Light pollution in European protected areas

Spatial variation of light pollution in Natura 2000 sites of the Member States of the European Union

Master thesis in Environmental Sciences

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Abstract

Natura 2000 sites are designated by the European Union under the Nature Directives, i.e. the 1979 Birds and 1992 Habitats Directives to counteract and mitigate biodiversity loss. Natura 2000 conservation sites are important areas to ensure the persistence of Europe's most precious and threatened habitats and species. The sites cover a total of 17.9% of the European Union's surface and 9.7% of its marine area. Among current environmental challenges, light pollution has been identified as an increasing threat – also for protected sites. In this thesis, light pollution was examined spatially explicitly across Europe for terrestrial and marine Natura 2000 sites using satellite data (VIIRS-DNB) from 2018 and 2019. Based on three published and two additional thresholds, the magnitude of light emissions (measured in nW) was categorised. Light emission values >=2 nW are recognized to have at least low level of ecological impact. Considering all terrestrial Natura 2000 sites across the EU, 96.13% of the areas were exposed to low (<2 nW) and 3.87% to light levels >=2 nW (0.17% to high light levels; >=20 nW). While this may at first not appear to be a cause for concern, further analyses of the Natura 2000 sites for individual biogeographical regions and EU Member States in which they are situated, revealed significant differences in light exposure. Whereas more than 90% of Natura 2000 areas in the Alpine and Boreal regions were in the lowest (<0.5 nW) light pollution class, in the Macaronesia region it was only 69.55%. Out of all seven biogeographical regions, the Macaronesia region also had the most Natura 2000 areas (0.77%) with high (>=20 nW) light pollution. Natura 2000 sites in Luxembourg (16.9%), Belgium (19.7%) and especially Malta (63.95%) were exposed by far to the highest amount of light greater than or equal to 2 nW. In comparison, only 1.09% of Natura 2000 sites in Estonia had a value >=2 nW and an astonishing 96.39% were in the lowest (<0.5 nW) light pollution class. Areas within Luxembourg, Belgium and Malta with the highest levels of light pollution have been identified and mapped. Built-up areas such as (nearby) airports, ports, industrial areas or greenhouses were found to be the source of high light exposure. The finding that a proportion of artificial areas are largely responsible for high light pollution was further supported by an analysis of land cover classes of Natura 2000 sites, e.g. sites containing wetlands were found to be the least exposed to light pollution. Marine Natura 2000 sites were studied within three buffer areas from the coast. Within 1000m, comparable light exposure was measured as for terrestrial Natura 2000 areas of the Macaronesia biogeographical region. However, starting at 1000m distance from the coast, the area within the lowest (<0.5 nW) light pollution class increased by 13.89% from 64.44% to 78.33%. The proportion of lowest light exposure continued to grow by 6.06% within a buffer between 2000-3000m from the coast. Between 2000-3000m were no more Natura 2000 sites with high light pollution. With only a few exceptions light exposure levels were higher in 2019 than in 2018 for both, terrestrial and marine Natura 2000 sites. Considering light pollution levels >=2 nW, the largest decrease was recorded in Natura 2000 sites of Luxembourg (-2.1%) and the highest increase in Belgium (+2.3%). Given my results, I conclude that light pollution is an important driver of environmental change for the 21st century. Mitigation measures based on state-of-the-art light technological development should therefore be implemented at various political levels in order to delineate sustainable lighting strategies.

Keywords: ALAN, Light emission, Light pollution, VIIRS, Natura 2000, Protected areas, Biogeographical regions, European Union

Contents

List of Abbreviations

ALAN	Artificial Light at Night
CLC	Corine Land Cover
CoE	Council of Europe
DG ENV	Directorate-General for the Environment
DMSP-OLS	Defense Meteorological Satellite Program Operational Linescan System
DNB	Day/Night Band
EEA	European Environment Agency
EPSG	European Petroleum Survey Group
Esri	Environmental Systems Research Institute
ETRS	European Terrestrial Reference System
EU	European Union
GEE	Google Earth Engine
LAEA	Lambert Azimuthal Equal-Area (projection)
LED	Light-emitting diode
MS	Member State
pSCIs	proposed Sites of Community Importance
SACs	Special Areas of Conservation
SCIs	Sites of Community Importance
SNPP	Suomi National Polar Partnership
SPAs	Special Protection Areas
UK	United Kingdom
UV	Ultra-violet
VIIRS	Visible Infrared Imaging Radiometer Suite

Introduction

Artificial light at night (ALAN) is crucial for human activities and has shaped life on many levels: it compensates for the limited human night-time vision, allows for goods and services processed and delivered 24h by people working in shifts (Boyce, 2019), decreases risks of traffic (Boyce, 2019; Raynham, Unwin, Khazova, & Tolia, 2020; Van Bommel, 2015), improves obstacle detection (Fotios & Uttley, 2018) as well as decreases night-time crime fear (Boyce & Gutkowski, 1995; Fotios, Monteiro, & Uttley, 2019; Fotios, Unwin, & Farrall, 2015; Suk & Walter, 2019). In contrast for these obvious benefits for humans, ALAN increases globally at unprecedented rates of 2% per year (Kyba et al., 2017), partly caused by the transition to light-emitting diodes (LEDs) (Falchi et al., 2016; Krames et al., 2007). Falchi et al. (2016) quantified light pollution worldwide and showed that over 80% of the world and more than 99% of the Europeans live under an illuminated sky at night. While the Mediterranean has recorded the greatest increase of light pollution, the Boreal, Arctic and montane systems experienced the lowest (Bennie, Duffy, Davies, Correa-Cano, & Gaston, 2015).

Light serves also a number of important functions in nature. It regulates the circadian rhythms of plants and animals and consequently determines its interactions. For example, foraging, growth, pollination and reproduction are influenced by light (Tovée, 1995). Concerning pollination, plants are visited throughout day and night by diurnal and nocturnal pollinators, which in turn are linked by plant-mediated interactions (Bascompte, Jordano, Melián, & Olesen, 2003; Knop et al., 2017). Birds are known to use day length as an indicator to start mitigating (Able & Able, 1995) and polarising ultra-violet (UV) light allows some animals to orientate (Tovée, 1995). Natural light has a major influence on insects. It affects their circadian rhythm and photoperiodism, intra-specific communication, reproduction and dispersal (Bowden, 1982; Frank, 1988; Tovée, 1995). Plants and animals have adapted to different light conditions during the day and at night through a wide range of modifications, as evidenced, for example, in the number of photoreceptors (Briscoe & Chittka, 2001; Hunt, Carvalho, Cowing, & Davies, 2009; Thomas & Vince-Prue, 1997).

Recently, reports on risks of natural environments exposed to ALAN have become alarming (Desouhant, Gomes, Mondy, & Amat, 2019; Hölker, Moss, et al., 2010; Hölker, Wolter, Perkin, & Tockner, 2010; Longcore & Rich, 2004; Owens & Lewis, 2018). ALAN may interrupt the circadian rhythm of plants as an unsynchronized internal clock can lead to reduced leaf chlorophyll content, reduced growth, reduced assimilation and increased mortality (Dodd et al., 2005). Other effects that have been observed are suppressed flowering and associated negative impacts on herbivores (Bennie, Davies, Cruse, Inger, & Gaston, 2015), earlier bud burst (Ffrench-Constant et al., 2016) and less fruit production in correlation with a reduction of nocturnal pollinators (Knop et al., 2017). Night darkness is just as important for insects as daylight. Diurnal need to rest, nocturnal species become active, and their activity relies on the absence of light (Frank, 1988; Lloyd, 2006). Eisenbeis and Hänel (2009) described a well-established phenomenon when insects fly near streetlamps. Three different flight-to-light effects may occur: the *fixation, crash barrier and vacuum cleaner effect*. The *fixation effect,* for example, traps the insect, which results in the insect orbiting the light endlessly until exhaustion or until it gets eaten. Similarly, birds are attracted by ALAN during their migration, especially when it’s cloudy. ALAN may lead to disorientation which can result in exhaustion or fatal collisions (Gautheraux Jr. & Belser, 2006).

Light pollution spreads not only in residential areas but also within biodiversity hotspots and protected areas (Davies, Duffy, Bennie, & Gaston, 2016; Garrett, Donald, & Gaston, 2020; Guetté, Godet, Juigner, & Robin, 2018). Even light sources which are not located in a conservation area, but in their immediate vicinity, may negatively affect ecological functions (Giavi, Blösch, Schuster, & Knop, 2020). However, its impact and distribution considering protected areas and biodiversity hotspots on a large spatial scale is still poorly studied (Guetté et al., 2018).

To reduce this research gap, ALAN exposure of the world's largest coordinated network of protected areas, the European Natura 2000 sites (Sundseth & Creed, 2008), was assessed in this thesis. The Natura 2000 network covers a total of 17.9% (European Environment Agency, 2019a) of the European Union's surface and 9.7% (European Environment Agency, 2019b) of its marine area. The EU Member State with the largest proportion of its land area designated as Natura 2000 sites is Slovenia (37.9%) and Denmark has the least (8.3%) (European Environment Agency, 2019a). *"The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species, listed under both the Birds Directive and the Habitats Directive"* (Directorate-General for Environment, 2021c). In 1979 (amended in 2009) the Birds Directive[1] was established based on the concerning decline of wild bird species. Annex I of the directive lists the current 194 species and sub-species for which each EU Member State must implement Special Protection Areas (SPAs). SPAs have been part of the Natura 2000 network since 1994 (Directorate-General for Environment, 2021a). The Habitats Directive on the conservation of natural habitats and of wild fauna was adopted in 1992. More than 1000 plant and animal species and 200 habitat types are listed in the Annexes of the directive (Directorate-General for Environment, 2021b). In order to protect the habitats in Annex I and the species in Annex II, Member States have to send proposed Sites of Community Importance (pSCIs) to the European Commission. These are subsequently reviewed for quality and approved as Sites of Community Importance (SCIs). The Member State will then be obliged to designate them as Special Areas of Conservation (SACs) within six years (Directorate-General for Environment, 2021d).

In this Master thesis, the magnitude and spatial extent of Natura 2000 sites exposed to light levels was quantified. For this, data from the Suomi National Polar Partnership (SNPP) satellite launched in 2011 was applied. Its Visible Infrared Imaging Radiometer Suite (VIIRS) instrument includes a day / night band (DNB) which gathers light emission data from the earth's surface. VIIRS-DNB data is considered superior to the commonly used Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) regarding resolution, dynamic range and calibrations (Elvidge, Baugh, Zhizhin, & Hsu, 2013; Xu, Wang, Jin, & Jin, 2019).

Research questions included:

- To what extent are terrestrial Natura 2000 sites exposed to ALAN? Are there obvious differences when sites are analysed by biogeographical region, Member State and land cover classes?
- How strongly are marine Natura 2000 sites impacted? How does the light exposure relate to increasing distance from the coast?
- How has light exposure in terrestrial and marine Natura 2000 sites developed in 2019 compared to 2018?

[1] *A "directive" is a legislative act that sets out a goal that all EU countries must achieve. However, it is up to the individual countries to devise their own laws on how to reach these goals* (EU law, 2020).

Materials and Methods

Study area

The study area to assess light pollution encompassed the Member States of the European Union as of 2020 (Fig. 1; Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom).

Data preparation

VIIRS-DNB

Light pollution data was prepared in Google Earth Engine (GEE). GEE is a geospatial processing service powered by Google's cloud infrastructure. There were two VIIRS-DNB versions in the GEE Data Catalog. The datasets were provided by the Earth Observation Group of the Payne Institute for Public Policy (Elvidge, Baugh, Zhizhin, Hsu, & Ghosh, 2017). In this thesis, the dataset "VIIRS Nighttime Day/Night Band Composites Version 1"[2] was chosen since it contained less cloud cover than the dataset "VIIRS Stray Light Corrected Nighttime Day/Night Band Composites Version 1"[3]. The band "avg_rad" contained monthly average radiance composite images. The amount of light emitted from the earth's surface into space at night is measured in radiance (nW/cm^2/sr) with a resolution of 15 arc-seconds. This implies that the grid resolution of the composite images varies depending on the degree of latitude. In Nicosia, 15 arc-seconds correspond to a grid resolution of about 378x463m and in Helsinki approximately 230x463m. In the GEE Code Editor, the annual average value was calculated for the years 2018 and 2019. The year 2020 could not be analysed, as data is currently (March 2021) not yet available for all months. The data was resampled to a constant grid resolution of 500x500m, projected into the coordinate reference system ETRS 1989 LAEA (EPSG: 3035) and exported as GeoTIFFs.

Natura 2000

The polygon dataset of Natura 2000 sites was downloaded from the European Environment Agency (EEA) data catalogue. The spatial data (boundaries of Natura 2000 sites) were submitted by each Member State of the European Union and validated by the EEA. Copyright holder is the Directorate-General for Environment (DG ENV). The latest available dataset "Natura 2000 End 2019 - Shapefile"[4] contained data from 2019 at a scale of 1:100'000. The shapefile included a unique alphanumerical code (SITECODE), name in the local language (SITENAME), country code of Member State (MS) and type (SITETYPE) per Natura 2000 site. The attribute SITETYPE had values A, B or C. Natura 2000 sites with value A are Special Protection Areas (SPAs) - sites designated under the Birds Directive, sites with value B are Sites of Community Importance (SCIs) and Special Areas of Conservation (SACs) - sites designated under the Habitats Directive and sites with value C are sites designated under both directives (Fig. 1). The dataset contained 27'845 sites with a total area of about 1'768'660 km^2 (A: 3'660 sites & 685'374 km^2, B: 22'178 sites & 913'117 km^2, C: 2'007 sites & 170'168 km^2).

[2] https://developers.google.com/earth-engine/datasets/catalog/NOAA_VIIRS_DNB_MONTHLY_V1_VCMCFG (Retrieved 22.10.2020)
[3] https://developers.google.com/earth-engine/datasets/catalog/NOAA_VIIRS_DNB_MONTHLY_V1_VCMSLCFG (Retrieved 13.02.2021)
[4] https://cmshare.eea.europa.eu/s/n5L8Lrs9aYD775S/download (Retrieved 20.10.2020)

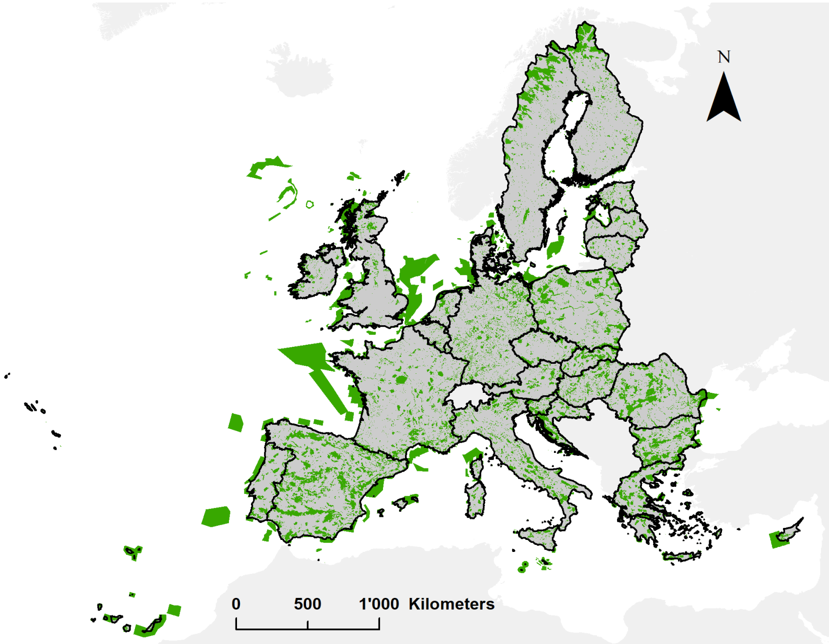

Fig. 1: Natura 2000 sites (Site types A, B, C) in green and EU Member States[5] in dark grey.

Biogeographical regions

The polygon dataset on biogeographical regions[6] was also retrieved from the EEA data catalogue. The latest version was published in 2016 and its resolution ranges from 1:1’000’000 to 1:10’000’000, depending on the region. The copyright holders are the Council of Europe (CoE) and the DG ENV. In Europe, a distinction is made between 11 biogeographical regions. Namely Alpine, Anatolian, Arctic, Atlantic, Black Sea, Boreal, Continental, Macaronesia, Mediterranean, Pannonian and Steppic. No Natura 2000 sites occurred in the Anatolian and Arctic regions. These regions were therefore omitted from further analysis. The Black Sea and Steppic regions encompassed only a very small area bordering the eastern part of the EU and were therefore reclassified to “Continental” (Fig. 2).

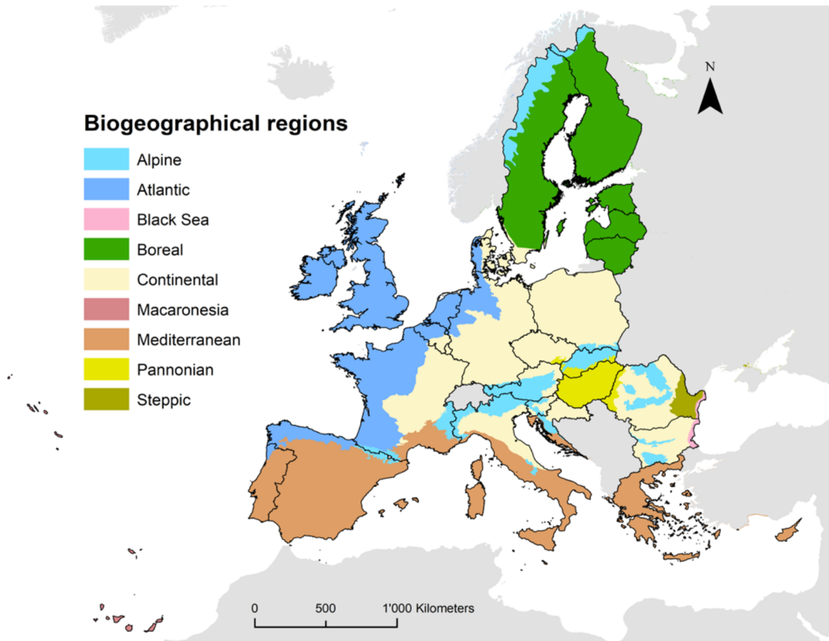

Fig. 2: Biogeographical regions of Natura 2000 sites

[5] https://gisco-services.ec.europa.eu/distribution/v2/countries/download/ref-countries-2020-01m.shp.zip (Retrieved 15.03.2021)
[6] https://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-3/zipped-shapefile-format-vector-polygon/zipped-shapefile-format-vector-polygon/at_download/file (Retrieved 08.11.2020)

Land cover (CLC)
For information on land cover within the study area, the "Corine Land Cover - 100 meter"[7] raster was used, which is provided by the EEA. It is one of the Corine Land Cover (CLC) datasets which was made as part of the pan-European component of the Copernicus Land Monitoring Service framework. The raster contained land cover data for 39 European countries, including all Member States of the European Union, for the year 2018 with a grid resolution of 100x100m. CLC included 44 land cover classes, which were reclassified into five classes (Artificial Surfaces, Agricultural areas, Forest and seminatural areas, Wetlands and Water bodies) according to the "CLC nomenclature guidelines"[8]. The reclassification was performed in order to obtain comparable land cover classes across Europe. Table 1 in the Annex shows the corresponding sub-categories of the five land cover classes.

Analysis

All spatial analyses were executed in ArcMap 10.8.1 supplied by Esri. In order to include all Natura 2000 sites, the spatial extent of the study area was defined as followed Top: 5500000, bottom: 900000, left: 700000, right: 7400000. The CLC raster was specified as "Snap Raster" to ensure that all grid cells of the different datasets are exactly aligned with each other. The Natura 2000 sites, biogeographical regions and CLC did not have to be projected into ETRS 1989 LAEA, as they already possessed this coordinate system. The most relevant steps of the geoprocessing workflow are presented hereafter.

The Natura 2000 sites and the biogeographical regions were converted into rasters with a cell size of 500x500m in order to match the resolution of the VIIRS data. A raster was created which represents all Natura 2000 sites combined (SITETYPE A, B & C). The reason why the different SITETYPES were not analysed separately was that some areas within each SITETYPE overlapped. It was assumed that this occurred due to inaccurate editing when the areas were included in the Natura 2000 dataset. In addition, a certain spatial accuracy was lost due to the transformation of the polygons to grid cells. For each of the five land cover types (CLC 100x100m), a single binary raster was produced and then aggregated to 500x500m to achieve a more accurate spatial representation of the land cover for each 500x500m pixel.

Terrestrial and marine Natura 2000 sites were analysed (Fig. 1). The raster of the biogeographical regions was used as a mask to obtain terrestrial and marine Natura 2000 sites separately. The marine Natura 2000 sites were analysed within three buffers to account for the decreasing exposure to artificial light with increasing distance from the coast. Buffers included 0-1000m, 1000-2000m, 2000-3000m from the coast. These buffers were converted to raster and used as a mask for the Natura 2000 sites. The masked Natura 2000 datasets (terrestrial and marine) were transformed into point features. Subsequently, cell values of biogeographical regions, CLC and VIIRS data at point feature locations were extracted.

The point data was exported as TXT file and further processed in R 3.6.1. Due to the strong influence of cloud cover and northern lights on light emission values, the Natura 2000 sites shown in Fig. 3 had to be removed. Only terrestrial sites were affected by this exclusion, namely 7% of all terrestrial Natura 2000 sites. The point data of the terrestrial Natura 2000 sites contained light emission values below zero and null values (zero). Shi et al. (2014) assumed that negative values are caused by background noise and outliers from data processing. Null values (zero) may occurred in areas where no light emission was detected, e.g. due to cloud cover (Elvidge et al., 2017). Therefore, negative and null values were removed and not considered for further analysis (0.001% of terrestrial Natura 2000 point data). No negative or null light emission values were observed in the marine Natura 2000 point data.

[7] https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download (Retrieved 08.11.2020)
[8] https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html/ (Retrieved 10.11.2020)

Statistics (Minimum, 1st quartile, median, mean, 3rd quartile, maximum) on light emission values for the years 2018 and 2019 were calculated per biogeographical region and EU Member State for terrestrial and for the considered marine Natura 2000 point data.

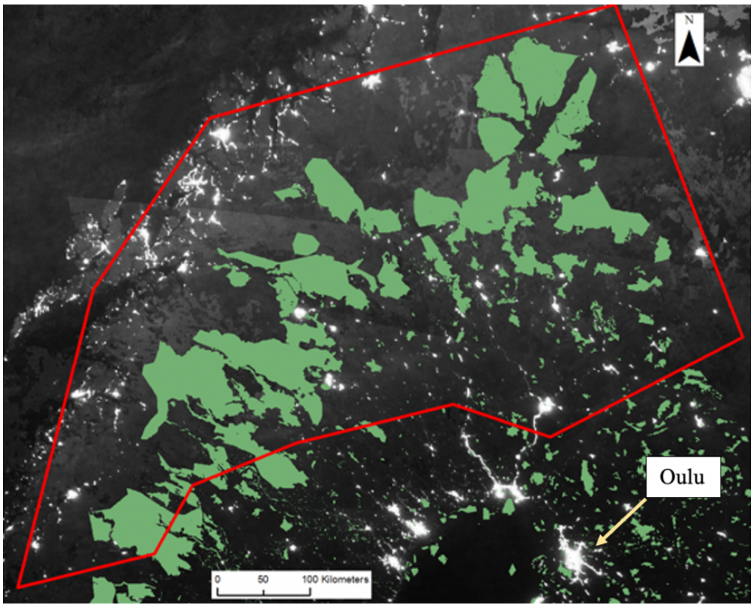

Fig. 3: Natura 2000 sites within the red polygon contained satellite processing artefacts and were therefore removed from the data set. For orientation: The black patch to the right of the scale is the Gulf of Bothnia.

Thresholds for light emission values

The light emissions of terrestrial and marine Natura 2000 point data were categorised according to the thresholds introduced by Hale and Arlettaz (2019) in their study on "Artificial lighting and Biodiversity in Switzerland". They defined light emission values >=2-10 nW/cm^2/sr as "low", values >=10-20 nW[9] as "medium" and values >=20 nW as "high" (Table 1). They justify their classification by the circumstance that in Switzerland "*2nW is a typical emission for part of a small village or low-density residential area, 10NW is typical for high-density residential areas of larger towns, and 20NW is typical of more mixed uses in larger settlements"* (Hale & Arlettaz, 2019, p. 69). To differentiate between very low light emission values, two additional thresholds (<0.5 nW and >=0.5-2 nW) were introduced in this thesis (Table 1). The justification for <0.5 nW is that a visual inspection has shown that light emission values below 0.5 nW differ unrealistically strongly between 2018 and 2019. In addition to the thresholds for the magnitude of light emissions, values >=2 nW were defined as values where at least low levels of ecological impact due to light emission are expected (Hale, Blumenstein, Carannante, & Arlettaz, 2018) (Table 1). For each threshold, the number of point data was determined and the relative area (proportion of Natura 2000 points within a threshold) was calculated.

Table 1: Thresholds for classification of light emission values in this thesis

Light emission (nW/cm^2/sr)	Description of light emission thresholds / classes in this thesis	Source
< 0.5	Lowest light emission values	
>= 0.5 - 2	Very low light emission values	
>= 2	At least low level of ecological impact expected	(Hale et al., 2018)
>= 2 - 10	Low light emission values	(Hale & Arlettaz, 2019)
>= 10 - 20	Medium light emission values	(Hale & Arlettaz, 2019)
>= 20	High light emission values	(Hale & Arlettaz, 2019)

[9] For the reader's convenience, the unit of light emissions [nW/cm^2/sr] is abbreviated as nW hereafter.

Results

The results are presented following the research questions:

- To what extent are terrestrial Natura 2000 sites exposed to ALAN? Are there obvious differences when sites are analysed by biogeographical region, Member State and land cover classes?
- How strongly are marine Natura 2000 sites impacted? How does the light exposure relate to increasing distance from the coast?
- How has light exposure in terrestrial and marine Natura 2000 sites developed in 2019 compared to 2018?

Terrestrial Natura 2000 sites across the EU

Considering Natura 2000 sites across the entire EU, the terrestrial Natura 2000 sites covered a land area of approximately 970'000 km^2 (Annex, Table 3). In 2019[10], the light emission values ranged from 0.0025 nW (one pixel value within the Natura 2000 site with SITECODE "ES7020043" in Spain; Fig. 5) and a pixel with 1'059.2659 nW in Estonia (SITECODE "EE0080310"; Fig. 6; Annex, Table 2). When considering the "lowest"[11] light emission class, terrestrial Natura 2000 sites in Estonia (96.39%; Annex, Table 6), Lithuania (94.84%; Annex, Table 9) and Latvia (93.76%; Annex, Table 8) exhibited the lowest light exposure. Proportionally, Malta (7.27%; Table 7), Belgium (0.86%; Table 6) and Portugal (0.52%; Annex, Table 28) had the most areas with "high" emission values. For the entire EU, the quartiles of light emission values within Natura 2000 sites were 0.2108 nW (1st), 0.2583 nW (median) and 0.3883 nW (3rd) (Annex, Table 2). This indicated that the vast majority of light emission values were in the "lowest" emission class. 96.13% of the relative areas were in the classes "lowest" and "very low" light emission values. 3.35% had "low", 0.35% "medium" and 0.17% "high" light emission values. 3.87% of the areas (approx. 38'000 km^2) had at least low level of ecological impact due to light emissions. In all light emission classes above 0.5 nW the light-exposed areas increased in 2019 compared to 2018. However, the increase was higher for relative areas in the "very low" and "low" emission classes compared to the "medium" and "high" exposure classes (Table 2).

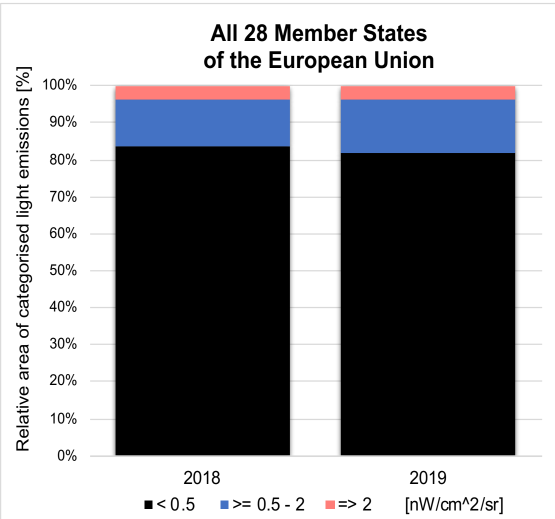

Fig. 4: The relative area of categorised light emissions in nW/cm^2/sr for terrestrial Natura 2000 areas in EU Member States in 2018 and 2019 shown in percentages.

Table 2: Relative areas of the light emission classes presented in Fig. 4. Please note that the class >= 2 nW/cm^2/sr represents the sum of three subcategories.

Light emission [nW/cm^2/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	83.52	82
>= 0.5 - 2	12.86	14.13
>= 2	3.62	3.87
>= 2 - 10	3.15	3.35
>= 10 - 20	0.33	0.35
>= 20	0.14	0.17

[10] Unless otherwise stated, the values in the text always refer to the year 2019, because the Natura 2000 dataset is derived from the year 2019.
[11] Definitions of light emission classes are presented in Table 1.

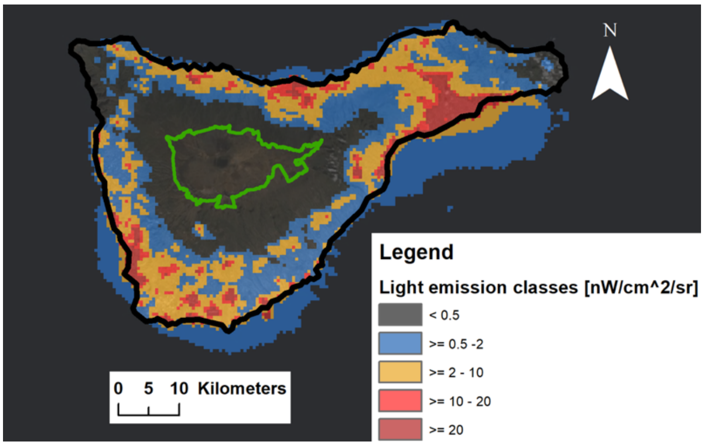

Fig. 5: Natura 2000 site with SITECODE "ES7020043" - Parque Nacional del Teide - marked in green. The SAC site is located in the centre of Tenerife. Only relative areas in the "lowest" emission class were located in this site. Please note that all other Natura 2000 sites are not displayed in the figure.

Fig. 6: Natura 2000 site with SITECODE "EE0080310" - Anne - marked in green. The SAC site is located about 3 km south-east of the city centre of Tartu. The figure is reddish, which means that "high" light emissions were measured everywhere. The main reasons for the "high" light emission values were probably the greenhouse to the north-east (No. 1 in the figure) and the highway to the west of the Natura 2000 site.

Terrestrial Natura 2000 sites across biogeographical regions of the EU

The biogeographical regions encompassing terrestrial Natura 2000 sites in the EU were ordered according to light emission values >=2 nW (emission values where at least low level of ecological impact due to light emissions is expected; Fig. 7 & Table 3). The areas of terrestrial Natura 2000 sites within each biogeographical region and their percentage per region can be found in Table 4 in the Annex. Natura 2000 sites within the Alpine and Boreal regions exhibited the lowest light exposure with over 90% of their relative area in the "lowest" light emission class and few relative areas with "very low" light emissions (6.74% and 4.73%) compared to the other regions. It is interesting that, although the relative areas with light emission values >=2 nW were larger in Natura 2000 sites of the Boreal region than in the Alpine region, the proportion of the "lowest" emission values were higher in the Boreal compared to the Alpine region. This is related to the lower values of light exposure in the quartiles of the Boreal region's Natura 2000 sites. The same applies when comparing the Continental with the Atlantic region. The proportions of relative areas with "lowest" light emissions were similar in the Pannonian, Continental, Atlantic and Mediterranean regions (83.67%, 78.74%, 79.55%, 79.11%). The percentage of relative areas >=2 nW, however, increased from the Pannonian to the Mediterranean region from 2.65% to 5.27%. The highest light exposure was observed for the Macaronesian region's Natura 2000 sites. The region stands out with the fewest areas in the "lowest" light emission class (69.55%), a higher proportion of areas with "very low" light emissions (22.46%) and the highest proportion of light exposure >=2 nW (7.99%). For Macaronesia, as the region with the largest percentage of relative areas >=2 nW, the highest percentages were also to be found in the other categories (low, medium, high emission values).

Comparing the light emission classes of the relative areas above 2 nW of the Boreal and Pannonian regions, it is evident that, although the proportion of “low” light emission values were larger in the Pannonian region, the proportion of relative areas with “medium” and “high” values were smaller than in the Boreal region. However, the Pannonian region was an exception. As the proportion of relative areas >=2 nW increased, the proportions in the “low”, “medium” and “high” emission categories also increased when comparing the other regions. Compared to 2018, the share of relative areas in the “lowest” light emission class has decreased in all regions and increased in all other classes. The only exception experienced the Natura 2000 sites of Macaronesia, where only the proportion of relative areas with “high” light emission values increased in 2019 compared to 2018 (Table 3).

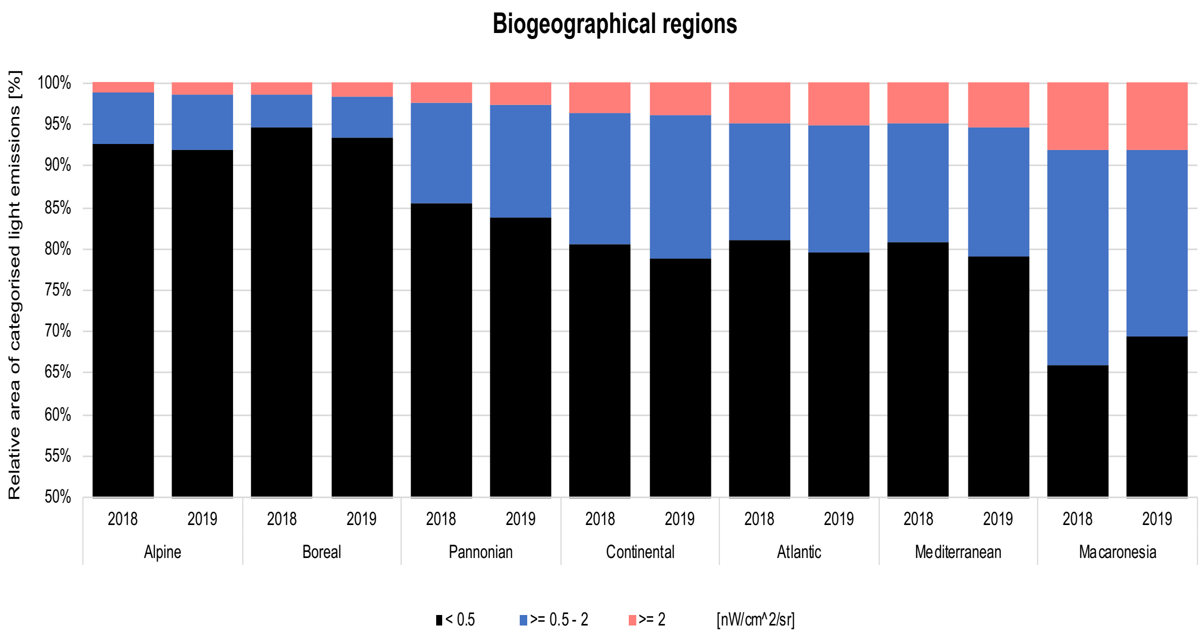

Fig. 7: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 sites within biogeographical regions of the EU in 2018 and 2019 shown in percentages. Please note that the y-axis is offset to 50% for better legibility.

Table 3: Relative areas of the light emission classes presented in Fig. 7. Please note that the class >=2 nW/cm²/sr represents the sum of three subcategories.

	Alpine		Boreal		Pannonian	
	2018	2019	2018	2019	2018	2019
Light emission [nW/cm²/sr]	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**
< 0.5	92.69	91.91	94.74	93.54	85.59	83.67
>= 0.5 - 2	6.11	6.74	3.83	4.73	12.13	13.67
>= 2	1.2	1.34	1.44	1.73	2.29	2.65
>= 2 - 10	1.14	1.27	1.22	1.44	2.08	2.42
>= 10 - 20	0.05	0.06	0.17	0.2	0.16	0.17
>= 20	0.01	0.01	0.05	0.09	0.05	0.06

	Continental		Atlantic		Mediterranean	
	2018	2019	2018	2019	2018	2019
Light emission [nW/cm²/sr]	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**	**Relative area [%]**
< 0.5	80.5	78.74	80.99	79.55	80.86	79.11
>= 0.5 - 2	15.84	17.49	14.27	15.38	14.26	15.61
>= 2	3.66	3.77	4.73	5.06	4.89	5.27
>= 2 - 10	3.36	3.45	4.1	4.41	4	4.3
>= 10 - 20	0.24	0.25	0.44	0.45	0.58	0.62
>= 20	0.06	0.07	0.19	0.2	0.31	0.35

Light emission [nW/cm²/sr]	Macaronesia 2018 Relative area [%]	2019 Relative area [%]
< 0.5	66.09	69.55
>= 0.5 - 2	25.85	22.46
>= 2	8.06	7.99
>= 2 - 10	6.29	6.25
>= 10 - 20	1.08	0.97
>= 20	0.69	0.77

Terrestrial Natura 2000 sites of individual EU Member States

The country with lowest relative areas with light emissions >=2 nW is Estonia. Followed by Romania, Latvia / Lithuania, Denmark, Sweden, Slovakia, Bulgaria, Ireland, Finland, Hungary, United Kingdom, Slovenia, Poland, Austria, Spain, Germany, Greece, Czech Republic, France, Croatia, Cyprus, Portugal, Netherlands, Italy, Luxembourg, Belgium and Malta (Table 4).

Table 4: Relative areas of Natura 2000 sites per Member State with light emissions >=2 nW.

Member State	Relative area with >= 2 nW	Tables	Member State	Relative area with >= 2 nW	Tables
Estonia	1.09 %	Annex, Table 6	Austria	3.42 %	Annex, Table 20
Romania	1.19 %	Annex, Table 7	Spain	3.65 %	Annex, Table 21
Latvia	1.31 %	Annex, Table 8	Germany	3.85 %	Annex, Table 22
Lithuania	1.31 %	Annex, Table 9	Greece	4.19 %	Annex, Table 23
Denmark	1.43 %	Annex, Table 10	Czech Rep.	4.44 %	Annex, Table 24
Sweden	1.53 %	Annex, Table 11	France	4.45 %	Annex, Table 25
Slovakia	1.65 %	Annex, Table 12	Croatia	4.6 %	Annex, Table 26
Bulgaria	1.67 %	Annex, Table 13	Cyprus	6.27 %	Annex, Table 27
Ireland	1.81 %	Annex, Table 14	Portugal	8.16 %	Annex, Table 28
Finland	2.24 %	Annex, Table 15	Netherlands	8.41 %	Annex, Table 29
Hungary	2.33 %	Annex, Table 16	Italy	9.25 %	Annex, Table 30
UK	2.88 %	Annex, Table 17	Luxembourg	16.9 %	Table 5
Slovenia	2.91 %	Annex, Table 18	Belgium	19.7 %	Table 6
Poland	2.92 %	Annex, Table 19	Malta	63.95 %	Table 7

Overall, in Estonia, an incredible 96.39% of the areas were in the “lowest” light emission class in 2019. At the same time, the highest emission value of all terrestrial Natura 2000 areas was measured in the site "EE0080310" in Tartu, the second largest city of Estonia (Fig. 6). With a few exceptions, the relative area of emission values >=2 nW has increased in all countries in 2019 compared to 2018. The exceptions are Ireland (-0.06% >=2 nW; Annex, Table 14), Slovenia (-0.04% >=2 nW; Annex, Table 18), Germany (-0.06% >=2 nW; Annex, Table 22), Cyprus (-0.18% >=2 nW; Annex, Table 27), Luxembourg (-2.1% >=2 nW; Table 5) and Malta (-0.3% >=2 nW; Table 7). In Belgium, the relative area >=2 nW increased the most (+2.3%; Table 6). Natura 2000 sites in Luxembourg (16.9%), Belgium (19.7%) and especially Malta (63.95%) emitted by far the highest amount of light >=2 nW (Fig. 8-10 & Table 5-7). Particularly in Malta, there were almost no Natura 2000 areas with “lowest” or “very low” light emissions (Table 7).

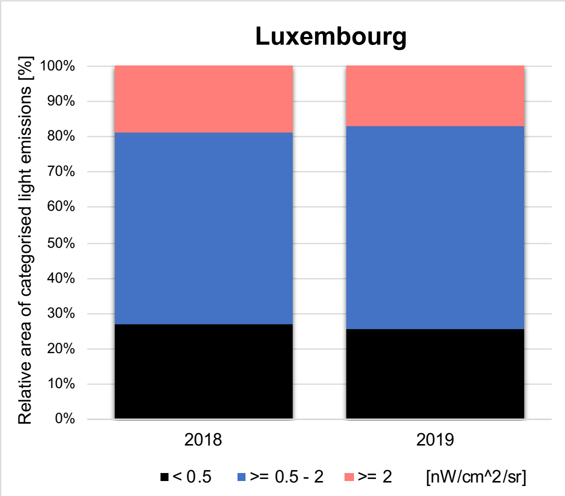

Fig. 8: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Luxembourg in 2018 and 2019 shown in percentages.

Table 5: Relative areas of the light emission classes presented in Fig. 8. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	26.92	25.73
>= 0.5 - 2	54.09	57.38
>= 2	19	16.90
>= 2 - 10	17.39	15.59
>= 10 - 20	1.35	1.15
>= 20	0.26	0.16

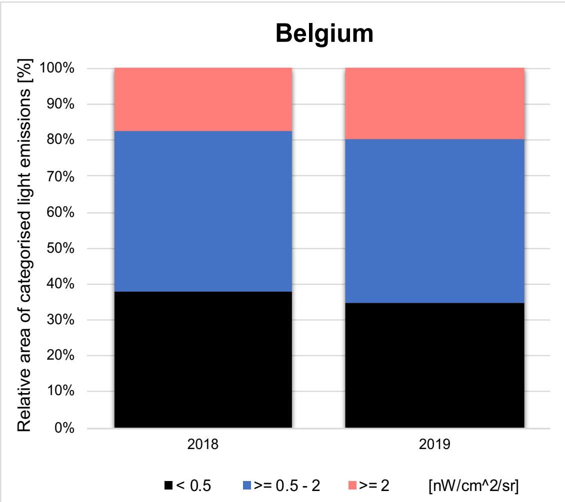

Fig. 9: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Belgium in 2018 and 2019 shown in percentages.

Table 6: Relative areas of the light emission classes presented in Fig. 9. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	37.81	34.66
>= 0.5 - 2	44.79	45.64
>= 2	17.4	19.7
>= 2 - 10	15.52	17.56
>= 10 - 20	1.16	1.28
>= 20	0.72	0.86

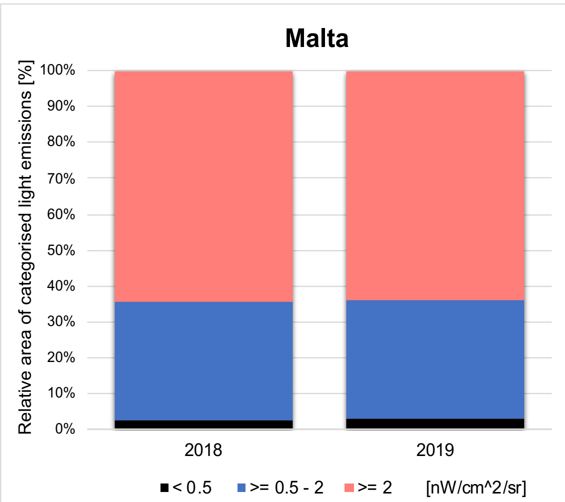

Fig. 10: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Malta in 2018 and 2019 shown in percentages.

Table 7: Relative areas of the light emission classes presented in Fig. 10. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	2.62	2.91
>= 0.5 - 2	33.14	33.14
>= 2	64.25	63.95
>= 2 - 10	48.84	47.67
>= 10 - 20	8.72	9.01
>= 20	6.69	7.27

Examples of terrestrial Natura 2000 sites with highest light emission levels: Luxembourg, Belgium and Malta

Luxembourg

In Luxembourg, “high” light emissions were measured at eight locations in 2019 (Fig. 11). The highest value (31.00083 nW; Annex, Table 2) occurred in the Natura 2000 site "LU0001022" - Grunewald, which is located north of the city of Luxembourg. The site has a total area of 31.5 km^2 and is one of the designated SACs under the Habitats Directive. The highest value was measured at the border of the site with the airport area (No. 2 in Fig. 12). Other high values in the site appeared in connection with the industrial area (No.1 in Fig. 12).

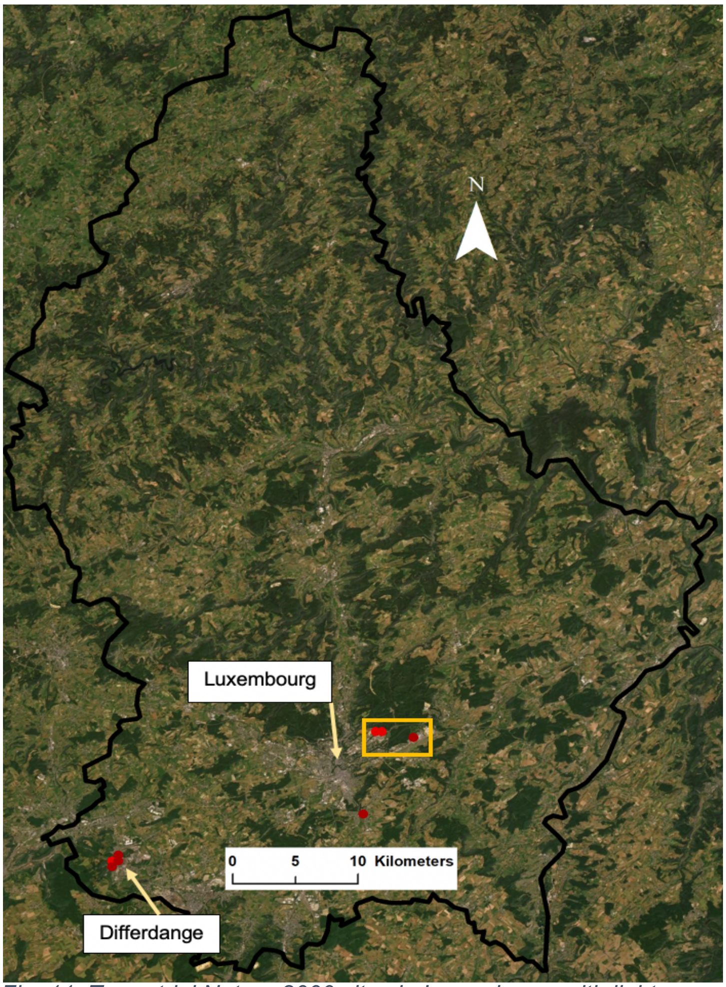

Fig. 11: Terrestrial Natura 2000 sites in Luxembourg with light emissions >=20 nW highlighted in red. The pixels with the five highest values in 2019 are marked in dark red. Basemap (World Imagery) supplied by Esri.

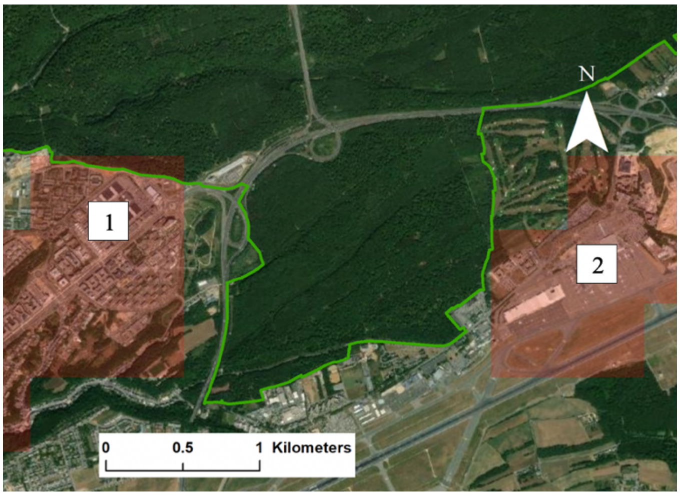

Fig. 12: Enlargement of the orange rectangle in Fig. 11. The pixels with a light emission value >=20 nW are highlighted in red. The outline of the Natura 2000 site “LU0001022” is marked in green. Basemap (World Imagery) supplied by Esri.

Belgium

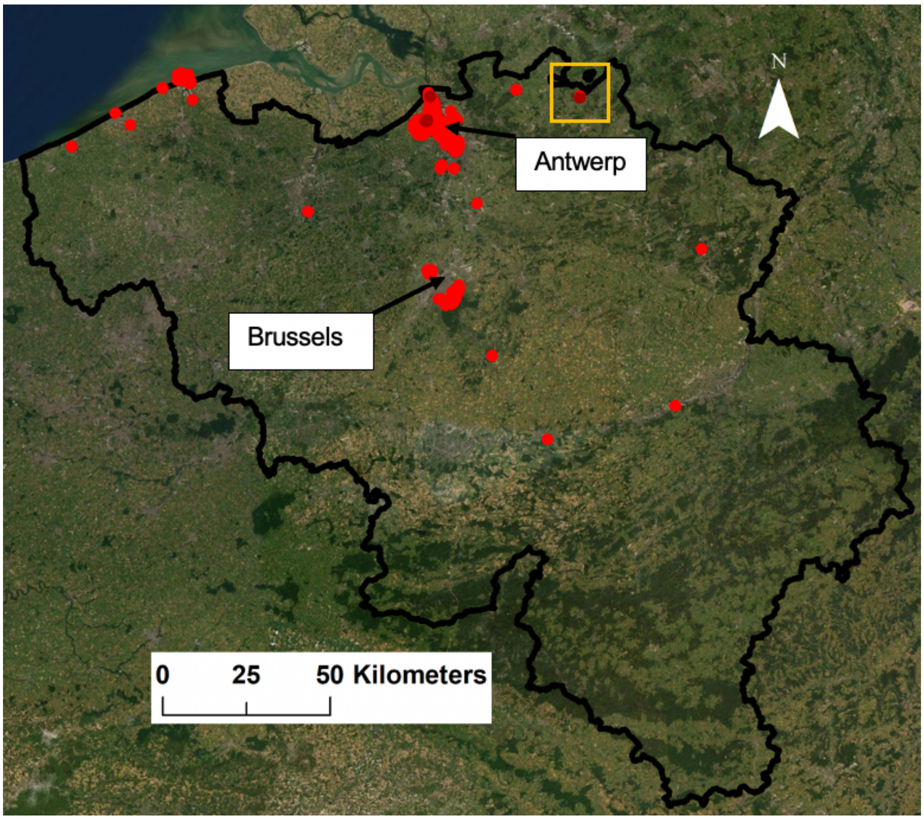

Fig. 13: Terrestrial Natura 2000 sites in Belgium with light emissions >=20 nW highlighted in red. The pixels with the five highest values in 2019 are marked in dark red. Basemap (World Imagery) supplied by Esri.

In Belgium, "high" light emissions were measured at 279 locations in 2019. It is noticeable that most of them appeared in areas near Antwerp and Brussels (Fig. 13). The highest value (131.0417 nW; Annex, Table 2) occurred in the Natura 2000 site "BE2100024" - Vennen, heiden en moerassen rond Turnhout, which is located in Turnhout. The site has a total area of 36 km^2 and is one of the designated SACs under the Habitats Directive. The highest value was observed in the direct vicinity of a greenhouse (No. 1 in Fig. 14).

Fig. 14: Enlargement of the orange rectangle in Fig. 13. The pixels with a light emission value >=20 nW are highlighted in red. The outline of the Natura 2000 site "BE2100024" is marked in green. Basemap (World Imagery) supplied by Esri.

Malta

In Malta, “high” light emissions were measured at 25 locations in 2019 (Fig. 15). The highest value (118.7308 nW; Annex, Table 2) was measured in the Natura 2000 sites "MT0000024” / “MT0000033" “MT0000024” has an area of 23 km^2 and belongs to the Habitats Directive (SAC) and “MT0000033” consists of 0.5 km^2 and is part of the Birds Directive (SPA). The highest value was measured in the vicinity of the “Malta Freeport” (No. 2 in Fig. 16). Other high values in the sites appeared in relation with industrial areas (No.1 in Fig. 16).

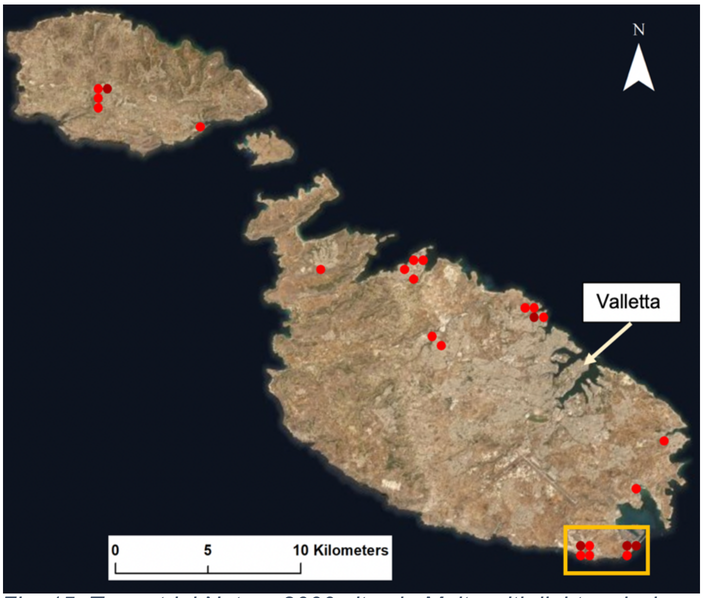

Fig. 15: Terrestrial Natura 2000 sites in Malta with light emissions >=20 nW highlighted in red. The pixels with the five highest values in 2019 are marked in dark red. Basemap (World Imagery) supplied by Esri.

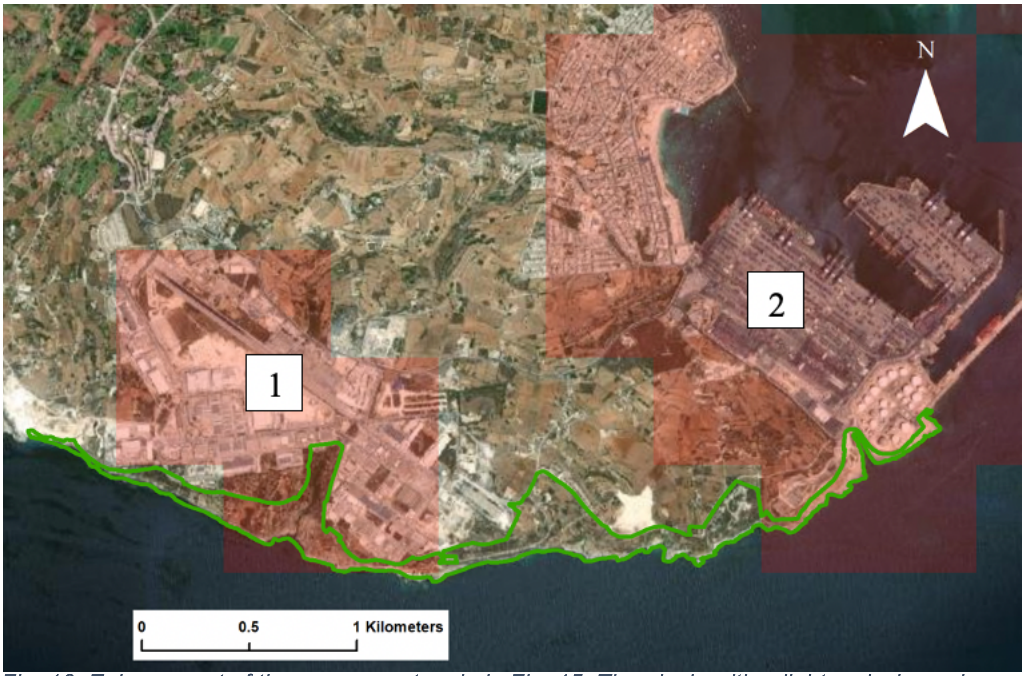

Fig. 16: Enlargement of the orange rectangle in Fig. 15. The pixels with a light emission value >=20 nW are highlighted in red. The outline of the Natura 2000 sites “MT0000024” and “MT0000033” are marked in green. “MT0000024” is even larger to the west, but this is not illustrated. In the area shown, both sites overlap. Basemap (World Imagery) supplied by Esri.

Light emissions change with various land covers of terrestrial Natura 2000 sites

The relationship between light emissions and artificial land cover of terrestrial Natura 2000 sites across the EU is shown in Fig. 17. Even with a proportion of >0-10% artificial surfaces, only 34% of the Natura 2000 areas were within the "lowest" light emission class. As the proportion of artificial surfaces increased, the relative areas in this class decreased more or less linearly, until at 90-100% of artificial surfaces, only approx. 6% were left. Relative areas with "very low" light emissions had a value of approx. 45% up to 30-40% artificial component and then dropped until only approx. 20% remained at 90-100%. The proportion of areas with "low" light emissions grew roughly linearly from approx. 19% to 45%. While the proportion of areas with "medium" light emissions increased constantly from approx. 1.5% to 10% between >0-10% and 80-90% of artificial surfaces, "high" light emissions increased only slightly between >0-10% and 40-50% but then rose at a similarly constant rate as the "medium" values until they reached approx. 6% at 80-90%. Between 80-90% and 90-100%, the areas of "medium" and "high" light emissions increased considerably to approx. 16% and 12% respectively (Fig. 17). It can therefore be concluded that high levels of light emissions were to be expected in areas with a large proportion of artificial surface.

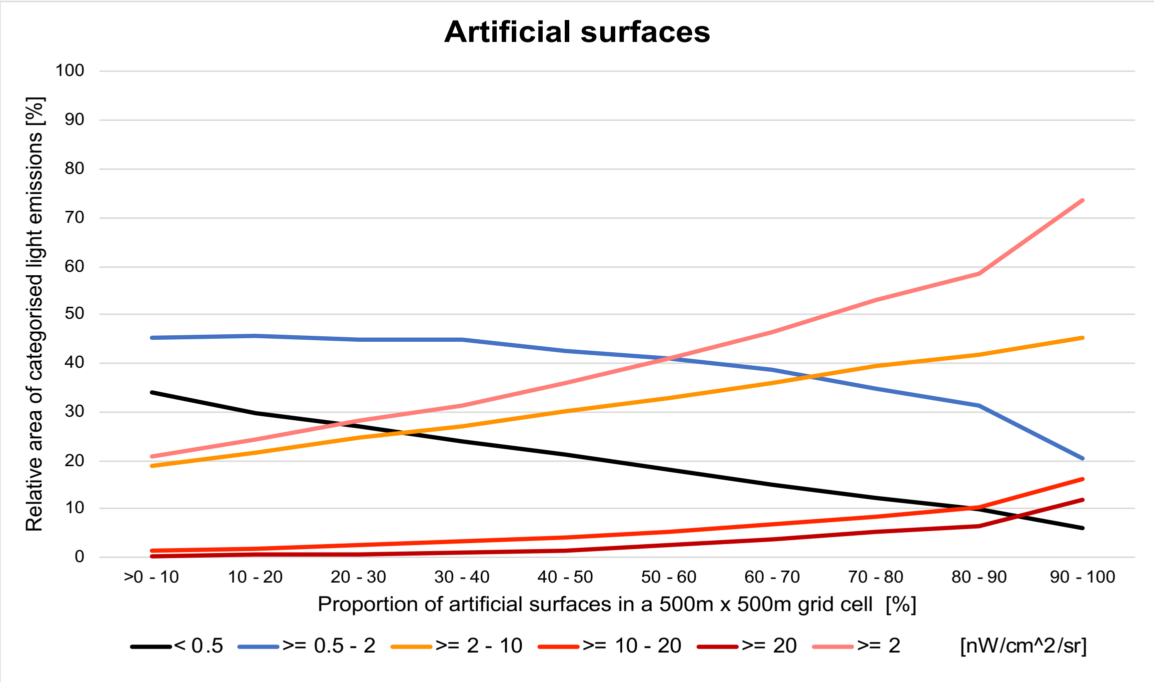

Fig. 17: The figure shows the relationship between the relative area of categorised light emissions in 2019 and the increase in the proportion of artificial surfaces in a 500x500m grid cell.

The four other land cover classes (agricultural areas; Annex, Fig. 26, forest and seminatural areas; Annex, Fig. 27, wetlands; Annex Fig. 28 and water bodies; Annex, Fig. 29) showed a rather distinct pattern compared to the artificial surfaces. The four classes had relatively different trends in the "lowest" and "very low" light emission classes, but they were quite similar in the "low", "medium" and "high" classes. While the proportion of relative areas in the "lowest" light emission class decreased when an agricultural part was present (except when (almost) the whole grid cell was agricultural land), the relative area in the "lowest" light emission class increased for the other land cover classes. The proportion of areas with "very low" light emissions expanded as the proportion of agricultural land increased but decreased for the other land cover classes as the respective land cover proportion increased. The low proportion of areas >=2 nW in all other land cover classes compared to the artificial surfaces is striking. "High" light emissions are almost non-existent in the four classes. In general, grid cells with a proportion of wetlands had the lowest light exposure. It is interesting to note that light exposure decreased significantly in all four cases when the proportion of land cover was 90-100%.

From this, it can be deduced that the high light emissions were associated to areas with a proportion of artificial surfaces. Considering all light emission classes, Natura 2000 areas containing wetlands are the least exposed to light pollution, followed by forest and seminatural areas.

Marine Natura 2000 sites across the EU

The marine Natura 2000 sites within the three buffer zones around coastlines of the EU Member States covered an area of approximately 40’000 km^2 (Annex, Table 31). Table 8 shows the minimum, the quartiles, the mean and the maximum of light emissions for Natura 2000 sites in the three zones. The values for 2018 can be found in Table 2 in the Annex.

Table 8: Statistics of light emission values for Natura 2000 sites within zones 1, 2 and 3.

Zone 1 (0-1 km)	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
2019	0.0792	0.2075	0.3267	1.2155	0.7925	221.0458
Zone 2 (1-2 km)	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2019	0.0425	0.18	0.2515	0.4135	0.4492	34.0933
Zone 3 (2-3 km)	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2019	0.045	0.1692	0.2267	0.3412	0.3692	19.7025

The quartiles and thus the light emissions, decreased with increasing distance from the coast. It is evident based on the quartiles as well as in Fig. 18 and Table 9 that between zones 1 and 2 the number of Natura 2000 areas with the “lowest” light emission increased significantly more (+13.89%; Table 9) than between zone 2 and 3 (+6.06%; Table 9). Areas with >=2 nW decreased strongly between zone 1 and 2 (-10.21%; Table 9) in comparison to zone 2 and 3 (-0.82%; Table 9). The mean also decreased significantly more between zones 1 and 2 (- 0.802; Table 8) than between 2 and 3 (-0.0723; Table 8), which indicates that in zone 1 more Natura 2000 areas with very high light exposure were observed. Most of the areas (463 pixels) with “high” light emissions were located in zone 1 in the Mediterranean bioregion, especially on the (south-)west coast of Spain and the south coast of France (Fig. 19). In zone 2 only 2 pixels and in zone 3 no pixels with “high” light emissions were measured. Compared to 2018, there were fewer relative areas in the “lowest” light emission class in all three zones in 2019. Accordingly, the light exposure increased between 0.01% and 2.45% (Table 9) or remained the same in the other classes (Table 9).

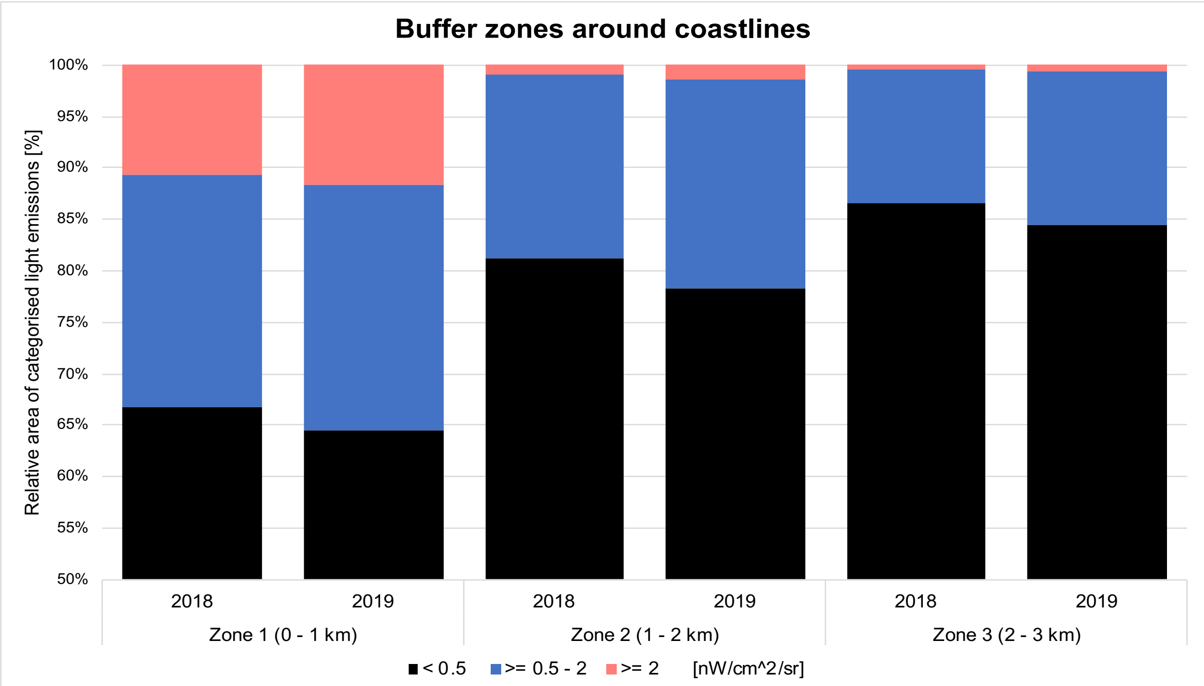

Fig. 18: The relative area of categorised light emissions in nW/cm2/sr for marine Natura 2000 areas within buffer zones in 2018 and 2019 shown in percentages. Please note that the y-axis is offset to 50% for better legibility.

Table 9: Relative areas of the light emission classes presented in Fig. 18. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

	Buffer zones					
	Zone 1 (0-1 km)		**Zone 2 (1-2 km)**		**Zone 3 (2-3 km)**	
Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**	2018 **Relative area [%]**	2019 **Relative area [%]**	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	66.83	64.44	81.16	78.33	86.59	84.39
>= 0.5 - 2	22.45	23.98	17.84	20.29	12.97	15.06
>= 2	10.71	11.58	1	1.37	0.43	0.55
>= 2 - 10	8.87	9.46	0.98	1.34	0.41	0.51
>= 10 - 20	1.33	1.45	0.02	0.03	0.02	0.04
>= 20	0.51	0.67	0.004	0.004	0	0

Fig. 19: Marine Natura 2000 sites within zone 1 with light emissions >=20 nW highlighted in red. Note the high number of points on the (south-)west coast of Spain and the south coast of France.

Example of a marine Natura 2000 site with highest light emission levels: The Netherlands

Overall, the lowest light emission value (0.0425 nW; Annex, Table 2) was measured in zone 2 in Latvia within the Natura 2000 site “LV0900300” and the highest value (221.0458 nW; Annex, Table 2) in zone 1 in the Netherlands in sites “NL9802026/NL9803061” (sites are overlapping; Fig. 20). The two pixels with the highest light emission values were located within the orange rectangle in Fig. 20. Both sites cover an area of approximately 440 km^2. “NL9802026” belongs to the Birds Directive and “NL9803061” is part of the Habitats Directive. The highest value was observed close to a greenhouse (No. 1 in Fig. 21). Further “high” light emission values were measured in the vicinity of a chemical factory site near Terneuzen (Fig. 20).

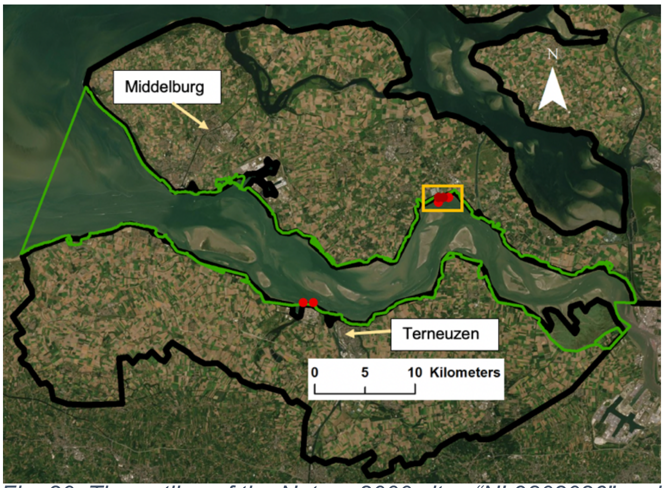

Fig. 20: The outline of the Natura 2000 sites “NL9802026” and “NL9803061” are marked in green. In the area shown, both sites overlap. Basemap (World Imagery) supplied by Esri.

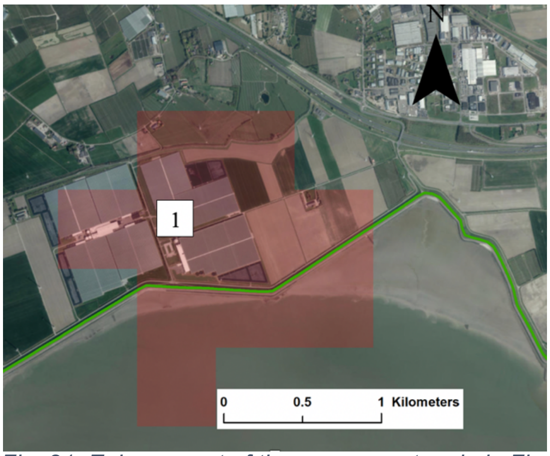

Fig. 21: Enlargement of the orange rectangle in Fig. 20. The pixels with a light emission value >=20 nW are highlighted in red. The outline of the Natura 2000 sites “NL9802026” and “NL9803061” are marked in green (sites are overlapping). Basemap (World Imagery) supplied by Esri.

Discussion

As for other protected areas worldwide, light pollution is a concerning issue for terrestrial and marine Natura 2000 sites. Major variations in light exposure were identified, when considering light pollution at different spatial scales. Regarding all terrestrial Natura 2000 sites within the EU, 3.87% (approx. 38'000 km^2) were exposed to light levels >=2 nW, where at least low level of ecological impact is expected and 0.17% to high light levels. Compared to 2018, the area with >=2 nW has increased by 0.25%. Natura 2000 sites within the Alpine and Boreal biogeographical regions exhibited the lowest and sites within the Mediterranean and Macaronesia regions the highest light exposure. Data on ALAN has been used as a proxy for population density (Bennie, Davies, Duffy, Inger, & Gaston, 2014). Here the opposite is attempted, i.e. to explain the differences in light exposure on the basis of population density. Overall, the population density in the Alpine and Boreal regions is significantly lower and thus artificial areas are less widespread than in the other two regions, which at least partly explains the large differences in light exposure. Compared to 2018, light levels have increased in 2019 in Natura 2000 sites in all biogeographical regions except for sites in the Macaronesia region. At the country level, the variation in light exposure was even more apparent. Regarding light levels >=2 nW, Natura 2000 sites in Luxembourg (16.9%), Belgium (19.7%) and Malta (63.95%) were exposed to the highest amount of light, while Natura 2000 sites in Estonia (1.09%) and Romania (1.19%) the least. It is noteworthy that in Estonia, remarkable 96.39% of Natura 2000 sites were within the lowest light level. The population density of the EU as of 2018 was 112[12] inhabitants per km^2. Luxembourg had 250, Belgium 377 and Malta 1514 inhabitants per km^2, whereas in Estonia only 30 and in Romania 85 people lived per km^2. Considering the great differences in population densities and the associated assumption that infrastructure also expands with increasing density, thus resulting in higher light exposure over a wide area, the differences in light exposure are at least partially explainable. By exemplarily highlighting locations in Luxembourg, Belgium and Malta, it could be demonstrated that built-up areas such as (nearby) airports, ports, industrial areas or greenhouses are the cause of very high light pollution levels within Natura 2000 sites. This is consistent with the finding of Hale and Arlettaz (2019) *"[…] that light emissions are often dominated by large contributions from a few point sources in or adjacent to urban areas"* (p. 4). Regarding light pollution levels >=2 nW, the largest decrease was recorded in Natura 2000 sites of Luxembourg (-2.1%) and the highest increase in Belgium (+2.3%). Natura 2000 sites with a wetland proportion were the least light-exposed, which is encouraging as these ecosystems are usually particularly worthy for protection. However, it needs to be noted that all Natura 2000 sites in the EU with a wetland component were considered in this analysis. Wetlands in e.g. Estonia could be significantly less exposed than the ones in e.g. Belgium. Marine Natura 2000 sites within 1000m of the coast were considerably higher exposed to light than sites 1000-2000m and 2000-3000m offshore. As the greatest amount of light exposure in marine nature reserves originates from the shore, apart from some bright offshore light sources (e.g. offshore infrastructure and ships) (Davies et al., 2016), it is not surprising that the light emissions from Natura 2000 sites already decreased sharply at 1000-2000m. No high light values were measured beyond 2000m. Overall, light exposure in all three buffer zones increased by 0.01 to 2.45%, depending on the light emission class, in 2019 compared to 2018.

Apart from the threshold values for the magnitude of light emissions published by Hale and Arlettaz (2019) no other thresholds were found in the literature. The two classes below 2 nW (<0.5 nW and >=0.5-2 nW) were added to differentiate between very small values. Hale et al. (2018) concluded that at least a small ecological impact can be expected for light emissions greater or equal to 2 nW. However, it is not yet possible to make strong statements about the magnitude and ecological impact of light pollution. It can be assumed that a value of e.g. 10 nW has a greater ecological impact than e.g. 2nW, but studies investigating this are missing (Hale, 2021).

[12] https://data.worldbank.org/indicator/EN.POP.DNST?locations=EU (Retrieved 12.05.2021)

The ecological impact also depends on the species being studied. The classification of Hale and Arlettaz (2019) was made on the basis of typical light emission values of swiss residential areas. If this classification were made according to emission levels of other countries, the highest light emission category (>=20 nW), for example, would be probably defined quite differently.

While the approach used to analyse light pollution is suitable for giving an indication of light pollution e.g. for Natura 2000 sites per Member State, it is impossible to state how the light pollution is distributed, i.e. whether particularly polluted areas within a Member State are only located in the vicinity of e.g. large settlements or are distributed over a wide area. Furthermore, the resolution of the Natura 2000 sites had to be adapted to match the resolution of the VIIRS data, which meant that a certain spatial accuracy was lost. Satellite data is considered helpful in locating light-exposed ecosystems (Bennie, Duffy, et al., 2015), but some further limitations exist. The satellite data is based on the light emitted from the earth towards the sky. Even under clear sky conditions some of the light might be scattered back to the ground by e.g., aerosols creating skyglow (which is common over cities) and is thus not detected correctly by the satellite (Ściężor & Czaplicka, 2020). Light can be shielded by trees and buildings or, for areas near water bodies, excessive light emission may be measured due to light reflection on the water surface (Hale & Arlettaz, 2019; Lynch, Dearborn, & Lock, 2011). Furthermore, lights from aurora, fires, boats and other temporal lights are not yet filtered as stated in the description[13] of the applied dataset (VIIRS Nighttime Day/Night Band Composites Version 1). Although the resolution of the VIIRS-DNB data is significantly better than that of the DMSP-OLS (Elvidge et al., 2013), it is not possible to distinguish whether, for example, 100 well shielded lights are present in a 500x500m cell or only a single bright one. This makes it impossible to accurately detect bright light sources in small-scale analyses using only satellite data. VIIRS-DNB data is collected at ~01:30 in local solar time and therefore misses the evening peak of light emissions (Kyba et al., 2015). (Street-) lights are increasingly being replaced by “white” LEDs with an emission range from 450 to 480 nm. VIIRS-DNB has hardly any spectral sensitivity below 500 nm, which means that a transition to LED will falsely be measured as a decrease in light pollution (Falchi et al., 2016; Kyba et al., 2015).

Given my results and given abundant literature on mostly adverse impacts of ALAN on biodiversity, I conclude that light mitigation measures are an urgent challenge. In contrast to established benefits of ALAN for humans such as reduced risks of traffic or night-time crime fear, Schuler, Schatz, and Berweger (2018) could not find any relationship between criminality and light intensity. Furthermore, road accidents were found to be normally distributed at low light levels. This needs to be further investigated, as a reduction in light intensity is necessary. Mitigation measures such as lowering light levels (Bolliger, Hennet, Wermelinger, Bösch, et al., 2020; Rowse, Harris, & Jones, 2018), or (given the transformation to LEDs) providing assessments on impacts of individual LED properties such as light colour (Bolliger, Hennet, Wermelinger, Blum, et al., 2020) based on state-of-the-art light technological development should be implemented at various political levels to set out sustainable lighting strategies. In addition, further research on the establishment of thresholds of harmful light pollution levels on ecological functions is essential.

[13] https://developers.google.com/earth-engine/datasets/catalog/NOAA_VIIRS_DNB_MONTHLY_V1_VCMCFG#description (Retrieved 02.05.2021)

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Annex

Table 1: CLC nomenclature guidelines (https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html/)

1. Artificial Surfaces	1.1 Urban fabric	1.1.1 Continuous urban fabric
		1.1.2 Discontinuous urban fabric
	1.2 Industrial, comercial and transport units	1.2.1 Industrial or commercial units
		1.2.2 Road and rail networks and associated land
		1.2.3 Port areas
		1.2.4 Airports
	1.3 Mine, dump and construction sites	1.3.1 Mineral extraction sites
		1.3.2 Dump sites
		1.3.3 Construction sites
	1.4 Artificial, non-agricultural vegetated areas	1.4.1 Green urban areas
		1.4.2 Sport and leisure facilities
2. Agricultural areas	2.1 Arable land	2.1.1 Non-irrigated arable land
		2.1.2 Permanently irrigated land
		2.1.3 Rice fields
	2.2 Permanent crops	2.2.1 Vineyards
		2.2.2 Fruit trees and berry plantations
		2.2.3 Olive groves
	2.3 Pastures	2.3.1 Pastures
	2.4 Heterogeneous agricultural areas	2.4.1 Annual crops associated with permanent crops
		2.4.2 Complex cultivation patterns
		2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation
		2.4.4 Agro-forestry areas
3. Forest and seminatural areas	3.1 Forest	3.1.1 Broad-leaved forest
		3.1.2 Coniferous forest
		3.1.3 Mixed forest
	3.2 Shrub and/or herbaceous vegetation associations	3.2.1 Natural grassland
		3.2.2 Moors and heathland
		3.2.3 Sclerophyllous vegetation
		3.2.4 Transitional woodland/shrub
	3.3 Open spaces with little or no vegetation	3.3.1 Beaches, dunes, sands
		3.3.2 Bare rock
		3.3.3 Sparsely vegetated areas
		3.3.4 Burnt areas
		3.3.5 Glaciers and perpetual snow
4. Wetlands	4.1 Inland wetlands	4.1.1 Inland marshes
		4.1.2 Peatbogs
	4.2 Coastal wetlands	4.2.1 Salt marshes
		4.2.2 Salines
		4.2.3 Intertidal flats
5. Water bodies	5.1 Inland waters	5.1.1 Water courses
		5.1.2 Water bodies
	5.2 Marine waters	5.2.1 Coastal lagoons
		5.2.2 Estuaries
		5.2.3 Sea and ocean

Table 2: Statistics of light emission values for terrestrial and marine Natura 2000 sites.

Terrestrial Natura 2000 sites						
EU	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0075	0.1942	0.24	0.5388	0.3608	824.2467
2019	0.0025	0.2108	0.2583	0.5789	0.3883	1059.2659
Biogeographical regions						
Alpine	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0792	0.1783	0.215	0.3120	0.2675	59.0192
2019	0.1033	0.2	0.2283	0.3407	0.29	52.9167
Atlantic	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0967	0.1917	0.2367	0.6226	0.3842	824.2467
2019	0.0875	0.2017	0.2475	0.6518	0.4092	487.1783
Boreal	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0708	0.1408	0.1562	0.2918	0.1875	574.8109
2019	0.0948	0.17	0.19	0.3552	0.2254	1059.2659
Continental	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0725	0.2017	0.2558	0.5292	0.4108	822.6517
2019	0.1042	0.225	0.2817	0.561	0.4425	837.7808
Macaronesia	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0142	0.28	0.375	1.0644	0.6183	104.1108
2019	0.0025	0.2525	0.3383	1.0626	0.5796	104.7417
Mediterranean	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0075	0.215	0.2625	0.6897	0.4042	436.1642
2019	0.0158	0.225	0.2775	0.7426	0.4333	496.0708
Pannonian	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1125	0.205	0.2467	0.4391	0.3525	89.89
2019	0.135	0.2292	0.2742	0.4918	0.3842	299.1809
Member States						
Austria	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1133	0.2125	0.2475	0.4898	0.41	42.5175
2019	0.1425	0.2125	0.2517	0.4918	0.4	34.9042
Belgium	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.185	0.3533	0.6958	1.6161	1.4675	115.94
2019	0.2058	0.3933	0.77	1.7671	1.635	131.0417
Bulgaria	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1233	0.19	0.2133	0.3487	0.2658	56.4417
2019	0.1342	0.2092	0.2342	0.38	0.2908	62.8917
Croatia	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1258	0.2075	0.2583	0.5824	0.4292	65.9925
2019	0.1225	0.2192	0.2775	0.603	0.4508	67.0667
Cyprus	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1867	0.2517	0.3392	0.8165	0.5417	104.1583
2019	0.1758	0.2533	0.3392	0.8	0.54	97.195

Czech Republic	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
2018	0.1058	0.2317	0.295	0.5739	0.46	38.1983
2019	0.145	0.25	0.3217	0.6323	0.5033	41.1658
Denmark	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.105	0.1658	0.1875	0.2971	0.2325	17.8083
2019	0.1133	0.1742	0.2058	0.3194	0.265	23.2858
Estonia	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0708	0.1442	0.165	0.2733	0.1867	574.8109
2019	0.0992	0.1633	0.18	0.3268	0.2042	1059.2659
Finland	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0717	0.135	0.1467	0.301	0.17	329.7683
2019	0.0948	0.1742	0.1931	0.4144	0.2279	438.0583
France	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1275	0.2117	0.2558	0.6112	0.3933	358.89
2019	0.1325	0.2292	0.2792	0.6434	0.4275	487.1783
Germany	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0725	0.2083	0.2725	0.549	0.4533	151.5808
2019	0.1217	0.225	0.2925	0.559	0.475	174.9433
Greece	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0075	0.2058	0.2417	0.5226	0.335	83.3292
2019	0.0158	0.2233	0.2625	0.5919	0.3775	130.355
Hungary	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.125	0.2017	0.2375	0.41	0.325	89.89
2019	0.135	0.2258	0.265	0.4636	0.3583	299.1809
Ireland	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1183	0.18	0.2042	0.3628	0.2533	38.975
2019	0.0958	0.19	0.2175	0.3630	0.2717	35.6542
Italy	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0242	0.2617	0.3408	0.9148	0.64	110.0875
2019	0.0192	0.2867	0.3742	1.0109	0.7067	126.3017
Latvia	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0883	0.1417	0.155	0.2281	0.1775	25.3483
2019	0.105	0.1683	0.1933	0.2928	0.2308	31.13
Lithuania	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0967	0.1458	0.1592	0.2666	0.1808	60.6583
2019	0.1108	0.1825	0.1992	0.3158	0.2292	52.5067
Luxembourg	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.2392	0.4833	0.765	1.5729	1.5383	39.1175
2019	0.2767	0.4958	0.7508	1.4323	1.435	31.0008
Malta	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.335	1.402	3.16	6.568	6.738	115.933
2019	0.3208	1.3785	2.9508	6.4913	6.6846	118.7308
Netherlands	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1167	0.2858	0.465	0.9737	0.8292	824.2467
2019	0.1217	0.301	0.505	1.0295	0.9258	357.8342

Poland	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
2018	0.1017	0.185	0.2333	0.4777	0.3658	822.6517
2019	0.1042	0.2075	0.2575	0.5004	0.3908	837.7808
Portugal	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1492	0.2433	0.3117	0.9263	0.5875	120.7117
2019	0.1608	0.2592	0.3283	0.9987	0.6275	126.8683
Romania	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0808	0.1717	0.2042	0.312	0.275	59.0192
2019	0.1242	0.2092	0.2433	0.3678	0.3225	53.2983
Slovakia	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1092	0.1917	0.2308	0.3707	0.3192	44.3608
2019	0.1267	0.2025	0.2425	0.3931	0.3358	41.7592
Slovenia	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.1333	0.2117	0.2558	0.4907	0.3917	88.7442
2019	0.1442	0.2125	0.2567	0.494	0.3925	90.2833
Spain	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0142	0.2092	0.2425	0.5858	0.3317	436.1642
2019	0.0025	0.2142	0.2483	0.6191	0.3425	496.0708
Sweden	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0733	0.145	0.16	0.2958	0.1942	44.6683
2019	0.095	0.1698	0.1906	0.3252	0.2225	57.3929
United Kingdom	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.0967	0.1692	0.1942	0.4374	0.265	125.7192
2019	0.0875	0.1725	0.1992	0.4507	0.275	319.8133

Marine Natura 2000 sites

Buffer zones

Zone 1 (0-1 km)	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
2018	0.0625	0.1917	0.3008	1.1021	0.725	88.3317
2019	0.0792	0.2075	0.3267	1.2155	0.7925	221.0458
Zone 2 (1-2 km)	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.04	0.1667	0.2308	0.3764	0.4067	24.8592
2019	0.0425	0.18	0.2515	0.4135	0.4492	34.0933
Zone 3 (2-3 km)	**Minimum**	**1st quartile**	**Median**	**Mean**	**3rd quartile**	**Maximum**
2018	0.035	0.1575	0.2092	0.3094	0.3308	15.8875
2019	0.045	0.1692	0.2267	0.3412	0.3692	19.7025

Terrestrial Natura 2000 sites

Table 3: Number of 500x500m cells and area in km² of all terrestrial Natura 2000 sites

No. of cells	Area [km²]
3’889’893	972’473.25

Table 4: Number of 500x500m cells, area in km² and proportion of Natura 2000 sites per biogeographical region

Biogeographical region	No. of cells	Area [km²]	Proportion [%]
Alpine	506’244	126’561	13.01
Atlantic	532’673	133’168.25	13.69
Boreal	314’525	78’631.25	8.09
Continental	1’286’457	321’614.25	33.07
Macaronesia	19’291	4’822.75	0.5
Mediterranean	1’088’163	272’040.75	27.97
Pannonian	142’540	35’635	3.66

Table 5: Number of 500x500m cells, area in km² and proportion of Natura 2000 sites per EU Member State

EU Member State	No. of cells	Area [km²]	Proportion [%]
Austria	68’275	17’068.75	1.76
Belgium	32’543	8’135.75	0.84
Bulgaria	186’133	46’533.25	4.79
Croatia	97’288	24’322	2.5
Cyprus	8’771	2’192.75	0.23
Czech Republic	60’681	15’170.25	1.56
Denmark	24’032	6’008	0.62
Estonia	45’651	11’412.75	1.17
Finland	91’576	22’894	2.35
France	416’773	104’193.25	10.71
Germany	390’591	97’647.75	10.04
Greece	165’310	41’327.5	4.25
Hungary	111’138	27’784.5	2.86
Ireland	63’646	15’911.5	1.64
Italy	292’535	73’133.75	7.52
Latvia	37’552	9’388	0.97
Lithuania	46’713	11’678.25	1.2
Luxembourg	5’049	1’262.25	0.13
Malta	344	86	0.01
Netherlands	30’810	7’702.5	0.79
Poland	300’008	75’002	7.71
Portugal	86’203	21’550.75	2.22
Romania	262’533	65’633.25	6.75
Slovakia	72’552	18’138	1.87
Slovenia	39’896	9’974	1.03
Spain	665’287	166’321.75	17.1
Sweden	149’966	37’491.5	3.86
United Kingdom	138’037	34’509.25	3.55

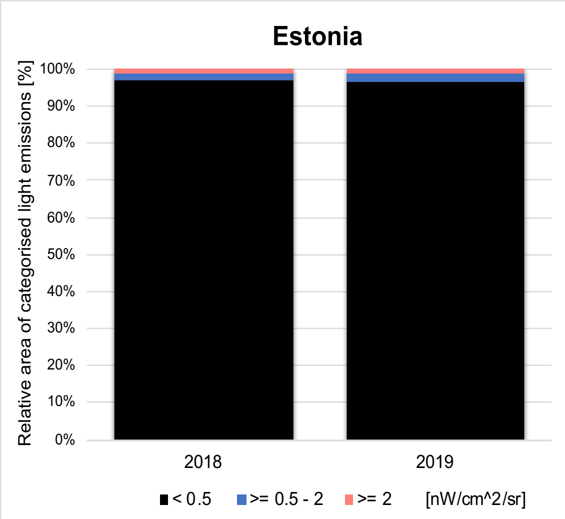

Fig. 1: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Estonia in 2018 and 2019 shown in percentages.

Table 6: Relative areas of the light emission classes presented in Fig. 1. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	96.94	96.39
>= 0.5 - 2	2.09	2.51
>= 2	0.96	1.09
>= 2 - 10	0.76	0.81
>= 10 - 20	0.16	0.19
>= 20	0.04	0.09

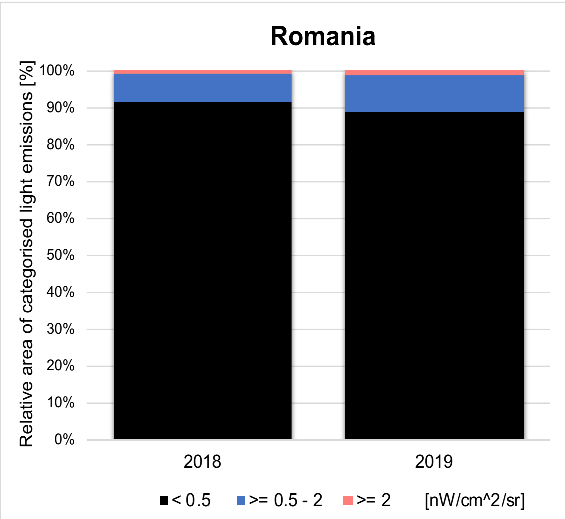

Fig. 2: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Romania in 2018 and 2019 shown in percentages.

Table 7: Relative areas of the light emission classes presented in Fig. 2. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	91.63	88.92
>= 0.5 - 2	7.43	9.89
>= 2	0.93	1.19
>= 2 - 10	0.85	1.1
>= 10 - 20	0.06	0.06
>= 20	0.02	0.03

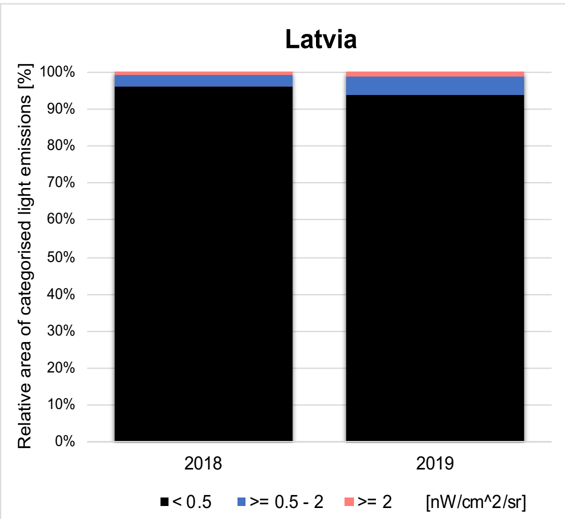

Fig. 3: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Latvia in 2018 and 2019 shown in percentages.

Table 8: Relative areas of the light emission classes presented in Fig. 3. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	95.96	93.76
>= 0.5 - 2	3.19	4.94
>= 2	0.84	1.31
>= 2 - 10	0.81	1.24
>= 10 - 20	0.03	0.06
>= 20	0.003	0.01

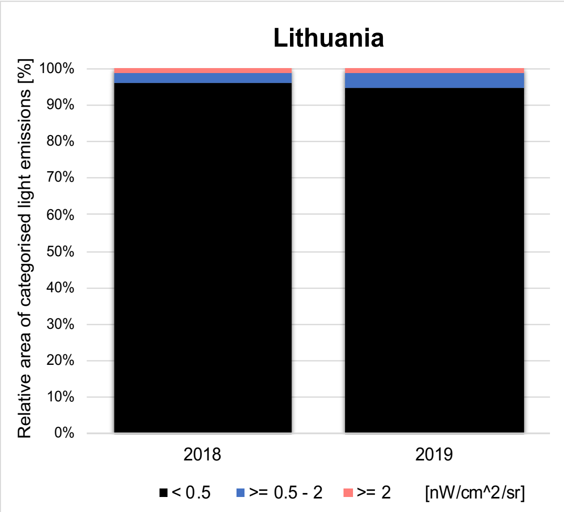

Fig. 4: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Lithuania in 2018 and 2019 shown in percentages.

Table 9: Relative areas of the light emission classes presented in Fig. 4. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 Relative area [%]	2019 Relative area [%]
< 0.5	96.07	94.84
>= 0.5 - 2	2.75	3.85
>= 2	1.19	1.31
>= 2 - 10	1	1.13
>= 10 - 20	0.14	0.14
>= 20	0.05	0.04

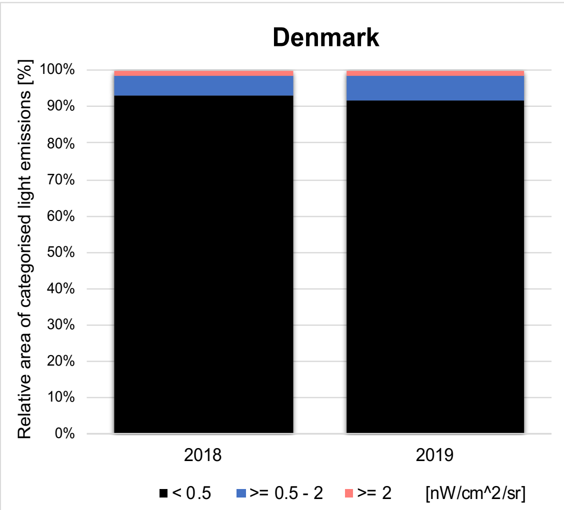

Fig. 5: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Denmark in 2018 and 2019 shown in percentages.

Table 10: Relative areas of the light emission classes presented in Fig. 5. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 Relative area [%]	2019 Relative area [%]
< 0.5	92.93	91.83
>= 0.5 - 2	5.66	6.74
>= 2	1.41	1.43
>= 2 - 10	1.36	1.38
>= 10 - 20	0.05	0.05
>= 20	0	0.004

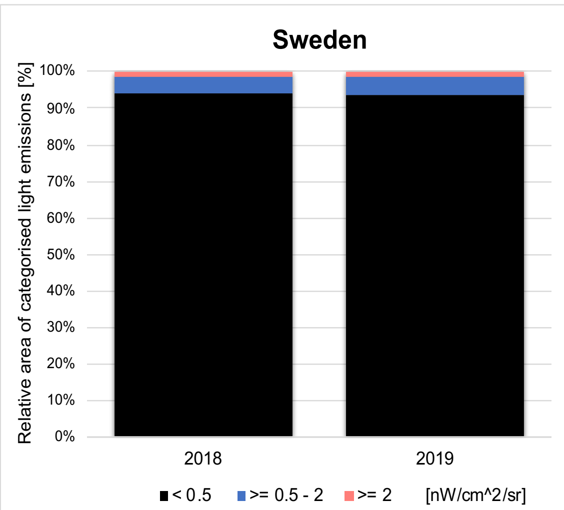

Fig. 6: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Sweden in 2018 and 2019 shown in percentages.

Table 11: Relative areas of the light emission classes presented in Fig. 6. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 Relative area [%]	2019 Relative area [%]
< 0.5	94.04	93.68
>= 0.5 - 2	4.47	4.79
>= 2	1.48	1.53
>= 2 - 10	1.28	1.31
>= 10 - 20	0.16	0.16
>= 20	0.04	0.06

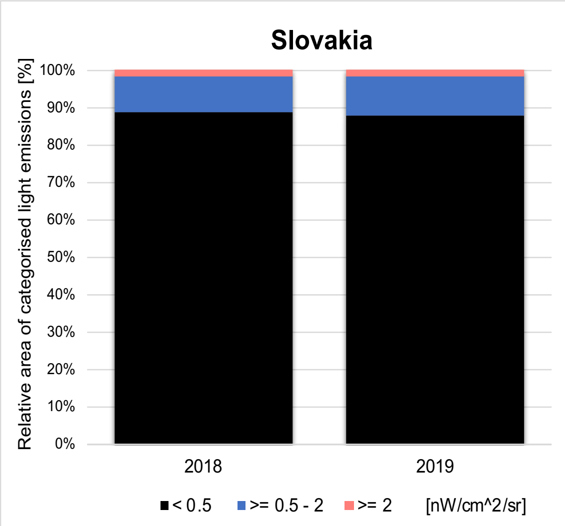

Fig. 7: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Slovakia in 2018 and 2019 shown in percentages.

Table 12: Relative areas of the light emission classes presented in Fig. 7. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	88.61	87.79
>= 0.5 - 2	9.9	10.56
>= 2	1.49	1.65
>= 2 - 10	1.35	1.5
>= 10 - 20	0.12	0.12
>= 20	0.02	0.03

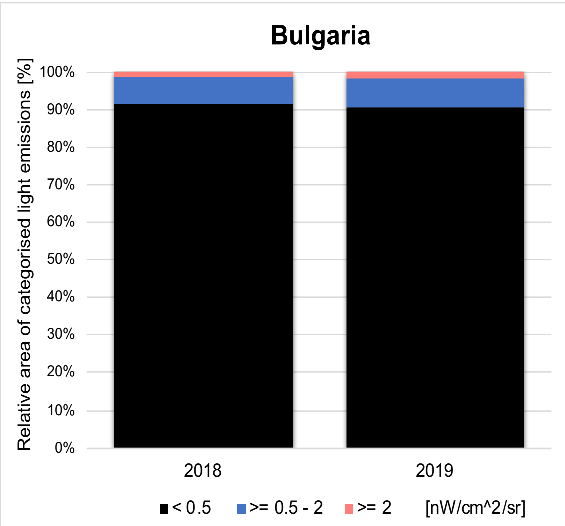

Fig. 8: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Bulgaria in 2018 and 2019 shown in percentages.

Table 13: Relative areas of the light emission classes presented in Fig. 8. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	91.54	90.45
>= 0.5 - 2	6.95	7.89
>= 2	1.51	1.67
>= 2 - 10	1.35	1.49
>= 10 - 20	0.13	0.14
>= 20	0.03	0.04

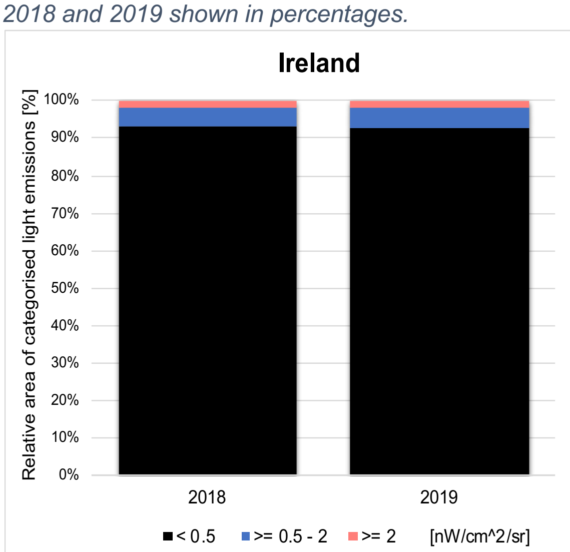

Fig. 9: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Ireland in 2018 and 2019 shown in percentages.

Table 14: Relative areas of the light emission classes presented in Fig. 9. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	93.15	92.62
>= 0.5 - 2	4.98	5.57
>= 2	1.87	1.81
>= 2 - 10	1.59	1.59
>= 10 - 20	0.23	0.19
>= 20	0.05	0.03

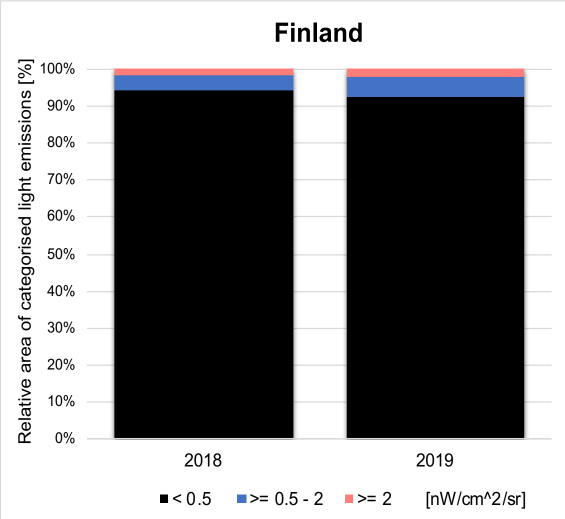

Fig. 10: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Finland in 2018 and 2019 shown in percentages.

Table 15: Relative areas of the light emission classes presented in Fig. 10. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	94.4	92.41
>= 0.5 - 2	3.97	5.36
>= 2	1.63	2.24
>= 2 - 10	1.35	1.8
>= 10 - 20	0.22	0.28
>= 20	0.06	0.16

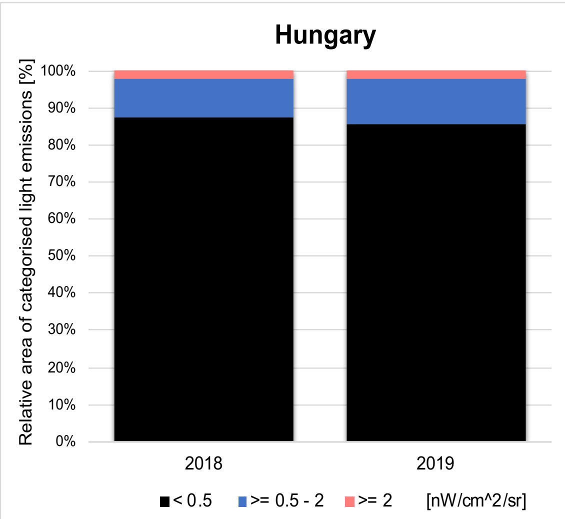

Fig. 11: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Hungary in 2018 and 2019 shown in percentages.

Table 16: Relative areas of the light emission classes presented in Fig. 11. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	87.65	85.74
>= 0.5 - 2	10.35	11.92
>= 2	2.01	2.33
>= 2 - 10	1.85	2.14
>= 10 - 20	0.12	0.14
>= 20	0.04	0.05

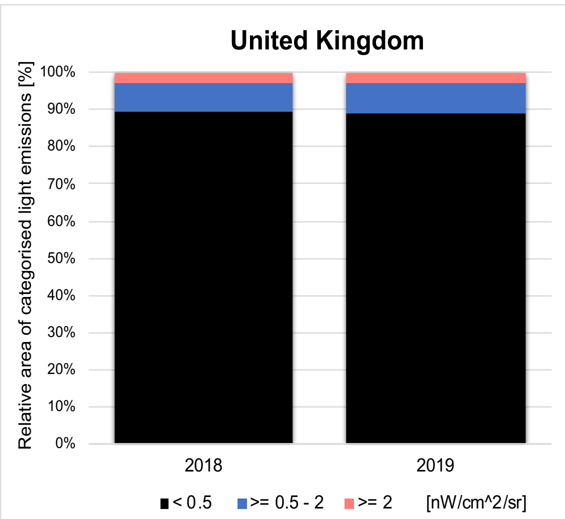

Fig. 12: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of the United Kingdom in 2018 and 2019 shown in percentages.

Table 17: Relative areas of the light emission classes presented in Fig. 12. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	89.59	89.1
>= 0.5 - 2	7.65	8.02
>= 2	2.77	2.88
>= 2 - 10	2.33	2.43
>= 10 - 20	0.33	0.33
>= 20	0.11	0.12

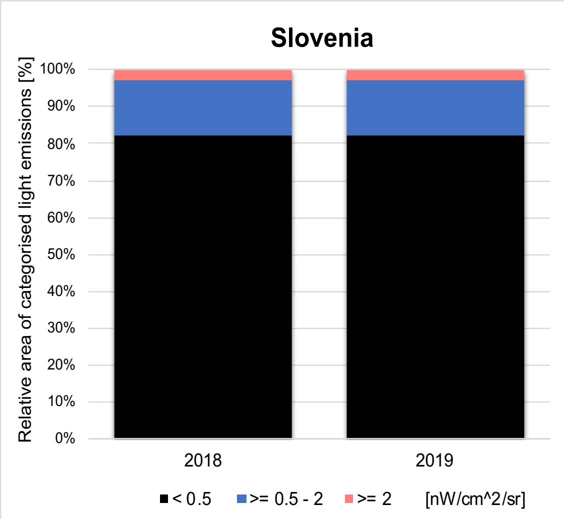

Fig. 13: The relative area of categorised light emissions in nW/cm2/sr for terrestrial Natura 2000 areas of Slovenia in 2018 and 2019 shown in percentages.

Table 18: Relative areas of the light emission classes presented in Fig. 13. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	82.1	82.24
>= 0.5 - 2	14.94	14.85
>= 2	2.95	2.91
>= 2 - 10	2.74	2.68
>= 10 - 20	0.15	0.16
>= 20	0.06	0.07

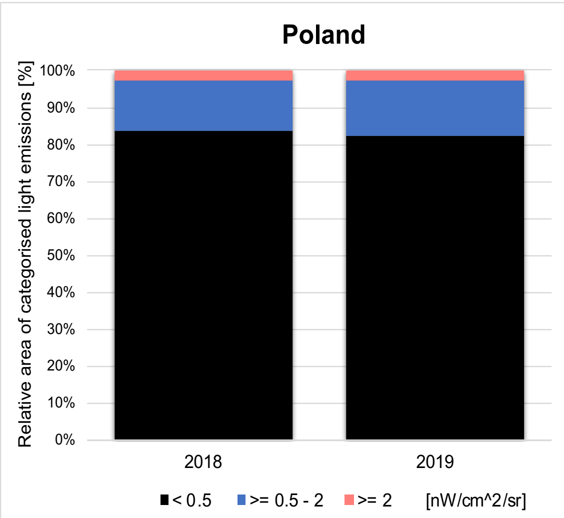

Fig. 14: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Poland in 2018 and 2019 shown in percentages.

Table 19: Relative areas of the light emission classes presented in Fig. 14. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	83.56	82.47
>= 0.5 - 2	13.56	14.6
>= 2	2.88	2.92
>= 2 - 10	2.62	2.67
>= 10 - 20	0.19	0.19
>= 20	0.07	0.06

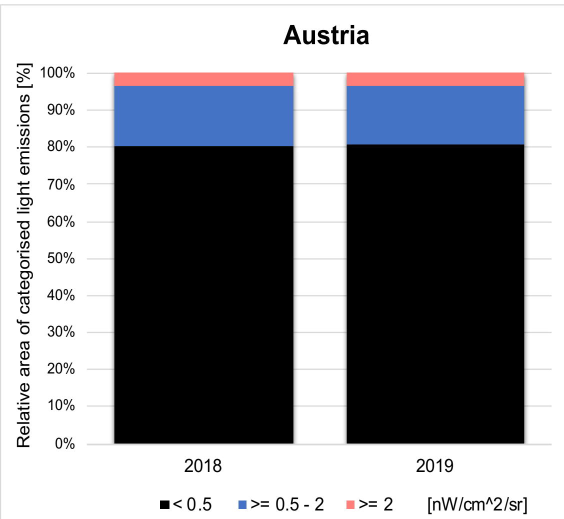

Fig. 15: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Austria in 2018 and 2019 shown in percentages.

Table 20: Relative areas of the light emission classes presented in Fig. 15. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	80.46	80.98
>= 0.5 - 2	16.15	15.6
>= 2	3.39	3.42
>= 2 - 10	3.27	3.27
>= 10 - 20	0.11	0.14
>= 20	0.01	0.01

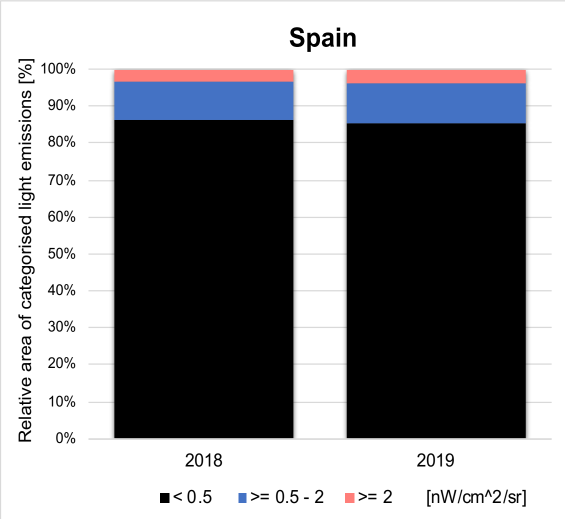

Fig. 16: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Spain in 2018 and 2019 shown in percentages.

Table 21: Relative areas of the light emission classes presented in Fig. 16. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	86.28	85.52
>= 0.5 - 2	10.26	10.83
>= 2	3.45	3.65
>= 2 - 10	2.72	2.87
>= 10 - 20	0.44	0.45
>= 20	0.29	0.33

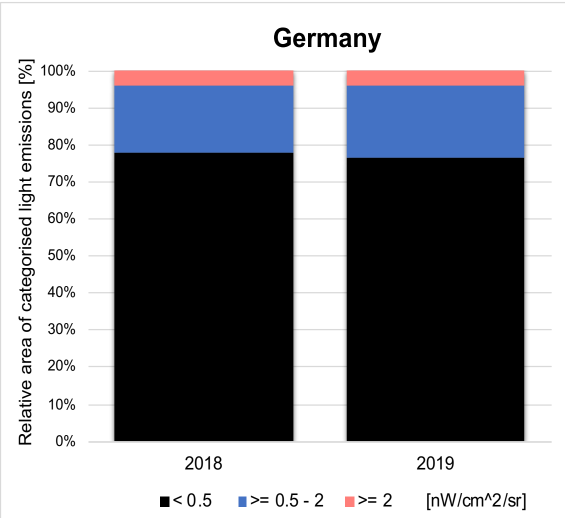

Fig. 17: The relative area of categorised light emissions in nW/cm2/sr for terrestrial Natura 2000 areas of Germany in 2018 and 2019 shown in percentages.

Table 22: Relative areas of the light emission classes presented in Fig. 17. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	77.89	76.6
>= 0.5 - 2	18.19	19.55
>= 2	3.91	3.85
>= 2 - 10	3.67	3.63
>= 10 - 20	0.19	0.17
>= 20	0.05	0.05

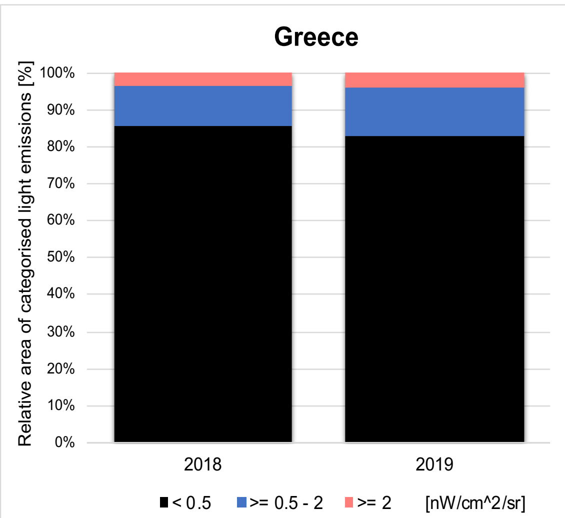

Fig. 18: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Greece in 2018 and 2019 shown in percentages.

Table 23: Relative areas of the light emission classes presented in Fig. 18. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	85.56	83.08
>= 0.5 - 2	10.79	12.73
>= 2	3.64	4.19
>= 2 - 10	3.18	3.61
>= 10 - 20	0.35	0.42
>= 20	0.11	0.16

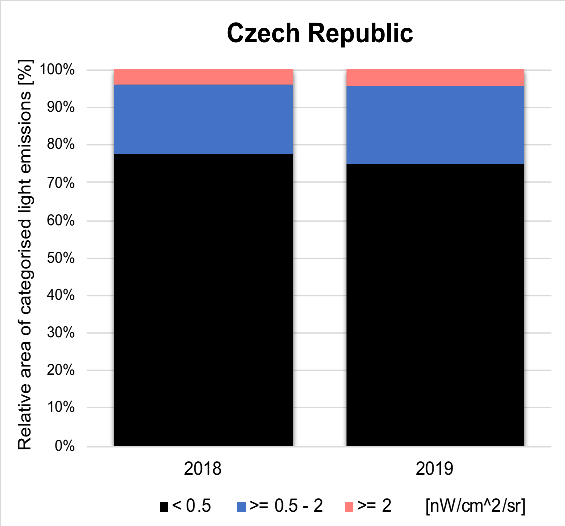

Fig. 19: The relative area of categorised light emissions in nW/cm2/sr for terrestrial Natura 2000 areas of the Czech Republic in 2018 and 2019 shown in percentages.

Table 24: Relative areas of the light emission classes presented in Fig. 19. Please note that the class >= 2 nW/cm^2/sr represents the sum of three subcategories.

Light emission [nW/cm^2/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	77.84	74.75
>= 0.5 - 2	18.29	20.81
>= 2	3.86	4.44
>= 2 - 10	3.52	4
>= 10 - 20	0.28	0.34
>= 20	0.06	0.1

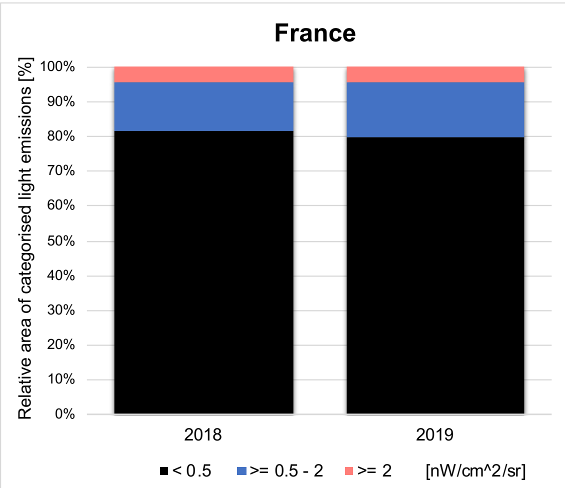

Fig. 20: The relative area of categorised light emissions in nW/cm2/sr for terrestrial Natura 2000 areas of France in 2018 and 2019 shown in percentages.

Table 25: Relative areas of the light emission classes presented in Fig. 20. Please note that the class >= 2 nW/cm^2/sr represents the sum of three subcategories.

Light emission [nW/cm^2/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	81.44	79.65
>= 0.5 - 2	14.24	15.89
>= 2	4.32	4.45
>= 2 - 10	3.68	3.79
>= 10 - 20	0.45	0.46
>= 20	0.19	0.2

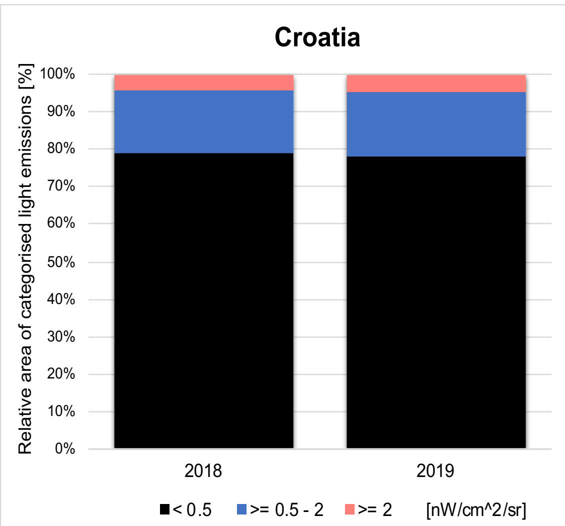

Fig. 21: The relative area of categorised light emissions in nW/cm^2/sr for terrestrial Natura 2000 areas of Croatia in 2018 and 2019 shown in percentages.

Table 26: Relative areas of the light emission classes presented in Fig. 21. Please note that the class >= 2 nW/cm^2/sr represents the sum of three subcategories.

Light emission [nW/cm^2/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	79.09	78.06
>= 0.5 - 2	16.42	17.33
>= 2	4.48	4.60
>= 2 - 10	4.1	4.19
>= 10 - 20	0.29	0.31
>= 20	0.09	0.1

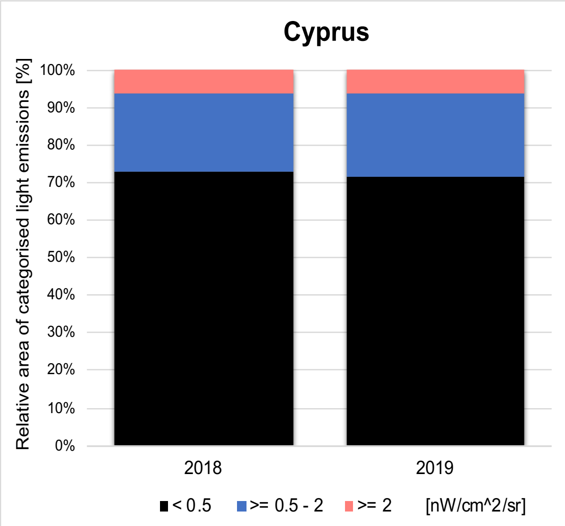

Fig. 22: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Cyprus in 2018 and 2019 shown in percentages.

Table 27: Relative areas of the light emission classes presented in Fig. 22. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	72.75	71.63
>= 0.5 - 2	20.81	22.1
>= 2	6.45	6.27
>= 2 - 10	5.42	5.27
>= 10 - 20	0.64	0.66
>= 20	0.39	0.34

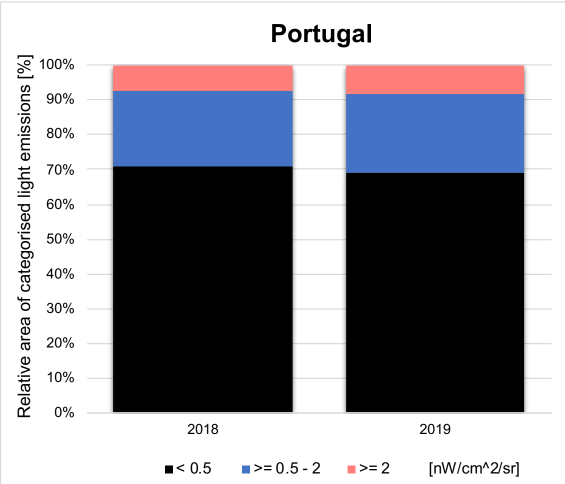

Fig. 23: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Portugal in 2018 and 2019 shown in percentages.

Table 28: Relative areas of the light emission classes presented in Fig. 23. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	70.81	68.94
>= 0.5 - 2	21.72	22.91
>= 2	7.48	8.16
>= 2 - 10	6.16	6.71
>= 10 - 20	0.86	0.93
>= 20	0.46	0.52

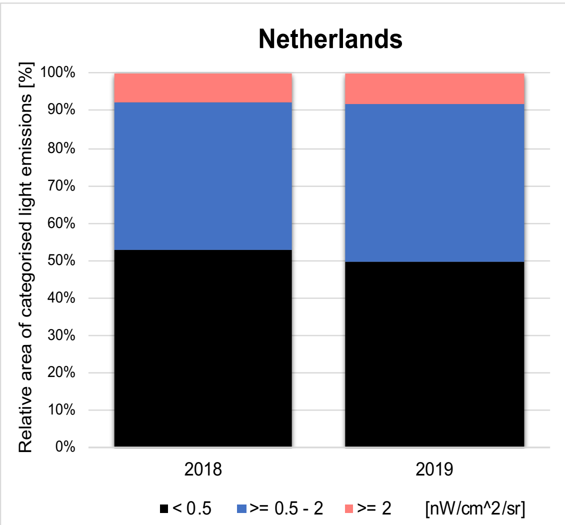

Fig. 24: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of the Netherlands in 2018 and 2019 shown in percentages.

Table 29: Relative areas of the light emission classes presented in Fig. 24. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	52.99	49.48
>= 0.5 - 2	39.22	42.11
>= 2	7.79	8.41
>= 2 - 10	7.17	7.84
>= 10 - 20	0.42	0.35
>= 20	0.2	0.22

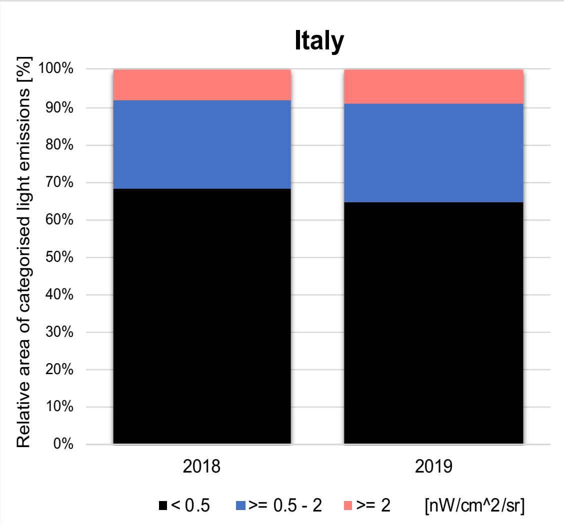

Fig. 25: The relative area of categorised light emissions in nW/cm²/sr for terrestrial Natura 2000 areas of Italy in 2018 and 2019 shown in percentages.

Table 30: Relative areas of the light emission classes presented in Fig. 25. Please note that the class >= 2 nW/cm²/sr represents the sum of three subcategories.

Light emission [nW/cm²/sr]	2018 **Relative area [%]**	2019 **Relative area [%]**
< 0.5	68.11	64.47
>= 0.5 - 2	23.51	26.29
>= 2	8.39	9.25
>= 2 - 10	7.28	7.94
>= 10 - 20	0.85	0.97
>= 20	0.26	0.34

Marine Natura 2000 sites

Table 31: Number of 500x500m cells and area in km² of marine Natura 2000 sites within buffer zones.

No. of cells	**Area [km²]**
157’179	39’294.75

Table 32: Number of 500x500m cells, area in km² and proportion of marine Natura 2000 sites within buffer zones.

Buffer zones	**No. of cells**	**Area [km²]**	**Proportion [%]**
0 - 1 km	68’617	17’154.25	43.66
1 - 2 km	48’609	12’152.25	30.93
2 - 3 km	39’953	9’988.25	25.42

Land cover

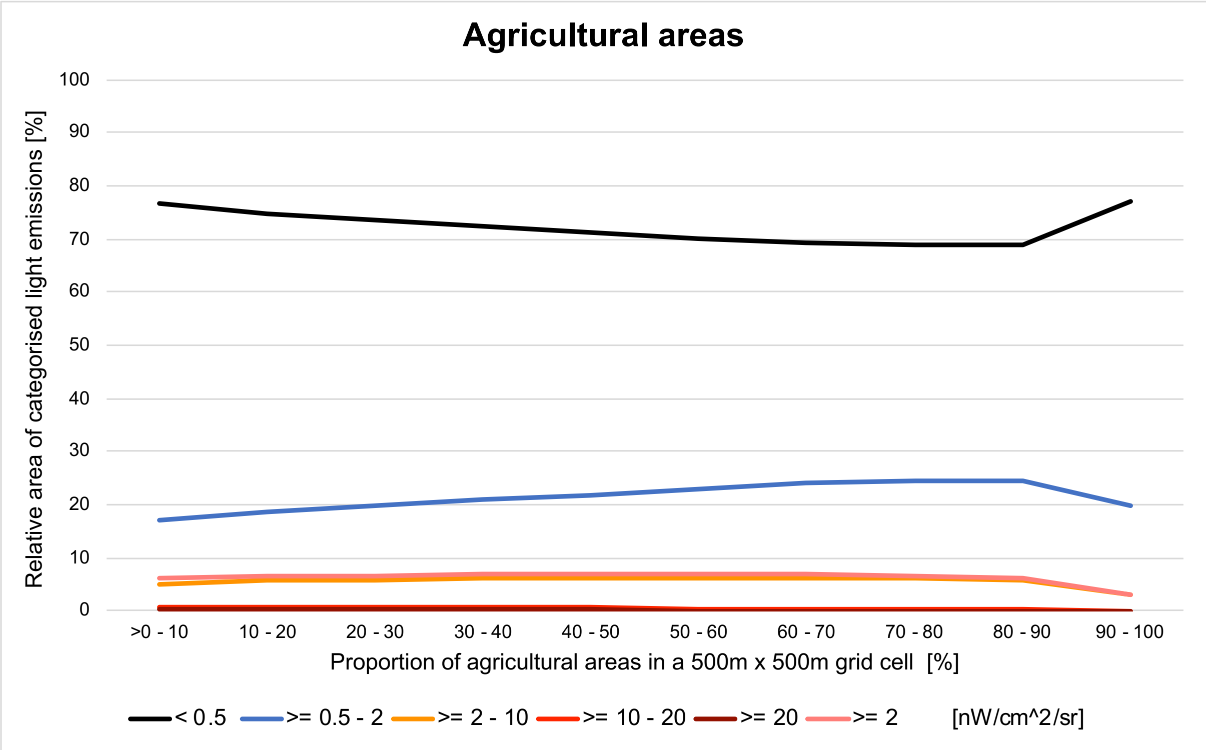

Fig. 26: The figure shows the relationship between the relative area of categorised light emissions in 2019 and the increase in the proportion of agricultural areas in a 500x500m grid cell.

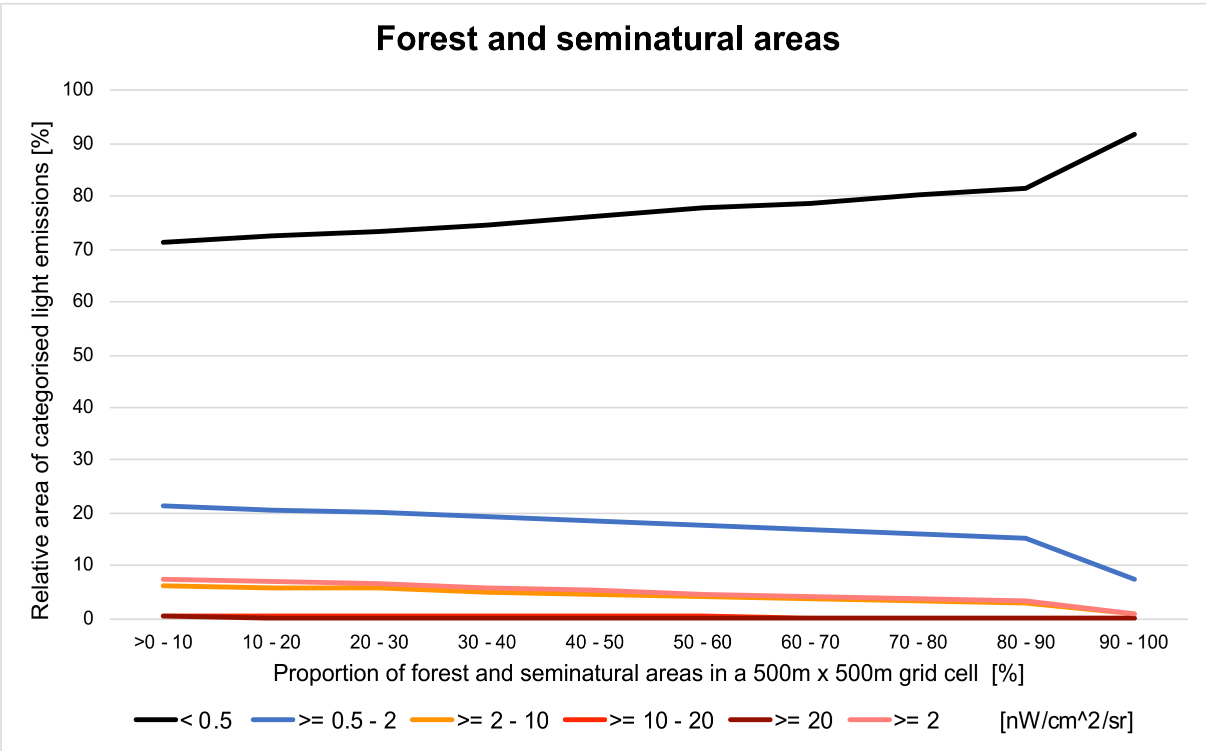

Fig. 27: The figure shows the relationship between the relative area of categorised light emissions in 2019 and the increase in the proportion of forest and seminatural areas in a 500x500m grid cell.

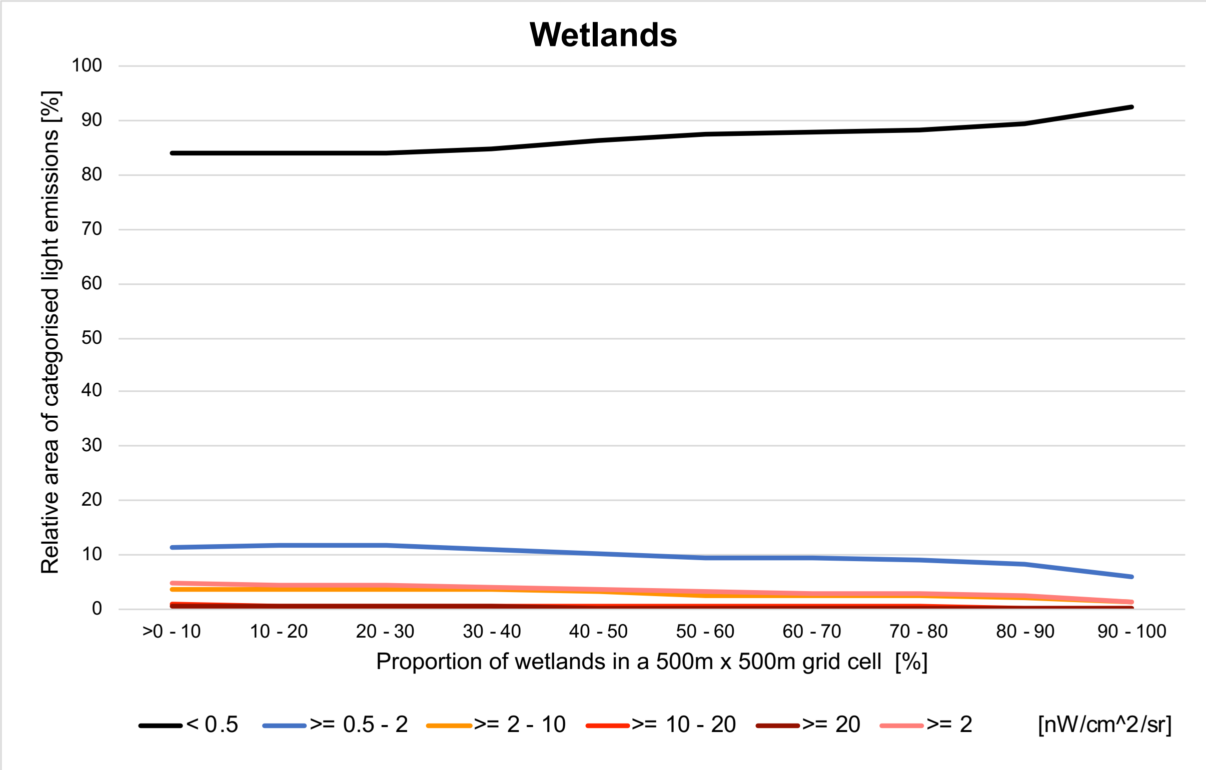

Fig. 28: The figure shows the relationship between the relative area of categorised light emissions in 2019 and the increase in the proportion wetlands in a 500x500m grid cell.

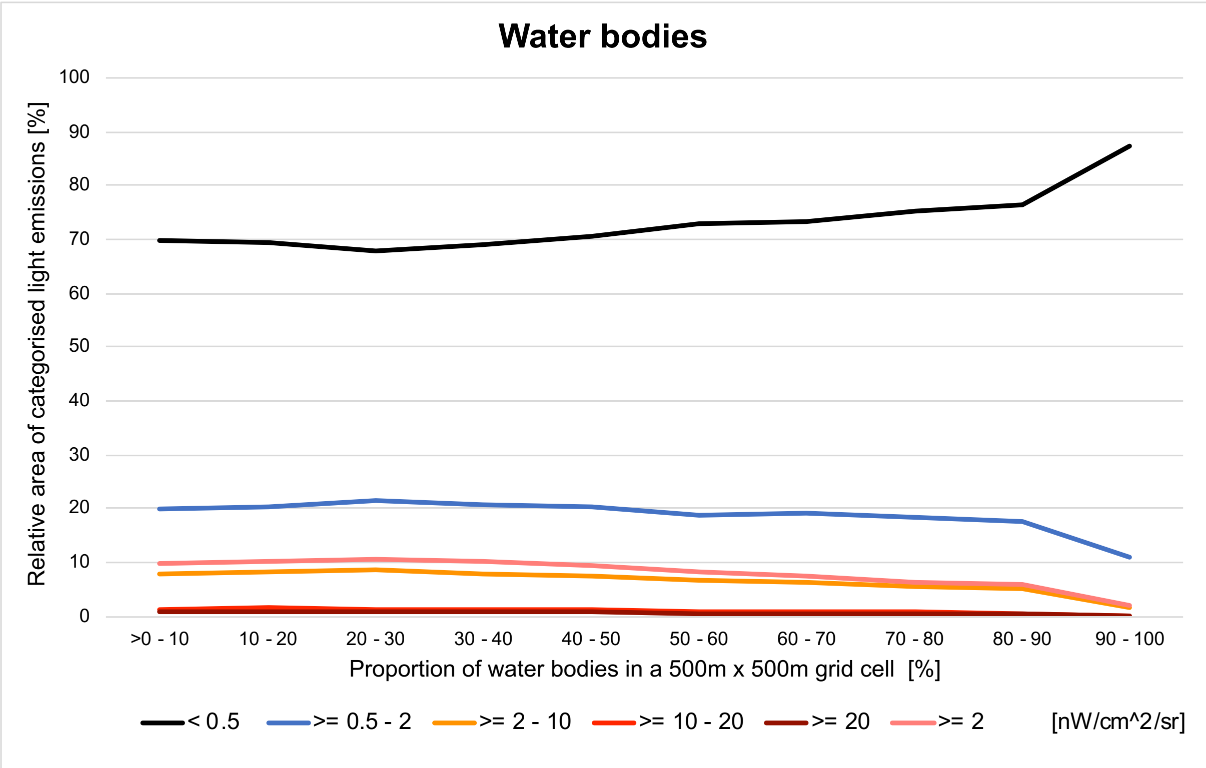

Fig. 29: The figure shows the relationship between the relative area of categorised light emissions in 2019 and the increase in the proportion of water bodies in a 500x500m grid cell.

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