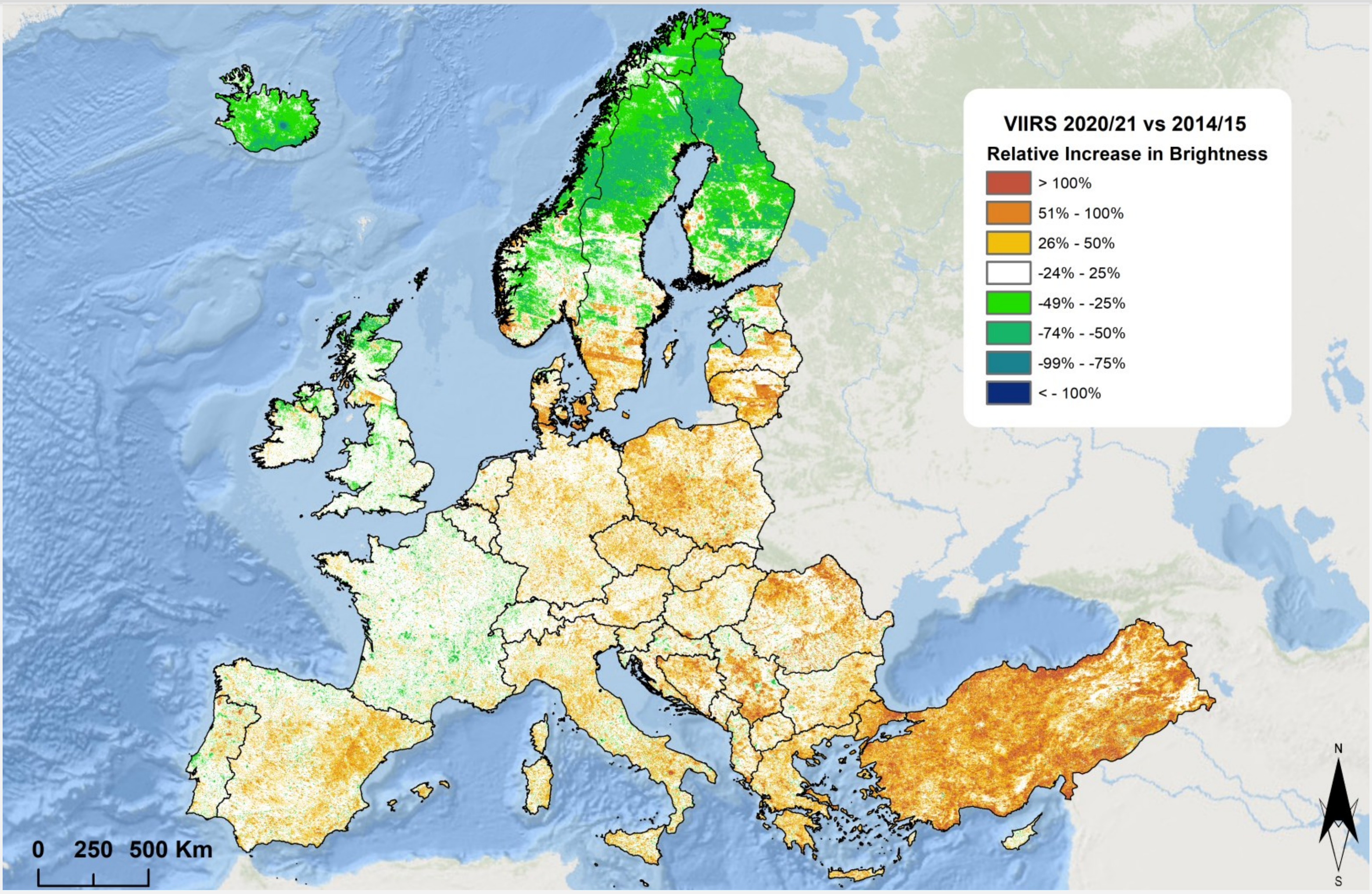
ETC-HE Report 2022/8

Review and Assessment of Available Information on Light Pollution in Europe



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Summary

The continuously growing world population coupled with a trend towards urbanization, associated development of human infrastructures and lowered lighting costs has led to an increase in anthropogenic light emissions, especially in large cities. Consequentially, night-time scattering of artificial light in the lower atmosphere may result in a steady brightening of the night sky and a constant absence of darkness in the surrounding nocturnal ecosystems, also known as light pollution. The increasing awareness of the science community about the negative effects of Artificial-Light-At-Night (ALAN/LAN) on human health, ecological processes and the celestial visibility have led to a recognition of light pollution as a global environmental issue among the society. Because Artificial-Light-At-Night is either abbreviated as ALAN or LAN in the published literature, these two acronyms are used interchangeable throughout this report. Since biological processes in species from different taxa are regulated by natural light regimes, concerns about exposure to ALAN are linked to its potential to induce atypical physiological responses resulting in negative health- or environment-related consequences. This report is a review aiming to assess the current knowledge on light pollution for the 38 European Environmental Agency (EEA) member states including those within the framework of the European Union's (EU) Zero Pollution Action Plan (i.e. EU-27).

First, the key impacts ALAN may elicit on human health, biodiversity and ecosystems are summarised. Disrupted sleeping patterns, development of cancer, depressive disorders and weight gain among various investigated unfavourable health outcomes received most scientific attention. Adverse effects on wildlife is mostly linked to the alteration of the innate circadian clock controlling the behaviour of animals via natural light cues. This has resulted in an alteration of behavioural patterns related to migration, reproduction or communication, changes in activity such as offset of emergence and timing to forage, and even altered physiological characteristics connected to genetics, the metabolism or the development. Negatively influenced ecosystems are the natural night sky, or dark environments functioning as sanctuaries for light-sensitive species. This is further associated with a disruption of trophic interactions and an over-proportional decrease in biodiversity due to a global decline in habitat connectivity.

Second, an analysis of the political basis in the EU Member States regulating light pollution revealed that currently no common EU policy exists. However, France, Croatia, Slovenia and the Czech Republic have a progressive national legal framework restricting light emissions, as do regions in Italy or Spain. Some EU countries such as Austria, Liechtenstein or Ireland have non-binding guidelines only, but no current policies. Globally, there are different political strategies aiming to mitigate light pollution. Some policies depend on strict metrics or are enforced with a parallel education of citizens. Others were incorporated in an existing law or formulated in close collaboration with the astronomy community.

Third, the methods to monitor light pollution levels are presented, with a focus on the role of remote sensing systems. By utilizing such satellite imagery, historical trends in Europe were modelled and light pollution levels were compared between EU countries. Overall, the terrestrial surface of Europe has experienced a net increase in anthropogenic light exposure, especially in the Eastern regions. Changes of the European light emissions were modelled for the two thresholds of 2 nW/cm^2/sr, at which at least a low ecological impact can be expected and of 0.5 nW/cm^2/sr, which are the lowest light emissions measured by VIIRS. Whereas the area exposed to light emissions below 2 nW/cm^2/sr has decreased by only 1 %, the 'truly dark spaces' minimally exposed to artificial light below 0.5 nW/cm^2/sr, have shrunk by 5.2 % in only the last eight years. Even though, 0.5 nW/cm^2/sr is no generally accepted threshold for a truly dark sky, this limit has been arbitrarily chosen because it reflects the natural luminance of the night sky with a margin for uncertainties. While, the Netherlands, Luxembourg, Poland and Belgium have experienced the largest increase in brightness in a comparison of the time periods 2014/15 with 2020/21 for the respective two limits, a reduction in light pollution was evident for Iceland, Ireland and France.

Finally, an analysis of the current research efforts in the EU showed that the most recent publications focused on the following three topics: ecosystem functioning and trophic interactions, socio-economic implementation of darkness protection and improvement of measuring methods. During our light

pollution research, we found that satellite imagery is highly dependent on the emitting light source the time of picture taken, the weather, environment and astronomic conditions, or the collecting sensor. Furthermore, evidence of a strong association between socio-economic status, urbanization and light exposure gives reason to believe that studies investigating the effects of light pollution are prone to be confounded by other factors and need to be analysed carefully.

1 Introduction

Light pollution is usually described as an increase of natural night sky brightness due to artificial light emitted in the lower atmospheric layer (Bennie et al., 2015; Falchi et al., 2016). In some definitions the negative nature of this phenomenon is emphasised by describing light pollution as a degradation of darkness, excessive or unwanted light emissions caused by wasted energy (Gallaway et al., 2010; Hölker et al., 2010; Lapostolle & Challéat, 2021; Teikari, 2007). Ecologists concerned with the deterioration of ecosystems due to light pollution suggest a differentiation between astronomical light pollution which is a decline in visibility of celestial objects due to the brightening of the sky caused by artificial light emissions while ecological light pollution refers to the adverse effects the global wildlife experiences due to disruptions of the nocturnal environment (Longcore & Rich, 2004). The research community investigating the negative effects of Artificial-Light-At-Night on human health, biodiversity or ecosystems abbreviate this term either with ALAN or LAN. Therefore, these acronyms are used interchangeably in this report. Since a variety of physiological processes are triggered by natural light stimuli, studies examining the impacts of ALAN exposure mostly focus on the potential to induce mistimed or misdirected responses resulting in adverse medical or ecological consequences (Sanders et al., 2021).

The most important sources contributing to light pollution are street lamps, security lighting illuminating construction sites or business buildings, floodlights used for sports facilities or on offshore oil platforms and advertisement lighting (Gaston et al., 2012). Especially visual is this rather modern environmental threat, when the sum of the artificial light emitted by a large urbanized area lingers in the sky due to the reflection of the luminance from water droplets in clouds, gas molecules or dust. This condition is called artificial skyglow and may in extreme cases result in the formation of a light dome over conurbations in industrialized countries (Cinzano et al., 2000). Besides skyglow, there are several forms of light pollution including light trespass, clutter or glare. Light trespass is defined as anthropogenic light that penetrates areas where it is unintended or unwanted. It is particularly detrimental in residential areas when directed into private houses resulting in a disruption of people's sleeping patterns or in areas with light-sensitive wildlife and ecosystems. Light trespass is often caused by street lighting, traffic lights, vehicle headlights, internal building lights or advertising signs and can be a constant nuisance to residents (Schreuder, 1986). The condition when the concentration of multiple light fittings within a given area is too great resulting in inconsistent and excessive illumination is called clutter. This is the case when the number and design of light fittings have gradually been added over time instead of being properly replaced (IDA, 2014). Glare may be explained with excessive direct light that causes visual discomfort to which animals and humans react with squinting. It alters the visual acuity which results in an instant disability to make out details of what is in the eye's focus and may even result in temporal blindness in extreme cases (Bullough et al., 2008). Over all, the sky conditions qualify as light-polluted if the natural brightness is elevated by at least ten percent (Falchi et al., 2016).

Linked to the immense growth of the global population, the fast development of human infrastructure and urban expansion, light pollution levels increased by around 20 % yearly in the second half of the 20th century (Hölker et al., 2010). Nowadays, more than 80 % of the global population and over 99 % of the people resident in Europe live under light-polluted skies. More than one third of humanity, including 60 % of Europeans are unable to see the Milky Way from their own home due to skyglow (Falchi et al., 2016). While the area of global artificially lit environments is estimated to increase by 2.2 % yearly, values of the annual intensification of light pollution in the most populated areas have been as high as 6 % (Kyba et al., 2017). The increasing brightness is a parallel trend to the global economic development and has multiple adverse effects on human health, biodiversity and natural ecosystems. A by-product of the human expansion is the lighting of new roads, business buildings and private housing which comes with a scattering of the light into the surrounding ecosystems (Bennie et al., 2015). Artificial light is reflected and dispersed by aerosols in the atmosphere, resulting in urban lights penetrating the surrounding ecosystems, protected landscapes and rural areas. The illumination of large urban centres is often visible over 160 kilometres away. Consequentially, 18.7 % of the terrestrial surface is exposed to night sky brightness categorized as light polluted (Longcore & Rich, 2004). Excessive man-made lighting is not just a source of pollution, but also a waste of resources in terms of electricity and carbon dioxide emissions contributing to global warming. Due to poorly designed lighting installations world-wide, 30 % of the artificial light is directed where it is not supposed to and therefore unexploited which adds up to almost 9 billion US dollars of economic loss yearly (Gallaway et al., 2010). In the last two decades, scientific publications investigating the effects of light pollution have increased tenfold, which is evidence for the growing concern and the intensification of this problem (Rodrigo-Comino et al., 2021).

Contemporary lighting strategies more and more frequently focus on energy efficient systems with low carbon output as a response to the ongoing climate crisis. As a result, many countries are transitioning from conventional light sources to white light emitting diodes (LED) that have a higher output of shorter wavelengths emitting light in the blue part of the spectrum (Gaston et al., 2012). While this light source appears brighter and therefore has the potential to save significant amounts of energy, it also negatively impacts the natural night sky brightness and has the potential to spread adverse ecological effects of light pollution well beyond the urban centres (Chen, 2010). Sustainable lighting systems are not only energy-efficient, but also cost effective; however, on a global scale this may lead to an increase in lighting of areas that have previously been dark, dimly lit or illuminated only during a short time period due to monetary restrictions (Kyba et al., 2017).

In the framework of this report we conducted a review aiming to address the following questions:

- What are the key impacts associated with light pollution in terms of human health, biodiversity and ecosystems? Are quantitative or qualitative assessments measuring the significance of such impacts available?
- What is the legislative basis in EU Member States or other progressive countries to monitor and control light pollution?
- Are there recognized standards and monitoring methods to assess the extent of light pollution?
- Is there evidence available to show the historical trends in light pollution at a country, EU or global level?
- What research is currently being carried out in Europe in relation to the monitoring of light pollution and its impacts?
- What role does satellite imagery play in readily assessing light pollution?
- Which emerging issues need to be considered when investigating light pollution?

2 Key Impacts of Light Pollution

Since the physiology and ecology of several animal species and also humans depend on cues given by the natural day-night cycle or seasonal patterns, scientists are concerned about what may happen when these functional systems are disrupted. Evidence for adverse effects caused by light pollution were found to be multidisciplinary and involve human health, global biodiversity and entire ecosystems.

Most knowledge about the impact of ALAN on human health comes from epidemiological studies that compare the health status of individuals with different light exposures. Thereby, four types of studies may be distinguished: cohort studies, case-control-studies, experimental studies and animal studies. In cohort studies different health parameters of large population cohorts are tracked over long periods of time and then matched with satellite data to assign light pollution levels dependent on place of residence. In a case-control study, participants are selected based on different health outcomes to retrospectively compare a variety of causal factors that may have led to the condition. Both study types provide evidence for an association if they are able to show that individuals exposed to higher levels of ALAN are more likely to have poorer health. In experiments, study participants with similar characteristics are randomly divided into two groups and then exposed to different light conditions. Immediate physiological and ecological changes previously identified as contributing factors to the development of a particular disease are investigated. Based on these findings, conclusions about the development of a poorer health status can be drawn related to light exposure levels. Similar studies are carried out with animals from different taxa to gain a better understanding about possible negative effects light pollution may elicit on humans. A variety of unfavourable human health outcomes have been investigated, from disrupted sleeping patterns or increased stress and anxiety levels leading to hormonal and metabolic changes. Health scientist have also attempted to find out if light exposure is a causal factor in severe diseases such as several cancer types, depressive disorder, atherosclerosis or Alzheimer’s disease.

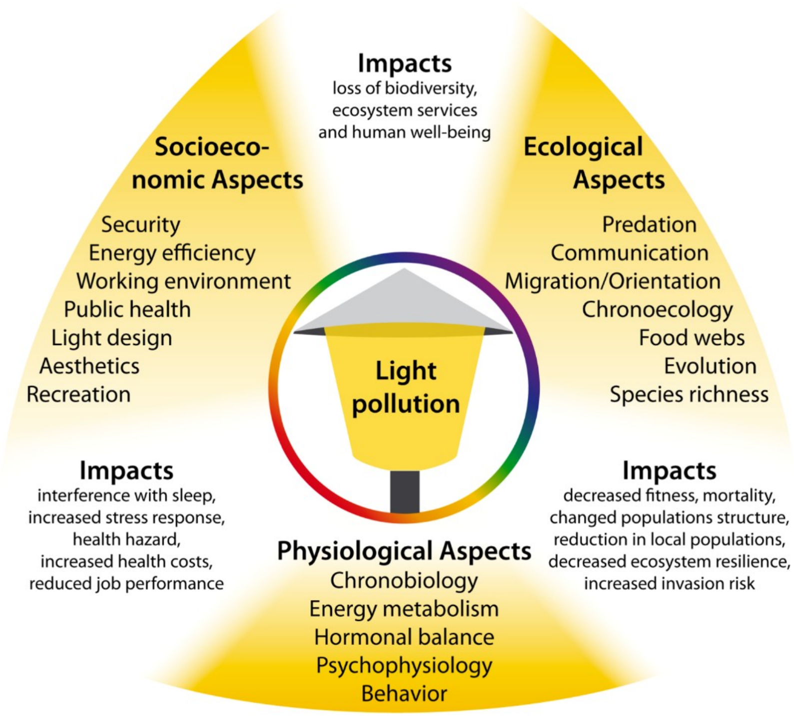
Negative effects on wildlife has primarily been investigated linked to the alteration of the circadian system functioning as an internal clock that guides the natural behaviour of different species groups. This has been further related to behavioural changes such as migration, foraging and reproduction or physiological alterations in connection with genetics, the metabolism or developmental impairment. Ecologists were able to provide evidence of disrupted predator-prey interactions, population dynamics and reduced survivability linked to light pollution.

Ecosystems most affected by light pollution are on one hand the natural night sky and its celestial objects, and on the other the dark environments where light is usually absent. However, any ecosystem in close proximity to a brightly lit area is under the influence of diffuse light and thus can be adversely affected.

These areas of research are highly interlinked and may therefore not be analysed just separately. The main impacts resulting from light pollution, both with respect to light intensity and colour spectra, emerge at the interface between the different physiological, ecological, and socio-economic aspects (Figure 2.1, Hölker et al., 2010).

Questions to be considered:
(1) What characteristics of light disrupt human health and ecological communities?
(2) How does light pollution interact with other stressors such as air, water and noise pollution?
(3) Which role does light pollution play in the ongoing climate change?

Figure 2.1: Interplay of adverse impacts related to light pollution at the interface of ecology, socio-economy and physiology



Source: Reproduced from Hölker et al., 2010.

2.1 Human Health

The human body has adapted to a naturally regulated day-night pattern long before artificial lighting systems were invented. Hence, the study of the relationships between exposure to ALAN and potential health effects began due to the concern that physical, mental, and behavioural mechanisms following this circadian rhythm could be disrupted (Chepesiuk, 2009).

2.1.1 Summarised Literature

We conducted a literature search from January to March 2022 on PubMed. By applying the search terms (light pollution OR light exposure) AND (health) a total of 1 361 published papers were found. A representative sample of the literature was selected to illustrate the key findings (summarised in Table 1). Only peer-reviewed articles, written in English and published in scholarly journals with an impact factor greater than two during 2000 and 2022 were considered. Current research predominantly focuses on four potential pathways how light pollution may be deleterious to the human health: cancer, sleeping disorder, depression & obesity. Therefore, the selected studies aim to provide an overview of the variety of study designs used to investigate these associations in particular and showcase the potential difficulties with confounding factors. Furthermore, a high number of publishing countries was targeted to minimize the influence of population-specific characteristics.

Table 2.1: Overview of studies on health effects associated with light pollution

Reference	Country	Study Design	Outcome	Main Results	Method
(Kliukiene et al., 2001)	Norway	Cohort study	Breast cancer	Breast cancer risk among totally blind women was 0.64 (95 % CI = 0.21-1.49) and for those who became blind before age 65 only 0.51 (95 % CI = 0.11-1.49)	15736 Norwegian women from the Norwegian Registry of Blindness data participated, 5 different categories of visual impairment assigned, health status followed over lifetime
(Lamphar et al., 2022)	Slovakia	Case-Control Study	Breast cancer	Positive association of increasing light pollution and breast cancer, mean increase of 10.9 breast cancer events per 100'000 population-year (95 % CI = 7.0-14.8)	Cancer incidents evaluated for rural vs. urban areas (25025 breast cancer cases, 16119 prostate cancer cases), level of light pollution evaluated based on satellite worldwide nighttime light collections (1999-2012)
(Parent et al., 2012)	Canada	Case-Control Study	Variety of cancer types	Cancer was associated with night work: lung cancer (OR = 1.76, 95 % CI = 1.25-2.47), colon cancer (OR = 2.03, 95 % CI = 1.43-2.89), for bladder cancer (OR = 1.74, 95 % CI = 1.22-2.49), for prostate cancer (OR = 2.77, 95 % CI = 1.96-3.92), for rectal cancer (OR = 2.09, 95 % CI = 1.40-3.14), for pancreatic cancer (OR = 2.27, 95 % CI = 1.24-4.15), for lymphoma (OR = 2.31, 95 % CI = 1.48-3.61)	3137 males (512 controls), with incident cancer participated (1979-1985), job histories and work hours were elicited, long working hours in the night associated with higher levels of light exposure
(Bauer et al., 2013)	Georgia	Case-Control Study	Breast cancer	Overall breast cancer incidence was associated with high light at night exposure (OR = 1.12, 95 % CI (1.04-1.20)	34053 Breast cancer patients (case) & 14458 lung cancer patients (control) from the Georgia Comprehensive Cancer Registry data (2000-2007) participated, light-at-night levels estimated based on DMSP-OLS Nighttime Light Time Series satellite images (1992-2007), light exposure extracted for each year prior to case/control diagnosis
(Cho et al., 2013)	Korea	Experi-mental study	Sleeping disorder	Exposure to light at night increased stage 1 sleep ($p < 0.05$), decreased the proportion of slow-wave-sleep ($p < 0.001$), decreased sleep maintenance parameters ($p < 0.1$) and increased the number of arousals per hour ($p < 0.01$)	10 healthy sleepers participated (groups: light on vs. light off), 2 polysomnography (PSG) sessions, sleep quality measured with rapid eye movement, REM/non-REM sleep epochs

Reference	Country	Study Design	Outcome	Main Results	Method
(Patel, 2019)	USA	Cross-sectio-nal study	Sleep depri-vation	Per 10-unit increase in nighttime light ($nW/cm^2/sr$) sleep duration declined by 5.59 min per day, odds of reporting insufficient sleep (< 7 hours) increased at MMSA level (13.77 %) and at county-level (2.19 %)	282,403 self-reports of sleep hours and insufficient sleep from the 2014 and 2016 metropolitan and micropolitan statistical area Behavioral Risk Factor Surveillance System and the prevalence of insufficient sleep during 2014 in 2,823 US counties from the County Health Rankings, paired with nighttime artificial light data from the cloud-free Visible Infrared Imaging Radiometer Suite (National Oceanic and Atmospheric Administration US)
(Esaki et al., 2019)	Japan	Experi-mental Study	Lower sleep quality	Actigraphy sleep parameters showed significantly lower sleep efficiency (80.1 % vs. 83.4 %, p = 0.01), longer log-transformed sleep onset latency (2.9 vs. 2.6 min, p = 0.01) and greater wake after sleep onset (51.4 vs. 41.6 min, p = 0.02) in the light group than in the dark group	175 outpatients with bipolar disorders participated (groups: light - >5 lux vs. dark - <5 lux), average LAN intensity in bedroom measured with portable photometer for 7 nights, sleep parameters evaluated with Insomnia Severity Index, adjustment for confounding variables
(Viola et al., 2008)	England	Experi-mental study	Lower sleep quality, lower concen-tration span	Compared with white light (4’000 K), blue-enriched white light (17’000 K) improved the subjective measures of alertness (p < 0.0001), positive mood (p = 0.0001), performance (p < 0.0001), evening fatigue (p = 0.0001), irritability (p = 0.004), concentration (p < 0.0001), and eye discomfort (p=0.002). Daytime sleepiness was reduced (p=0.0001), and the quality of subjective nocturnal sleep (p=0.016) was improved under blue-enriched white light	Baseline assessments of existing lighting conditions at work place of 94 white-collar workers, participants were exposed to 2 new lighting conditions, each lasting 4 weeks (blue-enriched white light – 17’000 K, white light – 4’000 K), subsequent questionnaires to rate alertness, mood, sleep quality, performance, mental effort, headache and eye strain, and mood throughout the 8-week intervention.
(Harb et al., 2015)	USA	Cohort study	Psychia-tric disorders, depress-sive symp-toms, low sleep quality	Cortisol levels (p = 0.008, ‘without window’ = 3.10-4.92, ‘with window’ = 2.80-3.40) and melatonin levels (p = 0.009, ‘without window’ = 2.94-4.14, ‘with window’ = 20.52-28.96) were significantly different between the groups, higher cortisol levels were positively correlated with minor	20 employees participated (groups: ‘with window’ vs. ‘without window’), activity & ambient light exposure measured with Actiwatch over 7 days, concentration of melatonin and cortisol measured from saliva, quantification of psychiatric disorders based on questionnaires, depression

Reference	Country	Study Design	Outcome	Main Results	Method
				psychiatric disorders and depressive symptoms, lower melatonin levels were correlated with depressive symptoms and poor quality of sleep	symptoms based on Montgomery-Asberg scale, quality of sleep based on Pittsburgh Sleep Quality Index
(Cissé et al., 2017)	USA	Animal experi-ment	Depres-sive-like behaviour (inheri-ted)	Chronic exposure of parents to light at night has multigenerational effect on offspring depressive-like behaviour, parental lighting altered offspring sucrose consumption ($p < 0.05$), 'dim'-offspring increased floating time ($p < 0.05$), maternal exposure decreased hippocampal GR expression ($p < 0.01$)	Adult Siberian hamsters (Phodopus sungorus) exposed to light at night for 9 weeks (groups: dark - 0 lux vs. Dim - 5 lux), paired males and females in full-factorial design and offspring gestated, tested in adulthood for hippocampal expression of glucocorticoid (GR), for melatonin (MT1) receptor expression, time spent floating in Porsolt swim test
(Min & Min, 2018)	Korea	Cross-sectio-nal study	Depres-sive symp-toms, suicidal behaviour	Compared with adults living in areas exposed to the lowest outdoor light at night, those living in areas exposed to the highest levels had higher likelihood depressive symptoms (OR = 1.29, 95 % CI = 1.15-1.46) or suicidal behaviors (OR = 1.27, 95 % CI = 1.16-1.39)	Korean inhabitants (n = 113,119 for depressive symptoms, n = 152,159 for suicidal behaviour) participated, outdoor LAN estimated via satellite data from the National Centers for Environmental Information, depression quantified based on Depression Scale, suicidal behaviour defined as the experience of suicidal ideation or attempt
(Rybnikova et al., 2016)	Israel	Cross-sectio-nal study	Higher body mass, obesity	Artificial light-at-night was a statistically significant positive predictor of overweight and obesity ($p < 0.05$)	Satellite images of nighttime illumination (US Defense Meteorological Satellite Program) combined with country-level data on female and male overweight and obesity prevalence rates (reported by the WHO), adjustment for confounding variables
(Fonken et al., 2010)	Israel	Animal experi-ment	Higher body mass, obesity	Mice housing in bright cycle increased body mass and reduced glucose tolerance significantly compared to mice in dark cycle. Food consumption of mice in bright cycle was 55.5 % compared to 36.5 % in dark cycle.	30 male Swiss-Webster mice exposed to different light/dark-cycles (groups: 16:8 bright cycle vs. 12:12 dark cycle), contributing factors determining obesity measured
(Obayashi et al., 2019)	Japan	Cohort study	Carotid atheroscle rosis	The group in the highest quartile of light-at-night exhibited a significant increase in mean carotid	989 elderly people participated, mean intensity of light-at-night evaluated (4 groups), carotid artery

Reference	Country	Study Design	Outcome	Main Results	Method
				artery intima-media thickness (IMT) (0.028, 95 % CI = 0.005-0.052, p = 0.019), compared to the group with lowest light-at-night exposure, relationship found between light at night and maximal carotid IMT (0.083, 95 % CI = 0.037-0.129, p < 0.001)	intima-media thickness (IMT) measured as proxy for risk of carotid atherosclerosis, adjustment for confounding variables
(M. Kim et al., 2018)	Korea	Animal experi-ment	Alz-heimer's disease	The lifespan of dim-light flies was significantly lower compared to dark-light flies (p < 0.001), flies overexpressing specific proteins in neurons showed significantly shorter lifespans compared to controls (p < 0.001), disrupted circadian rhythms, altered sleep-wake cycles due to increased proteins and neurodegeneration	*Drosophila* flies exposed to dim light-at-night (groups: dim – 10 lux vs. dark – 0 lux) for 3 days, aggregation of phosphorylated tau proteins in the brain, dysregulation of locomotion, increased memory defects measured as proxy for risk of Alzheimer's disease

The pathway of how people exposed to increased amounts of artificial light may develop cancer is built on the evidence that neurotransmitters located in the hypothalamus of the brain often react to light stimulation, which may result in the release of higher or lower amounts of selected hormones (Keshet-Sitton et al., 2016; Weiler et al., 1997). For example, the suprachiasmatic nucleus (SCN) in the brain is a photoreceptive system. This means it is controlled by light perceived by the retina of the eye. Thereby, the intrinsically photosensitive retinal ganglion cells (ipRGCs) are the most important photoreceptors regulating the internal clock and with that the hormone levels. Studies showed that the melanopsin release varies depending on light exposure and photoperiodic length. The stimulation of the ipRGCs is highest when exposed to light with a wavelength of 470 to 480 nm (blue range), which ultimately results in a suppression of the melanopsin production. However, this photopigment is essential for the biosynthesis of pineal melatonin, which may consequentially be downregulated due to ALAN (Paul et al., 2009). This hormone plays an important role for the immune system, especially in the detoxification process of radicals and the protection against inflammation. In the cancer disease progression, melatonin attenuates metastasis and tumor growth and has the potential to moderate the adverse effects of chemotherapy and radiotherapy. A successful immune response may be prevented resulting from a disruption of the natural melatonin production by a disturbed sleep-wake cycle due to ALAN (Moradkhani et al., 2019). Since melatonin is an especially important player in the progression of breast cancer (IARC, 2020), a common study design is to investigate the connection to light pollution by comparing the distribution of incidences with that of another cancer type that should be randomly distributed among the population (Bauer et al., 2013; Lamphar et al., 2022). Cancer rates were also elevated in people working shifts that are more often awake at night and therefore prone to disruption of the circadian cycle. Excessive light exposure has mostly been associated with an increased risk of breast and colon cancer, but a linkage to pancreatic, rectal, lymphoma or kidney cancer has also been investigated (Parent et al., 2012). Other hormones regulated by the circadian clock are estrogen, progesterone, or dopamine, which may result in similar clinical implications if not released to regular amounts (Liu et al., 2020).

Even small amounts of ALAN can disturb the part of the brain responsible for the sleep-wake cycle, which is once again the SCN located in the hypothalamus. Consequentially, LAN was associated with a decrease in sleeping quality, which was quantified as an increase of awake phases, increased brain activity, shallow sleep, or a delayed sleep onset (Cho et al., 2013). In some studies, participants were experimentally exposed to different intensities of LAN, while in others, levels of light exposure were assigned geographically through satellite imagery (Esaki et al., 2019; Patel, 2019). Since the influences on the circadian system vary with light exposure of different wavelengths, this factor is also considered in experimental studies regarding sleeping patterns. It was shown that blue light-enriched white light has the potential to improve sleep quality, performance, and concentration capacity (Viola et al., 2008).

For instance, ALAN was further linked to depressive-like or suicidal behaviour. Again, circadian disruptions were found to negatively affect mechanisms of brain regions responsible for the emotional well-being (Bedrosian et al., 2016). Experimental studies with rodents showed that the gene expression in the hippocampus can be altered under the influence of electrical light, which consequently led to behavioural changes (Cissé et al., 2017; Fonken & Nelson, 2013). These findings were confirmed by cross-sectional and cohort studies that found disparities between self-reporting of depressive symptoms of population groups experiencing different levels of light emissions (Harb et al., 2015; Min & Min, 2018). Some researchers were even able to draw a link between advanced mental disorders like Alzheimer's disease or Atherosclerosis by experimentally showing how subclinical markers worsened due to elevated levels of light exposure (Kim et al., 2018; Obayashi et al., 2019).

Global trends suggest an overlapping development of obesity rates and light pollution, which has been shown in georeferenced models relying on remote sensing data (Rybnikova et al., 2016). This association was explained through various mechanisms: low melatonin levels, a reduced glucose tolerance, a disrupted circadian rhythm, disturbed eating patterns. An increase in body mass index was also reported in mice that were exposed to unnaturally high levels of electrical light and linked to both behavioural and physiological changes in the animals (Fonken et al., 2010).

2.1.2 Critical Assessment

Box 2.1: Can we quantify the adverse health impacts of light pollution?

Conclusions drawn from scientific studies must be carefully analysed in order to accurately quantify health effects of excessive light exposure. The following limitations and knowledge gaps were identified:

Limitations

First, studies relying on remotely sensed data may find a correlation between health status and the light exposure. Yet, brightness is often used as a proxy for the level of urbanization, which might be associated with a number of socio-economic drivers like monthly income, quality of diet, sanitary facilities, levels of air pollution, etc. For this reason, it is impossible to say with certainty if ALAN is the causal factor that led to a poorer health or if one or even a combination of the other variables was responsible, when solely basing evidence on satellite data (Lamphar et al., 2022; Patel, 2019; Rybnikova et al., 2016). An environmental justice study conducted in the US found that the socio-economic status is strongly linked to artificial light exposure. On average, neighborhoods predominantly inhabited by White Americans were two times less exposed to light pollution compared to where socially underprivileged Black, Asian, or Hispanic communities house (Nadybal et al., 2020). Such confounding variables also need to be considered in studies concerned with only one specific population group (e.g. nurses, shift-workers, flight attendants, factory workers). Even though it might be reasonable to assume that the disturbance of the circadian system is more problematic in some work environments compared to others, potential health problems that accumulate in these groups may not be inevitably caused by the excessive exposure to LAN. Several factors related to the workplace may put pressure on health and therefore cannot be explained by light pollution only.

Second, light exposure experiments are often conducted on animals and subsequently, the findings are transferred to humans. In this case, an awareness of the physiological differences is essential. On one hand, it is legitimate to assume that a molecular change in the neurological tissue or an alteration of the genetic expression due to excessive artificial light exposure may also be an issue for humans if it was observed in animals (Bedrosian et al., 2016; Fonken & Nelson, 2013). On the other hand, we need to be careful when inferring discoveries of behavioural changes in animals to people. While a mouse might not be able to adjust its eating behaviour due to the lack of knowledge that brightness may not necessarily be equated to daylight, a human being might be able to do so (Fonken et al., 2010).

Third, the result of a light pollution study is highly dependent on the measurement method used to quantify light exposure on an individual level. Many approaches employed to make a light exposure assessment are timely and geographically limited potentially leading to a misclassification. This is a common limitation of studies relying on measurement with a large geographic scale such as satellite imagery or studies depending on self-evaluations using questionnaires. Inaccurate exposure-response relationships may also be drawn if historic light exposures are neglected when investigating a specific health outcome (Jones 2020).

Finally, it is crucial that natural and artificial light sources are separately analysed when interested in the effect of light pollution, since they greatly differ in characteristics like spectral composition and timing of exposure (Harb et al., 2015; Parrado et al., 2019).

Assessment

Overall, the literature provides evidence of how excessive exposure to ALAN may result in an increased risk of cancer. Cohort studies and a variety of case-control studies have reproduced the same findings, which were further explained with a physiological pathway that is comprehensible and also sensible (Bauer et al., 2013; Keshet-Sitton et al., 2016; Kliukiene et al., 2001; Parent et al., 2012). Likewise, exposure to LAN was shown to decrease the quality of sleep, which might even lead to further health problems such as chronic sleeping disorders (Cho et al., 2013; Esaki et al., 2019; Suh et al., 2018; Viola et al., 2008).

Animal experiments and epidemiological studies based on self-reporting suggest an association between light pollution and depressive symptoms. Whether this is an indirect effect of ALAN that may increase the incidence of a disruptive sleeping pattern needs to be further investigated (Bedrosian et al., 2016; Fonken & Nelson, 2013). The evidence for the association between light pollution and an increase in body mass or even obesity is lacking specificity, meaning that there might be a correlation, but we cannot infer causality. Since most of the studies investigating an association between light pollution and overweight provide evidence on the basis of satellite imagery and only a few animal studies were able to reproduce these findings, more research is necessary to correct for confounding factors and draw final conclusions. Remote sensing data has the potential to estimate artificial light exposure on a wide geographical scale, but is however limited in its ability to assign exposure data on an individual level.

While, the cohort study investigating a relationship between light pollution and atherosclerosis provided plausible results, the exhilarated development of Alzheimer's disease presumably caused by exposure to ALAN experimentally tested with flies and the transferability of these findings to the human physiology should be followed up with further research (Obayashi et al., 2019; Kim et al., 2018).

Knowledge Gap

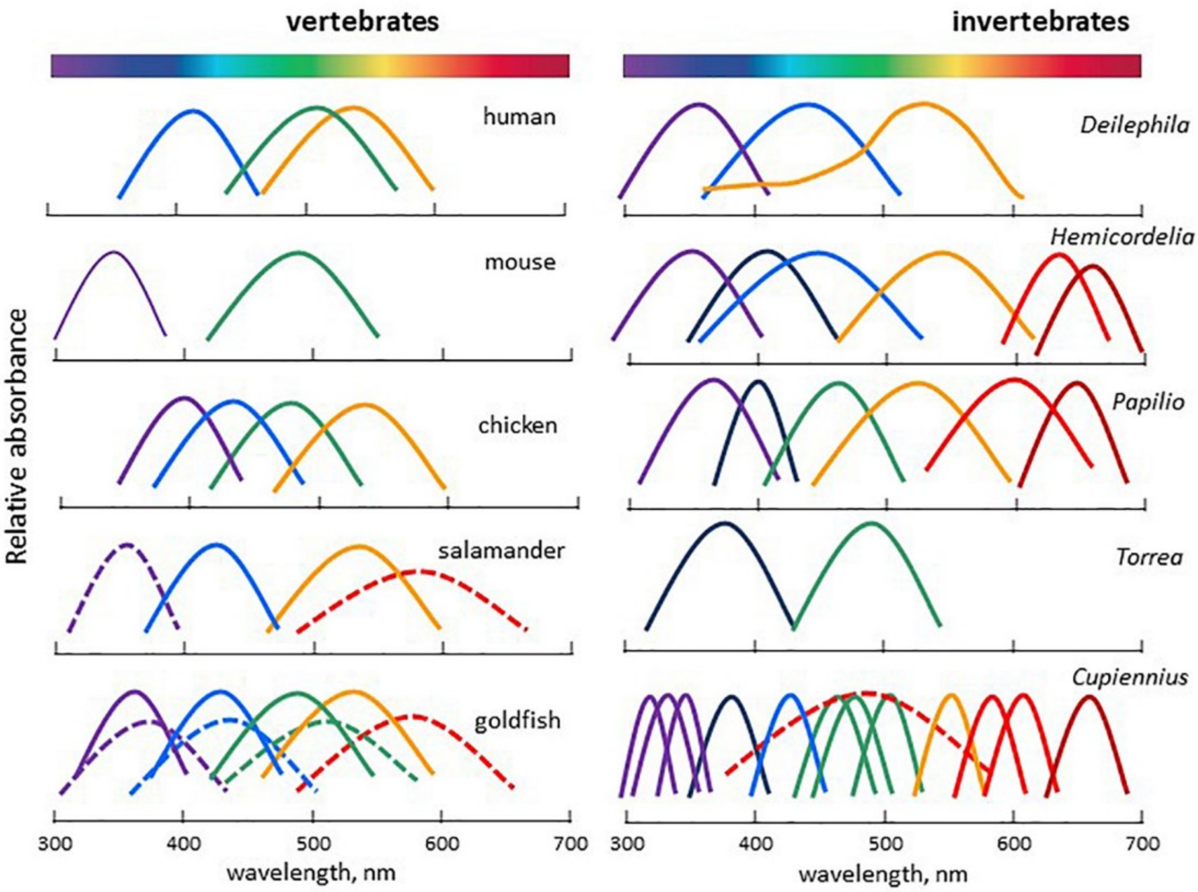
In conclusion, many studies advocate that excessive exposure to ALAN is likely to result in an increased risk of cancer or a sleeping disorder. To infer a causal relationship to depression and obesity, more studies with different study designs should be conducted to strengthen the found evidence. There is reason to believe that light pollution may also play a role in diseases such as atherosclerosis and Alzheimer's disease, which will need to be investigated in more detail. To correctly determine the health risks associated with light pollution and also further elucidate potential uncertainties in regard to cancer, additional studies should be conducted at the individual level over longer time periods and at small geographic scales, preferably including retrospective exposure estimates (Jones, 2020).

2.2 Biodiversity

Species from several taxa depend on a natural day-night cycle, hence cumulative encounters with artificial light sources disrupting this rhythm may alter their behaviour, activity and physiology. Especially affected by light disruptions are species triggered by seasonal day length stimuli or nocturnal species, whereby the negative effects on animals active at night are more pronounced (Sanders et al., 2021). This may be explained by the fact that lighting systems used to illuminate urban places are adapted to the human daytime eyes. However, nocturnally active organisms have dark-adapted eyes that perceive such light sources significantly brighter. Globally, 30 % of all vertebrates and 60 % of all invertebrates are nocturnal and therefore fall into a species group that immensely suffers under the influence of light pollution (Hölker et al., 2010). Compared to humans, most animals perceive different wavelengths, which makes a characterization of how excessive light emissions affect the wildlife difficult. While some animals may not see the long wavelengths (red or yellow) which we perceive, others are able to detect shorter wavelengths (white or blue) beyond the blue-violet part of the spectrum well into the ultraviolet area. The latter are especially sensitive to LED (light emitting diode) lights emitting mostly white and blue light that have gained increasing importance in the past decades due to their energy-efficiency (Commonwealth of

Australia, 2020). Figure 2.2 illustrates different species groups and their sensitivity to specific wavelengths on the spectrum in comparison to what the human eye perceives.

Figure 2.2: Spectral perception of species from different taxa



Note: Spectral sensitivity curves of selected vertebrate and invertebrate representatives, illustrating the wide variety of light detection systems encountered. **Vertebrates:** human *Homo sapiens,* mouse *Mus musculus,* chicken *Gallus domesticus,* Salamander *Salamandra,* goldfish *Carassius auratus.* **Invertebrates :** elephant hawk moth *Deilephila elpenor,* dragonfly *Hemicordulia tau,* butterfly *Papilio Xuthus,* annelid worm *candida,* nocturnal spider *Cupiennius salei.*

Source: Reproduced from Falcón et al., 2020.

Linked to light pollution, ecologists have found evidence of impaired migration patterns, foraging strategies, reproduction habits or communication systems which was further connected with increased mortality and altered community structures. Consequentially excessive artificial lighting negatively impacts the global biodiversity and plays an important role in changing ecological interactions (Sanders et al., 2021).

2.2.1 Behavioural Changes

Disorientation Threatening Migration and Survivability

Artificial lighting may impair the navigational skills of species from various taxa. A common example are the newborn sea turtles that were found to struggle in finding the ocean when emerging onto the beach after hatching. Usually their innate instinct navigates them away from dark constructs such as dunes or vegetation onshore. Nowadays, many beaches are artificially lit which gives the hatchlings a contradictory signal guiding them landward. Due to dehydration, exhaustion, or increased predation on land survival rates may suffer (Witherington & Martin, 2003).

Another species group experiencing that artificial light at night hampers with their sense of direction are nocturnally migrating birds. Once again, this may result in a significant loss of their energy reserves and increased morality. A variety of bird species orient themselves by making use of two navigational systems: first via celestial objects in the night sky and second through an inner compass depending on the global magnetic field. The first navigational tool becomes ineffective when the night sky is brightened and the visibility of the moon and the stars deteriorates. This phenomenon is most precarious in the North Sea or the Northern Gulf of Mexico where oil platforms are intensely lit with floodlights for nightly operations. Many nocturnal birds are attracted to these large light sources and get disoriented. The second orientation mechanism may also be impaired due to artificial lighting, because a bird's magnetic compass is wavelength conditioned. Experimental studies have shown that light containing less or no visible wavelengths are utilized for magnetic compass orientation. Therefore, light sources emitting the white, blue or green parts of the spectrum were found to have no significant impact on the bird's sense of direction whereas red light interfered with their inner compass and may cause them to lose their migratory routes (Poot et al., 2008). Another light-related source driving up mortality rates for several bird species, is the reflection of city lights in large constructs. Birds often fail to perceive business buildings or construction sites as barriers and are attracted by the reflected light, which may end in fatal collisions (Lao et al., 2020).

When investigating the adverse effects of anthropogenic light on insects, most research has been directed towards the increased mortality rates due to their attraction by lighting installations. Many insect groups show some kind of flight-to-light behaviour, where two scenarios are the most likely cause of death. Either individuals fly directly into the lamp and die due to the high temperature or as more often observed insects circle the light source for an unlimited amount of time until they are attacked by predators or perish due to exhaustion (Eisenbeis & Hänel, 2009). Mortality rates due to this phenomenon were shown to be temperature and also wavelength-dependent, whereas the impact was 48 % more severe for LED-based lighting installations (Pawson & Bader, 2014). Adjusted population behaviour was observed in a study comparing urban with rural moths. Individuals flying in areas with high densities of street lighting were found to be less attracted by light sources, which is most likely an evolutionary transition increasing survivability of urban moths (Altermatt & Ebert, 2016).

Reduced Reproductive Success

Many marine species time gamete release into the water based on natural light regimes. A classic example is the reproductive synchronization of the Pacific palolo worm. This species only mates once a year through cross-fertilization of epitokes (body parts containing gametes). Such spawning events are initiated by the exact lunar intensity of the third quarter moon and therefore a harmonized timing of the gamete release is dependent on the ability of both genders to perceive the moon cycles (Naylor, 2001). A similar reproductive periodicity is observed in coral colonies. Planulation (release of fertilized larvae) of several different species is timed according to lunar intensity (Tanner, 1996). Zooplankton also depends on light signals to synchronize their population behaviour, but this time related to the day-night rhythm. Usually, the decreasing light intensity at night is used as a signal to coordinate the timing to spawn. When the sunlight disappears, the zooplankton migrates towards the sea surface (Cohen & Forward Jr, 2009). In light polluted marine environments, skyglow caused by anthropogenic light emissions may however mask the moon light, negatively affecting reproductive success of the species.

Once again, the sea turtle is an oceanic species found to modify their reproductive behaviour. Adult female sea turtles avoid brightly lit beaches leading to an accumulation of nests on uninhabited shores exposed to low light intensities. Besides affecting the selection of the nesting site, light pollution was further found to play a major role in the success of the oviposition. Female turtles attempting to lay eggs, were observed to be stressed on beaches exposed to artificial lights which often resulted in a premature return to the water failing to complete the nesting procedure. This finding was consistent in six different species and linked to a global decline in population numbers (Witherington & Martin, 2003).

Furthermore, there has been an increase of endangered nocturnal amphibians because anthropogenic light at night runs interference with their mating procedure. The common toad (*Bufo bufo*) has been in the focus of research to study the effect of illumination on the male reproductive behaviour. Light-exposed males were found to take more time to find a female to pair with and would end the fertilization prematurely before the female oviposition was complete. The latter was a phenomenon never observed with natural light conditions (Touzot et al., 2020). On the other hand, female frogs were found to be less selective when choosing a mating partner in heavily light polluted regions. The presumed hypothesis for this behaviour adjustment is that females prefer to mate quickly to reduce activity when exposed to artificial light to a minimum. It might be an evolutionary adaptation to counteract the weaker performance of the other sex, however accepting qualitative declines in the offspring (Rand et al., 1997).

Artificial light was also found to alter reproductive patterns in terrestrial species such as the tammar wallaby. Individuals with a distribution range with close proximity to urbanized areas and therefore increased exposure to anthropogenic lighting were found to have an impaired sense of the seasonal rhythm, which was further connected to delayed delivery times and reduced survivability of the offspring (Robert et al., 2015).

Altered Communication Systems

A variety of species practice light-dependent communication and are therefore especially prone to disruptions by artificial lighting systems. Bioluminescent cues or lunar cycles are used by both terrestrial and aquatic species to send signals to other individuals of the same species (Davies et al., 2014). While, female glow worms use bioluminescent flashes to inform conspecific males of their willingness to mate on land, oceanic algae use bioluminescence as a defence mechanisms to attract large predators that may protect them against feeders in the ocean. Both communication systems were found to be altered by excessive light emissions and may result in mortality rates (Elgert et al., 2020; Haddock et al., 2010). Another terrestrial species known to use light as a sensory information system is the firefly. Populations living in heavily light polluted areas were found to significantly reduce their luminescent activities due to limited success in reaching other individuals from the same species (Firebaugh & Haynes, 2016).

2.2.2 Adjusted Activity Patterns

Adjusted Foraging Strategies

Several species either use darkness or light as a resource to forage. While the dark is utilized as protection from predators, the light is necessary to detect food sources. Depending on the balance of bright and dark, activity patterns may shift positively or negatively affecting organisms (Gaston et al., 2013). Especially prey species are forced to reduce their harvesting activity in areas affected by light pollution. In Florida, Santa Rosa beach mice were found to avoid brightly lit patches in their search for food (Bird et al., 2004). Artificial light was further shown to impair the ability of the grey tree frog to detect food sources and foraging activity was immensely reduced with illumination (Buchanan, 1998).

On the other hand, predatory birds were found to be increasingly active in artificially illuminated regions, extending their foraging periods. For instance, Northern mockingbirds were increasingly observed to feed on nestlings after sunset in areas affected by light pollution (Stracey et al., 2014). Several bat species are profiting from the white light emitted by energy-efficient streetlamps. They were found to orbit the streetlamps to forage on insects attracted and exposed by them (Blake et al., 1994).

Mis-timed emergence

Light intensity, colour and timing may affect emergence in several species. Bats roosting in areas affected by light pollution were found to leave their nest later than they would under natural light conditions. Delayed emergence may have a cascading effect resulting in lower success rates while foraging due to reduced time for food detection or missing out on the time period insect activity peaks (Downs et al., 2003; Rydell et al., 2017).

On the contrary, earlier emergence was observed for several bird species affected by light emissions in experimental studies. At what time blue tits would leave the nest was for instance found to be solely dependent on the light intensity directly before sunrise (Schlicht et al., 2014).

2.2.3 Physiological Alterations

Altered Hormone Regulation

Experiments with artificial lights and species from various taxa provide evidence for adverse effects on the metabolism and hormone levels which was further linked to immunological processes or the metabolism. Stress hormone levels were investigated in song birds and shown to be increased when repeatedly exposed to artificial light sources, especially those with high content of shorter wavelengths in the white part of the spectrum. This was further linked with reduced reproductive success (Ouyang et al., 2015). Another experimental study showed, that the illumination of nesting sites resulted in an altered immune response of newborn wild great tits. Different levels of two important markers needed to develop sufficient immune protection were found, compared to nestlings exposed to a natural day-night cycle (Ziegler et al., 2021).

Impaired development

Clownfish hatchlings use the onset of darkness as a cue to hatch, because under natural conditions hatching at night is much safer due to a reduced predation pressure. As a consequence of this congenital behaviour, eggs with constant light exposure fail to hatch, resulting in reduced offspring in heavily light polluted waters (Fobert et al., 2019). Another experimental study with European sea bass showed that a disruption of the natural day-night cycle through constant light exposure resulted in impaired larval development, numerous malformations and overall higher mortality (Villamizar et al., 2011). Experimental light treatment showed adverse effects in all developmental stages of the wood frog. While embryos were less successful in hatching and tadpoles shown to be more susceptible to parasitic infections, the size of adults was significantly increased during metamorphosis and swimming skills impaired (May et al., 2019).

Molecular mutations

Transcriptome-wide gene expression was investigated in tadpoles from brightly illuminated ponds. Mutations were mainly found in genetic regions responsible for the innate immune response but also the lipid metabolism (Touzot et al., 2022). Similar molecular analyses in mosquitos revealed a relationship between artificial light and altered genetic expression in genes regulating gametogenesis, immunology and metabolism. Additionally, evidence was found for sex-dependent reactions to light influence (Honnen et al., 2016).

Adverse effects on plant physiology

Plants depend on sunlight to produce energy via photosynthesis, to evaluate vicinity to competing vegetation, to orient themselves within the canopy and to detect seasonal changes via day length (Smith, 1982). Since artificial light has the power to obscure cues given through the natural light cycle, plants are prone to adverse effects caused by light pollution. Grassland was experimentally exposed to lighting levels typically measured in the suburban regions of England providing evidence for physiological changes in terms of flowering time, biomass, community composition and plant cover (Bennie et al., 2016). Accordingly, deciduous trees were found to bloom earlier and lose their leaves later in the year when part of an artificially illuminated ecosystem. Such drastic phenological alterations may further result in poorer health, survivability and reproductive success (Ffrench-Constant, R. H. et al,. 2016; Škvareninová et al., 2017). Invasive plants were found to flourish under artificially illuminated conditions resulting in reduced fitness of native plants and a significant change in species composition (Murphy et al., 2022). Research directed towards increasing the economic value of soybeans found that artificial lighting resulted in genetic changes, which was further linked to delayed flowering times, altered growth and yield loss (Kim et al., 2012). Altered plant physiology caused by anthropogenic lighting systems may spill over to pollinators and herbivores and have negative implications for entire food webs (Bennie et al., 2016).

2.2.4 Conclusive Remarks on the ecological consequences

Box 2.2: How can the ecological evidence be interpreted?

The published research reporting on the negative impacts artificial light elicits on the global biodiversity has shown that various animal species suffer from behavioural, habitual and physiological changes, which often results in a fitness loss. In case current light pollution trends progress, the proportion of ecosystems unaffected by artificial light regimes will continue to decline and with it these adverse effects will prevail or even increase.

However, the knowledge of ecological consequences caused by ALAN is still limited, and the field holds many possibilities for applied research to underline preliminary findings from the laboratory. In order to quantify the ecological threat, an assessment of species particularly vulnerable to changes in the natural day-night cycle paired with their potential of being exposed to anthropogenic light is necessary. The current body of literature is mainly focused on terrestrial animals, mostly insects, birds or amphibians, inhabiting the temperate climate zones, while other species groups and ecosystems have largely been neglected. The tropics are characterized by stable day lengths with minimal seasonal variations throughout the year and are therefore prone to disruptions by artificial light disturbing these constant patterns. Also highly under-researched are aquatic ecosystems, where natural light cues are of central importance for species dynamics. Furthermore, light pollution is often correlated with a variety of human disturbances such as noise, chemical contamination or construction, which may elicit cumulative and confounding effects on wildlife. Studies on natural populations involving complete ecosystems by regarding species dynamics and trophic interactions are rare. Up until today, artificial nighttime light has not completely established its recognition as an environmental threat and is often not included in the planning of conservation concepts or monitoring protocols that could reliably quantify the negative ecological consequences of light pollution (Davies et al., 2014; Gaston et al., 2012; Longcore & Rich, 2004).

2.3 Ecosystems

The increased night sky brightness caused by anthropogenic light emitted upwards and scattered through particles in the atmosphere has the potential to obscure the comparatively low natural luminance level of the night sky. Thereby, the impaired vision of celestial objects because of light pollution is a clearly visible ecological impact. On a moonless night, a light intensity of about 22 magnitudes per square arcsecond (mag/arcsec^2) is emitted by the stars, the Milky Way and the zodiacal light. If the artificial sky brightness exceeds 10 % of these natural light levels which is a luminance of more than 14 micro candela per square meter at the zenith (µcd/m^2), the condition classifies as light polluted sky. Today, 83 % of the global population and over 99 % of the people in Europe or North America live in light polluted environments (Falchi et al., 2016). Light pollution is not just a problem of urbanized areas but may also affect the night sky in rural settings. A city with approximately 1.5 million inhabitants has the potential to increase the sky brightness by 25 % at a locality up to 80 km away in the countryside. Additionally to this luminance, rural light sources intensify the sky glow (Gallaway et al., 2010). Light pollution may be further intensified depending on the weather conditions and amount of particles lingering in the lower atmosphere. For instance, cloud cover was found to amplify sky luminance by 2-10 times and an increase of selected aerosols was significantly linked to a brightening of the night sky. Under unfavourable atmospheric conditions, the combined luminance emitted by urban artificial light sources results in diffuse background lighting comparable to relatively bright summer moonlight typical for localities at high elevations. It has been estimated that 5 % of the global landmass is regularly exposed to such luminance levels, as is 23 % of North America, 37 % of the countries in the European Union and 54 % of Japan (Kocifaj & Barentine, 2021; Kyba et al., 2011).

Besides the explained astronomical light pollution, the term ecological light pollution has been defined as artificial light disrupting the natural light-dark cycle of ecosystems, putting the focus on the negative ecological consequences concerning trophic interactions and ecosystem functioning. At the beginning of this century, over 18 % of the global land mass was light polluted and this number was shown to increase yearly. Illuminated cruise ships, flares of hydrocarbon platforms and flood lights on fishing boats further disrupt the natural night skies over the world's oceans (Longcore & Rich, 2004). An example of how light pollution may negatively impact entire ecosystems is through reducing landscape connectivity. The permeability of the environment determines the ability of animals to move between habitats and is necessary to prevent a fragmentation into small subpopulations. Connecting habitat patches has been a priority in conservation practices, traditionally focusing on structural improvements such as building corridors, reducing barriers to movement or increasing patch size. Since anthropogenic light is an important non-structural driver negatively impacting landscape connectivity, it is important to incorporate light pollution into sustainable wildlife management plans (Laforge et al., 2019). Ecosystem dynamics may further be disrupted through impacts on trophic interactions. This was found to be especially problematic when a keystone species, serving as both a food source for predators and an important player in maintaining ecosystem health, experiences a fitness decline resulting in a reduced survivability due to light pollution (Jechow et al., 2021).

Depending on the lighting source the emitted light may differ in spectral, temporal and spatial characteristics. The values in all three categories may vary tremendously, making a quantification of the effect on natural light regimes difficult. In previous attempts to identify the ecological implications of light pollution such combined negative ecosystem effects were often not anticipated, which may have led to the general notion that negative ecological effects are rather localized or restricted to only a few light-sensitive species groups (Gaston et al., 2013).

3 Legislative Basis to Monitor and Control Light Pollution

Despite the concern that artificial light may negatively impact human health, biodiversity and ecosystems a common legal framework regulating light pollution across all the EU countries is currently missing. ALAN has not yet been accepted as a serious contaminant and therefore the adoption of policies to mitigate its adverse consequences is often not a priority. However, mandatory EU directives specifically aiming at lighting requirements are already in place. The European Ecodesign Directive and the Energy Labelling and Repealing Directive ensure an energy-efficient installation of lighting but lack a section addressing the adverse impacts of light pollution. These documents constitute an existing legal framework in which light pollution policies could possibly be incorporated in the future (European Commission, 2005; European Commission, 2010; European Council, 2000). Light pollution has also been considered as a disturbing factor in the Biodiversity Strategy, Birds and Habitats Directives and Pollinators Initiative, as well as in the EIA/SEA Directives set in place to assess environmental impacts and protect the species diversity (European Commission, 2001; European Commission, 2018). The European Union provides recommendations in the form of non-binding documents such as the *EU Green Public Procurement (GPP)* that promotes ways to reduce light pollution and its negative impacts on biodiversity and the visibility of celestial objects. The document was updated in 2019 with an "As Low as Reasonable Achievable (ALARA)" encouragement to reduce light levels in traffic and public streets to a minimum. Adherence to these recommendations is however still voluntary (Donatello et al., 2019; Testa et al., 2016). Furthermore, light pollution was included as a priority objective in the European Green Deal and the Zero Pollution Action Plan of the 8th Environment Action Programme targeted to protect the well-being of humans, animals and ecosystems, besides reducing risk factors in the environment (Council of the European Union, 2020; European Commission, 2019). Even in the Sustainable Finance Regulation light pollution was listed as a competent pollutant (European Commission, 2021).

3.1 EU Member States

The legislations concerning light pollution in EU countries can roughly be summarised into three categories: (1) Countries with national policies, (2) Countries with regional policies that vary in strictness, (3) Countries with no policies in place, but only non-binding documents providing guidelines to mitigating light emissions. The latter often have an existing legal framework where regulations to reduce light pollution could possibly be embedded. Below we will provide examples for each category.

3.1.1 National Policies

The Czech Republic became the first country in the EU with an existing national policy to reduce light pollution in 2002. In the Clean Air Act of the Czech law, light pollution was defined as artificial light dispersed to areas it is not supposed to illuminate, especially problematic if emitted above the level of the horizon. To actively prevent light pollution upper limits of light emissions were defined, shielding of streetlamps and changes of lighting installations to reduce upwards scattering of the light was made mandatory and municipal authorities were obliged to enforce the formulated measures ever since. Fines amounting up to 3,160 euros could be enforced for breaches of the law (The Parliament of the Czech Republic, 2002). Unfortunately, light pollution was omitted again as part of the amendments. In 2017, the Act No. 114/1992 on Nature and Landscape Protection was revised in response to concerns expressed to the government by the Czech Ministry of the Environment. Stricter regulations for the introduction of light sources in national parks were formulated to mitigate light pollution. Furthermore, rules to reduce light pollution became part of the state subsidy for the modernization of lighting systems, which from now on only supports lamps with 2700K or less light output as an example. In 2021, a lighting manual was published including recommendations for public lighting, private lighting facilities or architectural light installations, and new standards to limit the undesirable effects of outdoor lighting is currently being developed. Due to several memoranda, four regions with pristine night skies (Bystřická, Manětínská, Jizerská and Beskydská) within the Czech Republic have been protected (Ministry of the Environment and the Czech Republic, 2022).

Croatia introduced the law NN 14/2019 Act on Protection against Light Pollution with the main incentive to reduce the energy consumption of the country. The first version was developed in a 8-year-period starting in 2008, but was soon shown to be ineffective in reducing light pollution. Therefore, the legislation was just recently revised including new lighting management standards, restrictions related to excessive lighting systems and procedures to be included in the planning of the construction, maintenance or rebuilding of lighting installations (Croatian Parliament, 2019). More importantly was the NN 128/2020 Ordinance on Lighting Zones, Permitted Lighting Values and Methods of Managing Lighting Systems included in the article 9 of the existing law. It includes lighting zones with maximally permitted lighting limits, mandatory methods for lighting control and strict selection criteria for the installation of lighting products to ensure energy efficiency (Ministry of Economy & Sustainable Development, 2020). Additionally, the Ministry of the Economy and Sustainable Development is preparing an Ordinance on the Content, Formatting and Drafting the Lighting Plan and Action Plan for the Construction and/or Reconstruction of Outdoor Lighting as part of article 12 and 13 in the Act on Protection against Light Pollution, plus an Ordinance on the Measurement and Monitoring of Environmental Lighting to be included in article 10 (Ministry of the Environment of the Czech Republic, 2022).

Slovenia adopted a country-wide light pollution regulation in 2007. The very active astronomy community drew attention towards the increasingly light polluted skies and the related deterioration of star visibility. Public awareness grew accordingly and resulted in deliberations between experts and the government to formulate the law. A first draft of the policy in the Law on the Protection of the Environment was prepared by the Ministry of the Environment already in 1999 and meant to mitigate the adverse biological, astronomical, and economical effects of excessive light emissions. The final decree consisted of 31 articles providing lighting thresholds, technical restrictions on light installations and, inspection plans coupled with penalties. Policies regulate light emissions for the general population, including public spaces such as monuments, churches, airports, harbours, train stations or the freeway as well as for private office buildings production facilities. An example of a rather strict section formulated in the policy is that Slovenian municipalities may only spend a maximum of 44.5 kilowatt hours per inhabitant per year for lighting (The Parliament of Czech Republic, 2002).

Today, the French legal framework is one of the most progressive ways to restrict light emissions. The law was formulated in close collaboration with the national association for the protection of the sky and the nocturnal environment (ANPCEN), an amateur astronomical community that was concerned with the harmful effects of light pollution on the French population and the natural ecosystems. The Decree of 27 December 2018 on the prevention, reduction, and limitation of light pollution is a binding national policy with high standards. It regulates lighting for various places such as public and private streets, parks and gardens, churches and monuments, sports facilities and parking lots or non-residential and industrial buildings. Furthermore, clear lighting schedules for economically active areas or construction sites were enforced and thresholds of upward light ratio, flux emitted downward (to mitigate glare and intrusive lighting), and correlated colour temperature (to regulate the mixture of wavelengths or density of installed luminous flux) were defined. An important aspect of the French law is a strict lighting curfew prohibiting the illumination of industrial facilities during the early hours of the day and additionally obliging all exterior lighting to be switched off one hour after the last employee has left the office building. The phasing in of these policies has started in 2019 and it is planned to make them completely mandatory by 2025 (Ministre de la transition écologique et solidaire, 2018).

3.1.2 Regional Policies

Italy is considered to be the country with the oldest regional policies concerning light pollution. In 1942 a law to protect a dark sky zone around the astronomical observatory of Tuscolo was adopted in the community of Monte Porzio Catone in the East of Rome to sustain the possibility to star gaze (Simoneau et al., 2020). Over time robust policies were adopted in the rest of the Northern Lombardy region limiting light emissions, first being Veneto in 1997. Legislative texts regulate energy efficiency of lighting installations, impose curfews on the illumination of public buildings, define thresholds of light emissions and often include plans to educate the community to raise public awareness. Policies concerning protection zones around observatories are especially strict, as is light trespassing the horizontal expressly prohibited. While the regions Sardegna, Sicily, Calabria, Tentino Alto Adige and Molise are still missing a law to mitigate light emissions, regulations the other regions mostly differ in the application and control process. Nationally, the Italian standard rule provides guidelines that are non-binding and inadequate in protecting against the negative effects of light pollution (Marín et al., 2009).

In Spain only eight out of the seventeen autonomous communities have specific light pollution regulations in place: Andalucía, Canarias, Cantabria, Castilla y León, Catalunya, Extremadura, Illes Balears, and Navarra. Among these regions policies encourage an efficient use of exterior lighting, promote the preservation of natural ecosystems, aim to protect the dark skies around astronomical observatories, and help to minimize unnecessary light intrusions (Comunidad Autónoma de Cataluña, 2001). The law on the protection of the astronomical quality of the observatories Instituto de Astrofísica de Canarias was already adopted in 1988 by the government of the Canary Islands and is one of the most extensive regulations aiming to reduce light pollution in Spain (Ministerio de la Presidencia y para las administraciones territoriales, 2017).

In the Flemish region of Belgium, a legislation concerning light pollution from private light sources has been in place since 1996. The law was formulated as part of VLAREM II, the Flemish regulation for the environment with the aim to reduce light pollution. However, public lighting is still not regulated. Measures include type of lighting installations, removal of lighting systems and recommendations for the adaptation of outdated lighting. The Flemish government additionally regulates the installation of LED billboards in the immediate vicinity of roads to ensure traffic safety, which also positively affects light pollution (Parlement Wallon, 2019). Investigation on unnecessary lighting was launched in 2021 in regards to light pollution, electricity consumption and biodiversity protection (Ministry of the Environment of the Czech Republic, 2022).

3.1.3 No Policies, Only Non-Binding Guidelines

There is no specific law aiming to mitigate or reduce the adverse health effects caused by ALAN in Ireland. However, a manual protecting the night by the Mayo Dark Sky Park was developed in collaboration with the International Dark-Sky Association to inform the general public with data and facts about light pollution. This document also includes recommendations for local authorities about private and commercial lighting installations. No specific limits, but only guidelines have been formulated. For example, private lighting with low output, minimum scattering and warm colours have been suggested Furthermore, dimming and switching off lights at night has been recommended. New projects including the development of a lighting strategy are treated individually on a case-by-case basis (Dark Sky Ireland, 2019). In 2018, a group of stakeholders, intellectuals, national park representatives and astronomers was formed, called the Dark Sky Ireland with the purpose to raise awareness. They recently launched the Dark Skies For All program to organize events concerning policy development, education and public outreach (Dark Skies for All, 2022).

Austria is another country with no existing legal framework dealing with light pollution on a national level. The topic is addressed through non-binding documents or norms and measures may only be enforced in specific cases through different competences of the government similarly to the German legislative procedure. Binding policies to reduce the negative effects of artificial light could however be embedded in the protection of the environment, human health, construction law, and industry regulations. The publication of the document Guidelines for Outdoor Lighting in 2018 showed that light pollution is however of concern. These recommendations were developed in collaboration with most Austrian states and include technical limits in terms of light temperature and direction of light flux, also curfews to prohibited lighting during the night-time. Future policies will most likely be adopted by individual states before the inclusion of a binding legislative text concerning light pollution can be expected in the federal constitution (Austria Standards, 2016). The ÖNORM O 1052 standard has just been updated this year providing lighting recommendations based on collaborative work with the International Dark Sky Association (Austria Standards, 2022).

Liechtenstein is an example of a country that has already defined artificial light as source of potentially harmful radiation in the *Environment Protection Act*, which is a national binding document. However, according to this document threshold levels will only be enforced if there is clear evidence that light emissions negatively impact the safety, economic endeavours, or well-being of the public. A reformulation or extension of this existing legislation could sufficiently control the adverse consequences excessive lighting might cause. The report *Light Pollution in Liechtenstein* was released by the Environmental Protection Office in 2008 drawing attention towards the problematic features of artificial light (Amt für Umweltschutz, 2008).

Table 3.1: Overview of the European actions aimed to reduce light pollution

Country	Legislation[1]	Standard	Manual[2]	Other[3]
Austria	X	✓	✓	✓
Belgium	X	✓	✓	✓
Bulgaria	X	✓	X	X
Croatia	✓	X	X	✓
Cyprus	X	X	X	✓
Czech Republic	(✓)	(✓)	✓	✓
Denmark	(✓)	X	✓	✓
Estonia	X	X	X	✓
Finland	(✓)	X	(✓)	X
France	✓	X	X	✓
Germany	✓	X	✓	✓
Greece	✓	X	X	✓
Hungary	(✓)	X	✓	✓
Iceland	X	X	X	✓
Ireland	X	X	✓	✓
Italy	✓	✓	X	X
Latvia	(✓)	X	X	✓
Liechtenstein	X	X	X	✓
Lithuania	X	X	X	X
Luxembourg	X	X	✓	✓
Malta	✓	✓	(✓)	✓
Netherlands	(✓)	X	✓	✓
Norway	X	X	✓	X
Poland	X	X	X	✓
Portugal	X	X	✓	✓
Romania	X	X	X	✓
Slovakia	(✓)	X	X	✓
Slovenia	(✓)	X	✓	✓
Spain	✓	X	✓	✓
Sweden	✓	(✓)	✓	X
Switzerland	(✓)	✓	✓	✓
United Kingdom	✓	X	✓	✓

1 ✓ means that there is a designated legislative act (on local/regional/national level) addressing light pollution; (✓) means that there is no designated legislative act addressing light pollution, but provisions from other legislative acts can be used; X means that there is no legislation addressing light pollution

2 ✓ means that a guidebook/manual for correct lighting has been issued in the country; (✓) means that a guidebook/manual is underway; X means that n manual/guidebook is existing or in preparation

3 Others means the country e.g. Dark Sky Area, specific projects, dedicated to light pollution

Source: Ministry of the Environment of the Czech Republic, 2022.

3.2 Global Approaches to Mitigate Light Pollution

The analysis of the legal situation in the selection of EU countries demonstrates that light pollution may be most effectively reduced or mitigated with a nationally binding law. This reduces uncertainties among light users, decreases the possibility to cheat to a minimum and facilitates law enforcement for public authorities. On a global scale, there are several different approaches as to how such a country-wide law may be formulated. While some nations insist on strict thresholds and categorizations for various lighting installations, others rely on curfews and technological advances. Differences were further identified in the implementation process. Some governments supplement existing laws with a light pollution regulation, while others formulate an entirely new law standing on its own. In the following section we present different versions of global light pollution policies that were successful in decelerating the upward trend of light emissions.

3.2.1 Policy Depending on Strict Metrics

The Republic of Korea

The metropolitan government of Seoul adopted a national law called the ordinance on the prevention and management of light pollution in 2010. The policy provides regulations for lighting installations in the three fields: space lighting, decorative lighting, advertisement lighting and puts all regions of Korea in the following four categories: E1 (green areas for conservation), E2 (natural green areas and productive green areas), E3 (residential areas), E4 (Semi-industrial and commercial areas). The zones are defined in the Korean law on national land planning and use, allowing the highest lighting levels in commercial areas and simultaneously protecting the wilderness and their natural ecosystems in rural areas. Specific luminance thresholds are formulated for each light environment management zone leaving no room for legislative uncertainties. This very structured approach relieves the public from having to be proactive in enforcing policies and reduces conflict. Furthermore, in case of non-compliance, local authorities have the power to impose penalties that increase in amount depending on the number of offences. The Korean policy on light pollution is another example of a progressive political framework in terms of accountability, legal assertion and incentivization (Guanglei et al., 2019).

3.2.2 Policy Coupled with Educational Approach

Australia

The Australian government was one of the first officially recognizing artificial light as a source of pollution in the Environment Protection Act in 1997 and therefore defining it as a threat to the human and environmental health. Technical information to specifically guide the mitigation of light pollution and its adverse effects on threatened species part of listed ecological communities was additionally provided in the Environment Protection and Biodiversity Conservation Act in 1999. The Australian Standard was then adopted to limit the obtrusive effects of outdoor lighting, both physiological and psychological. A selection of changes in the design of lighting installations were enforced in order to simultaneously manage light pollution, maximize energy-efficiency and minimize the adverse impacts on the Australian population and wildlife. Agreed limits were defined for various lighting scenarios and curfews were imposed during the migratory season of selected species. The Australian policy makers have taken an educative approach, seeking to increase the engagement of citizens by highlighting the several negative effects of electrical light within light pollution policies and thus raise public awareness (Kyba et al., 2014)

3.2.3 Policy Incorporated in Existing Law

UK

In the English law, light pollution regulations have been added to existing regulations instead of adopting a new specific policy. This facilitated the implementation process tremendously and negative effects due to artificial light were quickly considered in common practices, however regulations repeatedly lack in effectiveness due their unspecific nature. Most lighting issues are handled in the statutory nuisance section of the law, meaning legal consequences follow only if an interference with personal discomforts due to light emissions can be directly linked to human health impacts. These individual cases are then regulated with the application of the Environmental Protection Act, which was formulated in 1990 (Department for Environment, Food and Rural Affairs, 2022). Another example is how light pollution is newly considered in the construction planning of new buildings. However, the focus of these regulations is less on the intrusive effects and more on the aesthetics. Just recently, a guidance note was published to revise these light pollution policies in the construction law, which resulted in a regulatory conflict confusing light installers and local authorities. Such problems may be easier resolved by depending on defined thresholds and hourly lighting restrictions (Department for Environment, Food and Rural Affairs, 2013). However, in the revised version of the legally binding Environment Act issued in 2020, light pollution was again not included as an environmental pollutant consequentially strict measures still cannot be taken (Dark Skies for All, 2022).

3.2.4 Policy Formulation in Collaboration with the Astronomy Community

Chile

Over the last few decades Chile has established its status as astronomical capital of the world due to strong political efforts protecting the night sky. As early as the 1990s, the astronomical community was critical of the increasing light pollution. Especially in the North of the country, where most of the observatories are located, cities were growing, and simultaneously lighting installations were accumulating illuminating the nights. This made the observation of celestial bodies increasingly difficult. However, Chilean policy makers reacted positively to these concerns which led to the formulation of the Supreme Decree No. 686 by the Ministry of Economy in 1998. Included were regulations on the features of outdoor lights mitigating upward light emissions and additionally the Office of Sky Quality in North Chile (OPCC) was founded. Currently, the Chilean government collaborates with the OPCC, a consortium of international observatories based in the country and the national Astronomical Society (SOCHIAS) to frequently update light pollution legislations keeping Chile's popular clear skies intact. In the last decade, energy efficient light-emitting diodes producing bright light primarily in the blue part of the spectrum, have gained popularity. Commonly the new technology was utilized for advertisement purposes as large LED flat screens threatening to generate more light pollution. With the advanced political framework in Chile it was possible to avert an increase in night sky brightness through the adoption of the new Supreme Decree No 43 by the Ministry of Environment in 2014. The new law strictly regulates the installation of lighting systems for advertisement, in the industry sector and for recreational areas. Most importantly it prohibits light emissions above the horizontal and only allows a minimal portion of the emitted light at blue frequencies (AURA & AURA-O, 2015).

4 Standards and Monitoring Methods to Assess Light Pollution

4.1 Quantifying Light in the Environment

The total brightness of the night sky is a combination of natural light sources and artificial light scattered from the Earth's atmosphere. Depending on the brightness of the latter, the visibility of celestial objects may decrease, which is also referred to as environmental light pollution. Therefore, night sky brightness (NSB) is often used as an indicator to quantify light pollution. For the assessment of NSB a distinction between including all natural light sources ('sky brightness') or only measuring in the range of star visibility ('sky background brightness') is important. Usually, two parameters are used to measure the light in the environment. While 'irradiance' is defined as the total amount of electromagnetic radiation on a surface, 'radiance' refers to the total brightness that appears within the field of view. Often, the radiance of a specific range of wavelengths measured, which is also called the spectral radiance. When this measurement spectrum is adjusted to the human perception, it is referred to as 'luminance' or 'illuminance' (Hänel et al. 2018).

Most common units to quantify NSB are either magnitude per arcsecond square (mag/arcsec^2), candela per meter square (cd/m^2) or lux (lx). The most common units for quantifying sky brightness are either magnitude per arcsecond squared (mag/arcsec^2), candela per square meter (cd/m^2), or lux (lx). Whereby, the magnitude system is the oldest of the three and was developed to quantify the sky brightness in terms of star visibility. A magnitude of 1 is defined by the luminous intensity of the brightest star visible to the naked eye and the darker the sky the lower the values measured in mag/arcsec^2. Once again, the measured radiance may be adjusted to the wavelengths perceived by the human eye by assessing the light emitted in the green V spectral band (v = visual). In this case, the unit mag/arcsec^2 can be converted into luminance (cd/m^2) with the following formula (Garstang, 1986):

$$cd/m^2 = 10.8 * 10^4 * 10^{-0.4 * mag_v}$$

While candela describes the luminous intensity of a light source (light density), lux is often used to measure the illuminance of a surface area and can be converted to lumen per square meter (lm/m^2). To account for this methodological difference, a multiplication of cd with the steradian (square radian, sr) is necessary for the conversion of these two units (Wei-Chung Cheng & Pedram, 2004):

$$lux = lm/m^2 = (cd * sr)/m^2$$

4.2 Commercial devices

4.2.1 Sky Quality Meter (SQM)

This rather affordable automatic device measures the night sky photometry and can easily be operated and installed at any preferred location. The SQM is a pocket-sized photometer mainly used by amateur astronomers and the general public. However, the SQM does not provide the most accurate measurements and comes with a couple disadvantages. It has a custom filter that does not exactly match any astronomical or photopic band but has an extra sensitivity at shorter wavelengths (blue light) (Cinzano, 2005). The displayed unit is often not compatible with the standard astronomical definition of magnitude, since luminance is measured in mag_{SQM}/arcsec^2 instead of mag_V/arcsec^2. Commercially available SQMs measure with error margin of 10 %, corresponding to 0.1 mag_{SQM}/arcsec^2 (Hänel et al., 2017).

4.2.2 Solar-Cell-Based Light Meter

This device is extremely weather resistant and was originally designed for long-term monitoring of light emissions. It measures the photoelectric current absorbed by the built-in solar cell, generating estimates for the illuminance as well as irradiance of a specific location. The device is repeatedly calibrated automatically to the sun, moon and twilight on site and thus does not require constant control. Since this light meter is also able to measure daylight, official time-series from the climate and meteorology research collecting data of total irradiance may be used for comparison and to verify the measurements of the instrument. It is a popular instrument in the science community. Solar cell-based light meters measure with an accuracy of 10 µlx and the sensor can cover the whole range of the human light perception (Hänel et al., 2017).

4.2.3 Lux Meter & Luminance Meter

The illuminance and the luminance can be measured with commercially available devices such as lux meters or luminance meters. Products in different price ranges are available and differ mainly in the accurracy of the measurement. While lux meters are inexpensive and easy to use, the comparison between measurements conducted with different brands are difficult due to a high dependency on environmental parameters (Lübke et al., 2021)). The main disadvantage of most of these meters is the low sensitivity at low light conditions. With the lux meter, measurements are already difficult at light intensities between 0.1 and 0.01 lux, and for luminance meters, the lower limit is usually between 0.01 to 0.001 cd/m^2. Digilum is a popular luminance meter that is photopically adapted to the wavelengths of human perception. It measures luminance from 0.1 mcd/m^2 up to 20 kcd/m^2 with a measurement accuracy of 5 % (Hänel et al., 2017).

4.2.4 Digital Cameras with Fisheye/Wide-Angle Lens

Digital cameras with fisheye lenses can also be used to determine the luminance of the night sky. Advantages are easy accessibility, affordability, and a minimal transportation effort. However, the accuracy of the measurement is highly dependent on the calibration procedure (Jechow et al., 2017). Dark frames (images with minimal exposure) are used to minimize confounding factors, which allows the photos to be comparable. The quality of the images also depends on the lens vignetting, the geometric distortion of wide-angle lenses and the colour sensitivity of the camera. With precise calibration and high quality of the camera, a measurement with up to 1 to 2 % accuracy can be achieved. Normally, however, an error of about 10 % should be expected in camera photometry (Hänel et al., 2017).

4.2.5 Star Counting

The luminance coming from highly light-polluted areas lingers in the sky and decreases the number of celestial objects that can be detected by the naked eye. Therefore, the number of visible stars can be used as an indicator of NSB. Counting stars is a tool that has repeatedly been used to collect global data on light pollution via citizen science. Several mobile applications, such as Dark Skies, Lost at night, Night Cities or How Many Stars are in use and motivate the general public to identify star constellations. Since this data is collected unsystematically, there are concerns about the reliability of these entries (Hecker et al., 2018).

4.3 High-End Methods

4.3.1 Satellite Imagery

Imagery of the Earth's surface that are taken from space at night provide information on the spatial distribution of light emissions, which can be used to evaluate changes in space and overtime. Until today, light emission data was collected by two satellite sensors:

a) From 1992 to 2013, the data came from the Operational Linscan System (OLS) of the Defence Meteorological Satellite Program (DMSP/OLS) satellites which quantify the visible and near-infrared (VNIR) emissions in "digital numbers" (DN) ranging from 0 to 63.

b) From 2012 until today, the data was and still is provided by the Day/Night Band (DNB) of the Visible Infrared Imaging Radiometer Suite (VIIRS) assembling radiometric measurements of light emissions in the unit nanowatts per centimetre squared per steradian (nW/cm^2/sr).

The two instruments have a number of important differences, and therefore cannot be directly used to evaluate changes from 1992 until the present. While the global satellite night-time images provided by the DMSP/OLS go temporally furthest back and are therefore able to show fluctuations in light pollution over time, VIIRS compiles data with a higher spatial resolution. The National Polar-orbiting Partnership satellite that flies VIIRS orbits the globe 14 times per day and photographs the Earth at a resolution of 15 arc-seconds and about 750 meters. In comparison, the DMSP measurements are between 40-90 times poorer resolved (Bennie et al., 2015). This improvement in resolution directly translates into a decrease in pixel size on VIIRS images, meaning that variations within the captured landscape is displayed more accurately (Elvidge et al., 2017). Additionally, astronauts on board the International Space Station provide photos with a high resolution. NASA gives access to these images via "The Gateway to Astronaut Photography of Earth", which however have less relevance in the science community (Kyba et al., 2014). Scientist utilizing satellite imagery are mostly interested in showing light pollution developments over time with the best data available. For this reason, VIIRS data has been used almost exclusively for the modelling of the last eight years. In addition, there is a great demand to convert the two data sets to the same unit, so that light emissions values from the nineties can be compared to measurements from today. There are two available datasets with combined data from both collecting data sources, VIIRS and DMSP/OLS. First the harmonized data with measurements from 1992 to 2020 , where all VIIRS data has been converted to the DMSP/OLS system (Li et al., 2020) and second the extended data with converted data in the VIIRS unit covering the time period 2000 - 2020 (Chen et al., 2021).

4.3.2 Spectroscopy

Spectroscopic measurements are mostly obtained at international astronomical observatories and research facilities. Usually, a regular telescope can be equipped with a spectrograph and a camera available for imaging and low-resolution spectroscopy, which quantify NSB in visible wavelengths. For spectroscopy, celestial objects are observed for 30 minutes up to an hour on moonless clear nights. Afterwards the night-sky part of the sky light can be extracted from the stellar spectrum, allowing identification of whether emission lines came from artificial and natural light sources. Each light source has a unique wavelength on the spectrum, which makes an identification of the most problematic emissions causing light pollution possible and therefore spectroscopic measurements very valuable. Quantitative analyses may further show changes in brightness over time (Liu et al., 2020).

4.3.3 All Sky Transmission Monitor (ASTMON)

Only a few ASTMONs were installed in observatories around the globe for scientific usage with the goal to determine the quality of the night sky. These devices were designed to be resistant even in extreme weather conditions and are able to continuously monitor the surface brightness of the complete night-sky. It functions fully automatic and can therefore be employed as a permanent monitoring station outdoors. A source detection algorithm is applied to the collected data, allowing to synchronize the several images via star mapping. The total light emissions are estimated based on the brightness of the detected stars. The acquired information may be used to derive the geographical distribution of light pollution, cloud coverage or the multiband atmospheric extinction at any location (Aceituno et al., 2018). In addition to luminance measurements in the typical unit mag_V/arcsec^2, the ASTMON also collects data in several other wavelengths (Hänel et al., 2017).

4.3.4 All-Sky Mosaic

This method can also be used to measure light emissions over a large area instead of local point measurements. Several successive wide-field images are taken. Within only twenty minutes light emissions of the whole sky can be mapped. In order to make an accurate measurement, this instrument must also be calibrated with official standards. Since this is again a photopic measurement approach, data is collected in units of cd or lux. For a light density measurement of an all-sky mosaic, an error in the range of µcd/m2 can be expected. Small portable computers with the software to perform all-sky mosaicking are commercially available, however, more often these systems are used for remote monitoring of specific sites of interest. An important shortcoming of all-sky mosaics is the low resolution, but the large pixel size allows fast processing times per image (Hänel et al., 2017).

4.4 Thresholds and Indicators for Monitoring

Several attempts have been made to quantify the luminance of a truly dark site, where all artificial light is absent. However, as previously described the night sky is never truly dark because of natural light sources and even such low luminance levels can be measured in mag/arcsec^2. The so called sky background brightness on a moonless night is generally believed to be 22 mag/arcsec^2 and the lowest value measured when assessing NSB (Falchi et al., 2016). A study investigating the accuracy of this value by measuring NSB at several protected sites around the globe found this measure to vary and suggested 22.7 mag/arcsec^2 as the best estimate for the natural night-sky-luminance (Alarcon et al., 2021). Other studies have shown that NSB fluctuates within a range of 2.7 mag/arcsec^2 (Hänel et al., 2018; Posch et al., 2018). When investigating NSB at various locations in the Polish mountains luminance levels where found to range between 0.27 and 1.71 mcd/m^2, this time evaluated in the unit of milicandela per square meter (Sciezor et al., 2012). In 2001, John E. Brotle proposed a method to assess the quality of the night sky by classifying measured luminance levels into nine categories, also known as the Brotle scale. Values are available as naked-eye limiting magnitude (NELM) and supposed to provide astronomers with information about the celestial visibility. A site with measurements above 7 NELM qualifies as a “typical truly dark site”, which translates to 22.4 mag/arcsec^2 (Brotle, 2001).

Light pollution threshold are a common political tool to control light emissions. However, the formulated regulations of the different countries vary in the unit how light emissions are measured, the type of lighting installations for which limits are defined or the allowed areal luminance levels. As a first example, the French have included strict metrics in their policy regulating luminance levels of outdoor lighting depending on the level of urbanity at a certain location. Light emissions are measured in lumen per square meter and three thresholds have been identified (French Order, 2018). Korea is another country that has formulated differing lighting standards depending on the environmental value of a particular region. Each area was divided into an environmental zone, with the lowest being the one harbouring the most light-sensitive species or most valuable ecosystems, and therefore the strictest luminance threshold. Additionally to the definition of four environmental zones, curfews with lower light emission tolerance are enforced. In table 4, the thresholds for maximally allowed luminance of road lights within the time period of an hour after sunset and before sunrise are listed (Lim et al., 2018). The Croatian policy makers used a similar strategy. All regions have been divided into the following five lighting zones: E0 are areas with pristine night skies and only natural light, E1 are dark landscapes that are minimally artificially lit, E2 are areas with low levels of artificial lighting, E3 defines areas with medium artificial lighting and E4 are areas with high levels of artificial lighting. For each zone a maximum vertical illuminance level was defined, which varies depending on the lighting installation. In table 4 is an example of limits formulated for safety lights in private buildings (Ministry of Economy & Sustainable Development, 2020). On the other hand the Italian policies are specifically formulated for certain types of lighting installations and formulated in the unit of candela per kilo lumen. As previously established, these regulations vary between the different regions of Italy and we therefore give an example from the regional light pollution of the Lazio region (Consiglio regionale, 2000). These discrepancies demonstrate the need to harmonize regulations to limit light pollution across the EU in order to facilitate comparisons.

Table 4.1: Political light emission thresholds

Type of light installation/illuminated area threshold is defined for	Threshold level defined in policy (unit)	Country	Reference
Astronomically/ecologically valuable zones	20 (lm/m^2)	France	(Ministre de la transition écologique et solidaire, 2018))
Rural zones	25 (lm/m^2)	France	(Ministre de la transition écologique et solidaire, 2018))
Urban zones	35 (lm/m^2)	France	(Ministre de la transition écologique et solidaire, 2018))
Zone E1	50 (cd/m^2)	Korea	(Lim et al., 2018)
Zone E2	400 (cd/m^2)	Korea	(Lim et al., 2018)
Zone E3	800 (cd/m^2)	Korea	(Lim et al., 2018)
Zone E4	1000 (cd/m^2)	Korea	(Lim et al., 2018)
Zone E0 (at sunrise or sunset/at night)	0.5 (lx) / 0 (lx)	Croatia	(Ministry of Economy & Sustainable Development, 2020)
Zone E1 (at sunrise or sunset / at night)	1 (lx) / 0 (lx)	Croatia	(Ministry of Economy & Sustainable Development, 2020)
Zone E2 (at sunrise or sunset / at night)	2 (lx) / 0.5 (lx)	Croatia	(Ministry of Economy & Sustainable Development, 2020)
Zone E3 (at sunrise or sunset / at night)	3 (lx) / 1 (lx)	Croatia	(Ministry of Economy & Sustainable Development, 2020)
Zone E4 (at sunrise or sunset / at night)	8 (lx) / 2 (lx)	Croatia	(Ministry of Economy & Sustainable Development, 2020).
Private buildings	1 (cd/klm)	Italy, Lazio region	(Consiglio regionale, 2000)
Street lights, lanterns	5 (cd/klm)	Italy, Lazio region	(Consiglio regionale, 2000)
Spotlights, projectors	10 (cd/klm)	Italy, Lazio region	(Consiglio regionale, 2000)
Ornamental lights	35 (cd/klm)	Italy, Lazio region	(Consiglio regionale, 2000)

Ecological threshold levels were formulated to evaluate light pollution levels in ecological zones of the terrestrial and aquatic Natura 2000 sites based on VIIRS night-time data (Hügli, 2021). The proposed threshold of 2 $nW/cm^2/sr$ in Table 4 corresponds to a typical light emission level for small villages or sparsely populated residential areas. Luminance values of 10 $nW/cm^2/sr$ are common of larger towns with a rather dense population. In larger settlements, where mixed lighting installations are used measurements typically range around 20 $nW/cm^2/sr$. Light emissions above 2 $nW/cm^2/sr$ are expected to impact ecosystems and its wildlife, at least to a small extent. The lowest threshold of 0.5 $nW/cm^2/sr$ has been proposed because light emissions around this level come from artificial light sources with a minimal lighting output so low that a distinction from natural night light coming from the moon and the stars becomes difficult and is associated with uncertainty (Hale et al., 2018; Hale & Arlettaz, 2019; Hügli, 2021).

Table 4.2: Thresholds to classify ecological light emissions (extracted from Hügli 2021)

Light emission ($nW/cm^2/sr$)	Description of light emission thresholds	Reference
< 0.5	Lowest light emission values	(Hügli, 2021)
0.5 – 2*	Very low light emission values	(Hügli, 2021)
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)

*At light emission above 2 $nW/cm^2/sr$ at least low levels of ecological impacts are expected.
Source: Hale et al., 2018.

Currently, the research community is developing new indicators to monitor light pollution. In order to facilitate the definition of maximum light emission values for policy makers, future indicators at high geographical resolution will make a direct linkage to specific emission sources (Bará et al., 2021, 2022; Falchi & Bará, 2021).

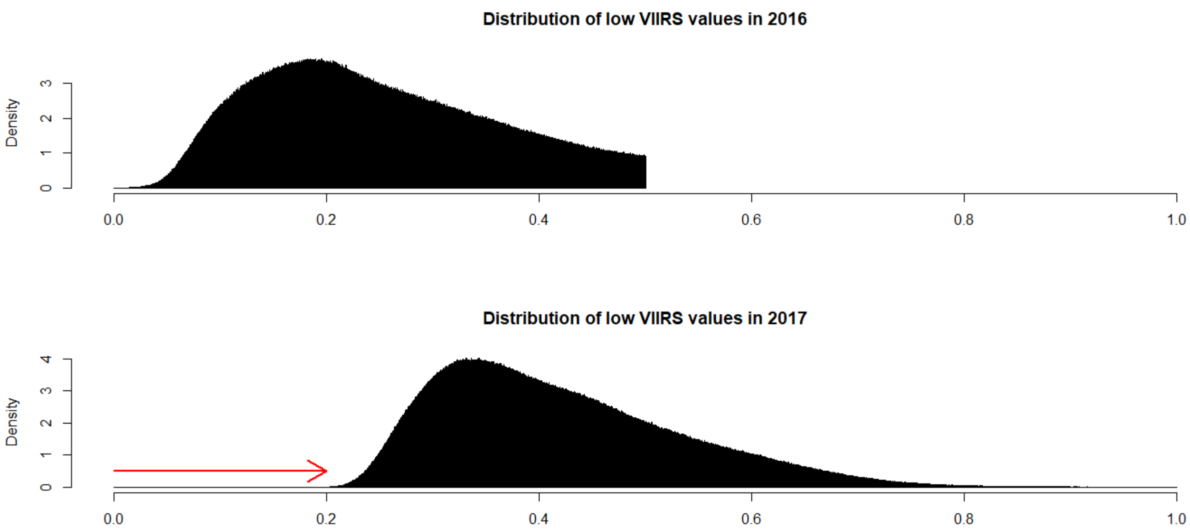
5 Temporal Trends of Light Pollution

5.1 Most Recent Trends

Monthly average radiance composite images of night-time data from VIIRS were used to show the latest developments in light emissions across Europe. In particular, the Stray Light Corrected Night-time Day/Night Band Composites Version 1 product (Elvidge et al., 2013, 2017) covering the years 2014 – 2021 was accessed via the Google Earth Engine API (Gorelick et al., 2017). This product is an alternative configuration of the VIIRS DNB using a procedure to correct for stray light. The correction procedure extends visible areas closer to the poles and improves dynamic range. This product excludes data impacted by cloud cover. The data source is measuring the light emitted from the earth's surface into space as radiance in the units of nW/cm²/sr. We have chosen thresholds to quantify artificial light emissions as presented in Table 4. Since converted values from luminance measurements were shown to be extremely low and associated with uncertainties depending on weather conditions, calibration and conversion factors, the analysis was conducted by using the thresholds available in the unit of VIIRS (Hale et al., 2018; Hale & Arlettaz, 2019; Hügli, 2021).

The analysed Stray Light Corrected Night-time Day/Night Band data as collected by the VIIRS satellite has been recalibrated in January 2017 (A. Sánchez de Miguel, personal communication, October 26, 2022). Figure 5.1 compares the distribution of the VIIRS values in areas with measurements of 0.5 nW/cm²/sr or lower in 2016 and the values in the same areas in 2017. A shift of +0.2 nW/cm²/sr is visible, especially in areas with extremely low light emissions, indicating a change in the measurement method and data output. To correct for this recalibration, the artificial value of 0.2 nW/cm²/sr was subtracted from all light emission values from January 2017 onward.

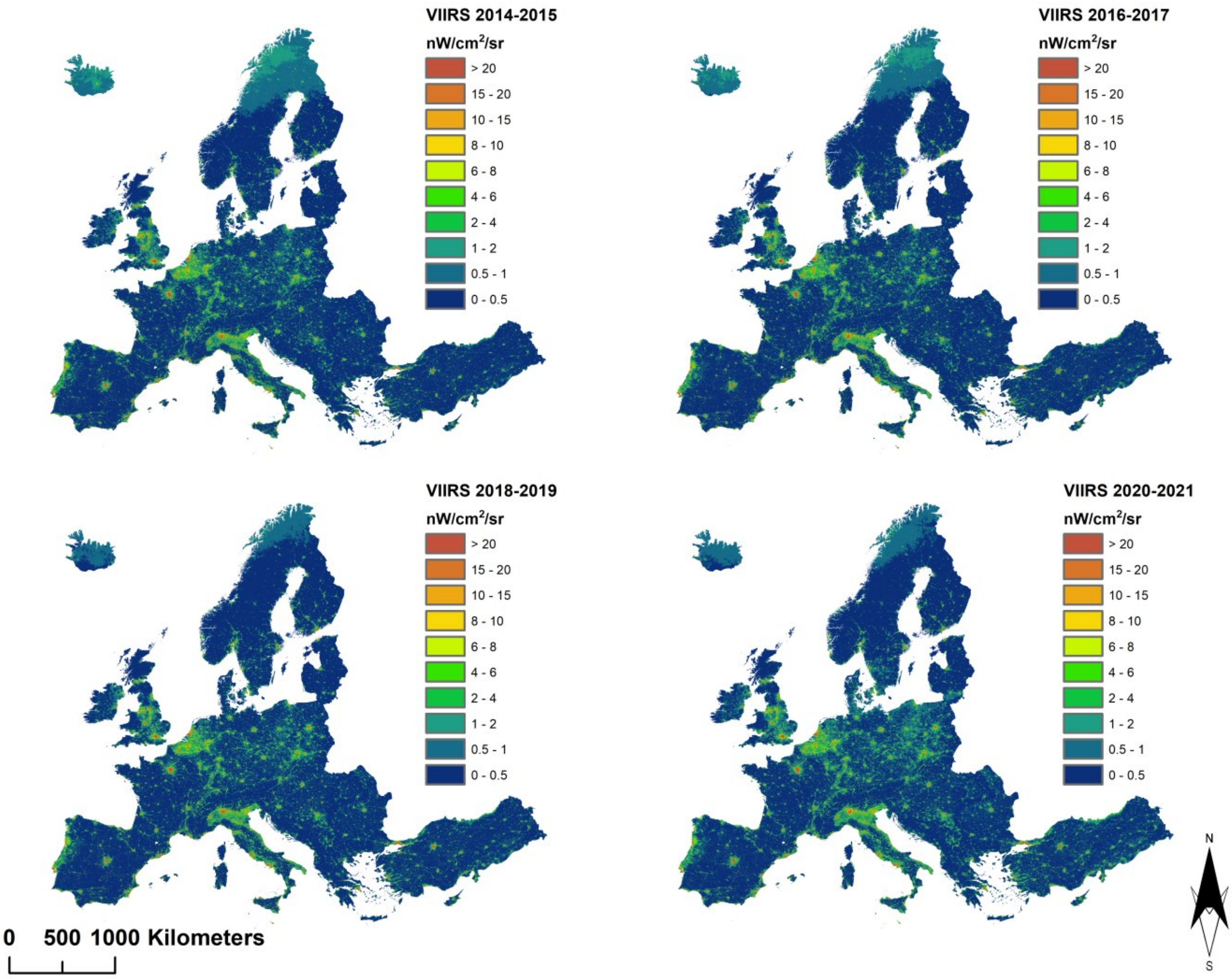
Figure 5.1: Density comparison of average values in European areas with light emission measurements ≤ 0.5 nW/cm²/sr (collected in 2016) for 2016 and 2017



Note: Density of measurements in pixels with average light emission levels ≤ 0.5 nW/cm²/sr in 2016 (upper panel) and the shift for mean values in the same pixels in 2017 (lower panel).
Source: Swiss TPH.

Figure 5.2 shows the running two-year averages of the resulting gridded light exposure levels (at 500 x 500 m² spatial resolution) covering the EEA 38 countries over the last eight years. Most light emissions are in the range of 2 to 6 nW/cm²/sr which is typical for sparsely populated rural and suburban areas. Extremely high levels of 20 to 35 nW/cm²/sr can be identified in the large cities such as Paris, London or Berlin. The comparison of the four time periods shows an increasing trend of total light emissions, especially within the low levels.

Figure 5.2: Comparison of 2-year-average light emissions in Europe from 2014 to 2021

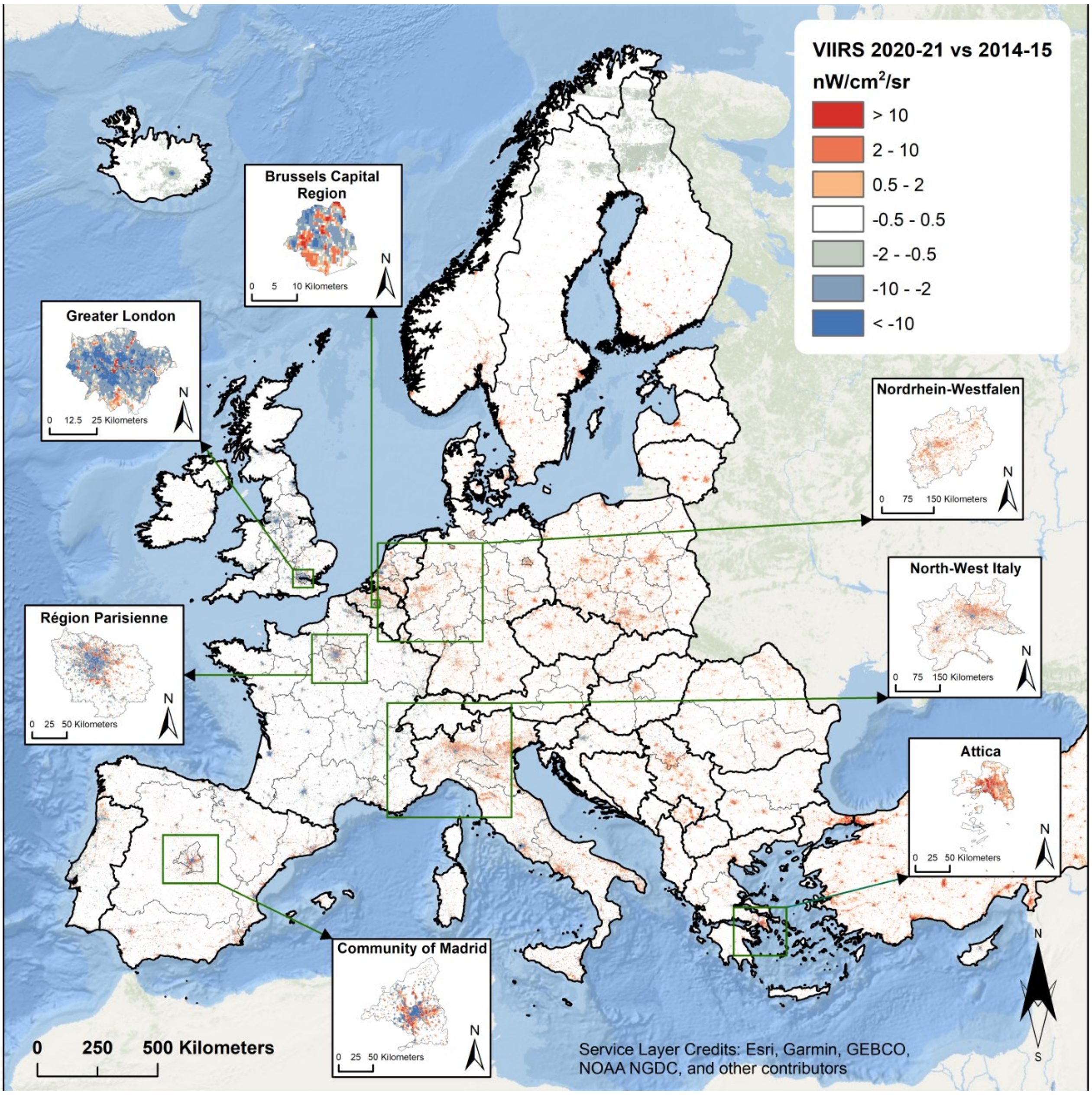


Note: Two-year averages of light emissions in the EEA38 countries over the past eight years (2014/15: upper left panel, 2016/2017: upper right panel, 2018/19: lower left panel, 2020/21: lower right panel). Legend shows thresholds of light emissions in $nW/cm^2/sr$. Maps were produced using satellite data obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) assembling radiometric measurements of light emissions.

Source: Swiss TPH.

Figure 5.3 depicts the differences in brightness between the last (2020/21) and the first (2014/15) averaging periods (in Figure 5.2) for each 500 x 500 m^2 pixel within Europe. It quantifies the net change in anthropogenic light exposure of the terrestrial surface in Europe over the past eight years. Differences between rural and urban regions are evident. Once again, the Eastern European regions show increasing light pollution trends, while the development of light emissions is rather neutral in France, Spain and Portugal. Changes in light emissions over the past eight years at densely populated centres such as Madrid, Brussels or London indicate a mix of patches with increasing and decreasing brightness levels.

Figure 5.3: The differences in brightness in EEA38 between the averaging periods of (2020/21) and (2014/15)

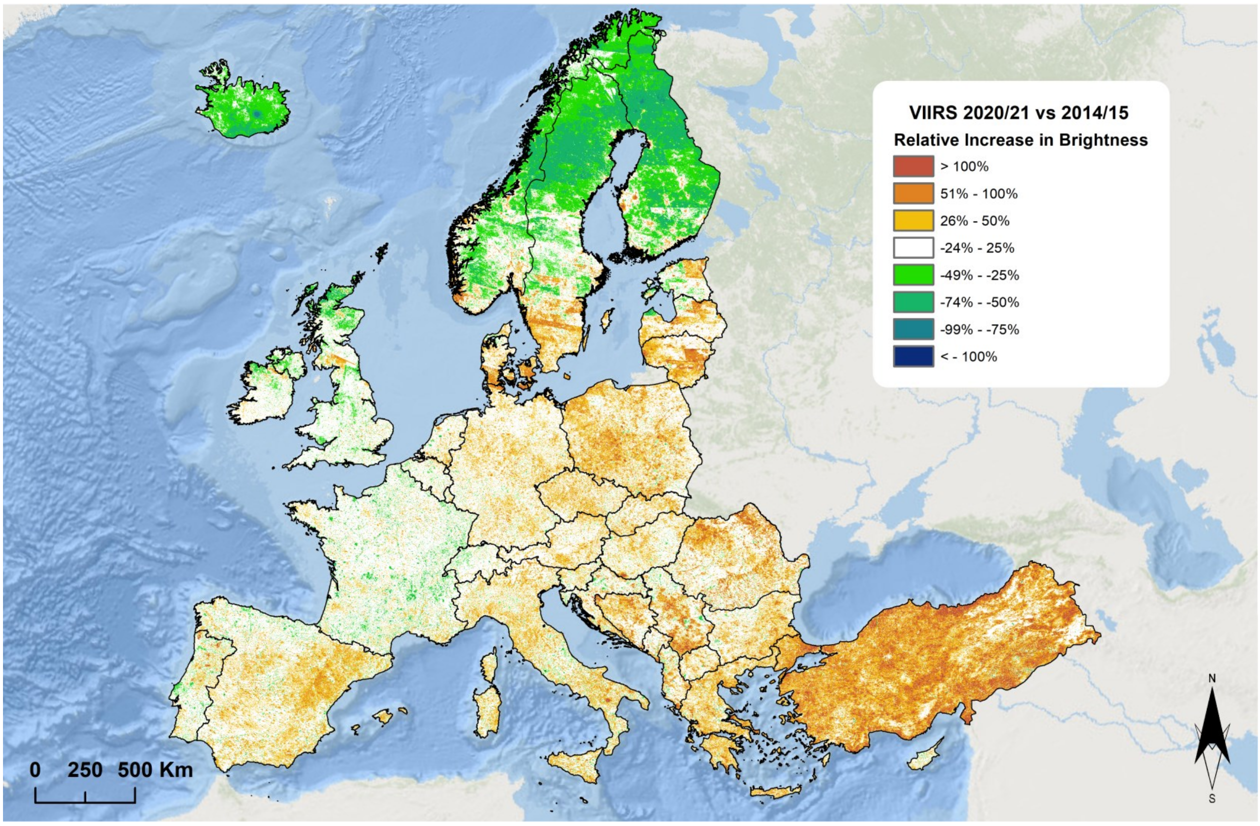


Note: Changes in brightness in Europe over the last eight years, calculated as the difference between the average light emissions in 2014/15 and 2020/21. Values of increasing (red colour) or decreasing (blue colour) artificial light vary between 0.5 - 10 nW/cm^2/sr. White colour denotes no change (i.e. differences lower than +/- 0.5 nW/cm^2/sr). The zoomed-in areas represent some of the level 1 subdivisions of the Nomenclature of Territorial Units for Statistics (NUTS 1) classification of the European Union.

Source: Swiss TPH.

Figure 5.4 shows the relative increase (%) in brightness in Europe over the last eight years; relative increase of more than 25 % is represented by yellow-red colours and relative decrease of more than -25 % with green-blue. White colour denotes no change (i.e. relative changes lower than +/- 25 %). A significant part of the continent has undergone a relative increase in brightness over 100 %, meaning that the light pollution levels more than doubled. This information has to be interpreted together with the absolute differences presented in figure 5.3, since these changes may not seem important in areas with initially low emissions. However, they clearly indicate an increasing trend across most of the European continent. A decreasing trend of light pollution is evident for regions in France and the UK. As previously explained progressive policies regulating light emissions have been recently adopted in these nations, which may possibly explain the changing light signal over the past 8 years. An even stronger relative decrease of light emissions is recorded in the higher latitudes of Europe. However, this is related to the fact that nocturnal light emission data collected by the VIIRS satellite are confounded by the radiance of Aurora events reflected from the Earth's surface as explained in section 7.1.2. This is particularly problematic in regions with extremely low light emission levels, in the range below 1 nW/cm^2/sr where a false impression of decreasing light pollution is created. Therefore, the indicated decrease of light emissions in Northern Europe may be accounted to a natural phenomenon rather than to a decrease of artificial light emissions. On the contrary, depicted trends in the rest of Europe may be explained by actual changes in the quantity of artificial lighting.

Figure 5.4: The relative increase in brightness in EEA38 between the averaging periods of (2020/21) and (2014/15)

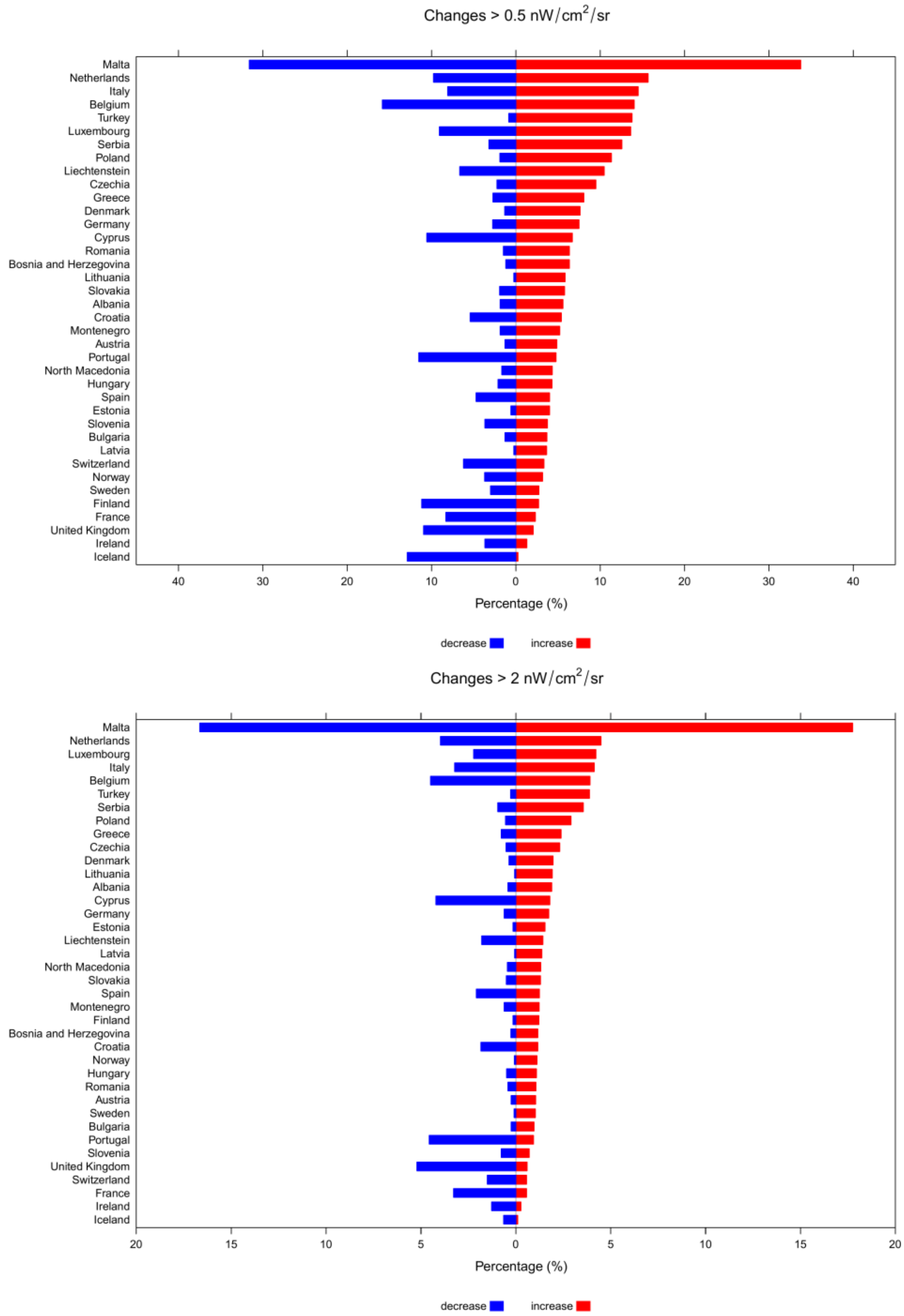


Note: Relative increase (%) in brightness in Europe over the last eight years, calculated as: $RI_{2020/21-2014/15}\,(\%) = 100 \times \frac{VIIRS_{2020/21} - VIIRS_{2014/15}}{VIIRS_{2014/15}}$. Relative increase above 25 % is represented by yellow-red colours and relative decrease more than -25 % by green-blue. White colour denotes no change (i.e. relative changes lower than +/- 25 %).
Source: Swiss TPH.

5.2 A Comparison of EEA Countries

Figure 5.5 illustrates the national differences between the first (2014/2015) and the last (2020/21) averaging periods using two threshold levels as presented in Table 4.2. The percentage of land surface area increasing or decreasing in brightness in each one of the 38 EEA countries was quantified for 2 nW/cm^2/sr (upper panel) and 0.5 nW/cm^2/sr (lower panel). Among the countries that experienced the largest increase in brightness over the past eight years are the Netherlands, Luxembourg, Poland and Belgium. A reduction in light pollution was evident for Iceland, Ireland and France for the two analysed thresholds. As previously discussed, the French legal framework regulating light pollution is progressive and strict compared to other European countries, which may have been a contributing factor to the decreasing trend. Another interesting example is Malta, where almost all the land surface experienced a change in light emissions over the past eight years. While about 32 % of the Maltese terrestrial surface experienced a decrease in brightness, up to 35 % of the area became brighter. When comparing the two threshold levels once again it is evident that the largest increase of artificial brightening happened within the lowest light emission level of 0.5 nW/cm^2/sr. The exact numerical values of areal increase in brightness per country are represented in table 5.1, further providing evidence for the different trends across Europe.

Figure 5.5: Land surface area change in brightness between the two time periods 2014/15 and 2020/21 - A country comparison



Note: Horizontal bars show the percentage of total land surface area within each country for which the artificial light has increased (red) or, decreased (blue) by at least 2 nW/cm^2/sr (upper panel) or at least 0.5 nW/cm^2/sr (bottom panel) between 2014/15 and 2020/21.
Source: Swiss TPH.

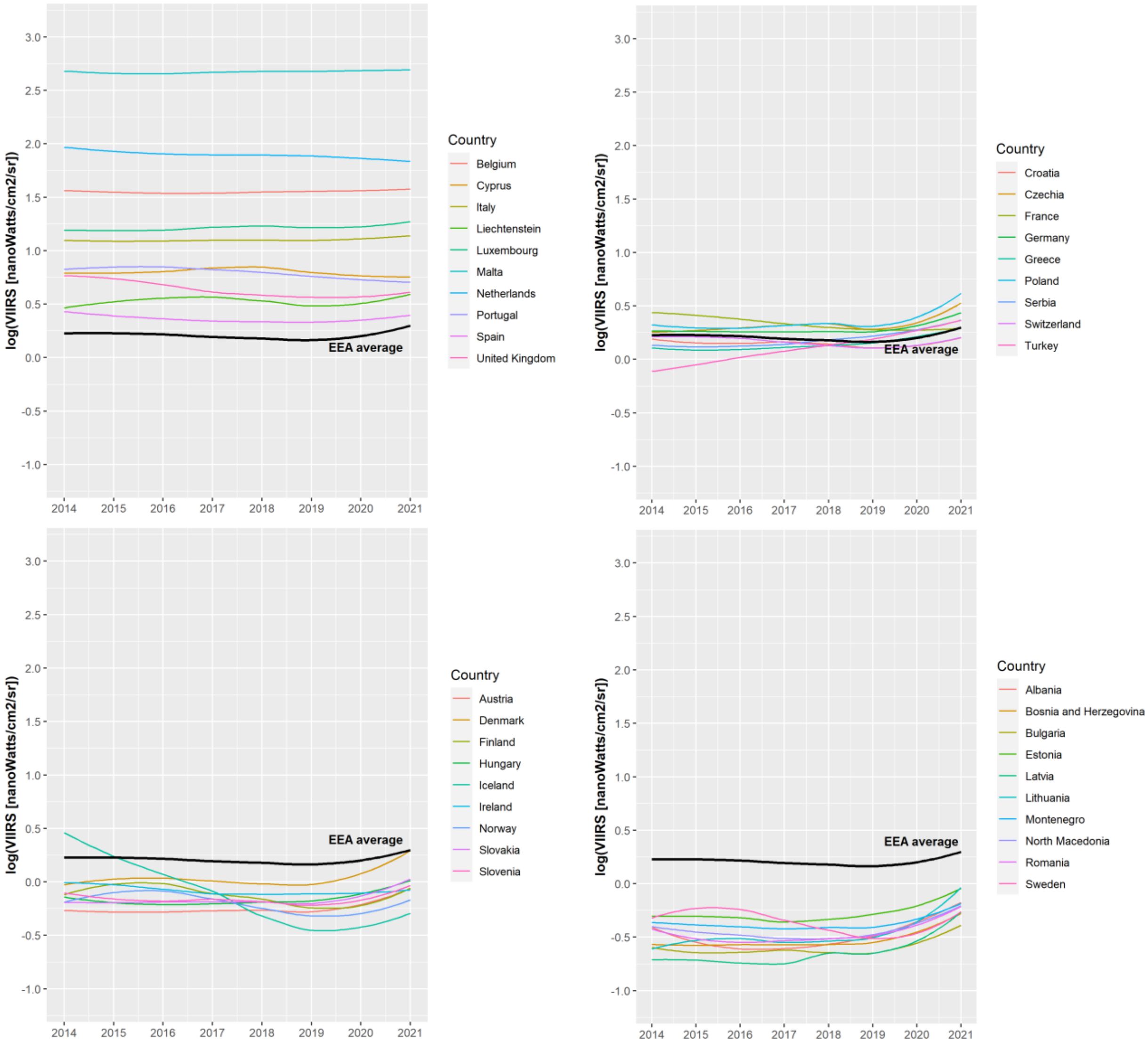
Table 5.1: Numerical values of land surface area change in brightness between the two time periods 2014/15 and 2020/21 - A country comparison

Country	Areal increase of > 0.5 $nW/cm^2/sr$ (%)	Areal decrease of > 0.5 $nW/cm^2/sr$ (%)	Areal increase of > 2 $nW/cm^2/sr$ (%)	Areal decrease of > 2 $nW/cm^2/sr$ (%)
Albania	5.6	1.9	1.9	0.4
Austria	4.9	1.3	1.0	0.3
Belgium	14.0	15.8	3.9	4.5
Bosnia and Herzegovina	6.3	1.2	1.2	0.3
Bulgaria	3.7	1.3	1.0	0.3
Croatia	5.4	5.4	1.2	1.8
Cyprus	6.7	10.6	1.8	4.2
Czech Republic	9.5	2.2	2.3	0.5
Denmark	7.6	1.3	2.0	0.4
Estonia	4.0	0.6	1.5	0.2
Finland	2.7	11.2	1.2	0.2
France	2.3	8.3	0.6	3.3
Germany	7.5	2.8	1.7	0.6
Greece	8.1	2.7	2.4	0.8
Hungary	4.3	2.1	1.1	0.5
Iceland	0.3	12.9	0.1	0.6
Ireland	1.3	3.7	0.3	1.3
Italy	14.5	8.1	4.1	3.2
Latvia	3.6	0.2	1.4	0.1
Liechtenstein	10.5	6.7	1.4	1.8
Lithuania	5.8	0.2	1.9	0.1
Luxembourg	13.6	9.1	4.2	2.2
Malta	33.8	31.6	17.8	16.7
Montenegro	5.2	1.9	1.2	0.6
Netherlands	15.7	9.8	4.5	4.0
North Macedonia	4.3	1.7	1.3	0.5
Norway	3.2	3.7	1.1	0.1
Poland	11.3	1.9	2.9	0.6
Portugal	4.8	11.5	0.9	4.6
Romania	6.4	1.5	1.1	0.4
Serbia	12.6	3.2	3.6	1.0
Slovakia	5.8	1.9	1.3	0.5
Slovenia	3.7	3.7	0.7	0.8
Spain	4.0	4.7	1.2	2.1
Sweden	2.7	3.0	1.0	0.1
Switzerland	3.3	6.2	0.6	1.5
Turkey	13.8	0.9	3.9	0.3
United Kingdom	2.1	10.9	0.6	5.2

Figure 5.6 shows the development of the average light emissions (on the log-scale) in the EEA38 countries during the past eight years (2014 - 2021). The upper left panel displays the nine countries with the highest (upper 25 % quantile) light pollution levels and the lower right panel shows the countries with the lowest (lower 25 % quantile) light emissions. A local polynomial regression (loess) function (Cleveland et al., 1992)

was fitted to the yearly average emission data (log-transformed) to graphically compare the temporal trends.

Figure 5.6: Annual mean VIIRS light emission trends during 2014 – 2021



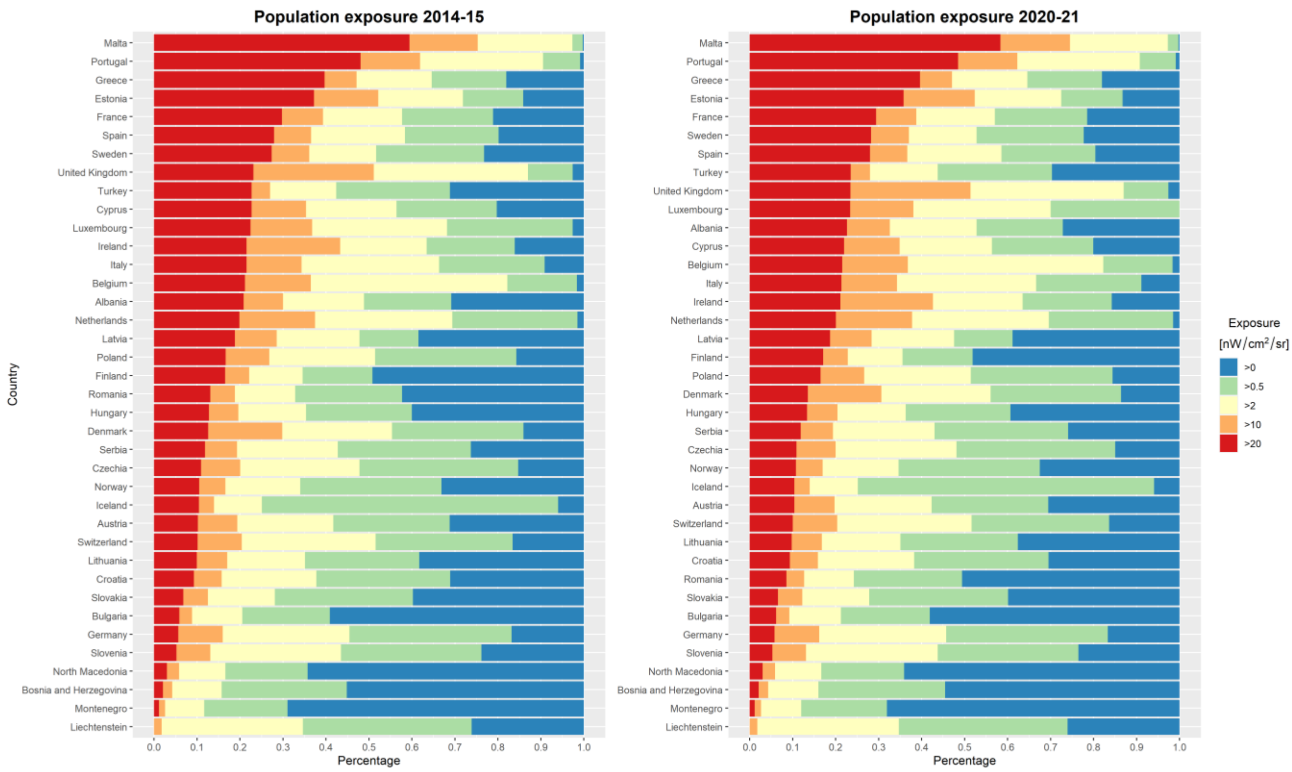
Note: The yearly-average light emissions (on log-scale) during 2014-2021 were computed for each EEA38 country from the monthly VIIRS data at 500 m^2 spatial resolution. A local polynomial regression (loess) smoothing function was fitted to the yearly average emission data (log-transformed) to graphically compare the temporal trends. The countries with the highest light emissions (upper 25 % quantile) are shown in the upper left panel, countries with the second highest light emissions (50 % – 75 % quantile) - in upper right panel, countries with the second lowest light emissions (25 % – 50 % quantile) - in lower left panel and countries with the lowest average light emissions (lower 25 % quantile) were grouped together in the lower right panel. The average light emissions of the entire EEA38 area is denoted with black bold curve in all four panels as a reference.

Source: Swiss TPH.

In Europe, Malta leads with the highest brightness, closely followed by the Netherlands and Belgium. However, it is important to mention that the size of a country, the density of the population and the level of infrastructure are the factors that may highly influence the country's light emissions; therefore, direct comparisons are not straightforward. The average light emission over the entire EEA38 area (denoted with black bold curve) may serve as a reference to compare the countries. Latvia used to be the country with the lowest light pollution levels up until 2018 but has now surpassed Bulgaria. It is evident that the countries with the least light pollution have experienced the highest changes in emissions recently. While the curves showing the light emission trends of the highest emitters are rather flat, a strong upwards trend can be observed for the countries with the lowest emission levels. The upward trend in the EEA average light exposure is also evident, especially after 2019.

Figure 5.7 shows the distribution of people exposed to different light emission levels (>0 $nW/cm^2/sr$, >0.5 $nW/cm^2/sr$, >2 $nW/cm^2/sr$, >10 $nW/cm^2/sr$ and >20 $nW/cm^2/sr$) in each EEA38 country. To achieve this, we overlayed the gridded population data from 2015 and 2020 (CIESIN, 2018) available at 1 km^2 spatial resolution with the VIIRS light emissions in 2014/15 and 2020/21 aggregated to the same spatial scale and calculated for each country the percentage of people living in areas corresponding to each exposure category. While over 50 % of the Maltese population is exposed to light emissions higher than 20 $nW/cm^2/sr$, in Liechtenstein, Montenegro or Bosnia almost no citizens experience such levels of brightness. In urbanized countries like Portugal, Greece or Sweden more than a third of the citizens are exposed to relatively high level of light pollution. Compared to the maps in Figure 5.2 showing the changes in the light exposure of terrestrial surface area over time (which indicate a clear temporal pattern), the changes in the percentage of people exposed to high light emissions between the two time periods (2014/15 and 2020/21) are less pronounced. This may indicate that the areal increase of light pollution may be accounted mostly to the growing global population and the related infrastructure developments and only to a lesser extent may be related to excessive lighting behaviours of the modern society.

Figure 5.7: The distribution of the percentage of people exposed to different light emission levels in each EEA38 country (2014/15 vs. 2020/21)



Note: Horizontal bars show the percentage of the total population exposed to different thresholds of artificial light (> 20 $nW/cm^2/sr$ – red, > 10 $nW/cm^2/sr$ – orange, > 2 $nW/cm^2/sr$ – yellow, > 0.5 $nW/cm^2/sr$ – green, > 0 $nW/cm^2/sr$ – blue) during the two time periods 2014/15 (left panel) and 2020/21 (right panel) per country.

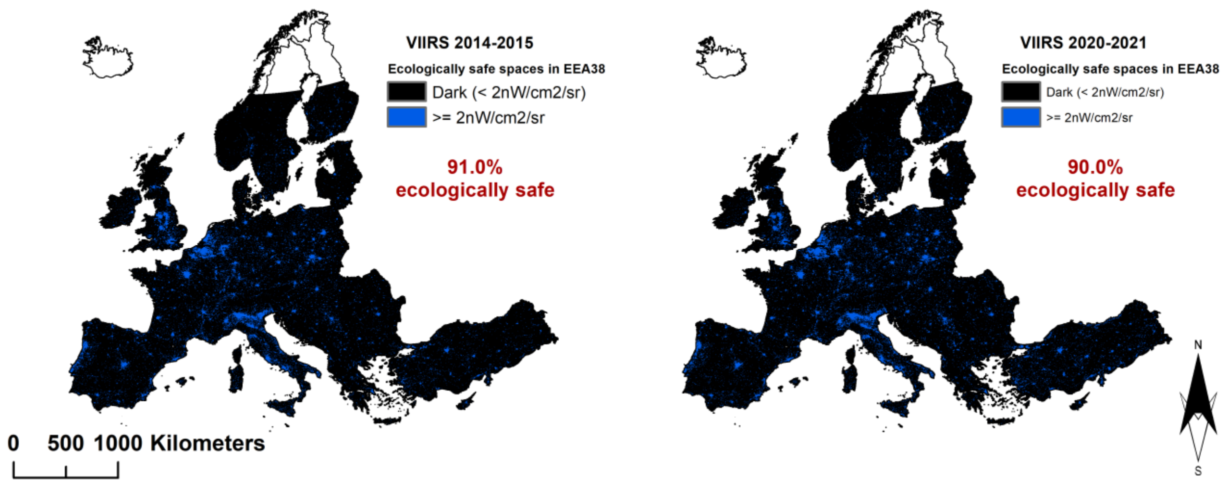
Source: Swiss TPH.

5.3 Signals Capturing Light Pollution Changes

The thresholds presented in Section 4.4 were used to develop signals capturing changes in light pollution across Europe. In particular, two signals were developed. One signal is based on the threshold of 2 $nW/cm^2/sr$, which serves as an indicator of ecological light pollution. Artificial light exposure above this limit is expected to elicit at least a small ecological impact. The second signal is based on the threshold of 0.5 nW/cm^2/sr, which is used as a proxy of areas with natural light conditions, because within this range light exposure qualifies as extremely low where a distinction of natural and artificial light sources becomes unreliable. In all four maps depicted in figure 5.7 and 5.8 the areas below either threshold level are depicted in black, while the terrestrial surface affected by light emissions above the selected limits is shown in blue. These maps need to be interpreted with caution because of uncertainties that are further explained in section 7. Due to the confounding effects of Aurora lights, the Northern region has been excluded as further explained in section 7.1.2.

Figure 5.7 shows the terrestrial surface of the 38 EEA countries with light emissions below the threshold of 2 nW/cm^2/sr above which a negative impact on ecosystems and its wildlife is expected, at least to a small extent. The regions, coloured in black, may be inhabited by wild species with only a minimal disturbance in terms of artificial light exposure. When comparing the areas with light emissions below 2 nW/cm^2/sr in the time period 2014/15 and 2020/21, there was a decrease from 91 % to 90 %. Even though this may not seem like a big change percentage-wise, this reduction in terrestrial surface that is labelled as 'ecologically safe' resulted in a decrease in habitat connectivity. Scattered spots of brightness may disrupt large contiguous tracts of land that used to be untouched by anthropogenic lighting installations and therefore very valuable for the preservation of the global biodiversity.

Figure 5.8: Signal 1 of ecological light pollution. Maps depict 'ecologically safe' areas affected by light emissions < 2 nW/cm^2/sr (2014/15 vs. 2020/21)

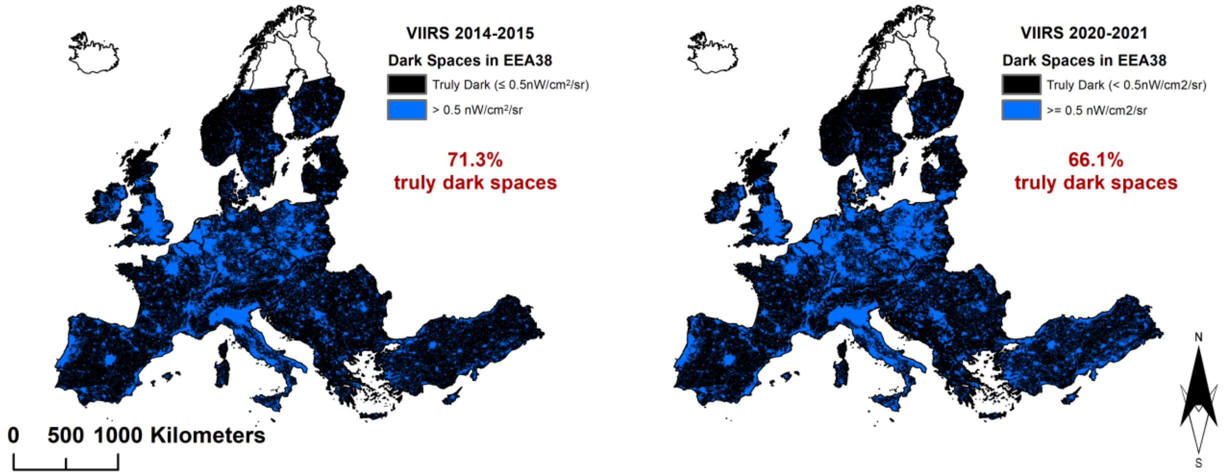


Note: European land surface with light emissions < 2 nW/cm^2/sr shown in black and areas with higher emissions in blue – a comparison between the two time periods 2014/15 and 2020/21. Exclusion of Northern region depicted in white due to confounding effect of Aurora lights. Proportion of "truly dark" spaces in red.

Source: Swiss TPH.

Figure 5.8 shows the terrestrial surface within the EEA territory below which wild species and also humans may experience relatively natural conditions (< 0.5 nW/cm^2/sr) unaffected by artificial lighting. The average terrestrial surface identified as 'truly dark' spaces within the 38 EEA countries amounted up to 71.3 % in 2014/15, but declined to 66.1 % over the last eight years. This corresponds to a total decrease of 5.2 % suggesting that a relatively large region of Europe has slightly increased in brightness, whereas there were not so many areas where the emission levels increased by high numbers. The impact of such small changes is however not well established, except in terms of deteriorating human views of the night sky.

Figure 5.9: Signal 2 of ecological light pollution. Maps depict 'truly dark' spaces affected by light emissions < 0.5 nW/cm²/sr (2014/15 vs. 2020/21)



Note: European land surface with light emissions < 0.5 nW/cm²/sr shown in black and areas with higher emissions in blue – a comparison between the two time periods 2014/15 and 2020/21. Exclusion of Northern region depicted in white due to confounding effect of Aurora lights. Proportion of 'truly dark' spaces in red.

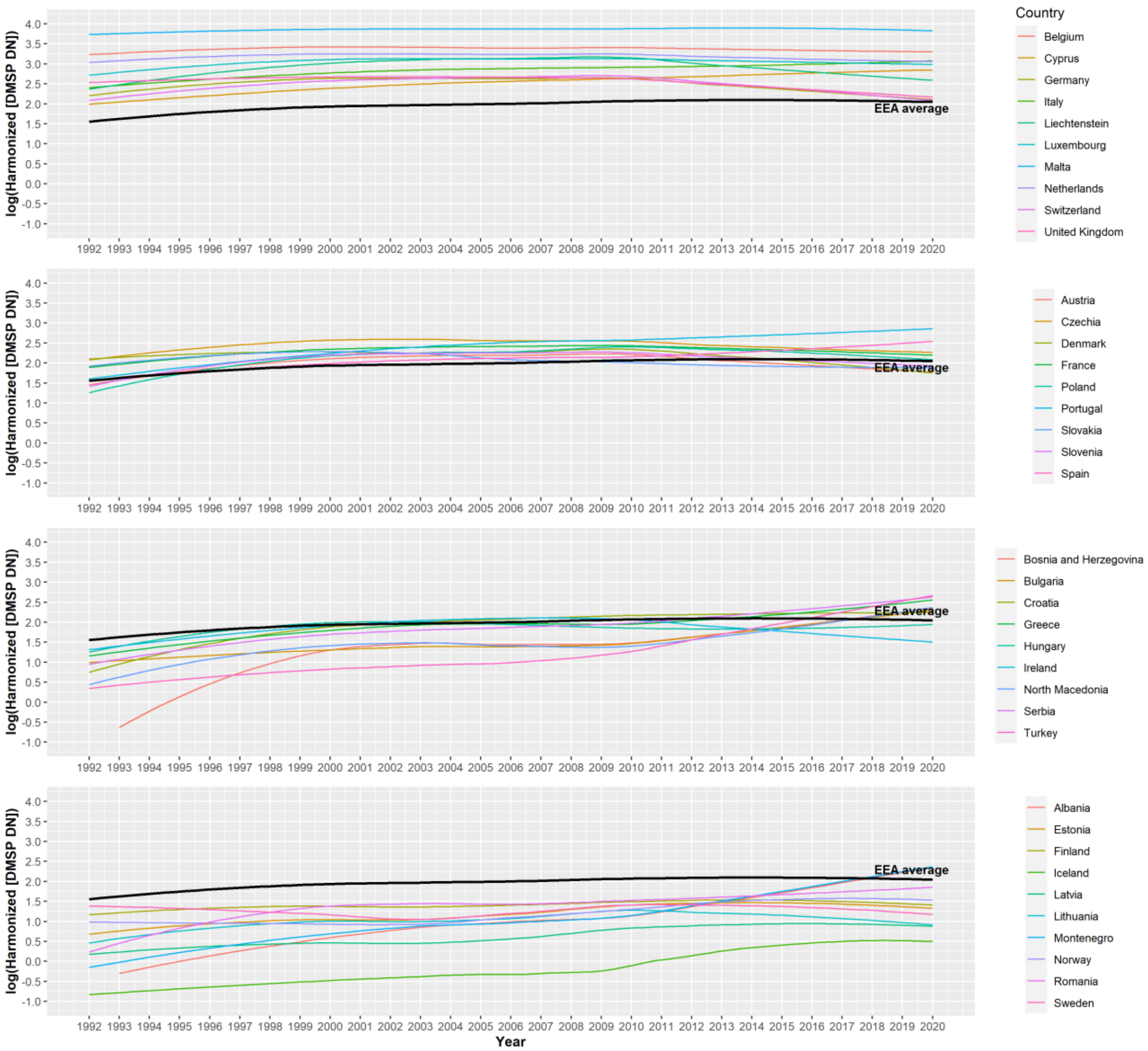
Source: Swiss TPH.

5.4 Historical Trends

As previously mentioned, two data sources are available synchronizing the night light emission measurements from the two remote sensing data sources i.e. DMSP and VIIRS. The "harmonized dataset" (Li et al., 2020) aligns the VIIRS data to the DMSP units and covers every year between 1992 and 2020. The "extended time-series data" (Chen et al., 2021), covers the period 2000 – 2020 and provides data in VIIRS units.

Figure 5.9 shows how the average light emissions in the 38 EEA countries developed since the nineties, making use of the harmonized DMSP data. The data is available at 1 x 1 km² spatial resolution and is measured in "digital numbers" (DN) ranging from 0 to 63. For a better comparison between the countries the trends are presented on a log-scale. Once again large differences between the light outputs of the countries may be observed. Countries in the lower half of the light emission ranking have experienced a steeper increase in brightness compared to the high-emitting countries. Overall, this data set is more consistent with historical DMSP data, whereas the VIIRS-derived results are more fluctuated during the period from 2015 onwards, especially for pixels with DN values lower than 10. This applies a larger uncertainty particularly to the regions with low luminance levels.

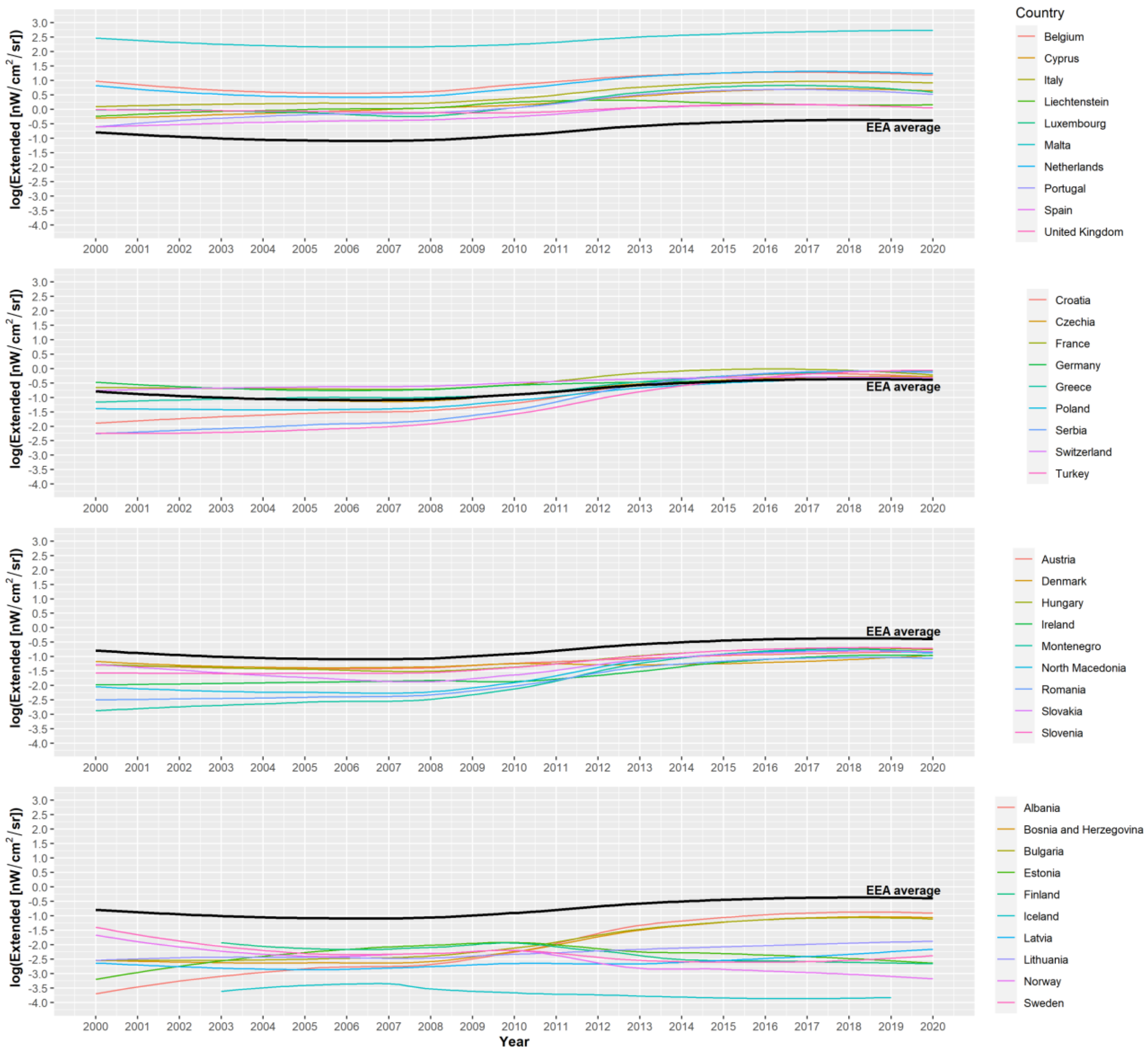
Figure 5.10: Annual mean light emission trends during 1992 - 2020 for each EEA38 country based on the harmonized historical dataset



Note: The yearly-average light emissions (on log-scale) during 1992-2020 were computed for each EEA38 country from the "harmonized dataset" data at 1 km^2 spatial resolution. A local polynomial regression (loess) smoothing function was fitted to the yearly average emission data (log-transformed) to graphically compare the temporal trends. The countries with the highest light emissions (upper 25 % quantile) are shown in the upper panel, countries with the second highest light emissions (50 % – 75 % quantile) - in the second panel, countries with the second lowest light emissions (25 % – 50 % quantile) - in the third panel and countries with the lowest average light emissions (lower 25 % quantile) were grouped together in the bottom panel. The average light emissions of the entire EEA38 area is denoted with black bold curve in all four panels as a reference.
Source: Swiss TPH.

Figure 5.10 depicts annual averages of light emissions over each EEA38 country between 2000 and 2020 based on the "extended time-series data" available at 500 x 500 m^2 spatial resolution. The measurement units are the same as in VIIRS (i.e. nW/cm^2/sr) and again a log-transformation was applied to the data for a more comprehensible picture. The main difference to the trends based on the harmonized data in Figure 9 is the fast increase in average light emissions around 2010. One limitation of this data is that for the years 2000, 2001 and 2002 here are missing values for some countries in Northern Europe.

Figure 5.11: Annual mean light emission trends during 2000 – 2020 for each EEA38 country based on the extended historical time series data



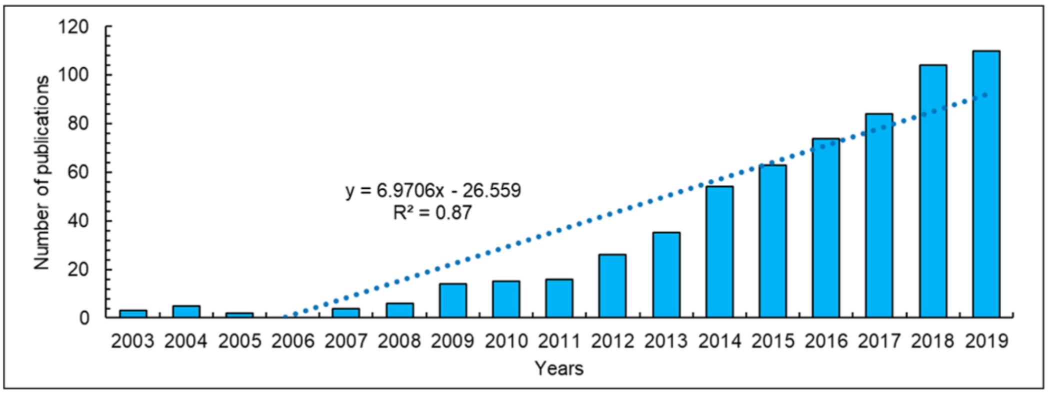
Note: The yearly-average light emissions (on log-scale) during 2000-2020 were computed for each EEA38 country from the "extended time-series data" data at 500 m^2 spatial resolution. A local polynomial regression (loess) smoothing function was fitted to the yearly average emission data (log-transformed) to graphically compare the temporal trends. The countries with the highest light emissions (upper 25 % quantile) are shown in the top panel, countries with the second highest light emissions (50 % – 75 % quantile) - in the second panel, countries with the second lowest light emissions (25 % – 50 % quantile) - in the third panel and countries with the lowest average light emissions (lower 25 % quantile) were grouped together in the bottom panel. The average light emissions of the entire EEA38 area is denoted with black bold curve in all four panels as a reference.

Source: Swiss TPH.

6 Current Research in Europe

As a parallel trend to the global increase in light pollution, the scientific body of literature concerned with the interdisciplinary impacts of artificial lighting has been growing. A literature search between 2003 and 2019 on the term "Light Pollution" showed a linear increase in scientific publications (Figure 6.1). A total of 57 countries are currently working on light-pollution related topics with the USA as front runner producing the most publications. Many research efforts also come from Germany, Australia, Spain, The Netherlands, UK and China (Rodrigo-Comino et al., 2021).

Figure 6.1: Linear increase of research on light pollution



Note: Number of scientific publications and recent trend on light pollution based on ISI Web of Science from 2003 to 2019.

Source: Rodrigo-Comino et al., 2021.

As a result, new methods to study ecosystem dynamics have been applied, the analysis and accuracy of remote sensing data has been improved and the public awareness due to the invention of progressive educational approaches has been increased. In the following section, we give an overview of the research currently carried out in different EU Member States aiming to tackle this environmental threat. A few examples of ongoing projects and recently published studies working with innovative methods across Europe were selected for this purpose. In the following section, we give an overview of the research currently carried out in different EU Member States aiming to tackle this environmental threat. A few examples of ongoing projects and recently published studies working with innovative methods across Europe were selected for this purpose.

6.1 Ecological Research

Various studies have provided evidence for negative consequences artificial lighting may elicit on a species level or even for entire taxonomic groups, however estimating the cascading effect such population changes may have for the entire ecosystem is more challenging. Recently, ecologist have aimed to quantify the potential of anthropogenic light sources to change ecosystem dynamics by disturbing trophic interactions.

Germany

The limnological institute in Konstanz has therefore chosen the approach to focus on one arthropod species known to be of pivotal ecological importance in aquatic habitats. Daphnia is an aquatic water flea that cleans the water from algal particles and at the same time serves as food source for a variety of species, placing this species in the centre of the food web. Zooplankton populations such as daphnia engage in diel vertical migration which is a light-dependent behaviour. During the night the entire population migrates towards the water layers at the surface until the onset of daylight makes them move back to the deep waters. On one hand, this creates a spatial and temporal window free of predators for phytoplankton and on the other it is an important nutrient transport for the next trophic level. The gene expression responsible for the circadian clock guiding this behaviour of Daphnia was found to be altered due to artificial light at night, which in turn may lead to a change in cyanobacterium growth (Cremer et al., 2022). The Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB) in Berlin invented a lighting installation emitting diffuse luminance to mimic different levels of skyglow and test the impact of artificial light on such ecosystem dynamics experimentally. The illumination system is innovative in its ability to produce a homogenous light field for an entire freshwater pond and thus enables the research of different light pollution scenarios under natural conditions with a special focus on phytoplankton-zooplankton interactions. The German research aiming to study the underlying mechanisms of ecological light pollution is part of the project Illuminating Lake Ecosystems (ILES), funded by the Leibniz Association and experiments are usually performed in the LakeLab (Jechow et al., 2021).

Further research launched by the IGB is directed towards understanding the effect of light pollution on the global insect communities. While the projects NaturLicht and Ausse are aiming to link the type of light source with insect species attracted by it, scientists of the BELLVUE projects work on the development of measurements that incorporate innovation light installations protecting the insect biodiversity (IGB, 2021).

Belgium

Another country investigating ecological effects by experimenting with innovative lighting systems imitating light pollution is Belgium. The Behavioural Ecology and Ecophysiology Group at the University of Antwerp installed LED lamps in boxes that are used for nesting by songbirds. In earlier work artificial light at night was linked to a disruption of behavioural patterns, physiological changes, decreasing fitness and higher levels of stress hormones. Nestlings were shown to be particularly vulnerable to the adverse effects of light pollution due to their immobility. The experimental construction allowed to test hypotheses in wild bird populations which were developed on the basis of results from the laboratory. In the most recent paper nesting great tits were exposed to low levels of light pollution for a week while characteristics related to the feathers, hormone concentrations and fledging success were assessed. Even though the treatment was limited to a relatively short period of time, consequences such as changes in feather density, metabolic alterations, and a reduction in body size were observed. These are typical indicators of physiological stress which may further result in a long-lasting decline of fitness. This experiment was performed as part of an FWO research project and funded by the University of Antwerp the FWO Flanders, the ANR, the CPER ECONAT and the European Commission (Grunst et al., 2020).

6.2 Research to Improve Measurement Methods

Today, the most conclusive data employed to model the global light pollution comes from satellite imagery, namely the two collecting remote sensing sources DMSP/OLS and VIIRS. Even though these two systems provide valuable temporal and spatial information about the artificial night-time lighting, the output is highly dependent on several technical factors. Some research is directed at improving the data analysis and the accuracy in the data collection process. Due to the high costs of remote sensing, alternative options to measure night-sky brightness are investigated in a similar manner and for the astronomical society methods to accurately measure the luminance on the ground level are also of importance.

Spain (& UK)

The collaborative Spanish and English work to improve the analysis of remote sensing data is part of three different projects: the Ecological Monitoring from International Space Station Images At Night (EMISSI@N) project, the Cities at Night project, and the Observing from the Stratosphere (ORISON) project. The EMISSI@N project was launched to improve the mapping of different artificial light sources and their spectral composition. The aim is to precisely quantify the biological consequences for humans and animals by making use of imagery from the International Space Station (EMISSI@N Project, 2022). Cities at Night project also makes use of photographs taken by astronauts on the ISS. Night-time photographs with high resolution are made accessible to the public with the goal to create a conclusive map of our planet at night by letting citizens catalogue, calibrate and georeference the collected data (Cities at Night, 2022). Within the framework of the ORISON project, an innovative device able to carry telescopes was developed

orbiting the earth in the lower layers of the atmosphere. This new technology is supposed to serve as an alternative for expansive remote sensing data collection systems (ORISON, 2022). Funding to finance this research comes from a NERC grant, the Fonds de Recherche du Québec - Nature et Technologies (FRQNT), the European Cooperation in Science and Technology (COST), the Loss of the Night Network the FPU grant from the Ministerio de Ciencia y Technologia and F. Sànchez de Miguel.
The latest scientific publication provided a guideline how to minimize imprecisions when estimating light pollution levels with DMSP/OLS and SNPP/VIIRS remote sensing data. A method to properly calibrate, process and georeference night-time images was suggested and the application explained using photographs of Spain as an example (de Miguel et al., 2021).

Poland

At the Electrical Engineering Faculty of the Bialystok University of Technology the research is directed towards increasing the measurement accuracy of night sky brightness using photometry. Since the luminance of the sky differs depending on the locality, a precise conversion factor to translate astronomical measurements to the visual photometric system is necessary in order to compare results in the astronomy community. The most recent polish scientific publication on light pollution has provided a possibility to convert results between the two photometric systems across the mesopic range, instead of the traditionally used photopic or scotopic range (Fryc et al., 2021).

6.3 Socio-Economic Research

In countries with an existing political framework in place to mitigate or reduce the negative impacts of light pollution, the scientific community works on the development of concepts to make the protection of darkness attractive for the citizens. Therefore, the research focuses on the socio-economic aspect of light pollution aiming to answer questions such as: How can we illuminate cities in an energy-efficient way and simultaneously keep the ecological impact at a minimum or how can we create incentives that increase the value of natural lighting conditions for the society?

France

The Interdisciplinary Carnot Laboratory of Burgundy (ICB) in Toulouse has developed an economic strategy to put a price on light pollution by turning darkness into a resource. It is an approach that in case of a successful implementation would likely result in a deliberate inclusion of reducing light emissions in urban city planning. Through case studies of two regions in the mountains it was shown that the economic value of good sky quality and an intact nocturnal landscape have the ability to compensate for the monetary profit that could have been achieved through other industrial activities. By simultaneously recognizing sustainable development and the preservation of biodiversity as a part of the national economy, rural regions with low levels of light pollution have the potential to gain economic relevance. This work has been developed through the French program Investissements d'Avenir which is funded by the National Research Agency (ANR). The aim of this initiative is to diversify and modernize economies by supporting innovation in neglected sectors (Lapostolle & Challéat, 2021). Another suggested method to increase the preservation efforts of natural light conditions and nocturnal environments is the concept of dark ecological networks. Population numbers of species from various taxa have been declining and community dynamics have been changing due to the loss and fragmentation of habitats. Whereby, anthropogenic light sources have been recognized as key factors in disrupting landscape connectivity both spatially and temporally. It has been shown that artificial night-time light has the potential to isolate individuals of the same species by creating lit areas that are difficult to cross thus acting as physical barriers or that it may disrupt the synchronization of behaviour in species groups that depend on light cues. To avert these negative ecological implications, dark ecological networks were designed to protect the nocturnal environment with the purpose of increasing ecological utility. The focus is the preservation of the most valuable core areas of darkness, which may then be surrounded by buffer zones, small patches in between dark spots and corridors to maximize habitat connectivity. By combining this structural approach with educational efforts informing citizens about wildlife movement, landscape use and the negative consequences of light pollution, societal and political awareness is expected to increase. In case of an incorporation of dark ecological networks into policy systems, land use planning and conservation actions the protection of the darkness should directly translate to the preservation of biodiversity. Besides the Investissements d'Avenir program, the development of this concept is part of the national research program on transport, infrastructure, territories, ecosystems and landscapes (ITTECOP), which was created by the French Ministry of Ecological Transition (MTE) in collaboration with the French Agency for the Environment and Energy Management (Ademe). The goal of this research is to implement the preservation of ecological frameworks and landscape structures into the planning of infrastructure projects. Dark ecological networks were invented as part of the CHIROLUM project dedicated towards reducing the ecological impacts of artificial light at night along public infrastructures. Also involved was the Conseil Régional Nord-Pas-de-Calais and the Fondation pour la Recherche sur la Biodiversité that manage the TRAME NOIRE project with the mission to protect the French biodiversity (Challéat et al., 2021).

Spain

At the University of Granada, researchers at the Department of Civil Engineering are concerned with the effect the transition to energy-efficient light emitting diodes (LED) may have on light pollution levels. The reason for this work is the worry that the low costs of the new light installations may lead to inconsiderate lighting practices and that white and blue wavelengths were shown to be more harmful to the wildlife compared to conventional light sources. The most recent published paper provided a comparison of white and yellow LED systems. Various lighting scenarios were simulated in rural regions with the aim to minimize light pollution without compromising lighting performance. Political tools adapted to the modern LED lamps were shown to primarily include regulations restricting the blue light component or Rayleigh scattering. However, a legislative basis beyond technical guidance including design suggestions that tackle safety issues and simultaneously ensure the achievement of sustainable development goals is apparently missing. Several suggestions to maintain visual performance at low luminance levels and to avoid light trespass to decrease ecological implications were provided (Peña-García & Sędziwy, 2020). Economists at the Faculty of Business and Management, also from the University of Granada, investigate design innovations with minimal light pollution to decrease monetary losses and increase energy efficiency. Instead of an ecological stand point, they promote the concept of circular economy and investigated how sustainable energy use can be improved in rural communities. As a result a local biomass plant able to feed the public light system with electricity was invented (Molina-Moreno et al., 2018).

Slovakia

A research group at the Faculty of Natural Science of the Matey Bel University in Banská Bystrica conducted a site-evaluation to find the best locations for astrotourism. This provides evidence for the economic value of a clear night sky and shows that the importance of preserving a high sky-quality is recognized. In the survey the night sky brightness was recorded with sky quality meters (SQM) and the investigated sites were categorized by potential for astrotourism development. Given that policy makers plan to maintain these valuable locations for astronomers, this is another way how the mitigation of light pollution can be included socio-economically (Kanianska et al., 2020).

7 Emerging Issues

7.1 Technical Issues with Satellite Imagery

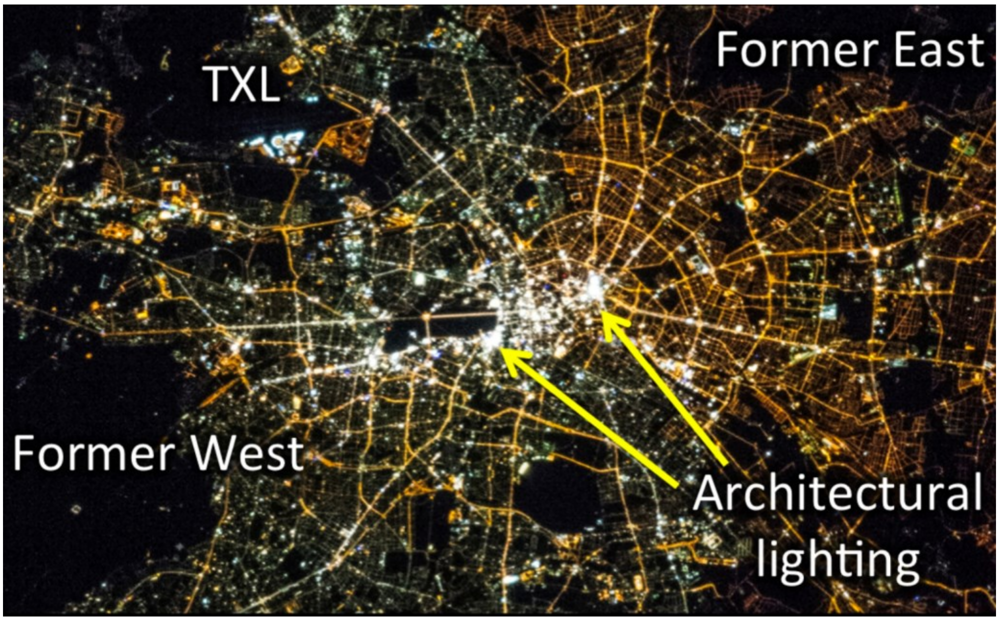
How light emissions appear on a satellite image is highly dependent on different factors such as type of emitting light source, time of picture taken, weather condition, or collecting data source.

7.1.1 The Characteristics of the Emitted Light

Depending on the utilized lighting system, the colour scheme and light intensity appearing on a satellite image may vary. Each emitting light sources gives off a characteristic set of wavelengths which is distinctive in its spectral composition. Traditional sodium-dependent street lamps that were mostly installed during industrial times emit wavelengths in a narrow range around 598.3 nm perceived as orange or yellow by the human eye. Newer lighting technologies such as LED-lamps may emit light in a wide bandwidth of different wavelength around 400 and 700 nm from the white until the ultraviolet part of the spectrum and are perceived as much brighter light sources. Captured by a satellite, light emitted by mercury and metal-halide powered lamps or fluorescent and LED light sources appear white, while high or low-pressure sodium lamps are displayed in orange. The replacement with energy-efficient lighting technology is lagging behind in the Eastern part of Berlin compared to the Western part reflecting the divided history of these city districts. While the emitted light in the West appears white, the Eastern area is still orange (Kyba et al., 2014).

Satellite imagery may further help to identify the direction of light emitted by a particular light installation. Whereas architectural lighting systems often shine directly upwards rather than illuminating a building itself, streetlights or lit signs are often shielded and appear less bright from space. Image 7.1 shows an image of Berlin taken from the ISS. Clear differences in colour of the emitting light sources can be detected between the East and the West. Bright spots in the urban centre represent architectural lighting systems with direct upward light. These light sources would be detected as white but may appear blue on the photograph which is most likely caused by the colour balance of the photograph (Kyba et al., 2014).

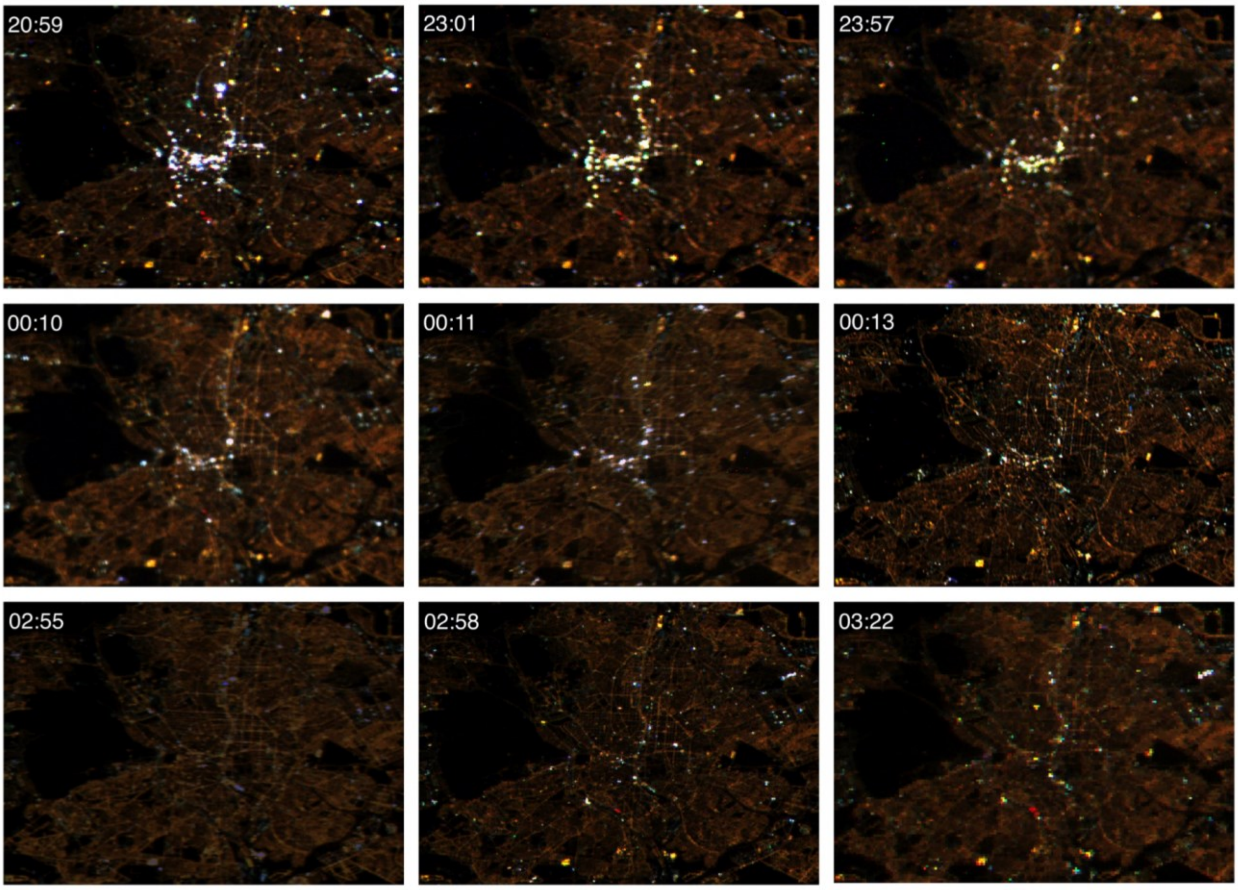
Image 7.1: Satellite imagery of Berlin showing different light sources



Note: Cropped portion of another image of Berlin taken from the ISS (iss035e17210). Tegel airport is labeled with "TXL". Image courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.
Source: Reproduced from Kyba et al., 2014.

While some light sources such as airports, train stations or ports are almost constantly lit, most lighting systems are switched on for only a limited period during the night. Image 7.2 shows the total light emissions coming from Madrid at different time points. As the night progresses, the use of individual light sources consistently decreases resulting in a decline of the total night sky brightness. This illustrates how the quantification of light pollution is highly dependent on the time of the remote sensing analysis (Kyba et al., 2014).

Image 7.2: Satellite imagery of Madrid at different times during the night

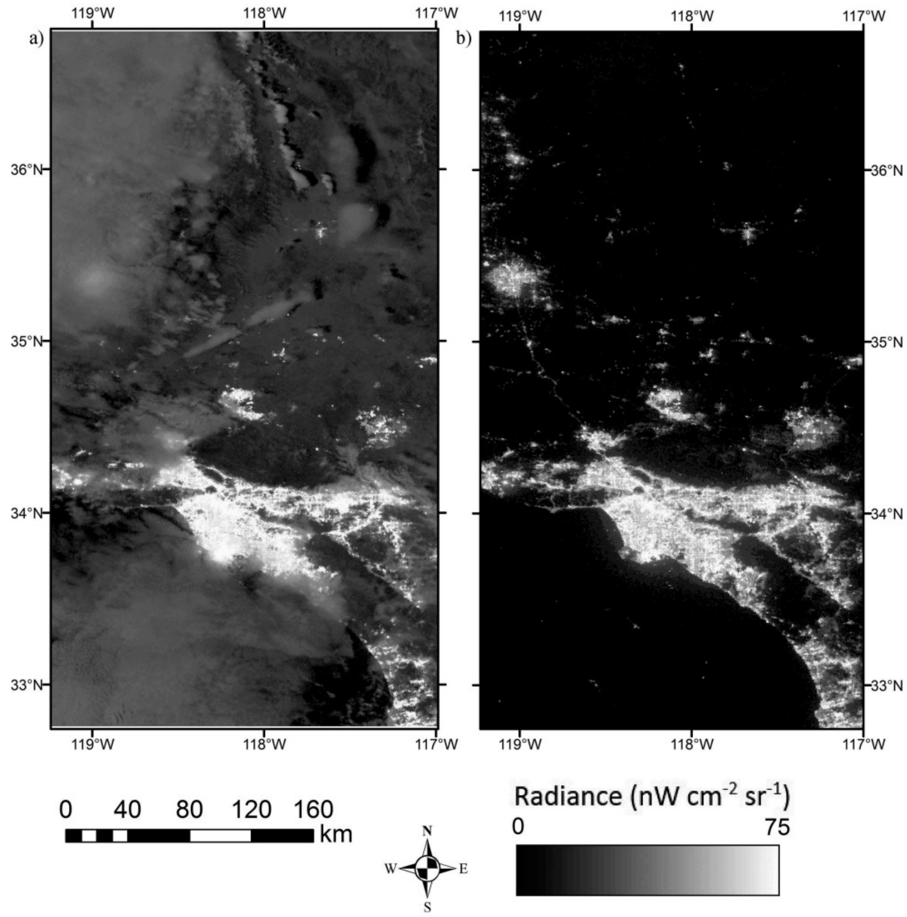


Note: Nine photographs of Madrid at different times of night. The images are arranged to show increasingly late times from top left to bottom right. Images courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.
Source: Reproduced from Kyba et al., 2014.

7.1.2 The Influence of Weather, Moon Light Conditions and Aurora Events

Satellite data is also highly dependent on the weather conditions. The sky was found to be brightened by a factor of 2.8 - 10.1 due to cloud cover depending on the urbanity of the area (Kyba et al., 2011). In a similar way, snow cover has the potential to significantly increase the luminance of the sky by reflecting any type of lighting. The effect is even more pronounced in areas with high levels of skyglow (Aubé, 2015). Another natural factor having the potential to increase light pollution levels is the elevation of the moon. Its natural brightness has the capability to illuminate the earth's surface to an extent that clouds and structural features of the landscape may be detectable on a satellite image. Conversely on a moonless night, the weather conditions are less likely to skew artificial light emission measurements. In image 7.3, a satellite image of the American West Coast taken during full moon is compared to a photo from a night during new moon. While faint outlines of the landscape can only be seen upon close inspection in the dark setting, the coast is clearly visible and the clouds strongly reflect the luminance of the full moon in the picture on the left (Elvidge et al., 2017).

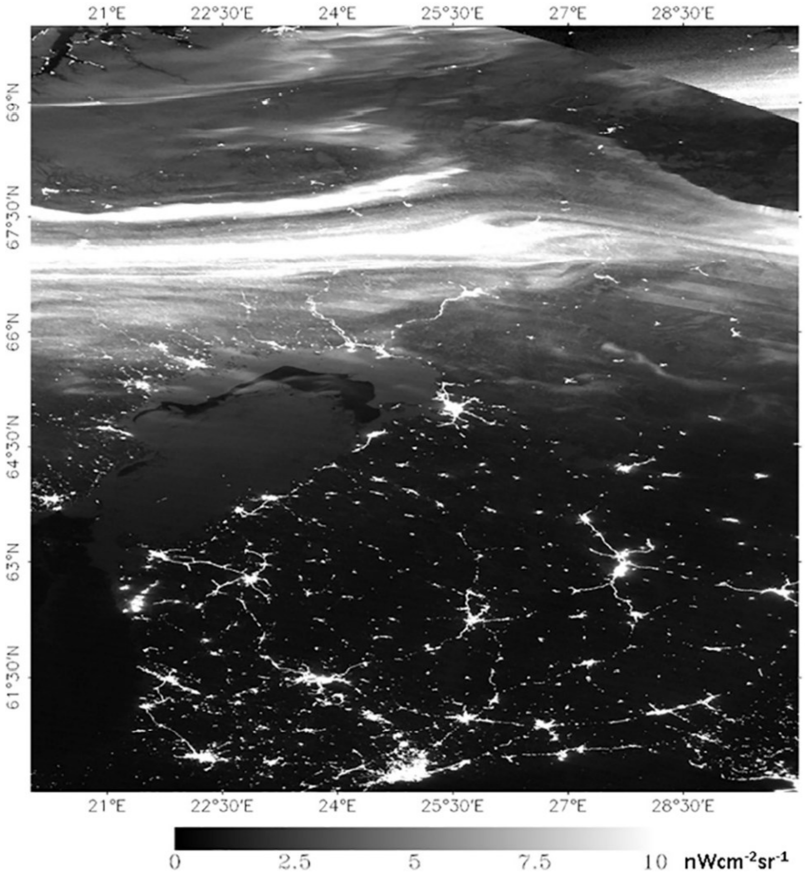
Image 7.3: Satellite imagery during different moon light conditions



Note: Full moon versus new moon image of the Los Angeles region captured by the VIIRS.
Source: Reproduced from Elvidge et al., 2017.

Additionally nocturnal light emission data as collected by the VIIRS satellite may be influenced by the radiance of Aurora events reflected from the Earth's surface. VIIRS is able to detect extremely low levels of light emissions in the visible wavelength range of 500 to 900 nm. Since the Aurora lights contain emission lines of atomic oxygen with a bandwidth of 557 to 630 nm and molecular nitrogen emission lines within 600 and 700 nm, this light signal is also captured (Seaman & Miller, 2013; Wang et al., 2021). Image 7.4 was taken during a moonless night showing the reflected aurora lights in the higher latitudes of Europe.

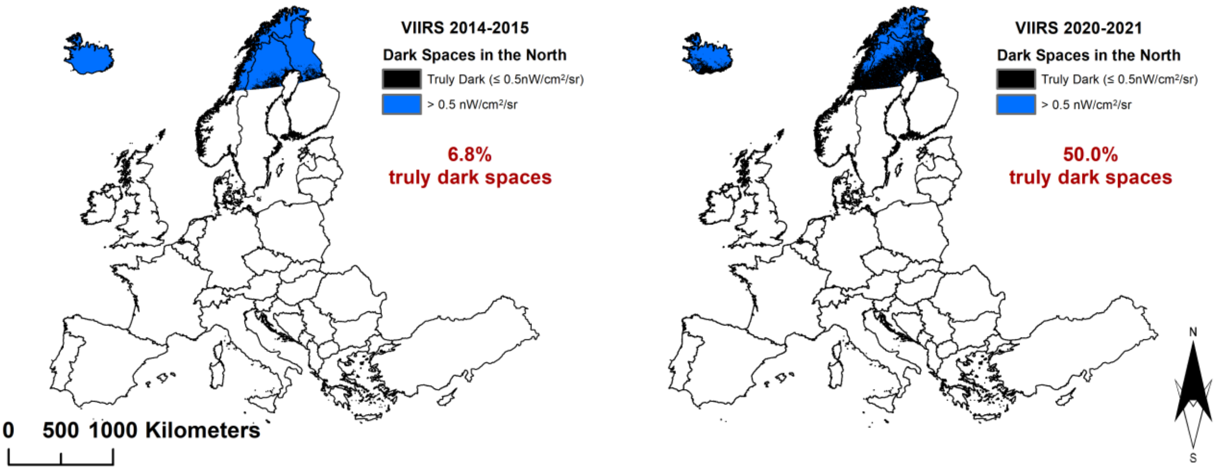
Image 7.4: Satellite imagery capturing Aurora event



Note: Aurora event in Northern Europe as captured by the VIIRS satellite in 2018.
Source: Reproduced from Wang et al., 2021.

When analysing the VIIRS data to produce the figures in section 5, this phenomenon was found to be a confounding factor in regions with extremely low light emission levels, in the range below 1 nW/cm^2/sr. As an example, figure 7.1 shows light emissions below 0.5 nW/cm^2/sr in black and areas with higher light levels in blue for the two time periods 2014/15 and 2020/21 in Northern Europe. The increase of black parts in the map gives the impression of a decreasing light pollution trend. However, the higher light emission levels in 2014/15 may be accounted to a natural phenomenon.

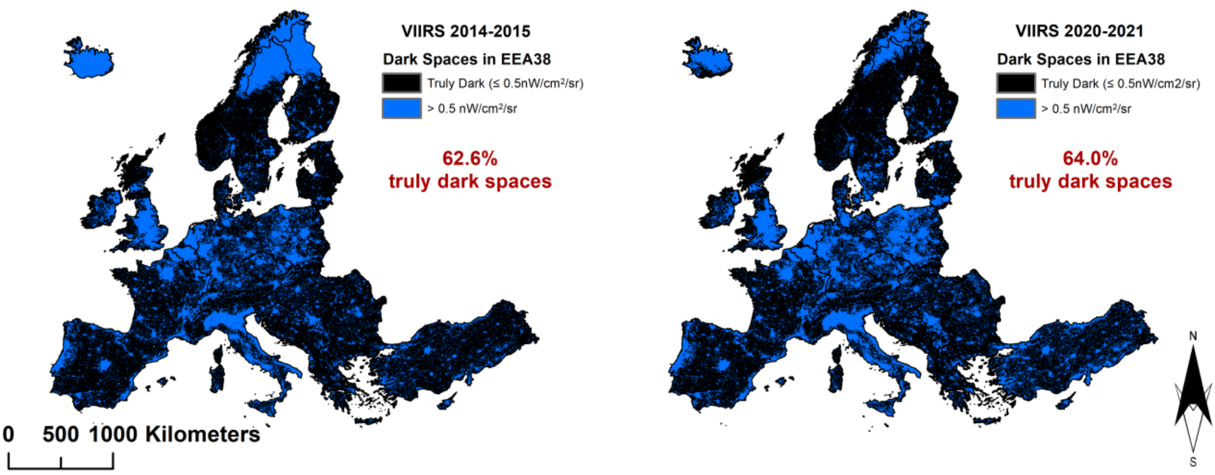
Figure 7.1: Increasing areas with light emissions below 0.5 nW/cm²/sr in Northern Europe due to Aurora events



Note: Land surface in Northern Europe with light emissions < 0.5 nW/cm²/sr shown in black and areas with higher emissions in blue. Proportion of "truly dark" spaces in red.
Source: Swiss TPH.

On the contrary, the increasing light emissions recorded in the rest of Europe show the actual trend of growing areas impacted by artificial lighting (as discussed in section 5). But when analysing pixels covering all 38 EEA countries, the area with a light signal < 0.5 nW/cm²/sr as captured by the VIIRS satellite seems to have increased by 1.4 % giving a false sense of decreasing light pollution levels due to Aurora lights in the North.

Figure 7.2: Average decrease of areas with light emissions below 0.5 nW/cm²/sr in all EEA38 countries showing confounding trend



Note: Land surface of EEA38 countries with light emissions < 2 nW/cm²/sr shown in black and areas with higher emissions in blue. Proportion of "truly dark" spaces in red.
Source: Swiss TPH.

7.1.3 Limitations of the Collecting Data Source

The quantification of light pollution may vary based on the satellite imagery system collecting the data. For instance, the VIIRS is characterized by its near infrared sensitivity but relative insensitivity to blue light. While areas near oil wells or volcanoes are estimated brighter than what the human eye perceives, the satellite source is virtually blind to the increasingly popular LED-lighting systems, which account for a large portion of the total light emissions. Especially, lighting installations emitting lights with wavelengths below 500 nm may not be perceived. Blue light scatters more than red or yellow light, which makes it more difficult for the satellite to capture these light emissions. Because VIIRS measures over a wide range of wavelengths, but not all of the thermal detectors of the sensor are operating at maximum power, the measured values of light at lower wavelengths are less accurate (Pérez Díaz et al., 2021). This may result in optimistic displays of a global reduction in light pollution, creating a false impression (Kyba et al., 2017; Lyytimäki, 2020). Comparatively, DMSP/OLS data may overestimate light emissions in urbanized settlements because of the relatively low resolution, also known as the blooming effect. Bright lights may scatter into neighbouring grid cells resulting in an underestimation of the spatial heterogeneity and therefore an increase of the estimated overall light pollution (Huang et al., 2014).

7.2 Interplay of light pollution with other pollutants

It has been shown that the level of light pollution is highly dependent on the number of particles in the sky. Aerosols and water droplets in the lower atmosphere cause a scattering of the artificial light emitted upwards, which consequentially results in a lingering of the illumination and an increase in light pollution. Yet, the interaction of light pollution with other pollutants is still poorly understood and therefore a growing concern of the science community. Related to this, a quantitative model for urban skyglow was developed in the Slovak Academy of Science in Bratislava. Aerosols differ in chemical composition and density distribution eliciting a varying effect on the scattering effect of light emitted upward from anthropogenic light sources. The light cones lingering over urban centres were analysed via remote sensing data. The detected distribution of the diffuse light gave insights into the aerosol properties, which were detailed enough to allow a quantification of air pollution levels. Based on these findings, a practical method was invented to record the size and composition distribution of aerosol particles through satellite imagery (Kocifaj & Barentine, 2021). This provides evidence that other pollutants have the potential to amplify the negative effects of light pollution.

7.3 Light pollution linked to Population Movement

The amount of light pollution was found to be highly linked to urban expansion and human activity (Dunnett, 2015; Lamphar, 2020). Images taken at night via remote sensing techniques are often used as a proxy for the socio-economic status, level of urbanity and economic wealth. This however implies that any connection between light pollution and another factor related to human or ecosystem health is likely to be confounded (Nadybal et al., 2020).

7.4 Limited Evidence to Establish Light Pollution Thresholds

To date, there generally recognized threshold values that would define acceptable light intensities below which negative impacts on human health or ecological implications are non-existent or at least only minor are missing. When analysing ecological zones based on VIIRS night-time data, at least a low negative impact on ecosystems and biodiversity was established at locations with light emission above 2 nW/cm^2/sr (Hale et al., 2018). Whether this limit is low enough for the areas to be called ecologically safe has not been sufficiently researched yet (Hale & Arlettaz, 2019). A variety of different light intensities have been tested in experiments or studies examining an association between adverse health effects and ALAN, but a threshold below which human health is unaffected is still unknown (Esaki et al., 2019; M. Kim et al., 2018; Patel, 2019; Viola et al., 2008). Because values are expected to vary with individual characteristics and the sensitivity range of each species the definition of such limits is difficult. In order to mitigate the ecological impact caused by light pollution, dark environments which light-sensitive species may use to retreat should be maintained and protected. Additionally, future research should aim to support methods for an environmental and ecological impact assessment of artificial light. A better understanding of the spectral composition, periodicity and spatial distribution of anthropogenic light coupled with a systematic knowledge of ecological relationships and how these are influenced by a disruption of the natural light cycles is necessary (Gaston et al., 2013). In general, light pollution thresholds at which an impact on human health are expected to be higher compared to the limit at which ecological implications begin.

List of Abbreviations

Abbreviation	Name
ALAN	Artificial Light At Night
$arcsec^2$	square arcsecond
cd	candela
cm^2	square centimetre
DMSP	Defence Meteorological Satellite Program
DN	Digital Numbers
DNB	Day/Night Band
EEA	European Environmental Agency
EU	European Union
kcd	kilocandela
klm	kilolumen
IGB	Leibniz Institute of Freshwater Ecology and Inland Fisheries
ipRGCs	intrinsically photosensitive retinal ganglion cells
LAN	Light At Night
LED	Light Emitting Diode
LP	Light Pollution
lx	Lux
m^2	square meter
mcd	milicandela
mag	magnitude
mag_V	magnitude emitted in the green V spectral band (v = visual)
mag_{SQM}	magnitude measured with a sky quality meter
NELM	Naked-Eye Limiting Magnitude
nL	nanolamberts
NSB	Night Sky Brightness
nW	nanoWatt
OLS	Operational Linscan System
PSQI	Pittsburgh Sleep Quality Index
SCN	Suprachiasmatic nucleus
SQM	Sky Quality Meter
sr	steradian
UK	United Kingdom
US, USA	United States of America
VNIR	Visible and Near-Infrared
VIIRS	Visible Infrared Imaging Radiometer Suite
WHO	World Health Organization

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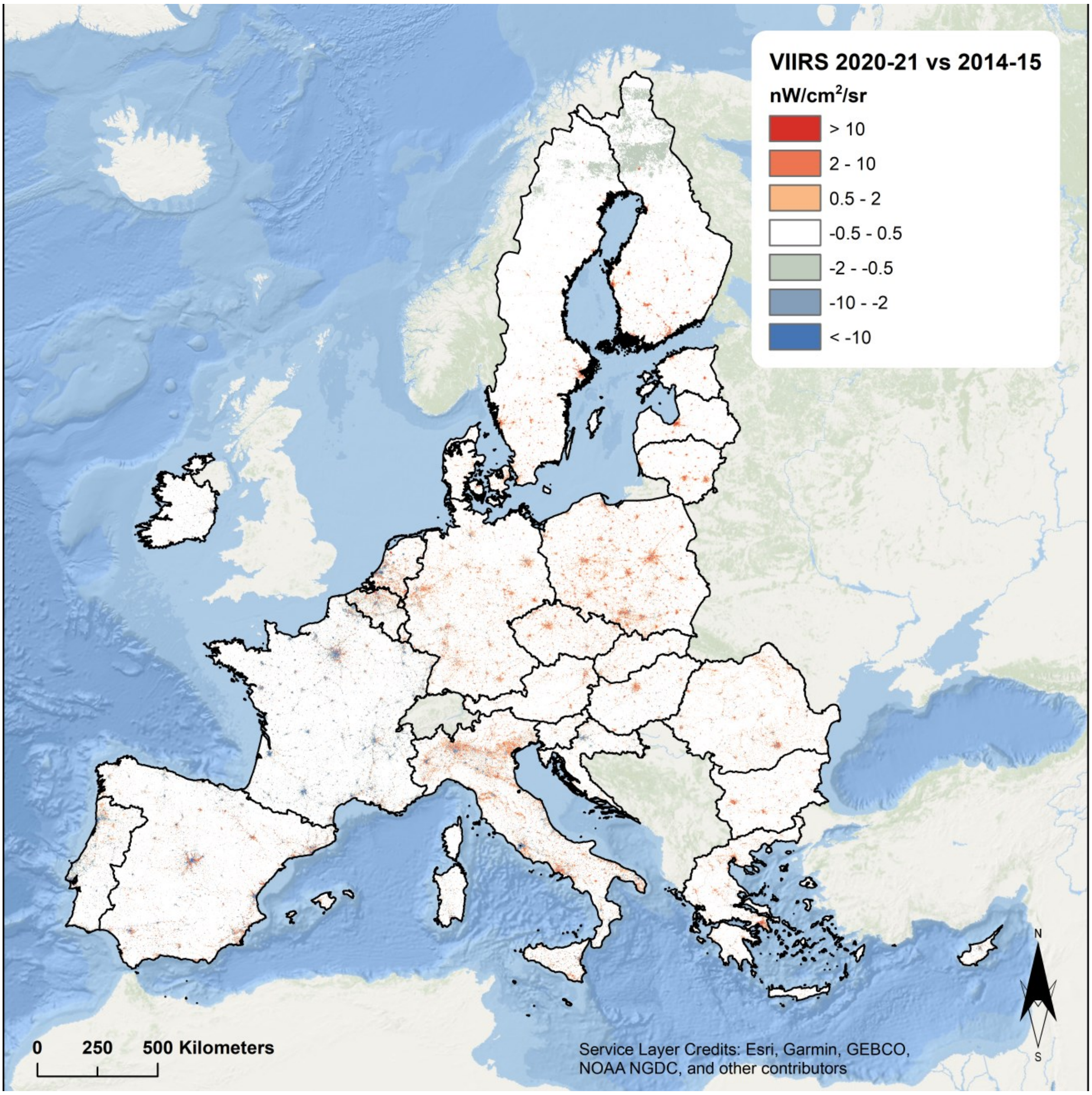
Annex

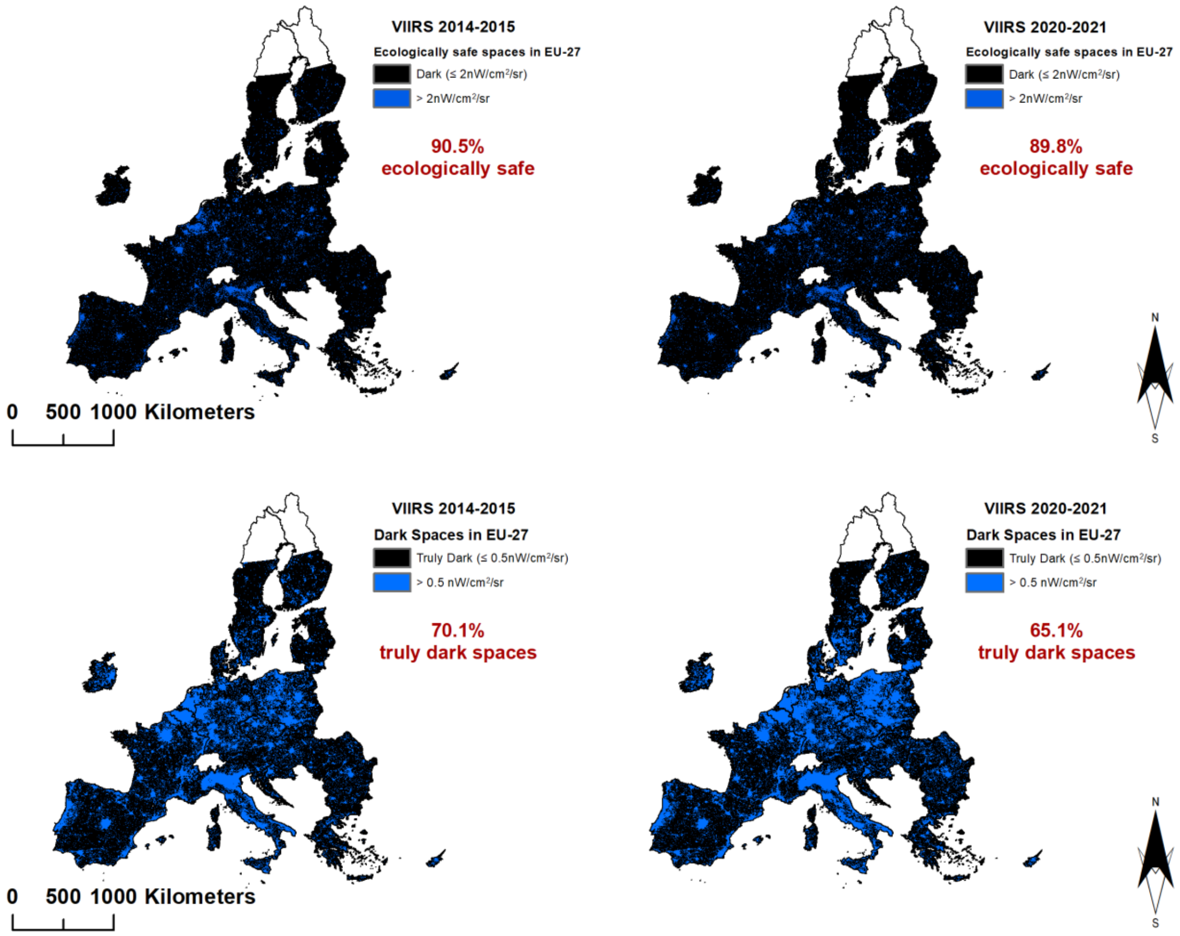
Figure A1: The differences in brightness in the member countries of EU27 between the averaging periods of (2020/21) and (2014/15)



Notes: Changes in brightness in the European countries in EU27 over the last eight years, calculated as the difference between the average light emissions in 2014/15 and 2020/21. Values of increasing (red colour) or decreasing (blue colour) artificial light vary between 0.5 - 10 nW/cm^2/sr. White colour denotes no change (i.e. differences lower than +/- 0.5 nW/cm^2/sr). The zoomed-in areas represent some of the level 1 subdivisions of the Nomenclature of Territorial Units for Statistics (NUTS 1) classification of the European Union.

Source: Swiss TPH.

Figure A2: **Signals of ecological light pollution for the countries in EU27. Maps on top indicate "ecologically safe" areas (< 2 nW/cm²/sr) and on the bottom "truly dark" spaces (< 0.5 nW/cm²/sr)**



Notes: Land surface with light emissions < 2 nW/cm²/sr (upper maps)/ < 0.5 nW/cm²/sr (lower maps) shown in black and areas with higher emissions in blue (exclusion of Northern region depicted in white due to confounding effect of Aurora lights) – a comparison between the two time periods 2014/15 and 2020/21

Source: Swiss TPH.

Table A1: Annual mean light emissions during 2014 - 2021 for each EEA38 country based on the VIIRS dataset

Country	2014	2015	2016	2017	2018	2019	2020	2021
Albania	0.67	0.58	0.53	0.57	0.55	0.62	0.71	0.84
Austria	0.77	0.75	0.75	0.78	0.76	0.77	0.78	0.95
Bosnia and Herzegovina	0.57	0.55	0.56	0.58	0.54	0.60	0.61	0.77
Belgium	4.76	4.72	4.68	4.59	4.77	4.71	4.74	4.85
Bulgaria	0.56	0.51	0.51	0.57	0.50	0.53	0.57	0.68
Switzerland	1.23	1.24	1.20	1.20	1.11	1.13	1.12	1.23
Denmark	0.97	1.04	1.04	0.99	1.00	0.97	1.05	1.35
Spain	1.54	1.48	1.43	1.42	1.38	1.41	1.40	1.50
Estonia	0.76	0.68	0.81	0.65	0.70	0.83	0.70	1.01
Greece	1.12	1.09	1.08	1.15	1.11	1.18	1.24	1.34
Cyprus	2.21	2.20	2.22	2.31	2.35	2.22	2.09	2.15
Czechia	1.29	1.31	1.33	1.40	1.37	1.40	1.28	1.75
Germany	1.30	1.32	1.28	1.29	1.31	1.29	1.35	1.56
France	1.55	1.52	1.46	1.39	1.36	1.31	1.32	1.34
Finland	0.89	0.97	1.02	0.88	0.83	0.86	0.69	0.99
Croatia	1.22	1.14	1.16	1.20	1.14	1.13	1.11	1.24
Hungary	0.88	0.80	0.82	0.82	0.82	0.86	0.86	1.03
Ireland	0.99	0.99	0.95	0.86	0.93	0.88	0.89	0.93
Iceland	1.60	1.25	1.02	1.00	0.69	0.62	0.71	0.72
Italy	3.00	2.96	2.95	3.05	2.95	3.03	3.02	3.13
Liechtenstein	1.59	1.70	1.71	1.79	1.71	1.60	1.66	1.81
Lithuania	0.55	0.57	0.65	0.53	0.60	0.64	0.61	1.01
Luxembourg	3.29	3.29	3.31	3.32	3.53	3.31	3.35	3.59
Latvia	0.47	0.55	0.45	0.46	0.55	0.53	0.53	0.80
North Macedonia	0.67	0.64	0.60	0.63	0.57	0.64	0.68	0.82
Malta	14.60	14.29	14.03	14.63	14.43	14.52	14.73	14.71
Montenegro	0.69	0.70	0.65	0.68	0.64	0.69	0.69	0.84
Netherlands	7.17	6.84	6.77	6.61	6.66	6.63	6.38	6.29
Norway	0.84	0.88	0.95	0.84	0.76	0.77	0.69	0.87
Romania	0.66	0.58	0.59	0.58	0.60	0.62	0.65	0.82
Serbia	1.15	1.10	1.14	1.16	1.16	1.31	1.24	1.47
Poland	1.39	1.31	1.37	1.35	1.42	1.41	1.35	1.92
Portugal	2.29	2.32	2.34	2.29	2.19	2.19	2.02	2.04
Sweden	0.72	0.80	0.82	0.68	0.66	0.61	0.58	0.79
Slovenia	0.91	0.84	0.84	0.84	0.85	0.79	0.83	0.97
Slovakia	0.83	0.81	0.83	0.84	0.81	0.85	0.83	1.05
Turkey	0.90	0.95	1.00	1.12	1.10	1.24	1.30	1.45
United Kingdom	2.12	2.17	1.98	1.80	1.84	1.74	1.74	1.85
EEA38_average	**1.25**	**1.25**	**1.25**	**1.21**	**1.19**	**1.20**	**1.18**	**1.36**

Table A2: Annual mean light emissions during 1992 - 2020 for each EEA38 country based on the harmonized historical dataset

Country	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Albania	0.26	0.68	0.80	1.43	1.25	0.95	1.31	1.82	1.89	1.86	2.13	2.25	2.67	2.95	2.51	2.87	3.00	2.87	2.76	3.23	3.36	3.63	7.21	6.68	6.07	9.36	8.68	9.81	7.88
Austria	4.71	4.76	4.57	6.58	6.26	6.07	7.94	7.99	8.75	9.59	9.10	8.82	8.00	9.44	8.07	8.30	8.62	9.74	10.61	8.81	10.70	9.29	5.50	5.44	5.55	6.44	6.50	6.93	6.40
Bosnia and Herzegovina	0.30	0.51	0.59	1.22	1.91	2.46	3.31	3.44	4.03	4.45	4.12	4.30	3.87	4.97	3.82	3.91	4.54	4.09	4.21	4.72	5.25	4.45	6.75	6.98	7.28	9.73	9.72	10.07	8.07
Belgium	25.98	25.68	26.37	29.42	29.02	28.52	28.92	30.63	31.70	31.64	33.42	32.78	27.18	29.12	27.94	28.30	29.78	29.60	34.62	28.82	32.16	30.52	26.22	26.22	26.11	26.57	27.44	28.26	28.54
Bulgaria	2.51	3.42	2.54	3.77	3.26	2.43	3.48	3.20	4.20	4.30	4.81	3.50	3.69	4.50	3.39	3.97	4.46	4.25	4.37	4.33	4.95	4.12	7.57	7.23	7.29	9.40	8.80	9.56	7.95
Switzerland	8.80	8.15	8.53	11.08	10.40	11.08	13.27	13.53	13.55	13.10	13.43	14.96	12.57	16.12	12.92	13.57	14.62	15.07	16.80	13.72	16.07	14.94	8.77	8.65	8.57	9.48	8.85	9.63	8.88
Denmark	8.35	7.51	7.92	12.40	9.07	8.67	10.69	10.73	11.11	9.71	6.92	10.36	10.45	9.31	9.24	9.67	8.54	9.66	15.86	9.46	11.87	10.23	6.15	6.16	6.47	6.23	7.19	6.80	6.31
Spain	4.88	4.97	4.86	6.17	6.07	6.21	6.69	7.13	7.46	7.83	7.76	7.79	8.10	8.37	8.19	8.85	8.37	8.98	8.59	8.53	8.67	8.17	10.87	10.71	10.46	12.15	11.86	12.59	11.38
Estonia	1.50	2.30	2.87	2.42	2.21	3.64	3.08	3.01	2.85	2.94	0.09	2.54	2.64	3.47	2.89	3.14	3.44	3.88	6.17	3.92	5.29	4.27	3.72	2.93	4.53	3.44	5.86	4.99	3.00
Greece	3.19	3.70	3.67	4.63	4.22	4.61	5.13	5.87	6.26	6.23	6.85	6.81	7.20	7.33	7.05	7.36	6.88	7.12	7.02	6.68	7.18	7.13	9.91	9.72	9.66	11.67	11.10	12.47	11.17
Cyprus	7.80	7.50	7.51	9.03	8.95	9.28	9.79	10.90	11.15	11.26	11.69	12.12	12.19	12.62	13.43	13.63	13.08	13.64	14.38	13.66	14.70	14.52	15.53	15.51	15.49	17.23	16.97	17.61	16.24
Czechia	9.36	8.18	7.90	11.43	11.09	9.38	13.60	11.72	13.38	15.43	16.82	13.04	11.33	13.54	12.05	10.71	11.27	14.05	16.99	12.15	15.13	11.28	8.46	8.58	8.88	10.81	11.04	10.90	9.60
Germany	10.25	9.11	9.07	12.46	11.97	12.43	14.43	13.90	14.23	14.18	15.43	14.47	13.22	13.86	12.36	12.76	12.88	14.37	18.45	13.46	15.22	13.55	8.25	8.44	8.15	9.13	9.43	9.31	9.30
France	6.98	6.99	6.74	8.88	8.83	9.77	9.62	10.17	10.70	11.24	10.88	10.85	10.81	11.23	10.67	11.21	11.04	11.73	12.24	10.68	11.72	11.38	9.73	9.46	9.25	9.68	9.46	9.73	9.25
Finland	2.64	3.46	3.87	4.66	3.42	3.78	4.31	5.16	3.33	3.23	0.00	4.81	3.89	4.22	3.44	3.83	4.25	4.35	5.46	4.11	5.40	5.24	3.51	4.51	4.54	4.60	5.30	4.63	3.44
Croatia	1.88	2.77	2.78	4.26	4.93	4.96	6.24	5.98	6.45	7.14	6.65	7.84	6.71	9.10	7.66	8.01	8.27	8.45	9.11	8.36	10.28	8.91	8.77	8.35	8.56	9.86	9.91	10.02	8.83
Hungary	3.47	4.17	3.90	6.38	5.74	5.70	7.25	6.59	7.34	8.34	6.83	8.99	6.29	8.30	6.24	6.30	6.61	6.44	6.93	6.04	6.99	5.76	6.27	5.72	6.02	6.79	6.62	7.47	6.60
Ireland	4.05	3.91	4.43	4.69	4.95	5.34	5.90	6.92	6.94	7.55	6.60	7.84	8.71	8.10	7.25	8.42	7.78	8.16	9.03	7.08	8.08	7.68	4.77	4.93	4.81	4.77	5.30	4.95	5.00
Iceland	0.37	0.57	0.41	0.49	0.78	0.01	0.49	0.54	0.59	0.00	0.00	0.65	0.69	0.87	0.73	0.99	0.86	0.53	0.80	1.02	0.88	0.94	1.72	6.10	1.47	1.39	2.47	1.18	1.34
Italy	11.75	11.21	11.73	13.92	13.53	13.61	14.83	15.39	16.12	16.71	17.56	17.45	17.18	17.84	17.40	18.09	17.71	18.55	18.39	18.29	19.95	18.68	19.19	18.97	18.93	20.81	20.50	22.16	21.38
Liechtenstein	11.13	12.23	11.76	16.20	15.00	13.64	21.64	22.64	19.58	20.40	22.15	24.38	20.19	26.07	21.13	21.21	21.60	23.04	25.14	27.45	25.82	24.58	11.83	12.50	12.39	15.66	15.24	16.24	14.45
Lithuania	1.58	1.56	2.34	1.73	2.61	2.47	3.49	2.54	2.86	2.31	3.38	2.53	2.64	3.08	2.59	2.80	2.78	2.61	6.24	4.67	4.55	3.19	2.36	1.92	2.82	2.60	3.68	3.20	2.32
Luxembourg	17.05	14.98	15.16	18.70	21.94	19.77	21.82	19.75	20.39	23.55	29.86	24.93	20.15	21.83	21.16	20.35	22.44	21.38	28.77	21.95	25.06	23.36	18.61	18.57	18.90	19.56	21.98	20.02	21.01
Latvia	1.14	1.11	1.53	1.39	1.55	1.66	1.69	1.46	1.69	1.70	1.65	1.51	1.34	1.93	1.68	1.65	1.90	1.80	3.72	2.50	2.83	2.30	2.22	1.82	2.59	2.33	3.52	3.15	1.85
North Macedonia	1.36	2.25	1.99	3.03	2.90	2.91	3.46	3.97	4.78	4.32	4.97	3.95	4.11	4.74	3.67	4.20	4.09	3.95	3.72	3.94	4.56	4.08	7.63	7.41	7.12	9.69	8.94	10.12	8.11
Malta	42.74	40.43	43.23	47.29	46.77	47.77	44.88	45.31	47.42	48.44	49.57	48.82	47.94	46.41	48.13	49.10	47.15	46.56	48.75	47.74	49.35	50.66	49.92	49.27	48.49	49.56	49.11	50.60	41.55
Montenegro	0.92	1.01	0.90	1.39	1.43	1.31	1.76	1.91	2.27	2.10	2.12	2.56	2.19	2.96	2.71	2.77	2.87	2.66	2.89	3.66	3.67	3.72	6.15	6.74	6.70	10.03	9.75	10.16	7.33
Netherlands	20.98	22.13	21.03	25.37	23.71	23.97	24.75	25.87	27.96	26.42	26.13	26.84	23.97	24.99	23.89	24.62	25.16	25.47	29.95	23.93	26.85	25.16	20.82	20.80	20.36	21.05	21.37	22.80	22.84
Norway	1.91	2.60	3.41	3.32	3.45	2.38	2.26	2.75	2.08	2.25	0.01	3.27	2.53	3.04	2.25	3.50	3.30	3.30	4.55	3.65	4.16	4.25	3.32	7.44	4.52	5.73	5.89	4.98	3.43
Romania	1.22	1.68	1.53	2.82	2.80	2.87	4.00	3.25	4.38	4.24	5.03	4.18	4.15	4.35	3.40	3.86	4.28	4.57	4.57	5.35	5.88	4.60	5.06	4.66	4.85	5.81	6.53	6.68	5.98
Serbia	2.73	2.90	2.62	4.14	4.26	4.67	5.50	4.88	5.00	5.72	6.08	6.30	5.88	7.46	5.89	6.46	6.60	7.01	7.32	7.64	8.52	7.19	10.33	10.08	10.20	12.13	12.22	13.62	12.38
Poland	4.14	3.75	3.71	6.88	6.42	5.98	9.66	8.43	8.31	9.86	12.05	8.86	8.99	9.62	9.70	8.43	8.61	10.42	15.97	11.84	14.25	10.17	8.09	7.18	7.98	8.74	10.20	9.19	8.22
Portugal	5.13	5.50	5.31	7.18	7.31	7.37	8.35	8.87	8.90	10.33	10.62	10.72	11.64	12.24	12.36	13.44	12.85	12.81	12.77	13.44	13.54	12.56	15.57	15.49	15.68	16.98	16.26	17.71	16.13
Sweden	3.28	3.34	4.29	4.84	3.98	3.83	4.51	4.58	3.38	2.69	1.07	3.96	3.47	3.52	3.30	3.68	3.59	3.43	5.41	4.11	4.64	4.12	2.89	4.09	3.56	3.39	4.43	3.87	2.85
Slovenia	3.98	5.02	4.77	6.91	7.51	7.11	8.70	9.20	9.60	9.50	8.80	9.86	8.34	10.16	9.10	9.09	8.94	10.33	11.17	8.82	10.38	9.29	6.89	6.51	6.82	7.44	8.07	7.63	6.98
Slovakia	8.03	6.84	6.65	9.79	8.80	7.35	10.19	9.07	10.70	11.02	11.94	8.79	7.95	9.34	7.41	6.85	7.03	7.31	8.75	7.45	8.86	8.09	5.42	5.58	5.94	6.99	6.84	7.36	6.40
Turkey	1.27	1.78	1.52	1.96	1.89	1.70	2.17	2.39	2.71	2.16	2.54	2.29	2.75	2.54	2.45	3.16	3.29	2.95	3.34	3.75	4.56	4.27	8.74	9.02	9.25	11.40	10.85	12.55	11.62
United Kingdom	13.00	12.88	12.39	14.11	13.36	13.95	13.80	15.02	14.88	14.94	13.42	15.19	14.71	14.16	13.80	14.33	13.33	14.09	15.37	12.82	13.78	13.41	9.86	9.93	9.48	9.19	9.82	9.75	9.30
EEA38_average	**4.79**	**4.92**	**5.03**	**6.40**	**6.05**	**6.05**	**6.90**	**7.05**	**7.03**	**7.13**	**6.70**	**7.53**	**7.12**	**7.53**	**6.94**	**7.37**	**7.33**	**7.73**	**9.08**	**7.73**	**8.73**	**7.91**	**7.50**	**8.04**	**7.69**	**8.58**	**8.87**	**6.79**	**8.11**

Table A3: Annual mean light emissions during 2000 – 2020 for each EEA38 country based on the extended historical time series data

Country	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Albania	0.02	0.02	0.05	0.05	0.07	0.07	0.06	0.07	0.09	0.06	0.08	0.16	0.21	0.36	0.36	0.32	0.29	0.36	0.38	0.43	0.46
Austria	0.25	0.29	0.28	0.29	0.18	0.29	0.27	0.22	0.24	0.23	0.32	0.30	0.44	0.33	0.35	0.29	0.38	0.46	0.48	0.45	0.39
Bosnia and Herzegovina	0.08	0.07	0.07	0.10	0.05	0.12	0.07	0.07	0.09	0.06	0.10	0.13	0.25	0.24	0.27	0.25	0.30	0.35	0.35	0.37	0.35
Belgium	2.34	2.40	2.44	2.73	1.26	1.84	1.66	1.71	2.10	1.86	2.42	2.21	3.51	3.52	3.41	3.19	3.42	3.57	3.77	3.49	3.22
Bulgaria	0.08	0.07	0.08	0.08	0.07	0.10	0.09	0.09	0.11	0.08	0.10	0.15	0.23	0.27	0.27	0.28	0.29	0.35	0.33	0.34	0.34
Switzerland	0.47	0.42	0.52	0.73	0.38	0.71	0.46	0.54	0.54	0.50	0.71	0.59	0.81	0.64	0.73	0.66	0.74	0.78	0.74	0.77	0.69
Denmark	0.34	0.31	0.18	0.32	0.25	0.27	0.29	0.27	0.19	0.19	0.52	0.23	0.38	0.31	0.24	0.14	0.43	0.35	0.39	0.38	0.33
Spain	0.53	0.57	0.65	0.63	0.56	0.64	0.75	0.81	0.69	0.69	0.57	0.94	1.03	1.15	1.13	1.10	1.10	1.16	1.13	1.15	1.05
Estonia	0.03	0.06	0.00	0.11	0.06	0.11	0.13	0.11	0.11	0.12	0.22	0.11	0.18	0.11	0.10	0.04	0.13	0.09	0.15	0.13	0.04
Greece	0.33	0.28	0.38	0.34	0.34	0.37	0.42	0.43	0.36	0.35	0.34	0.44	0.56	0.77	0.75	0.74	0.76	0.89	0.87	0.93	0.94
Cyprus	0.74	0.75	0.88	0.82	0.77	0.73	1.18	1.22	1.06	0.92	1.14	1.24	1.30	1.82	1.85	1.86	1.90	2.08	2.15	1.99	1.85
Czechia	0.34	0.46	0.59	0.43	0.24	0.42	0.37	0.27	0.30	0.30	0.58	0.37	0.69	0.59	0.68	0.53	0.65	0.80	0.83	0.81	0.70
Germany	0.56	0.55	0.63	0.65	0.39	0.50	0.44	0.45	0.47	0.45	0.77	0.53	0.72	0.55	0.65	0.61	0.64	0.69	0.78	0.70	0.69
France	0.47	0.54	0.54	0.62	0.41	0.50	0.53	0.54	0.48	0.47	0.51	0.65	0.80	0.94	0.98	0.93	0.97	0.96	0.93	0.86	0.83
Finland				0.18	0.10	0.10	0.13	0.10	0.12	0.13	0.19	0.09	0.19	0.08	0.05	0.00	0.08	0.08	0.00	0.15	0.04
Croatia	0.16	0.15	0.17	0.26	0.14	0.29	0.24	0.24	0.24	0.22	0.28	0.29	0.63	0.67	0.74	0.66	0.77	0.86	0.82	0.82	0.74
Hungary	0.25	0.30	0.26	0.33	0.16	0.31	0.27	0.22	0.25	0.17	0.26	0.23	0.48	0.43	0.44	0.31	0.48	0.51	0.54	0.55	0.42
Ireland	0.14	0.15	0.13	0.16	0.13	0.15	0.16	0.17	0.16	0.16	0.17	0.16	0.16	0.15	0.38	0.37	0.37	0.38	0.42	0.33	0.38
Iceland				0.03	0.02	0.03	0.04	0.04	0.03	0.03	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.00
Italy	1.05	1.02	1.44	1.35	1.10	1.21	1.26	1.41	1.27	1.26	1.12	1.70	2.21	2.33	2.41	2.37	2.40	2.67	2.55	2.63	2.58
Liechtenstein	0.78	0.65	1.05	1.49	0.60	1.61	1.09	0.90	0.82	0.94	1.58	1.64	1.95	1.18	1.07	0.99	1.16	1.18	1.28	1.18	1.14
Lithuania	0.06	0.08	0.16	0.09	0.06	0.10	0.11	0.08	0.08	0.05	0.16	0.11	0.15	0.10	0.12	0.08	0.15	0.13	0.18	0.18	0.12
Luxembourg	0.59	1.19	1.69	1.41	0.73	0.92	0.85	0.69	0.91	0.65	1.22	1.16	1.85	1.87	2.11	1.87	2.32	2.18	2.72	2.16	1.61
Latvia	0.06	0.08	0.09	0.05	0.04	0.07	0.08	0.06	0.06	0.04	0.12	0.07	0.10	0.06	0.05	0.05	0.12	0.10	0.12	0.12	0.09
North Macedonia	0.14	0.09	0.14	0.11	0.10	0.15	0.11	0.09	0.13	0.10	0.11	0.21	0.33	0.36	0.37	0.39	0.37	0.43	0.42	0.44	0.45
Malta	10.43	12.51	11.30	9.49	8.54	6.70	9.99	10.13	8.97	8.18	8.22	11.54	9.79	13.98	13.99	13.79	13.48	14.15	14.26	15.66	15.90
Montenegro	0.06	0.05	0.07	0.08	0.06	0.11	0.07	0.08	0.11	0.06	0.10	0.20	0.21	0.36	0.38	0.41	0.39	0.46	0.46	0.45	0.46
Netherlands	2.21	1.94	1.88	2.13	1.26	1.69	1.45	1.63	1.76	1.56	1.83	2.21	3.44	3.28	3.53	3.07	3.48	3.61	3.76	3.71	3.46
Norway	0.17	0.18	0.00	0.12	0.07	0.07	0.08	0.10	0.09	0.10	0.15	0.08	0.13	0.06	0.04	0.02	0.07	0.08	0.10	0.09	0.02
Romania	0.08	0.08	0.10	0.09	0.07	0.11	0.11	0.09	0.11	0.07	0.12	0.18	0.28	0.28	0.29	0.26	0.31	0.34	0.35	0.37	0.36
Serbia	0.11	0.11	0.10	0.16	0.09	0.22	0.18	0.15	0.20	0.12	0.21	0.33	0.59	0.63	0.73	0.69	0.75	0.82	0.89	0.95	0.91
Poland	0.20	0.27	0.35	0.24	0.18	0.30	0.31	0.21	0.24	0.20	0.49	0.34	0.58	0.45	0.63	0.49	0.64	0.66	0.80	0.74	0.66
Portugal	0.49	0.64	0.82	0.76	0.74	0.85	0.94	1.02	0.92	0.79	0.75	1.47	1.67	1.83	1.77	1.83	1.89	1.99	1.88	1.93	1.66
Sweden	0.24	0.18	0.21	0.13	0.09	0.09	0.11	0.09	0.09	0.07	0.17	0.10	0.14	0.08	0.05	0.03	0.12	0.09	0.08	0.12	0.07
Slovenia	0.22	0.18	0.20	0.30	0.15	0.24	0.24	0.20	0.18	0.22	0.30	0.21	0.43	0.39	0.44	0.37	0.48	0.55	0.52	0.52	0.46
Slovakia	0.22	0.27	0.37	0.20	0.14	0.25	0.20	0.15	0.17	0.10	0.22	0.21	0.41	0.39	0.36	0.26	0.40	0.47	0.50	0.47	0.40
Turkey	0.11	0.09	0.14	0.11	0.11	0.10	0.14	0.17	0.17	0.13	0.16	0.25	0.39	0.56	0.57	0.61	0.69	0.83	0.86	0.94	0.96
United Kingdom	1.00	1.04	0.82	1.13	0.82	0.91	1.03	1.01	0.88	0.85	0.80	0.88	1.05	1.05	1.28	1.14	1.21	1.17	1.18	1.09	1.04
EEA38_average	**0.41**	**0.43**	**0.47**	**0.39**	**0.28**	**0.34**	**0.36**	**0.37**	**0.35**	**0.32**	**0.39**	**0.43**	**0.58**	**0.59**	**0.62**	**0.58**	**0.65**	**0.69**	**0.70**	**0.72**	**0.66**

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