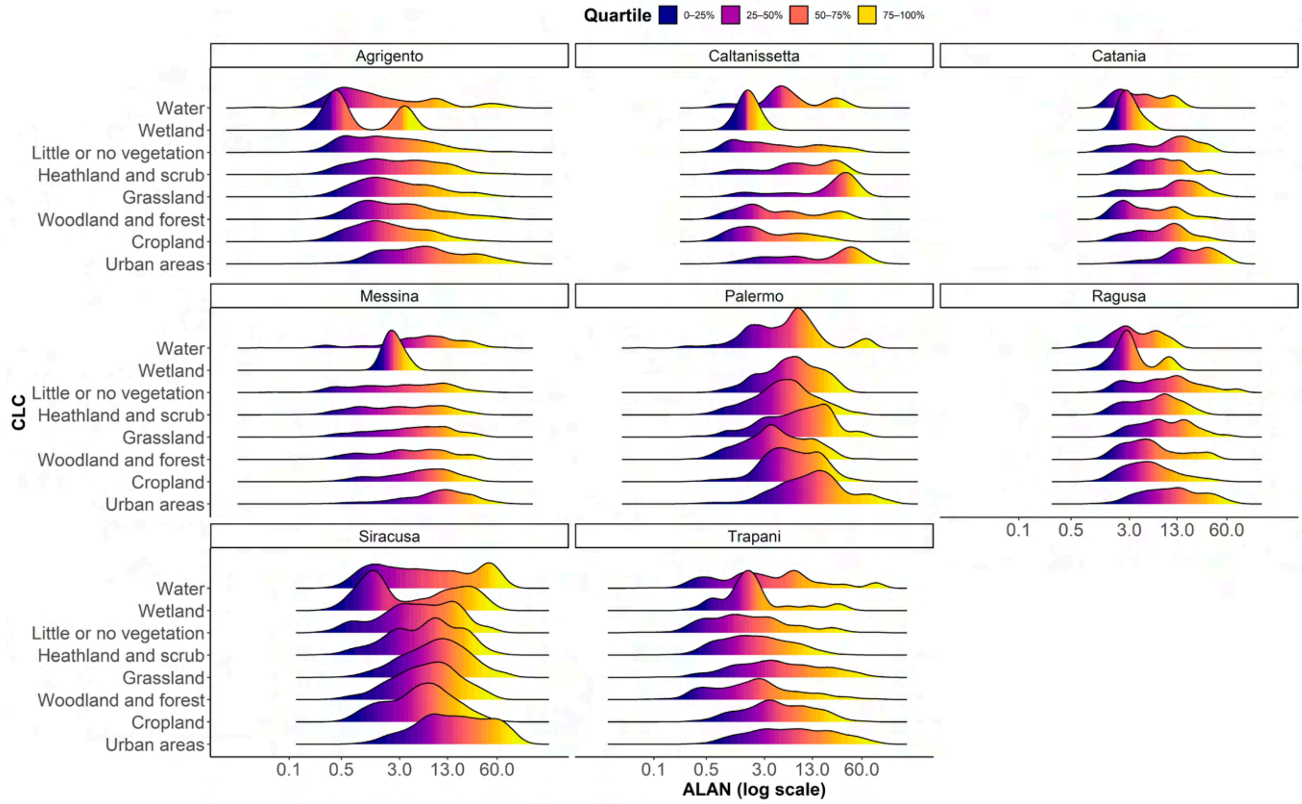

Figure 3. Density plots summarize the eight Level I Corine Land Cover types in spatial domains (SDs) in the eight Sicilian coastal provinces using the geodatabases (GD1).

3.4. Results of ALAN on Natura 2000

The ANOVA test showed statistically significant differences in ALAN levels based on various factors such as years (F= 34.706, $p < 0.01$), domains (F = 1231.205, $p < 0.01$), provinces (F = 2212.51; $p < 0.01$), and conditions (F = 88019.51; $p < 0.01$), as well as their interactions. The eta squared coefficients indicated that the condition had the largest effect (18.18%), with significantly higher light pollution being observed outside natural areas. Minor effects were registered for provinces (9.34%) and domains (6.49%), while the year factor showed minimal impact (0.05%). The negligible variance explained by the year factor suggests that ALAN levels may not be changing significantly over time.

Density plots in Figure 4 illustrate how the ALAN was distributed among domains, categorized into protected and non-protected areas.

Natura 2000 areas, both on land and in marine regions, exhibit significantly lower ALAN levels, reflecting the protective impact of these zones on light pollution. Non-Natura 2000 areas have much higher levels of light pollution, particularly in land domains, indicating a strong influence of human activity and infrastructure. ALAN levels decrease as distance from the coast increases in both Natura 2000 and non-Natura 2000 marine areas, but non-protected regions consistently have higher values.

In Natura 2000 land areas, the average ALAN value is 2.25 nW/cm^2/sr, median 0.82 nW/cm^2/sr, covering 48.64% of the surfaces considered. In marine areas located 1 km from the coast, the average ALAN value drops to 1.53 nW/cm^2/sr, median 0.68 nW/cm^2/sr, covering 12.84% of the surfaces. At 1 nautical mile from the coast, the average ALAN value decreases to 0.3763 nW/cm^2/sr, medina 0.26 nW/cm^2/sr, representing 19.21% of the surfaces. Overall, in natural areas, the average ALAN value is 1.87, spread over a surface area that accounts for 16.59% of the total.

In non-Natura 2000 land areas, a higher average ALAN value is observed, amounting to 12.82 nW/cm^2/sr, covering 51.36% of the surfaces. In the Sea 1 km domain, the average ALAN value is 5.63 nW/cm^2/sr, with a coverage of 18.32%. In the Sea1 nm domain, the average ALAN value reduces to 0.58 nW/cm²/sr, affecting 18.16% of the surfaces. The overall average ALAN value in non-natural areas is 12.21 nW/cm²/sr, median 6.74 nW/cm²/sr, distributed over a surface area accounting for 14.88% of the total.

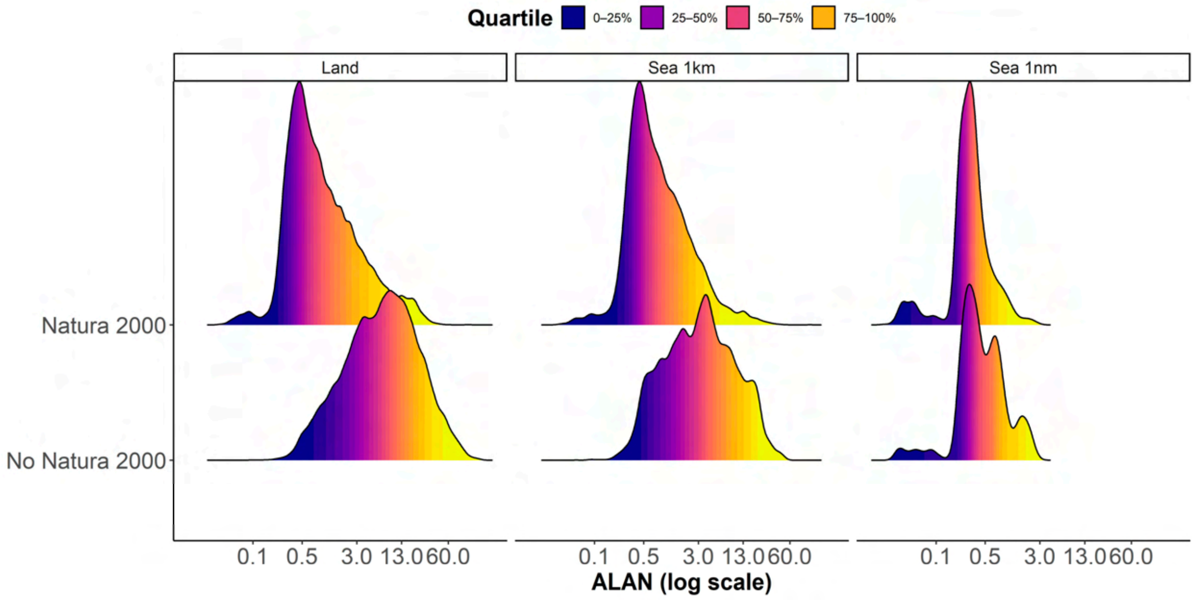

Figure 4. Measurement of ALAN in Natura 2000 habitats compared to areas outside Natura 2000 protection across three distinct coastal domains (SDs), with geodatabases (GD2) utilized for ALAN assessment.

Density plots of the distribution of ALAN among different provinces indicate Caltanissetta and Catania as the most polluted provinces. They exhibit the highest ALAN values, indicating that these provinces have the greatest concentration of light pollution compared to others. Even in protected areas, Natura 2000, high levels of ALAN are noted, suggesting that light pollution impacts extend into these conservation zones (Figure 5).

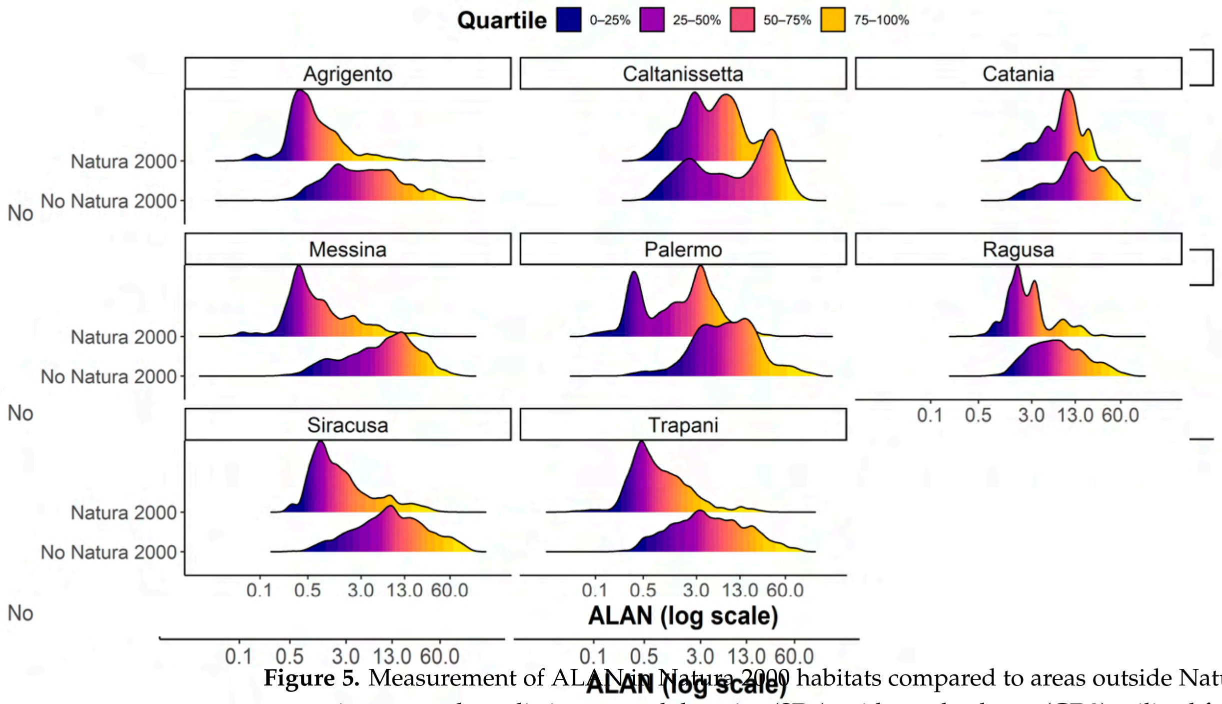

Figure 5. Measurement of ALAN in Natura 2000 habitats compared to areas outside Natura 2000 protection across three distinct coastal domains (SDs), with geodatabases (GD2) utilized for ALAN assessment in the eight Sicilian coastal provinces.

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3.5. Results of Alan on Posidonia

The results of the ANOVA test revealed statistically significant differences in ALAN levels among years ($F = 3.255$, $p < 0.01$), domains ($F = 1781.587$, $p < 0.01$), provinces ($F = 200.924$, $p < 0.01$), and condition ($F = 1272.787$, $p < 0.01$), as well as their interactions. The condition has the largest effect (percentage of explained variance = 4.71%), followed by domains (4.25%) and provinces (3.54%), while the years have a negligible effect (percentage of explained variance = 0.05%).

Density plot of ALAN in Posidonia and No Posidonia areas among different domains indicate that the areas with an absence of Posidonia have slightly higher values of light pollution than areas with Posidonia in all domains. In areas with Posidonia, the average value of ALAN is 2.03 nW/cm^2/sr, median 0.84 nW/cm^2/sr, in a total area of 827.41 km^2, with higher values in the Sea 1 km domain (average rises to 2.59 nW/cm^2/sr, median 0.84 nW/cm^2/sr) compared to the Sea 1 nm domain (average decreases to 0.67 nW/cm^2/sr; median 0.47 nW/cm^2/sr). In areas with an absence of Posidonia, a significantly higher average value is observed, amounting to 4.73 nW/cm^2/sr, median 0.56 nW/cm^2/sr, in a total area of 1870.23 km^2. In the Sea 1 km condition domain, the average ALAN value was 5.11 nW/cm^2/sr, median 0.84 nW/cm^2/sr, while in the Sea 1 nm domain, it is 0.76 nW/cm^2/sr, median 0.47 nW/cm^2/sr.

The difference between the Sea 1 km and Sea 1 nm domains is notable, suggesting that proximity to the coast (1 km from the shore) has a marked influence on the data values in both conditions (Figure 6).

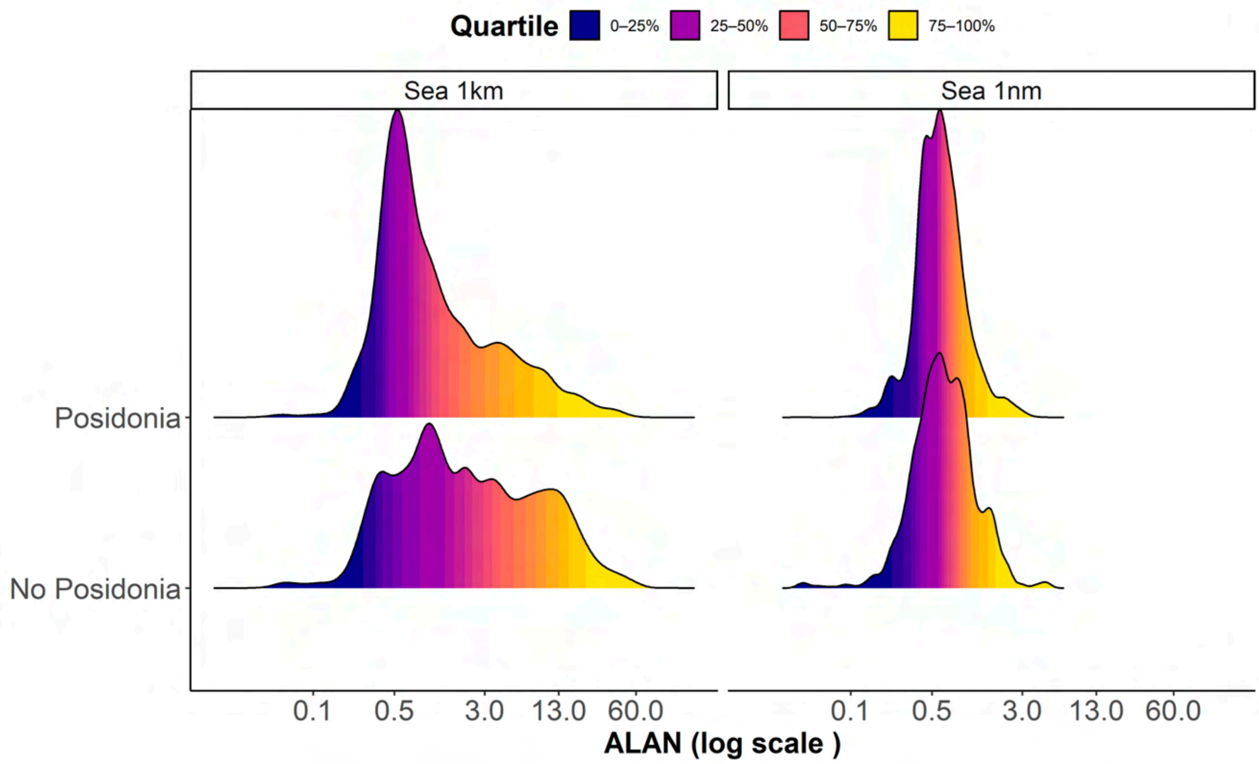

Figure 6. Measurement of ALAN in *Posidonia oceanica* habitats compared to areas outside Posidonia meadows across two distinct coastal domains (SDs), with geodatabases (GD2).

Density plots of the distribution of ALAN among different provinces highlight significant patterns of light pollution. Catania is identified as the most polluted province, with a notable difference in ALAN levels between areas with and without Posidonia. Palermo, Ragusa, and Siracusa, while still experiencing significant light pollution, do not have a clear distinction in ALAN levels between areas with and without Posidonia (Figure 7).

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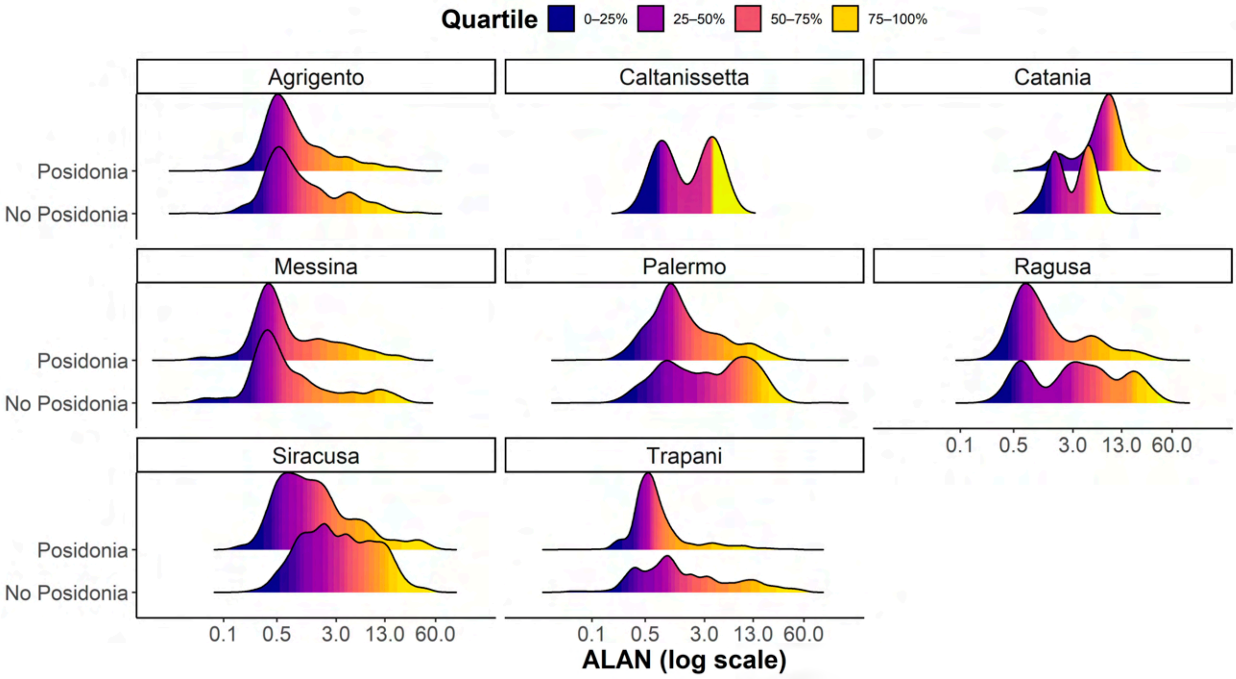

Figure 7. Measurement of ALAN in *Posidonia oceanica* habitats compared to areas outside Posidonia meadows among eight Sicilian coastal provinces.

4. Discussion

The analysis results highlight the spatial and temporal variations in ALAN and its significant impact on both coastal and marine ecosystems, focusing on the Sicilian coasts. A comparative analysis with similar studies from other countries provides valuable context to assess the broader implications of these findings. For instance, research conducted in the United Kingdom by Davies et al. [29] emphasizes the ecological consequences of ALAN on marine habitats, particularly seagrass meadows, which mirrors the impact observed in *Posidonia oceanica* habitats along the Sicilian coast. Similarly, studies in Australia [30] have documented the disruption of nocturnal foraging behaviors in marine species due to artificial lighting, echoing the challenges faced by Sicilian coastal ecosystems. These comparisons underscore the universality of ALAN as a global issue while highlighting region-specific ecological sensitivities that require tailored interventions.

4.1. Relationship Between ALAN and Corine Land Cover

This manuscript presents an analysis of artificial light at night (ALAN), highlighting spatial and temporal dynamics in various land-cover types (as classified by Corine Land Cover).

The significant differences observed for the year factor, while statistically evident ($F = 11.513$, $p < 0.01$), reveal a very small effect size, as indicated by the eta squared coefficient of 0.00045. This suggests that only 0.045% of the total variance in ALAN is explained by temporal variations across the years, implying a negligible practical impact. Although changes in ALAN over time appear significant in a statistical context, they do not represent a substantial shift in overall ALAN levels. This may reflect short-term fluctuations or external events that, while detectable, did not lead to a lasting impact on ALAN. Such changes could be linked to temporary factors such as adjustments in public lighting policies, climate variations, or shifts in energy demand. For example, Hao et al. [31] showed that temporal variations in ALAN in urban areas of China were primarily attributable to seasonal shifts in energy consumption and temporary events, rather than long-term trends.

Several studies suggest that year-to-year differences in satellite-detected lighting may stem from intrinsic variations between the sensors used [32]. Additionally, temporal dynamics related to nighttime activities, such as streetlights, illuminated windows in residential and commercial buildings, and vehicular movement, can further contribute to ALAN variability over time and align with previous studies, such as those by Kyba et al. and Barà et.al [33,34]. Moreover, the impact of annual changes on ALAN may be modulated by regional energy regulation measures that vary across geographic contexts [33,34].

By contrast, spatial factors such as "province" demonstrated a larger effect (explaining 5% of the variance), highlighting the more pronounced influence of geographic differences, local policies, or regional infrastructures compared to annual temporal changes, in line with the evidence found by Xiao et al. [35]. Similarly, the domain factor, while contributing less than the province factor, still explains a more relevant portion of the variance than the year factor, emphasizing the predominance of spatial elements in understanding ALAN variance.

Moreover, the results revealed that the domains exert a significant impact on ALAN, indicating that the geographic context, whether terrestrial or marine, plays a crucial role in determining different light pollution levels [36].

The Land, which represents the coastal terrestrial domain, likely exhibits the highest levels of ALAN due to its proximity to urbanized regions. Coastal areas are often densely populated and developed, leading to significant artificial lighting, particularly from residential areas, commercial establishments, and infrastructure such as roads and ports, as evidenced from Halpern [37]. This pattern is consistent with previous studies that have identified coastal regions as major hotspots for light pollution, due to intense human activities [38–40]. Urban areas tend to exhibit much higher levels of artificial light compared to rural areas [41], a trend that can be attributed to ongoing urbanization [42], shifts in public lighting policies, or the increasing use of artificial lighting in various regions [41].

The Sea 1 km domain, which extends from the coastline up to 1 km offshore, likely experiences moderate levels of ALAN. Light from coastal sources can still penetrate this marine area, though its intensity diminishes with distance. The effect of ALAN in these marine domains might be influenced by factors such as the proximity of coastal cities, industrial activities, and maritime infrastructures. Studies have shown that light pollution can extend into marine environments, affecting marine ecosystems, particularly in areas close to the shore [4,22].

According to Smyth's results [43], the 1 nm sea domain, which extends from 1 km to 1 nautical mile offshore, likely experiences the lowest levels of ALAN, as it is farther from direct coastal light sources. However, light from ships, fishing activities, offshore installations, and distant urban areas may still contribute to ALAN spread. The lower intensity of ALAN in this area could mitigate some of the ecological impacts compared to the nearer coastal regions. Nonetheless, research has indicated that even low levels of light pollution can disrupt marine life, particularly in areas with sensitive ecosystems [1,44,45].

The provinces factor shows the most significant effect on ALAN, underscoring the importance of provincial boundaries in explaining its distribution. This result suggests that variations in urban development, population density, and local policies across different provinces play a critical role in determining light pollution levels because the regional differences in light pollution have been linked to local governance, urban planning, and economic activity [45–48]. This finding aligns with previous research that emphasizes the importance of considering regional dynamics in studies of light pollution [36,46,49].

The analysis of Corine Land Cover Level I showed significant differences in the ALAN values among the different types of land use [3,50]. Previous studies, focusing on the use of ALAN data at the regional dynamics scale, have often failed to adequately explain how NTL signals respond to different land-use/land-cover types as well as socioeconomic activities, such as population distribution, energy consumption, and building density. A thorough understanding of the relationship between illuminated pixels and the associated land surface features and human activities could advance the application of nighttime light data, but this aspect has not been adequately explored in prior research [51–54].

The obtained results do not show significant differences in ALAN values between year and domains. This suggests that each domain is characterized by its specific level of light pollution over time, further supporting the effect of the spread of anthropogenic light on coastal and marine domains [46,55].

In contrast, the interaction between year and provinces is significant, indicating that the ALAN values have been maintained over time across different provinces. This result reinforces the idea that the observed phenomenon is closely tied to territorial characteristics, such as variability in orographic features, land use patterns, local policies, or developments in lighting infrastructure, which have changed at different rates in different provinces [22].

However, other interaction effects, such as those between year and domain or year and CLC Level I, do not show a significant influence on ALAN. This indicates that the main effects of these factors are largely independent, with limited synergistic impacts. The lack of significant interaction effects, except for the year * provinces interaction, suggests that, while the individual factors are important, their combined influence on ALAN is not pronounced. This pattern has been observed in other studies where the main drivers of light pollution acted independently rather than interactively [56]. The significance of the interaction between the factors of year and CLC Level I suggests that, over the study period, different land use types consistently showed significant differences in ALAN levels. These findings highlight that, within the scope of this study, temporal variations did not substantially modify the established relationship between land-cover types and ALAN. Furthermore, the result reinforces the understanding that ALAN is strongly dependent on land use characteristics, emphasizing its spatial variability based on different land use patterns and their specific attributes at the local scale [1,57,58].

Finally, the interactions between year, domain, and provinces, as well as between year, provinces, and CLC, show very low F-values, indicating no significant interactions. This suggests that the combination of these factors does not significantly influence the annual variations in ALAN levels. Despite the presence of multiple factors that could potentially explain differences in ALAN at a local scale, no significant differences were detected. This finding, supported by cross-correlation analyses, further confirms that while ALAN may vary on a broader scale, its patterns are strongly defined and characterized at the local level [1,55].

In conclusion, the analysis showed that spatial and temporal factors, particularly provinces and domains, are the main determinants of ALAN levels, while interactions between these factors and land-cover types do not appear to have a significant impact.

These results underscore, as highlighted in other studies [59,60], the importance of considering local and regional differences in lighting management policies to better understand and mitigate the impact of artificial light on the environment and human health [61].

4.2. Discussion on Natura 2000

This study's observation that protected areas, such as those within the Natura 2000 network, exhibit significantly lower ALAN levels aligns with research by Mu et al. [62], who highlighted the ALAN in protected areas. The findings further corroborate the work of Falchi et al. [3], who reported that protected areas in Europe generally experience lower light pollution levels due to stricter regulations and reduced anthropogenic activities.

The analysis showed that the effect of the year is highly significant, highlighting how the amount of artificial light at night (ALAN) has varied considerably over time (Table 2). This finding is consistent with the global trend of increasing light pollution observed in recent decades, as reported by various studies [46].

The effect of the domain is extremely significant, and this is in accordance with existing literature which indicates that urban or entropized areas tend to show higher levels of ALAN compared to more natural habitats [3,61,63].

Similarly, the effect of provinces is highly significant, underlying the importance of geographic distribution in determining ALAN levels. Previous studies have highlighted significant variations in light pollution at the regional level, often influenced by factors such as population density and economic activity [64–66].

Regarding the condition factor (e.g., whether it is a protected area like Natura 2000 or not), the effect is also extremely significant, suggesting that protected sites may have very different levels of ALAN compared to unprotected ones. The literature supports this idea, indicating that protected areas tend to have stricter light management policies, thereby reducing light pollution [41,66].

The interaction between the factors of year and condition is significant, suggesting that the ALAN intensity has been maintained differently over time between Natura 2000 and non-protected sites, likely reflecting the effect of differentiated management policies over time.

Similarly, the interaction between factors of year and provinces and condition and provinces showed significant differences, suggesting that the variation in ALAN value levels has been maintained differently across provinces, possibly due to local policies or different urban development, as highlighted in others' results of this study topic.

Furthermore, the highly significant interaction between condition and domain indicates that the effect of condition (Natura 2000 vs. No Natura 2000) is strictly dependent on the type of habitat and ecological domain considered in this study.

This complex three-way interaction, involving condition, domain, province, and condition, domain, year, shows that the combined effect of these factors on ALAN does not present significant differences in either case. This reinforces the hypothesis that ALAN remains a stable and constant value at the local scale, indirectly defining the levels of anthropogenic pressure in different habitats and domains.

Moreover, interactions such as year * domain and other more complex interactions (e.g., year * domain * provinces; year * condition * domain * provinces) did not show significant differences, suggesting that the time variation in ALAN levels is not influenced by the complex interaction of these factors. This may indicate that, while some effects are significant, not all combinations of factors significantly influence ALAN levels.

The results of this ANOVA indicate that factors such as year, domain, province, and condition significantly influence ALAN levels in both Natura 2000 and non-Natura 2000 sites. The interactions among some of these factors suggest that the impact of ALAN is complex and may vary depending on the specific combination of environmental and geographical conditions. These findings are consistent with existing literature highlighting that light pollution is a varied phenomenon, strongly dependent on both anthropogenic and natural factors.

The observed differences in ALAN between Natura 2000 areas and non-protected areas (No Natura 2000) align with existing studies that highlight the impact of anthropogenic activities on light pollution. For instance, Falchi et al. [3] have shown that urbanized areas tend to have much higher levels of light pollution compared to natural and protected areas. The fact that No Natura 2000 areas exhibit an ALAN value of 12.82 nW/cm^2/sr in the land domain, which is significantly higher than the 2.25 nW/cm^2/sr observed in Natura 2000 areas, underscores the effectiveness of conservation efforts in mitigating light pollution in protected areas.

The Sea 1 km and Sea 1 nm domains also reflect this trend, with ALAN values in non-protected areas (5.63 nW/cm^2/sr and 0.58 nW/cm^2/sr, respectively) being consistently higher than those in protected areas (1.53 nW/cm^2/sr and 0.3763 nW/cm^2/sr). This is consistent with research by Kyba et al. [31], which indicates that coastal and marine environments, especially those near urbanized regions, are increasingly affected by ALAN, posing risks to marine ecosystems.

The overall average ALAN value of 6.36 nW/cm^2/sr across all surfaces highlights the pervasive nature of light pollution, but the stark contrast between natural and non-natural areas emphasizes the role of land management and protection status in controlling light pollution. Jägerbrand et al. [67] discusses how areas with stricter environmental regulations, such as Natura 2000 sites, are better equipped to limit the spread of ALAN, thus preserving both terrestrial and marine biodiversity.

4.3. Discussion Alan on Posidonia

The extension of light pollution into marine environments has been widely documented, with studies like that of Pothukuchi et al. [59] showing that light from coastal cities and industrial activities penetrates offshore areas, affecting marine ecosystems [59]. This study complements these findings by highlighting the diminishing intensity of ALAN as distance from the coast increases, with the Sea 1 nm domain experiencing the lowest levels of light pollution. Such results are consistent with the work of Davies et al. [43], who reported that light pollution in marine areas decreases sharply beyond the immediate vicinity of coastal sources

The ANOVA analysis performed to assess the effects of artificial light at night (ALAN) in *Posidonia oceanica* meadows reveals insights into how this pollutant is spread in areas covered and not covered by meadows (condition factor).

The condition factor, which distinguishes between areas with and without Posidonia meadows, is also highly significant (Table 1). The presence of Posidonia seems to drastically influence ALAN levels, which could suggest that Posidonia either mitigates the effects of artificial lighting or that areas with Posidonia are less exposed to ALAN due to protective regulations. A third hypothesis could be considered: Posidonia meadows are more likely to thrive in areas with low ALAN [68].

Firstly, the year factor is statistically significant (Table 2). This indicates that the levels of ALAN have changed significantly over the years studied. Such changes could be attributed to evolving regulations, infrastructure development, or other environmental and societal shifts, not excluding the technological upgrade of public lighting through LED technologies.

Similar to the other datasets analysed in this study, the analysis of single factors, like domain or province, shows a very high level of significance (Table 1), indicating that ALAN values decrease progressively from land to sea. This finding suggests that geographical and ecological differences play a crucial role in determining the exposure of different ecosystems to artificial lighting. Such variations may be influenced by local factors, including population density, urban planning policies, and regional approaches to managing light pollution.

Multiple interaction between year * domain and year * condition show non-significant differences (Table 2). This result, as in the other cases analysed, confirms how the domain and condition factors, even when combined with the year factor, do not exhibit significant differences. This supports the conclusion that the spread of ALAN is primarily influenced by the type and proximity to the main sources of diffusion.

However, the interaction between year and provinces is significant (Table 2), implying that the effect of provinces on ALAN has changed over the years. This could be due to changes in provincial policies or shifts in urban development patterns.

The more complex interactions, such as year * domain * provinces (Table 1) and year * condition * domain * provinces (Table 2), are not significant, indicating that ALAN does not have a meaningful impact on the results for the factors of year, domain, and province.

On the other hand, the interaction between multiple factors that show highly significant differences (Table 2) suggests the impact of ALAN on Posidonia when multiple factors are considered.

The characterization of the phenomenon is further strengthened by the results, which reveal significant differences in the multiple interactions between ALAN and condition * domain, condition * province, year * province, year * domain * province, and year * condition * domain * province. All these findings confirm the influence of these factors in shaping the phenomenon on a local scale that had a trend that was maintained over time.

The existing literature supports the notion that artificial light can have detrimental effects on marine ecosystems, particularly in coastal areas where species like *Posidonia oceanica* are found. Gaston et al. [41,50] and Longcore and Rich [69] have documented how ALAN can interfere with healthy nocturnal biological processes and disrupt biodiversity in coastal ecosystems. The findings of this study align with these observations, suggesting that the presence of Posidonia may offer some protection against the impacts of ALAN, although this protection appears to vary depending on the geographical and ecological context [70].

The data provided reveal notable differences in average values of artificial light at night (ALAN) between marine areas with *Posidonia oceanica* and those without. Here is a detailed analysis based on the scientific context.

Posidonia oceanica meadows can significantly affect the penetration of light into the water column. The dense meadows of Posidonia can reduce the amount of light reaching the seafloor, which might explain the lower ALAN values in areas with Posidonia. This effect is consistent with the findings that areas with Posidonia show a lower average ALAN value compared to areas without [71,72].

The higher ALAN values in areas without Posidonia suggest that these regions experience less attenuation of artificial light [73–75]. The absence of vegetation means there is less filtering of light, leading to higher observed values [68]. This is particularly evident in the Sea 1 km domain where the difference in ALAN values between areas with and without Posidonia is most pronounced.

The variation in ALAN values between different domains (1 km and 1 nm) highlights the spatial influence of Posidonia. In the Sea 1 nm domain, ALAN values are generally lower in the presence of Posidonia, likely due to its impact on light attenuation over a smaller spatial scale. Additionally, the differences in ALAN values between areas with and without Posidonia in the 1 nm domain are smaller, partly due to greater depths and the resulting homogeneity in backscattering, which diminishes the distinctive effect of vegetation on artificial light at night.

Conversely, the absence of Posidonia results in higher ALAN values, as seen in the broader Sea 1 km domain [76].

The results indicate a clear distinction in ALAN values between marine areas with and without *Posidonia oceanica*. Areas with Posidonia exhibit lower average ALAN values, which is consistent with the known effects of seagrass meadows on light attenuation. These findings suggest that Posidonia may play a significant role in modifying the distribution and intensity of artificial light in marine environments. Further research involving direct measurements could explore the specific mechanisms by which Posidonia affects ALAN and investigate other environmental factors that might contribute to these observations

5. Conclusions

This study highlights the significant influence of temporal, geographic, and administrative factors on the distribution of artificial light at night (ALAN) across Corine Land Cover (CLC) classes, successfully achieving its primary research objective of identifying key drivers of light pollution in Sicilian coastal and marine areas. The domain factor highlights how geographic context, ranging from coastal terrestrial areas to marine zones, influences light pollution levels. The coastal land domain is most affected, followed by the immediate offshore areas, with the outer marine zones experiencing the least impact. Additionally, the provincial factor emerges as a critical determinant, reflecting the importance of regional differences in understanding the dynamics of light pollution. These results contribute to a growing body of literature that seeks to understand the complex interplay of factors influencing ALAN and offer valuable insights for future research and policymaking in this field [56,77–79].

Moreover, the results of this study confirm the importance of the European Union to suggest national and regional policies in managing and mitigating nighttime light pollution (ALAN) along the coasts. These policies are reflected in a complex regulatory framework that includes specific laws on light pollution, the promotion of LED technologies to reduce energy consumption and environmental impact, and strategic maritime planning [80].

5.1. About the Legislation and Policies on Light Pollution Mitigation

In Italy, Law No. 22/97 on environmental protection from light pollution, also known as the "Veneto Regional Law", was one of the first regional laws to introduce specific regulations for controlling light pollution [81]. This law promotes the use of low-consumption and low-environmental-impact lighting sources. It was followed by various regional regulations that established rules to limit light dispersion upwards and towards unnecessary areas, with particular attention to protecting natural areas and parks [82].

The introduction of LED technologies, also promoted by the European Directive 2012/27/EU on energy efficiency, has played a crucial role in reducing energy consumption [83]. Compared to incandescent bulbs, LED lamps emit light more directly and with less dispersion, reducing the amount of light that escapes into the night sky. Furthermore, LEDs offer the ability to control the colour temperature of the light, an important factor in managing environmental impact. However, it is essential to consider that, if not properly managed, LED installations can contribute to light pollution due to their high efficiency and luminous intensity.

Unlike incandescent lamps, which emit light in all directions and consume more energy to produce the same amount of light, LED lamps are more efficient and can be designed to minimize light dispersion. This results in a significant reduction in ALAN, especially in urban and coastal areas where artificial light sources are more intense [80,84].

5.2. About the Integration of ALAN into European Directives

The Marine Strategy Framework Directive (2008/56/EC) mentions the distribution of energy in the marine environment as a critical element to be monitored and managed. However, this directive primarily focuses on energy forms such as underwater noise and vibrations, largely neglecting the impact of ALAN on marine ecosystems. Despite growing evidence that light pollution can have detrimental effects on marine organisms, particularly in coastal areas and protected sites like *Posidonia oceanica* meadows, ALAN is not yet adequately integrated into maritime spatial planning policies.

This study emphasizes the need to update existing regulations and incorporate artificial light at night (ALAN) into the good environmental status (GES) indicators of the Marine Strategy Framework Directive (MSFD), similar to other pollutants. Adopting a more integrated approach to maritime spatial planning could help mitigate the impact of light pollution, protect sensitive marine habitats, and enhance the environmental sustainability of coastal areas.

5.3. Conclusions Based on the Results

The results obtained clearly show how light pollution varies significantly depending on the geographical domain, with coastal terrestrial areas being more affected than offshore marine areas. A plausible explanation for the lower ALAN levels observed in protected areas, such as those within the Natura 2000 network, is that these areas are subject to regulatory constraints that indirectly limit light pollution. Specifically, the prohibition of activities associated with land cover classes (CLC) characterized by higher ALAN emissions may contribute to this difference, highlighting the indirect protective effect of conservation measures. The use of LED technologies has demonstrated the potential to reduce the impact of ALAN, but it requires careful management to avoid negative side effects.

This study highlights the potential for systematic monitoring and analysis of ALAN trends over time to better understand the evolution of light pollution in Sicily. By identifying priority coastal areas with elevated ALAN levels, the findings can guide policymakers in developing targeted regulatory and management strategies aimed at mitigating ALAN impacts and preserving ecological and cultural heritage [3,4,50,73,78]. In a historical moment where public awareness and knowledge of anthropogenic contaminants are growing, focusing attention on ALAN is increasingly relevant. The creation of detailed maps for monitoring ALAN levels across different geographical contexts would provide valuable tools for assessing its spread and impact. Such an approach could contribute additional insights for evaluating progress toward achieving the good ecological status of ecosystems, aligning with broader environmental conservation goals [1,85].

In conclusion, to reduce the impact of ALAN on the Sicilian coasts and marine ecosystems, it is essential to continue implementing and strengthening conservation policies at both the European and national levels, with a particular focus on integrated approaches that include light pollution control in spatial planning and marine strategies. These interventions not only protect biodiversity but also contribute to the long-term sustainability of marine resources, in line with the United Nations' sustainable development goals.

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References

1. Marangoni, L.F.B.; Davies, T.; Smyth, T.; Rodríguez, A.; Hamann, M.; Duarte, C.; Pendoley, K.; Berge, J.; Maggi, E.; Levy, O. Impacts of Artificial Light at Night in Marine Ecosystems—A Review. *Glob. Change Biol.* **2022**, *28*, 5346. [CrossRef] [PubMed]
2. Coll, M.; Piroddi, C.; Steenbeek, J.; Kaschner, K.; Ben Rais Lasram, F.; Aguzzi, J.; Ballesteros, E.; Bianchi, C.N.; Corbera, J.; Dailianis, T. The Biodiversity of the Mediterranean Sea: Estimates, Patterns, and Threats. *PLoS ONE* **2010**, *5*, e11842. [CrossRef] [PubMed]
3. Falchi, F.; Cinzano, P.; Duriscoe, D.; Kyba, C.C.M.; Elvidge, C.D.; Baugh, K.; Portnov, B.A.; Rybnikova, N.A.; Furgoni, R. The New World Atlas of Artificial Night Sky Brightness. *Sci. Adv.* **2016**, *2*, e1600377. [CrossRef] [PubMed]
4. Gaston, K.J.; Duffy, J.P.; Gaston, S.; Bennie, J.; Davies, T.W. Human Alteration of Natural Light Cycles: Causes and Ecological Consequences. *Oecologia* **2014**, *176*, 917–931. [CrossRef]
5. Aurelle, D.; Thomas, S.; Albert, C.; Bally, M.; Bondeau, A.; Boudouresque, C.; Cahill, A.E.; Carlotti, F.; Chenuil, A.; Cramer, W.; et al. Biodiversity, Climate Change, and Adaptation in the Mediterranean. *Ecosphere* **2022**, *13*, e3915. [CrossRef]
6. Beunen, R.; van der Knaap, W.G.M.; Biesbroek, G.R. Implementation and Integration of EU Environmental Directives. Experiences from The Netherlands. *Environ. Policy Gov.* **2009**, *19*, 57–69. [CrossRef]
7. Boyes, S.J.; Elliott, M. Marine Legislation—The Ultimate 'Horrendogram': International Law, European Directives & National Implementation. *Mar. Pollut. Bull.* **2014**, *86*, 39–47. [CrossRef]
8. Boyes, S.J.; Elliott, M.; Murillas-Maza, A.; Papadopoulou, N.; Uyarra, M.C. Is Existing Legislation Fit-for-Purpose to Achieve Good Environmental Status in European Seas? *Mar. Pollut. Bull.* **2016**, *111*, 18–32. [CrossRef] [PubMed]
9. Maccarrone, V.; Filiciotto, F.; de Vincenzi, G.; Mazzola, S.; Buscaino, G. An Italian Proposal on the Monitoring of Underwater Noise: Relationship between the EU Marine Strategy Framework Directive (MSFD) and Marine Spatial Planning Directive (MSP). *Ocean Coast. Manag.* **2015**, *118*, 215–224. [CrossRef]
10. Meiner, A. Integrated Maritime Policy for the European Union—Consolidating Coastal and Marine Information to Support Maritime Spatial Planning. *J. Coast. Conserv.* **2009**, *14*, 1–11. [CrossRef]
11. Blasiak, R.; Pacheco, E.; Furuya, K.; Golden, C.D.; Jauharee, A.R.; Natori, Y.; Saito, H.; Sinan, H.; Tanaka, T.; Yagi, N.; et al. Local and Regional Experiences with Assessing and Fostering Ocean Health. *Mar. Policy* **2016**, *71*, 54–59. [CrossRef]
12. Fleming, L.E.; McDonough, N.; Austen, M.; Mee, L.; Moore, M.; Hess, P.; Depledge, M.H.; White, M.; Philippart, K.; Bradbrook, P.; et al. Oceans and Human Health: A Rising Tide of Challenges and Opportunities for Europe. *Mar. Environ. Res.* **2014**, *99*, 16–19. [CrossRef] [PubMed]
13. Bowen, R.E.; Depledge, M.H. Rapid Assessment of Marine Pollution (RAMP). *Mar. Pollut. Bull.* **2006**, *53*, 631–639. [CrossRef]
14. United Nations Environment Programme. *UNEP Frontiers 2016 Report: Emerging Issues of Environment Concern*; UNEP: Osaka, Japan, 2016; ISBN 978-92-807-3553-6.
15. Ferretti, M.; Rossi, F.; Benedetti-Cecchi, L.; Maggi, E. Ecological Consequences of Artificial Light at Night on Coastal Species in Natural and Artificial Habitats: A Review. *Mar. Biol.* **2025**, *172*, 5. [CrossRef]
16. Grillo, F.; Marrone, A.; Gauci, A.; Deidun, A. Maltese Coastline Never Sleeps: The Effects of Artificial Light at Night (ALAN) on the Local Infralittoral Assemblages—A Case Study. *J. Mar. Sci. Eng.* **2024**, *12*, 1602. [CrossRef]
17. Sanna, G.; Domenici, P.; Maggi, E. Artificial Light at Night Alters the Locomotor Behavior of the Mediterranean Sea Urchin Paracentrotus Lividus. *Mar. Pollut. Bull.* **2024**, *206*, 116782. [CrossRef] [PubMed]

18. Weschke, E.; Schligler, J.; Hely, I.M.H.; Roost, T.; Schies, J.-A.; Williams, B.; Dworzanski, B.; Mills, S.; Beldade, R.; Simpson, S.D.; et al. Artificial Light Increases Nighttime Prevalence of Predatory Fishes, Altering Community Composition on Coral Reefs. *Glob. Change Biol.* 2024; *in press*. [CrossRef]
19. Caley, A.; Marzinelli, E.M.; Byrne, M.; Mayer-Pinto, M. Antagonistic Effects of Light Pollution and Warming on Habitat-Forming Seaweeds. *Ecol. Evol.* **2024**, *14*, e70420. [CrossRef]
20. Elvidge, C.D.; Zhizhin, M.; Ghosh, T.; Hsu, F.C.; Taneja, J. Annual Time Series of Global VIIRS Nighttime Lights Derived from Monthly Averages: 2012 to 2019. *Remote Sens.* **2021**, *13*, 922. [CrossRef]
21. Elvidge, C.D.; Baugh, K.; Zhizhin, M.; Hsu, F.C.; Ghosh, T. VIIRS Night-Time Lights. *Int. J. Remote Sens.* **2017**, *38*, 5860–5879. [CrossRef]
22. Gaston, K.J.; Bennie, J.; Davies, T.W.; Hopkins, J. The Ecological Impacts of Nighttime Light Pollution: A Mechanistic Appraisal. *Biol. Rev.* **2013**, *88*, 912–927. [CrossRef]
23. Davies, T.W.; Duffy, J.P.; Bennie, J.; Gaston, K.J. Stemming the Tide of Light Pollution Encroaching into Marine Protected Areas. *Conserv. Lett.* **2016**, *9*, 164–171. [CrossRef]
24. Gaston, K.J.; Duffy, J.P.; Bennie, J. Quantifying the Erosion of Natural Darkness in the Global Protected Area System. *Conserv. Biol.* **2015**, *29*, 1132–1141. [CrossRef]
25. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2013.
26. Ghosh, T.; Anderson, S.; Elvidge, C.; Sutton, P. Using Nighttime Satellite Imagery as a Proxy Measure of Human Well-Being. *Sustainability* **2013**, *5*, 4988–5019. [CrossRef]
27. Bocci, M.; Markovic, M.; Mlakar, A.; Stancheva, M.; Borg, M.; Carella, F.; Barbanti, A.; Ramieri, E. Land-Sea-Interactions in MSP and ICZM: A Regional Perspective from the Mediterranean and the Black Sea. *Mar. Policy* **2024**, *159*, 105924. [CrossRef]
28. Barbanti, A.; Farella, G.; Sarretta, A.; Campillos-Llanos, M.; Cervera Nunez, C.; Gómez-Ballesteros, M.; Bassan, N.; Gissi, E.; Innocenti, A.; Manea, E.; et al. Document Information Editing. Available online: https://maritime-spatial-planning.ec.europa.eu/media/12637 (accessed on 1 September 2024).
29. Smyth, T.J.; Wright, A.E.; Edwards-Jones, A.; McKee, D.; Queirós, A.; Rendon, O.; Tidau, S.; Davies, T.W. Disruption of Marine Habitats by Artificial Light at Night from Global Coastal Megacities. *Elementa* **2022**, *10*, 25–419. [CrossRef]
30. Longcore, T.; Rich, C. Ecological Light Pollution. *Front. Ecol. Environ.* **2004**, *2*, 191–198. [CrossRef]
31. Hao, Y.; Wang, P.; Zhang, Z.; Xu, Z.; Jia, D. A Review of the Characteristics of Light Pollution: Assessment Technique, Policy, and Legislation. *Energies* **2024**, *17*, 2750. [CrossRef]
32. Elvidge, C.D.; Baugh, K.E.; Zhizhin, M.; Hsu, F.-C. Why VIIRS Data Are Superior to DMSP for Mapping Nighttime Lights. *Proc. Asia-Pac. Adv. Netw.* **2013**, *35*, 62. [CrossRef]
33. Kyba, C.C.M.; Garz, S.; Kuechly, H.; de Miguel, A.S.; Zamorano, J.; Fischer, J.; Hölker, F. High-Resolution Imagery of Earth at Night: New Sources, Opportunities and Challenges. *Remote Sens.* **2014**, *7*, 1–23. [CrossRef]
34. Bará, S.; Rodríguez-Arós, A.; Pérez, M.; Tosar, B.; Lima, R.C.; Sánchez de Miguel, A.; Zamorano, J. Estimating the Relative Contribution of Streetlights, Vehicles, and Residential Lighting to the Urban Night Sky Brightness. *Light. Res. Technol.* **2018**, *51*, 1092–1107. [CrossRef]
35. Xiao, Q.; Zhou, M.; Lyu, Y.; Lu, J.; Zhang, K.; Figueiro, M.; Wang, J.; Bauer, C. County-Level Artificial Light at Night (ALAN) in the Contiguous US (2012-2019): Spatial Variations, Temporal Trends, and Environmental Justice Analyses. *Environ. Sci. Pollut. Res. Int.* **2023**, *30*, 115870–115881. [CrossRef]
36. Tavares, P.; Ingi, D.; Araújo, L.; Pinho, P.; Bhusal, P. Reviewing the Role of Outdoor Lighting in Achieving Sustainable Development Goals. *Sustainability* **2021**, *13*, 12657. [CrossRef]
37. Halpern, B.S.; Walbridge, S.; Selkoe, K.A.; Kappel, C.V.; Micheli, F.; D'Agrosa, C.; Bruno, J.F.; Casey, K.S.; Ebert, C.; Fox, H.E.; et al. A Global Map of Human Impact on Marine Ecosystems. *Science* **2008**, *319*, 948–952. [CrossRef]
38. Davies, T.W.; Duffy, J.P.; Bennie, J.; Gaston, K.J. The Nature, Extent, and Ecological Implications of Marine Light Pollution. *Front. Ecol. Environ.* **2014**, *12*, 347–355. [CrossRef]
39. Bennie, J.; Davies, T.W.; Inger, R.; Gaston, K.J. Mapping Artificial Lightscapes for Ecological Studies. *Methods Ecol. Evol.* **2014**, *5*, 534–540. [CrossRef]
40. Peregrym, M.; Pénzesné Kónya, E.; Savchenko, M. How Are the Mediterranean Islands Polluted by Artificial Light at Night? *Ocean Coast. Manag.* **2020**, *198*, 105365. [CrossRef]
41. Kyba, C.C.M.; Kuester, T.; De Miguel, A.S.; Baugh, K.; Jechow, A.; Hölker, F.; Bennie, J.; Elvidge, C.D.; Gaston, K.J.; Guanter, L. Artificially Lit Surface of Earth at Night Increasing in Radiance and Extent. *Sci. Adv.* **2017**, *3*, e1701528. [CrossRef] [PubMed]
42. Rybnikova, N.; Portnov, B.A.; Charney, I.; Rybnikov, S.; Li, X. Delineating Functional Urban Areas Using a Multi-Step Analysis of Artificial Light-at-Night Data. *Remote Sens.* **2021**, *13*, 3714. [CrossRef]
43. Smyth, T.J.; Wright, A.E.; McKee, D.; Tidau, S.; Tamir, R.; Dubinsky, Z.; Iluz, D.; Davies, T.W. A Global Atlas of Artificial Light at Night under the Sea. *Elementa* **2021**, *9*, 00049. [CrossRef]
44. Miller, C.R.; Rice, A.N. A Synthesis of the Risks of Marine Light Pollution across Organismal and Ecological Scales. *Aquat. Conserv.* **2023**, *33*, 1590–1602. [CrossRef]
45. Ulpiani, G. On the Linkage between Urban Heat Island and Urban Pollution Island: Three-Decade Literature Review towards a Conceptual Framework. *Sci. Total Environ.* **2021**, *751*, 141727. [CrossRef] [PubMed]

46. Hölker, F.; Moss, T.; Griefahn, B.; Kloas, W.; Voigt, C.; Henckel, D.; Hänel, A.; Kappeler, P.; Völker, S.; Schwope, A.; et al. The Dark Side of Light: A Transdisciplinary Research Agenda for Light Pollution Policy. *Ecol. Soc.* **2010**, *15*, 13. [CrossRef]
47. Levin, N.; Kyba, C.C.M.; Zhang, Q.; Sánchez de Miguel, A.; Román, M.O.; Li, X.; Portnov, B.A.; Molthan, A.L.; Jechow, A.; Miller, S.D.; et al. Remote Sensing of Night Lights: A Review and an Outlook for the Future. *Remote Sens. Environ.* **2020**, *237*, 111443. [CrossRef]
48. Bennie, J.; Davies, T.W.; Duffy, J.P.; Inger, R.; Gaston, K.J. Contrasting Trends in Light Pollution across Europe Based on Satellite Observed Night Time Lights. *Sci. Rep.* **2014**, *4*, 3789. [CrossRef] [PubMed]
49. Kyba, C.C.M.; Altıntaş, Y.Ö.; Walker, C.E.; Newhouse, M. Citizen Scientists Report Global Rapid Reductions in the Visibility of Stars from 2011 to 2022. *Science* **2023**, *379*, 265–268. [CrossRef]
50. Gaston, K.J.; Gaston, S.; Bennie, J.; Hopkins, J. Benefits and Costs of Artificial Nighttime Lighting of the Environment. *Environ. Rev.* **2015**, *23*, 14–23. [CrossRef]
51. Cao, X.; Chen, J.; Imura, H.; Higashi, O. A SVM-Based Method to Extract Urban Areas from DMSP-OLS and SPOT VGT Data. *Remote Sens. Environ.* **2009**, *113*, 2205–2209. [CrossRef]
52. Henderson, M.; Yeh, E.T.; Gong, P.; Elvidge, C.; Baugh, K. Validation of Urban Boundaries Derived from Global Night-Time Satellite Imagery. *Int. J. Remote Sens.* **2003**, *24*, 595–609. [CrossRef]
53. Zhao, M.; Cheng, W.; Liu, Q.; Wang, N. Spatiotemporal Measurement of Urbanization Levels Based on Multiscale Units: A Case Study of the Bohai Rim Region in China. *J. Geogr. Sci.* **2016**, *26*, 531–548. [CrossRef]
54. Liu, X.; Hu, G.; Ai, B.; Li, X.; Shi, Q. A Normalized Urban Areas Composite Index (NUACI) Based on Combination of DMSP-OLS and MODIS for Mapping Impervious Surface Area. *Remote Sens.* **2015**, *7*, 17168–17189. [CrossRef]
55. Mayer-Pinto, M.; Jones, T.M.; Swearer, S.E.; Robert, K.A.; Bolton, D.; Aulsebrook, A.E.; Dafforn, K.A.; Dickerson, A.L.; Dimovski, A.M.; Hubbard, N.; et al. Light Pollution: A Landscape-Scale Issue Requiring Cross-Realm Consideration. *UCL Open Environ.* **2022**, *4*, e036. [CrossRef]
56. Kaushik, K.; Nair, S.; Ahamad, A. Studying Light Pollution as an Emerging Environmental Concern in India. *J. Urban Manag.* **2022**, *11*, 392–405. [CrossRef]
57. Rubinyi, S.L.; Park, H.; Ghosh, T.; Laroe, J.; Holmes, C.M.; Schad, T. Nightlight Intensity Change Surrounding Nature Reserves: A Case Study in Orbroicher Bruch Nature Reserve, Germany. *Remote Sens.* **2022**, *14*, 3876. [CrossRef]
58. Górniak-Zimroz, J.; Romańczukiewicz, K.; Sitarska, M.; Szrek, A. Light-Pollution-Monitoring Method for Selected Environmental and Social Elements. *Remote Sens.* **2024**, *16*, 774. [CrossRef]
59. Pothukuchi, K. City Light or Star Bright: A Review of Urban Light Pollution, Impacts, and Planning Implications. *J. Plan. Lit.* **2021**, *36*, 155–169. [CrossRef]
60. Zielinska-Dabkowska, K.M.; Bobkowska, K. Rethinking Sustainable Cities at Night: Paradigm Shifts in Urban Design and City Lighting. *Sustainability* **2022**, *14*, 6062. [CrossRef]
61. Hirt, M.R.; Evans, D.M.; Miller, C.R.; Ryser, R. Light Pollution in Complex Ecological Systems. *Philos. Trans. R. Soc. B Biol. Sci.* **2023**, *378*, 20220351. [CrossRef]
62. Mu, H.; Li, X.; Du, X.; Huang, J.; Su, W.; Hu, T.; Wen, Y.; Yin, P.; Han, Y.; Xue, F. Evaluation of Light Pollution in Global Protected Areas from 1992 to 2018. *Remote Sens.* **2021**, *13*, 1849. [CrossRef]
63. Fobert, E.K.; Miller, C.R.; Swearer, S.E.; Mayer-Pinto, M. The Impacts of Artificial Light at Night on the Ecology of Temperate and Tropical Reefs. *Philos. Trans. R. Soc. B Biol. Sci.* **2023**, *378*, 20220362. [CrossRef] [PubMed]
64. Gallaway, T.; Olsen, R.N.; Mitchell, D.M. The Economics of Global Light Pollution. *Ecol. Econ.* **2010**, *69*, 658–665. [CrossRef]
65. Cox, D.T.C.; de Miguel, A.S.; Dzurjak, S.A.; Bennie, J.; Gaston, K.J. National Scale Spatial Variation in Artificial Light at Night. *Remote Sens.* **2020**, *12*, 1591. [CrossRef]
66. Ji, M.; Xu, Y.; Yan, Y.; Zhu, S. Evaluation of the Light Pollution in the Nature Reserves of China Based on NPP/VIIRS Nighttime Light Data. *Int. J. Digit. Earth* **2024**, *17*, 2347442. [CrossRef]
67. Jägerbrand, A.K.; Bouroussis, C.A. Ecological Impact of Artificial Light at Night: Effective Strategies and Measures to Deal with Protected Species and Habitats. *Sustainability* **2021**, *13*, 5991. [CrossRef]
68. Dalle Carbonare, L.; Basile, A.; Rindi, L.; Bulleri, F.; Hamedeh, H.; Iacopino, S.; Shukla, V.; Weits, D.A.; Lombardi, L.; Sbrana, A.; et al. Dim Artificial Light at Night Alters Gene Expression Rhythms and Growth in a Key Seagrass Species (*Posidonia oceanica*). *Sci. Rep.* **2023**, *13*, 10620. [CrossRef] [PubMed]
69. Longcore, T.; Rich, C. Ecological and Organismic Effects of Light Pollution. In *eLS*; American Cancer Society: Atlanta, GA, USA, 2016; pp. 1–8. ISBN 978-0-470-01590-2.
70. Sanders, D.; Frago, E.; Kehoe, R.; Patterson, C.; Gaston, K.J. A Meta-Analysis of Biological Impacts of Artificial Light at Night. *Nat. Ecol. Evol.* **2020**, *5*, 74–81. [CrossRef]
71. Duarte, C.; Quintanilla-Ahumada, D.; Anguita, C.; Silva-Rodriguez, E.A.; Manríquez, P.H.; Widdicombe, S.; Pulgar, J.; Miranda, C.; Jahnsen-Guzmán, N.; Quijón, P.A. Field Experimental Evidence of Sandy Beach Community Changes in Response to Artificial Light at Night (ALAN). *Sci. Total Environ.* **2023**, *872*, 162086. [CrossRef]
72. Short, F.T.; Wyllie-Eciieverria, S. Natural and Human-Induced Disturbance of Seagrasses. *Environ. Conserv.* **1996**, *23*, 17–27. [CrossRef]
73. Dekker, A.; Brando, V.; Anstee, J.; Fyfe, S.; Malthus, T.; Karpouzli, E. Remote Sensing of Seagrass Ecosystems: Use of Spaceborne and Airborne Sensors. *Seagrasses Biol. Ecol. Conserv.* **2007**, 347–359. [CrossRef]

74. Dierssen, H.M.; Chlus, A.; Russell, B. Hyperspectral Discrimination of Floating Mats of Seagrass Wrack and the Macroalgae Sargassum in Coastal Waters of Greater Florida Bay Using Airborne Remote Sensing. *Remote Sens. Environ.* **2015**, *167*, 247–258. [CrossRef]
75. Costa, V.; Serôdio, J.; Lillebø, A.I.; Sousa, A.I. Use of Hyperspectral Reflectance to Non-Destructively Estimate Seagrass Zostera Noltei Biomass. *Ecol. Indic.* **2021**, *121*, 107018. [CrossRef]
76. Trethewy, M.; Mayer-Pinto, M.; Dafforn, K.A. Urban Shading and Artificial Light at Night Alter Natural Light Regimes and Affect Marine Intertidal Assemblages. *Mar. Pollut. Bull.* **2023**, *193*, 115203. [CrossRef]
77. Han, P.; Huang, J.; Li, R.; Wang, L.; Hu, Y.; Wang, J.; Huang, W. Monitoring Trends in Light Pollution in China Based on Nighttime Satellite Imagery. *Remote Sens.* **2014**, *6*, 5541–5558. [CrossRef]
78. Zielinska-Dabkowska, K.M. Make Lighting Healthier. *Nature* **2018**, *553*, 274. [CrossRef] [PubMed]
79. Ściężor, T. Effect of Street Lighting on the Urban and Rural Night-Time Radiance and the Brightness of the Night Sky. *Remote Sens.* **2021**, *13*, 1654. [CrossRef]
80. Méndez, A.; Prieto, B.; Aguirre i Font, J.M.; Sanmartín, P. Better, Not More, Lighting: Policies in Urban Areas towards Environmentally-Sound Illumination of Historical Stone Buildings That Also Halts Biological Colonization. *Sci. Total Environ.* **2024**, *906*, 167560. [CrossRef]
81. Bills, Laws and Ordinances—Light Pollution in Italy—Pierantonio Cinzano Web Pages. Available online: http://www.lightpollution.it/cinzano/en/page95en.html (accessed on 28 October 2024).
82. Velásquez, C.; Espín, F.; Castro, M.Á.; Rodríguez, F. Energy Efficiency in Public Lighting Systems Friendly to the Environment and Protected Areas. *Sustainability* **2024**, *16*, 5113. [CrossRef]
83. Gonzalez-Torres, M.; Bertoldi, P.; Castellazzi, L.; Perez-Lombard, L. Review of EU Product Energy Efficiency Policies: What Have We Achieved in 40 Years? *J. Clean. Prod.* **2023**, *421*, 138442. [CrossRef]
84. Boyes, D.H.; Evans, D.M.; Fox, R.; Parsons, M.S.; Pocock, M.J.O. Is Light Pollution Driving Moth Population Declines? A Review of Causal Mechanisms across the Life Cycle. *Insect Conserv. Divers.* **2021**, *14*, 167–187. [CrossRef]
85. Schroer, S.; Huggins, B.J.; Azam, C.; Hölker, F. Working with Inadequate Tools: Legislative Shortcomings in Protection against Ecological Effects of Artificial Light at Night. *Sustainability* **2020**, *12*, 2551. [CrossRef]