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Monitoring, trends and impacts of light pollution

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ABSTRACT

Light pollution has increased globally with 80% of the total population now living under light polluted skies. In this Review, we elucidate the scope and importance of light pollution and discuss techniques to monitor it. In urban areas light emissions from sources such as streetlights lead to a zenith radiance 40 times larger than that of an unpolluted night sky. Non-urban areas account for over 50% of the total night-time light observed by satellites, with contributions from sources such as transportation networks and resource extraction. Artificial light can disturb the migratory and reproductive behaviours of animals even at the low illuminances from diffuse skyglow. Additionally, lighting (indoor and outdoor) accounts for 20% of global electricity consumption and 6% of CO₂ emissions, leading to indirect environmental impacts and a financial cost. However, existing monitoring techniques can only perform a limited number of measurements throughout the night and lack spectral and spatial resolution. Therefore, satellites with improved spectral and spatial resolution are needed to enable time series-analysis of light pollution trends throughout the night.

[H1] Introduction

Artificial light has dramatically modified the Earth's biosphere. The illuminance of night skies in areas near artificial lights can be 10,000–1,000,000 times larger than in the absence of artificial light^{1,2}. This artificial light causes various environmental impacts³, including mass casualties of insects⁴ and migrating birds^{5–7}; changes to plant phenology^{8–10} and insect–plant pollination networks¹¹; habitat loss; loss of landscape connectivity^{12–14}; and changes to the diurnal vertical migration of zooplankton¹⁵. Light pollution also has physical and societal impacts, for example, it can alter atmospheric chemistry by providing enough energy to initiate night-time ground-level ozone production¹⁶ and hamper astronomy. Additionally, generating the electricity to produce artificial light has an environmental^{17,18} and financial cost.

Throughout this Review, light pollution is used to refer to "an increased volume concentration of photons in the nocturnal environment above naturally expected values"^{19,20}. As with many other pollutants, the environmental impacts of light pollution are an unintended byproduct of a desired service: in this case, providing light for human beings. The use of Artificial Light At Night (ALAN) to extend productive and social hours, to promote safety and for advertising, aesthetics, food production, and pest and predator control²¹ (**Figure 1**) has led to substantial increases in global light emissions²². However, access to ALAN varies between regions. Although 80% of the world's population lives in brightly-lit areas²³ there are still hundreds of millions

of people who lack access to a stable electricity supply²⁴. Globally, around 10% of people do not have access to electricity. In particular, regions of Low and Middle Income Countries (LMICs) can have very low access rates; for example, the Democratic Republic of Congo with an access rate of 9% or South Sudan with 7%²⁵. Additionally, there are some regions that have an electricity supply but do not have the infrastructure to meet human demand for light.

Decisions about how much light is needed are not generally based on scientific evidence²⁶ and are heavily influenced by public opinion. Historically darkness was linked to increased danger²⁷. However, in some cases, changes in night-time lighting have resulted in no substantial changes in night-time safety (linked to crime or traffic collisions). Additionally, awareness of the negative effects of light pollution on astronomy is increasing²⁸, which is also affecting the public perception of night-time light. Therefore, further research into the impact of ALAN on night-time safety is needed to ensure that light is used efficiently²⁹⁻³¹.

Developments in sensing technologies, such as night-time observation satellites and ground based photometers specifically designed to measure sky brightness, have improved measurements of light emissions by providing systematic and inter-comparable data^{32,33}. Additionally, growing recognition that artificial light is a form of pollution has led to a rapid expansion of research into the ecological impacts of light³⁴ and increased efforts to reduce light emissions through legislation, non-binding guidelines and voluntary actions^{35,36}. However, further improvements in satellite measurements of night-time light are needed to understand the implications of light pollution for ecology, environment, economy, policy, safety, health, and characterisation³⁷.

In this Review, we assess global light pollution trends and impacts and discuss existing monitoring techniques, with a focus on space-based measurements. First we introduce the primary measurement techniques currently in use. We then outline global patterns of artificial lighting, the temporal evolution of light emissions, projected future trends and the impacts of light pollution. We then focus on the use of remote sensing measurements of night-time light as proxies of human activities and environmental health. Finally, we offer suggestions for further work, including future satellite concepts focused on night-time observations. This Review arose out of the European Space Agency (ESA) programme entitled New Earth Observation Mission Ideas (NEOMI), in which a mission concept was developed to address scientific gaps related to outdoor light at night. This Review focuses on the effects of outdoor artificial lighting rather than indoor lighting exposure.

[H1] Measuring light pollution

There are multiple definitions of the term light pollution. For example, light pollution frequently refers to the use of artificial light and its effects. [Dark Sky International](#) defines it as "inappropriate and excessive use of artificial light", which adversely affects nature and humans^{38,39}. Light pollution can also sometimes refer to the (mostly human-centered) effects of light, which include glare (disruption of vision owing to overly high luminance), light trespass (light shining where it is not needed or desired), and skyglow (**Figure 1, inset**; the artificial brightening of the sky produced when photons from anthropogenic sources are scattered by atmospheric molecules and particles). Environmental light can be monitored by measuring direct light emissions or skyglow; therefore, it is best practice to specify what was measured, rather than referring to light pollution as a whole. This section defines the complexities of the light field of the Earth's atmosphere and discusses the strengths and weakness of various ground-based and remote sensing techniques for performing such measurements.

[H2] The behaviour of light

The propagation and environmental impact of emitted light are influenced by the properties of the light and the environment it propagates through. Light emitted from a source propagates (including being reflected by objects or the ground, and or scattered by particles in the atmosphere), until it is absorbed or escapes into space (**Figure 2**). The details of this propagation, and the environmental impact of the emitted light depend on the properties of the light (for example, its spectrum and intensity), and where it is absorbed (for example an eye, leaf, or concrete surface). Lighting technologies emit a range of wavelengths, which often include ultraviolet and near infrared (NIR). It can be challenging to confirm the properties of emitted light because these emissions change over time^{22,40}, and the measured properties of light often depend strongly on the location^{23,41} and angle at which it is measured^{42,43} as well as the spectral sensitivity of the sensor.

The field of artificial light around the Earth is too complex to fully measure or model owing to the many factors that influence it. Instead assessments of the light field must choose what data are needed (for example zenith radiance, that is the brightness of the sky in the zenith direction, throughout the night), and which information will not be recorded (for example, the light direction, polarisation and spectrum). Artificial light can be measured from anywhere (including caves) but measurements are typically performed from the ground, air or space. Most light pollution measurements focus on direct light emissions (photons travelling directly from the source to the observer or measuring device) or skyglow, and detailed reviews of remote sensing³², skyglow¹, and biological field techniques⁴⁴ to measure ALAN are available. All of these techniques use some form of radiometer (for example camera or spectrometer) to obtain one or more instantaneous measurements of the radiance for a specific field of view.

Light pollution modelling aims to reproduce the interactions between electromagnetic radiation and the molecules and aerosols that constitute the atmosphere. Models developed in the 1970s were based on semi-empirical propagation laws that

estimated the zenith brightness produced by towns (considered as point like sources)^{45–47}. Numerical models have since improved continuously⁴⁸ and complex models using satellite data can take into account the heterogeneity of artificial light sources and compute multiple orders of scattering^{49,50}. These models can estimate sky brightness at small (1–10 m)⁵¹ or large (hundreds of meters to hundreds of km)^{52,53} distances. However, such models require detailed information about the light sources and environment.

[H2] Ground-based techniques

Ground-based techniques are used to observe sky brightness with a range of viewing angles and durations. Ground-based measurements with all-sky cameras, such as GONet⁵⁴, measure the radiance from all directions, generally in multiple spectral bands (**Figure 2**). All-sky measurements can also be obtained with systems such as Sky Quality Camera (SQC)⁵⁵, IRIS, ImageJ, PyASB⁵⁶ and DiCaLum⁵⁷, which calibrate Digital Single Lens Reflex (DSLR) cameras for light pollution measurements. However, all-sky cameras are rarely left permanently in the field, and therefore do not capture a time-series of data. Ground-based radiometers such as the Sky Quality Meter (SQM)⁵⁸ and the Telescope Encoder Sky Sensor (TESS)⁵⁹ provide time-series, but acquire data only in one specific viewing direction (unless they are redirected between measurements^{60,61}) and usually in only one spectral channel. Devices with extended spectral ranges such as COSQM⁶² and TESS-4C have been developed by adding color filters but these techniques are not yet widely used to measure light pollution.

Despite their usefulness, ground-based measurements of skyglow have some limitations. First, they are limited to a single location (unless the instrument is moved^{63,64}); therefore, these techniques predominantly provide information about scattered light from sources within a few kilometres of the detector. Second, ground-based measurements can involve substantial cost and effort for individual researchers. Finally, ground-based techniques cannot be used to research other aspects of light pollution, such as its influence on individual organisms⁵⁵. Citizen science could help to address some of these limitations by mobilizing large groups to obtain numerous measurements. This approach has been already used to observe the impact of light on human vision⁴⁰, or to conduct lighting inventories⁶⁵.

Ground-based observations by amateur and professional astronomers, and citizen scientists could, in principle, be mined to obtain information about long-term changes in sky brightness. However, these observations are not evenly distributed across the globe and are generally not obtained within cities. Additionally, increased global coordination (for example, using the same types of instruments that have been intercalibrated and sharing the data), is needed to enable the comparison of results between locations. Networks of sensors, similar to those used to monitor meteorological parameters, could be used to regularly monitor skyglow. Indeed, several local governments have set up networks of ground-based sensors^{58,59}, which could improve tracking of artificial light emissions during the mid to late 21st century.

[H2] Remote sensing

Satellite radiometers could be used to measure skyglow from light sources across large distances (hundreds of km)⁶⁶. Additionally, space-based measurements can provide insight about variables that cannot be measured efficiently with ground-based techniques such as average light exposure¹⁰ or the effect of light on animal behaviour⁶⁷. However, these measurements often only provide one observation per night, and existing instruments lack the sensitivity and spectral bands to be useful for this purpose.

The only satellite radiometer that currently acquires regular night-time imagery of the whole Earth is the Day/Night Band (DNB) of the Visible Infrared Imaging Radiometer Suite (VIIRS), which was designed for meteorological observations using reflected moonlight not light pollution monitoring. Its single-band sensor and relatively low spatial resolution (750 m) both greatly limit its performance in monitoring light pollution. For example, transitions of lighting technology from high-pressure-sodium (HPS) to light emitting diode (LED) lamps, which produce the same amount of light emissions, are reported as darkening by the sensor^{22,68,69} because the emissions are shifted towards wavelengths that cannot be detected by the sensor. Additionally, there is large variability in the radiance of individual pixels observed by VIIRS DNB near bright objects⁷⁰. Such variability limits the precision of monthly or annual composites⁷¹, making it difficult to measure rates of change, and places a limit on the size of the change that can be identified from time series⁷². It is likely that this variability is caused by changes in imaging angle⁷³ or in the projection of pixels onto Earth's surface between data acquisitions⁷⁴.

A small number of other satellites can acquire night-time data, but these data are typically uncalibrated (or with insufficient research on the quality of the calibration), are not regularly acquired, and in the case of commercial operators often expensive (**Table 1**). Currently, DSLR cameras on board the international space station (ISS), SDGSAT-1 and JL-1 are the only multispectral sensors available. However, astronauts on board the ISS⁷⁵ do not systematically take images; the spectral response of SDGSAT-1 is not optimised for human vision and has limited sensitivity⁷⁶; and JL1 is a commercial satellite constellation with very high resolution but very narrow field of view, limited sensitivity and the follow-up missions are unknown⁷⁷. These limitations are not inherent to night-time satellite imagery. Thus, there is a compelling need for the development and launch of a new satellite mission tailored to improve the spatial and spectral resolution of night-time measurements³⁷.

However, even an optimal satellite mission would not always provide a reliable proxy for true light exposure (**Figure 2**). For example, satellites cannot capture the movement of organisms that remain within a single pixel of the satellite image such as plants, or small and slow moving ground dwelling organisms. Additionally, shading from vegetation or an animal's shelter or a bright local source of light could prevent satellite imagery from reliably capturing the true light exposure experienced by the animal⁷⁸. The exposure of animals to light can be directly measured by affixing radiometers directly to animals^{79,80} or by photographing an experimental field site⁸¹. Therefore, a combination of complementary sensors will be needed to facilitate long-term skyglow monitoring¹.

[H1] Global variability in light emissions

This section outlines human and environmental factors that induce spatial and temporal variability in light emissions and exposure, making it difficult to monitor light pollution with existing techniques.

[H2] Spatial variability

Although direct exposure to artificial light is primarily caused by light sources situated within meters to a few kilometers, light emissions can have pervasive global impacts. Direct light emissions (that is, unscattered light travelling directly from the source to the detector) have been observed across 26.5% of the land area within latitudes 59°N and 55°S, and diffuse skyglow, which can be detected hundreds of kilometers from its source⁸², can be observed over 46.5% of land within the same latitudinal boundaries⁸³. Therefore, around 80% of people worldwide live under light polluted skies. However, light emissions and exposure are extremely heterogeneous and in Europe and the USA this fraction is over 99%, whereas in regions such as Chad, Central African Republic, and Madagascar over 75% of the population live in areas with little to no skyglow, owing to a lack of electrification²³. Additionally, per capita light emissions are highly variable within individual countries^{84,85}.

On land, artificial light emissions are often associated with cities and towns and these emissions increase with increasing population density⁸³. Clear sky zenith radiance within cities can be more than 40 times brighter than that of a sky devoid of artificial photons^{23,41}. Additionally, this increased brightness is even more substantial with overcast skies^{86,87} because photons are scattered back to the ground by the water molecules that form the clouds. Indeed, a 6–17 times increase in the brightness (depending on the spectral range measured) owing to the presence of clouds has been reported by independent measurements under different meteorological conditions^{88–90}. In small communities light emissions are often dominated by public street lighting with over 300 million street lights installed worldwide⁹¹. However, in large cities street lights account for a minority of light emissions^{74,92,93} with sources such as advertising, private lighting and sports lighting having a larger contribution, but further work is needed to quantify this contribution⁹⁴.

Nevertheless, 54.9% of the global total direct light emissions between 2012 and 2019 came from non-urban areas⁸³. Outside of cities, light sources are often associated with transport infrastructures, such as the 41,000 airports or aerodromes worldwide ([World Factbook](#)), as well as seaports and road networks. Additionally, resource extraction facilities such as flares^{95,96} and outdoor workplace lighting, and agricultural facilities such as greenhouses^{97,98} are often particularly bright sources and are estimated to produce 10% of total direct light emissions⁸³. Lights are also often found close to coasts, rivers, and other biodiversity hotspots^{99–102}, and in 2014, 22% of coastlines were estimated to be affected by light pollution¹⁰³.

Water bodies also have sources of artificial light emissions, including oil extraction platforms, windmills, and ships. Worldwide, there are an estimated 3.7 million fishing ships¹⁰⁴, and 98,000 merchant ships¹⁰⁵. Lights are often used to increase yield in fishing^{106,107}. Thus, satellite sensors can monitor the ALAN associated with this practice to assess whether laws regarding fishery closures are being obeyed and plan enforcement actions (for example, more than 900 fisheries are monitored by night-time remote sensing in the Philippines alone)¹⁰⁸.

[H2] Temporal variability

Many sources of artificial light vary over time. For example, light emissions associated with human settlements have a large variation over the course of the night because lights are turned off when people go to bed^{93,109}; therefore, sky brightness decreases throughout the night (with the rate of decrease depending on the spectrum being measured)^{90,110}. Additionally, there are likely to be differences in light emissions between weekdays and weekends, but this aspect remains relatively under-explored. Seasonal changes in light emissions can arise from human festivals involving light¹¹¹ as well as seasonal population changes, such as the migration linked to the Chinese spring festival^{112,113}. There are also non-cyclic variations in light emissions owing to instability in electricity supply (especially in LMICs, as well as disasters such as earthquakes, hurricanes^{114,115}, and war¹¹¹). In addition to temporal variability, light emissions (and their reflections from the ground and other surfaces) also vary as a function of angle¹¹⁶, for example, all-sky brightness maps often show more than tenfold differences in radiance between different areas of the sky for the same location⁶⁴.

Independent of changes in light emissions, light exposure and the amount of light seen from space are also influenced by environmental factors. For example, changes in snow and leaf cover induce seasonal variability in the amount of light reaching

space, the former by increasing ground albedo and thus the amount of photons that reach satellite sensors, and the latter by absorbing and scattering upward emission back to the ground^{89,117}. Clouds have a substantial influence on the light exposure experienced by organisms on Earth and although clouds used to darken the Earth's surface before the advent of artificial outdoor lighting, in urban areas they can now amplify skyglow to illuminances similar to that of bright twilight^{87,88}. Atmospheric changes such as humidity and aerosol content have complex influences on the the shape, colour, and radiance of skyglow, albeit to a lesser extent than clouds¹¹⁸. Finally, natural night-time illumination is itself variable, owing to changes in the radiance of moonlight and airglow (that is, light emitted by the decay of excited states in the upper atmosphere triggered by the high-energy solar radiation), and changes in the position of the Moon and Milky Way in the sky¹¹⁹.

[H2] Implications of variability

The spatial and temporal variability of light emissions and exposure can make it difficult to assess light pollution patterns using satellite measurements. For example, single satellites in sun-synchronous orbits (for example Suomi-NPP and NOAA-20) will typically only observe each location once or twice a night, and therefore cannot explore the full diel cycle. Such measurements are likely to misrepresent the use of light in areas where energy is used more sparingly¹²⁰. For example, light sources associated with market transactions in informal communities are often hung in the evening and taken down at the end of business each day. It could be the case that much of the variability in satellite-based measurements of light pollution⁷¹ arises from the data acquisition approach, rather than actual changes in light emissions, especially if different observation times and angles are used.

[H1] Trends in light emissions

Despite a lack of long-term consistently acquired data for global upward light emissions (from space) or sky brightness (from ground) in the human visual bands a few general trends can be observed. These trends and the ways in which they could evolve in the future are discussed here.

[H2] Past trends

Total light emissions are estimated to have increased by 3–6% per year during the second half of the 20th century³⁸ owing to the rise of electric lighting. As with the global distribution of light, these rates of change are spatially heterogeneous and trends in local light emissions do not always correspond to global brightening trends (**Figure 3**). Satellite data shows that light emissions (in the 500–900 nm band) from LMICs are increasing at a higher rate than those from high-income countries⁴⁰. For example, of countries with a population of at least one million for which gross domestic product (GDP) was available, the 20 countries with the lowest GDP per capita had an average increase in light emissions of 8% per year during 2012–2016, whereas in the 20 countries with the highest GDP per capita light emissions grew at 1.3% per year. However, a small rate of change in a country with high light emissions could represent a greater total growth than a large relative change in a country with low light emissions. Observations of stellar visibility by citizen scientists suggest that artificial skyglow could be increasing much more rapidly (worldwide average of ~ 10% per year⁴⁰) than upward emissions viewed by satellites (worldwide average of ~ 2% per year^{22,68}). The reason for this difference is unknown, but is likely to be related to differences in the time of observation, spectral effects²², near-field¹²¹ or intraocular scattering¹²², or the rate of change in the lighting type used (for example, increasing contribution of advertising signs to light emissions relative to streetlights).

During 2011 to 2020 the market share of LEDs for new outdoor lighting in the USA increased from under 1% to over 66%⁹¹. White LED lights emit a portion of their light in the 400–500 nm range (blue light). These blue light emissions are estimated to have increased by 24% in Europe during 2012 and 2020(ref. ¹²³). However, satellites such as VIIRS DNB have no sensitivity in this range and there have been few direct observations of blue light in isolation from the rest of the spectrum with ground-based radiometers¹²⁴. The lack of data for changes in the emissions of such wavelengths is problematic for time series analysis for several reasons: human low-radiance condition vision (scotopic sensitivity) is more sensitive in the blue than in high-radiance conditions (photopic sensitivity)^{125–127}; blue light is strongly scattered by the atmosphere^{128,129}; and blue light on average has stronger impacts on animals than longer wavelengths¹³⁰. Consequently, the lack of data on changes in blue light emissions makes time series analysis incomplete and prone to incorrect conclusions.

[H2] Projected trends

Future trends in light emissions and pollution are likely to be influenced by a combination of socio-technological factors. The continued expansion of access to electricity¹³¹ and the growth of cities to accommodate the rising population are likely to increase light emissions and the artificially illuminated area, respectively. However, increasing recognition that light is a form of pollution could lead to increased regulation²⁸ or voluntary action^{132,133} to reduce light emissions. Additionally, pressure to reduce energy consumption or carbon emissions could drive reductions in light emissions. For example, from 2010 to 2016 67% of streetlights in Madrid were changed from 180 W HPS to 100 W HPS and 33% from 250 or 150 W HPS to 150 or 70 W LEDs, leading to a 41% reduction (during 2009–2017) in the 500–900 nm wavelength range (**Figure 3**).

The impact that technological innovations in lighting will have on light emissions and the associated energy consumption is unclear. During the 20th century, the overall energy consumption associated with outdoor lighting increased remarkably, despite increases in the luminous efficiency of light sources (Jevons paradox)¹³⁴. For example, although luminous efficacy in the UK doubled between 1950 and 2000, per capita electricity consumption for lighting increased fourfold¹³⁵. Continued reductions in the cost of light could lead to an increase in light emissions throughout the 21st century¹³⁶, but careful lighting design and new technologies (for instance lighting on demand¹³⁷) will allow light to be used more precisely. For example, replacing ornamental lighting in Slovenian churches with more efficient and less luminous lamps combined with masks to ensure no light is emitted directly to the sky¹³⁸, achieved a 96% reduction in electrical power consumption and a ten-fold reduction in the brightness of the church's façade¹³⁹. Thus, an increasing demand for darkness^{140,141} could lead to an environmental Kuznets curve for light¹⁴². With the right developments it should be possible for large urban centres to enjoy both functional lighting and starry skies¹⁴³.

The lack of consistent long-term and global monitoring complicates efforts to project the influence of these socioeconomic factors on light pollution. Improvements in satellite technologies that can directly measure artificial skyglow (by viewing unlit areas) will enable global lighting trends to be monitored. To be effective, these satellites (and their retrieval algorithms) will need to reduce the variability between images, for example, by carefully controlling the angle of observation⁴². Until satellite constellations or geostationary night-time light satellites are available, ground-based observations will be needed to monitor the evolution of light emissions throughout the night. Such monitoring will become increasingly important if smart city lighting is adopted to better match light supply to human demand, which could increase light variations throughout the night. In addition to monitoring sky brightness, observations from horizontal-viewing cameras^{93,144} and citizen science approaches^{145,146} could be used to examine changes at the scale of individual light sources, thus providing light-emission trends for different angles and small scales.

[H1] Light pollution impacts

Artificial light changes the night-time environment, impacting organisms and ecosystems (**Figure 4**). The limitations of existing measurement methodologies present some difficulties for assessing light pollution and its impacts. For example, satellite-measured data do not represent the environment under tree canopies or cloud cover. Despite these limitations, available data demonstrate the physical, environmental, and social impacts of light pollution, as discussed here.

[H2] Physical impacts

In regions near artificial lights, the surface and atmospheric illuminance stop decreasing during twilight (the period when the Earth's surface is no longer directly illuminated by sunlight). Therefore, light conditions during astronomical night (the period when the sun is 18 degrees or more below the horizon and scattered sunlight is no longer visible) are permanently elevated relative to the night-time conditions when life evolved. This increased illuminance can mask or attenuate natural light cycles, such as those produced by movement of the Moon and the Milky Way. The masking of the light of stars and galaxies by skyglow is a major problem for astronomers and led to some of the first research into light pollution being undertaken by astronomers in the context of decisions on where to build astronomical observatories¹⁴⁷⁻¹⁴⁹. In this case, skyglow is produced when photons directed upwards (directly or after reflection from a surface) are scattered back towards Earth by atmospheric molecules and particles. Optically thick low-level clouds can brighten skyglow directly below them, and prevent skyglow from propagating horizontally and above the cloud layers^{86,87,150}.

Light can influence atmospheric chemistry, for example, sunlight can trigger photolysis of chemicals, such as nitrate radicals (for example, the transformation of NO₃ to NO₂), which are present in the troposphere and contribute to air pollution. Similarly, the propagation of direct light and skyglow through the atmosphere has a measurable impact on atmospheric chemistry^{16,151} and increases ozone levels near the Earth's surface. Additionally, the propagation distance of light through the atmosphere, which is longest for horizontally directed light, influences the impact of the light on atmospheric chemistry¹⁵² by altering the actinic flux (the number of photons incident at a point¹⁵³). However, further research into the impact of light pollution on atmospheric chemistry is needed, particularly in the context of megacities, where bright light emissions can extend for over 100 km.

[H2] Environmental impacts

Natural cycles of light and darkness affect all environmental domains (marine, freshwater, terrestrial, and airspace)¹⁵⁴, across a broad range of habitat types and at all levels of biological organisation, from genes to ecosystems¹⁵⁵. Organisms rely on three primary light cycles (daily¹⁵⁶, seasonal¹⁵⁷, and lunar¹⁵⁸) to anticipate environmental changes and synchronise endogenous rhythms. Almost the entire biotic environment can be thus modified by the presence of artificial light. ALAN has been introduced at locations and times that do not occur naturally¹⁵⁹ and the impacts on the biotic environment will depend mainly on light properties such as spatial light distribution, spectral composition as well as duration and intensity of light exposure¹⁵⁵.

Even at brightness levels akin to moonlight and starlight, light pollution disrupts this synchronisation¹⁶⁰, affecting vital processes such as the production of melatonin, which can influence health, fitness and survival^{156, 161}.

Artificial light substantially impacts behaviour and physiology across plant and animal species, including changing singing patterns, reproductive timings, and migratory schedules^{79, 162–164}. Examples include common European songbirds starting their dawn singing earlier, passerine birds laying eggs earlier, and songbirds advancing the timing of their spring migration. ALAN also expedites the onset and prolongs the duration of the growing season in many plants, effectively extending it^{8, 164–166}. The introduction of ALAN even at illuminances equivalent to skyglow^{167, 168}, can trigger maladaptive responses in nocturnal organisms that use natural light cycles for orientation and circadian regulation¹⁶⁹. For example, ALAN can alter the daily migration of zooplankton¹⁷⁰ and the hunting periods of nightjars¹⁶⁷ as well as disorienting sea turtles hatchlings, which head towards dangerous artificially illuminated areas instead of the sea¹⁷¹. Despite these obvious harmful effects, some species use ALAN for orientation in otherwise challenging conditions¹⁷², for example dung beetles, which normally navigate using the Milky Way, can also use urban lights to orient themselves when natural starlight is obscured, which could potentially lead to maladaptation¹⁶⁹. Additionally, ALAN can also disrupt crucial wildlife corridors^{14, 173–175}. For instance, several bat species use woodland edges and tree lines to fly between their roost and feeding locations; however, where there are gaps in such corridors due to roads, road lighting can interfere with the crossing behaviour of bats¹⁷³. Therefore, artificially lit structures such as roads, can increase landscape resistance during movement and migration^{6, 173, 176}. Alterations in migration caused by ALAN can influence the transfer of energy and nutrients across various ecosystems because migrations affect biomass flux^{177–180}.

The diversity of species-specific responses to ALAN can lead to the formation of novel biotic communities around illuminated areas, even extending to microbial sediment communities^{181, 182}. Light-induced changes in these communities can alter the photosynthetic ability of photoautotrophs and the predator–prey dynamics of the community, as well as interspecific interactions such as plant–pollinator and host–parasite relationships^{11, 181, 183, 184}. Therefore, the effects of artificial light can cascade through interaction networks and influence species that are not directly exposed to light¹⁸⁵. The shifts in community composition and ecosystem function can thus impact provisioning (for example, leading to the loss of light-sensitive species and genotypes), regulating (for instance, pollination or seed dispersal by nocturnal insects and bats) and cultural ecosystem services (for example, aesthetic value of natural dark nightscapes)^{186–188}.

The ecological impacts of ALAN are not confined to the direct effects of light. The life cycle of artificial lighting, including the extraction of raw materials (involving mining that can lead to habitat destruction, water pollution, and greenhouse gas emissions¹⁸⁹), manufacturing of fixtures, installation and maintenance, and end-of-life disposal or recycling, all contribute to its total environmental footprint^{190, 191}. Additionally, LED lamps contain many electronic components and approximately 60 different materials, making them difficult to recycle; therefore, by 2016, LED lights accounted for 49,000 tons of electronic waste¹⁹². Additionally, the electricity used to generate artificial lighting accounts for around 20% of global electricity consumption and 6% of CO₂ emissions¹⁹³.

[H2] Societal impacts

Light pollution hinders society from relating with and appreciating the cosmos, diminishing motivation for conservation efforts. Furthermore, increased night-time brightness can lead to a shifting baseline syndrome, whereby people develop an altered perception of what a normal nocturnal light environment is. Such perception shifts can explain how gradual changes over decades have radically altered the night-time environment in highly urbanized regions without most people realizing it¹³⁴. Starry skies are critically important for indigenous people, many of whom rely on stars as a map, textbook, law book and memory space¹⁹⁴.

Although artificial light can be beneficial for societies, it also has negative economic and health impacts. For example, communal lighting accounts for up to 50%¹⁹⁵ of municipal electricity consumption, increasing the pressure on municipal budgets. Furthermore, correlations between satellite-measured outdoor light and an increased risk of various health conditions¹⁹⁶ including cancer^{197–199}, obesity²⁰⁰ and diabetes²⁰¹, as well as negative impacts on people's mental health²⁰² and sleep quality, have been observed. However, it is difficult to confirm whether a causal relationship exists because numerous environmental parameters correlate with light emissions, which could also be responsible for these health impacts²⁰³, and satellite observations are an imperfect proxy for true light exposure.

Additionally, light exposure is unevenly distributed. For example, in high income countries, low-income groups more likely to live in areas with high light pollution^{204–206}. In low income countries, the absence of reliable electricity increases the poverty penalty²⁰⁷ of low-income groups and results in the use of informal lighting that is often unshielded. Therefore, the negative societal impacts of light pollution exacerbate existing social disparities and add to existing environmental deprivation experienced by low-income groups (for example air pollution, heat islands and a lack of green infrastructure)^{208, 209}.

[H1] Night-time light as a proxy

Human beings are diurnal; therefore, artificial light is often needed to allow humans to safely move through both urban and natural environments at night. Thus, ALAN is one of the most prominent indicators of human activity and economic development that can be observed from space (**Figure 5**).

Light emissions observed from space are correlated with GDP and population^{210,211}. However, this relationship is not simple, and often varies between countries^{32,212}. Increased ALAN has historically been used as an indicator of growing wealth²¹³; however, in high-income countries low-income neighbourhoods are now sometimes more brightly lit than high-income neighbourhoods^{214,215}. In low-income countries, light emissions can be an indicator of access to electricity supply^{115,216}. The close association between light and human settlement means that light emissions are often used to determine the creation, boundaries, and growth of settlements^{217,218}. Similarly, light emissions are sometimes used to assess material stock, such as steel, copper and other metals, and its flow²¹⁹. In some cases, the rate of change of the radiance, rather than the radiance value itself, can be a useful indicator of economic growth or decline²²⁰. For example, during 2012 to 2022 a 200% increase in radiance coincided with a 140% GDP increase in Wuhan, China²²¹.

Light emissions observed from space can also provide insight into historical, cultural, economic, and legal differences between places. For example, an East–West divide, remained visible in satellite images of Berlin well into the 21st century, with East Berlin emitting more light per capita than West Berlin and using different lighting technology²¹². Additionally, images of ALAN reveal the boundary between North and South Korea, with North Korea in almost complete darkness and South Korea highly illuminated. Differences in roadway illumination practices can also be observed from satellite images of ALAN; for example, the ringroad around London is illuminated, whereas the ringroad around Berlin is not²¹².

Artificial light emissions can provide information on other human activities. For example, in unpopulated regions ALAN can indicate material extraction facilities (whether official or illicit²²²), fishing boats and other ships²²³, and agricultural lighting such as greenhouses^{224,225}. In regions with military conflict changes in artificial light emissions can provide information about war situations²²⁶. Within cities ALAN can help to identify changes in lighting technologies and monitor population movement due to tourism, for instance skiing resorts in the Alps during winter show a greater brightness than in summer nights (**Figure 5**).

ALAN can also be used as a proxy for monitoring environmental changes. For example, cloud, snow, ice, and leaf cover, as well as soil moisture²²⁷ all influence the proportion of light from stars, airglow, and the Moon that is reflected. Additionally, some natural phenomena such as volcanism, wildfires and bioluminescence²²⁸ emit light directly, allowing them to be observed at night from space. The movement of air masses in the upper atmosphere can also be detected in satellite imagery through the impact of such movement on airglow²²⁹.

The boundaries between naturally and artificially illuminated areas can indicate landscape connectivity for flying, terrestrial, and aquatic organisms^{175,230}. Skyglow is visible in satellite imagery adjacent to artificially illuminated areas, and remains brighter than natural airglow over ten kilometers from bright sources⁶⁶. Thus, space-based measurements could be used to monitor skyglow and therefore landscape connectivity in the future. Such measurements could also be used to remotely assess the energy consumption associated with light emissions.

[H1] Summary and future perspectives

Global night-time light emissions increased by 3–6% per year during the second half of the 20th century, an aggregated 49% from 1992 to 2017, and by 2–10% per year from 2011 to 2022. The availability and types of lighting as well as the rate of change vary between regions, owing to many factors including, economics, culture, and disasters (including war). ALAN impacts nearly all ecological systems either directly through light exposure or indirectly owing to the pollution produced during the life-cycle of lighting. Monitoring ALAN can provide information related to human development and activities. However, current data acquisition techniques have important limitations for assessing light pollution.

Improved night-time remote sensing is needed to better understand light pollution and its various impacts. Proposals for future satellites often agree on several main improvements^{37,231}. First, multispectral imagery must be obtained in the 400–900 nm range. Second, the spatial resolution should be at least at the scale of individual buildings (40 m). Third, the dynamic range should be large enough to observe dim lights and avoid saturation in bright city centers. Fourth, the instrument must have an accurate radiance calibration, which is currently lacking in many commercial products. Some future missions could focus on obtaining information from different angles, or at different times of night whereas other goals could be better served by observations obtained at a consistent angle or time. For example, a satellite mission concept called Night Watch has been proposed under the ESA's NEOMI programme, prioritizing high sensitivity, high dynamic range, and consistent observations.

One satellite cannot by itself address all of these goals; therefore, scientific groups and space agencies will need to work together to develop complementary missions. For example, low Earth orbit satellites could focus on obtaining imagery at

high spatial resolution with global coverage, detailed spectral information or frequent revisits for selected targets, similar to Landsat or the European Sentinel programme. Meanwhile, satellites in geostationary or other high-altitude orbits could provide continuous observations of temporal variability over the course of the night. NASA's geostationary Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument could soon provide the first evidence of the benefits of such an approach.

Efforts are also needed to coordinate satellite and ground-based observations. Specifically, the sharing of data between existing ground-based instruments such as SQMs and astronomical observatories should be improved. Such sharing would allow existing data, including numerous colour filter measurements, to be mined to obtain long-term trends of sky brightness at observatory sites. Ground-based metrology and instruments must continue to be developed, ideally with a link to the satellite development so that ground and space-based data can be directly compared.

Although new satellite missions will be key to better understanding light pollution, the overwhelming number of satellites currently orbiting Earth threatens natural skies worldwide²³². Reflected light and radio emissions from satellites are already interfering with astronomical observations^{233,234}. Reflections from small debris, which include defunct satellites, spent rocket stages and fragments from disintegration and collisions, in orbit around the Earth already brightens the night sky by roughly 10%²³⁵. Such brightening will be exacerbated if plans for mega constellations come to fruition, leading to drastic changes in the night sky. These impacts and the increasing risk of catastrophic collisions²³⁶ do not appear to be receiving the attention they deserve. Thus, the potential impacts of new satellite missions on the night-time environment must be carefully considered.

Light pollution is intricately linked to energy consumption and the well-being of ecosystems. Methods to reduce light pollution already exist, and ground-based and space-based measurements can be used to measure the resulting changes in light pollution. Consequently, a coordinated effort is needed to implement changes in lighting policy and infrastructure to reduce light pollution and monitor their success.

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Related links

Dark Sky International <https://www.darksky.org>

IRIS <http://www.astrosurf.com/buil/us/iris/iris.htm>

ImageJ. <http://imagej.nih.gov/ij/>

The World Factbook <https://www.cia.gov/the-world-factbook/field/airports/country-comparison/>.

Data Availability

The Radiance Light Trends webtool used to obtain the data plotted in Figure 5 is available as <https://doi.org/10.5880/GFZ.1.4.2019.001>.

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Competing interests

The authors declare no competing interests.

Author contributions

H.L.A., A.A., T.D., F.H., A.J., M.K., A.S.d.M., K.W. and C.C.M.K. researched data for the article. H.L.A., A.A., M.A., T.D., B.R.E., G.G., F.H., M.K., A.S., K.W. and C.C.M.K contributed substantially to discussion of the content. H.L.A., A.A., T.D., F.H., A.J., M.K., A.S.d.M., K.W. and C.C.M.K. wrote the article. H.L.A., A.A., A.S. and C.C.M.K. reviewed and/or edited the manuscript before submission.

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Table 1. Night-time satellite missions characteristics

Satellite	Orbit	Coverage	Overpass time (local)	Revisit period (days)	Swath (km)	Spatial resolution (m)	Spectral response (nm)	Data availability
SUOMI NPP with VIIRS DNB	Polar 830 km; Sun-synchronous orbit	Global; daily	~01h30	16	3,000	750	PAN 500–900	2012–
DMSP with OLS	Polar 830 km; Sun-synchronous orbit	Global; every 14h	~20h30	–	3,000	2,700	PAN 400–1,100; low <500; >900	1992–2014
LUOJIA 1-01	Polar 645 km; Sun-synchronous orbit	Global; every 15 days	–	15	250	130	PAN 460–800	2019
JINLIN-1	Polar 480 km; Sun-synchronous orbit	–	~ 21h30	3.3	17	PAN 0.7; multi 3	RGB	2017–
SDGSAT-1 with LLL	Polar 505 km; Sun-synchronous orbit	Global	~ 21h30	11	300	PAN 10; multi 40	PAN 450–900; RGB	2021–
Eros-B	Polar 516 km	Global	~ 1h30	–	7×7; 7×250	0.7	PAN 500–900	2006–
SkySat	Polar Sun-synchronous; Inclined non-sun-synchronous 53°	Global	-	6–12 per day	8	PAN 0.9; multi 2	PAN 450–900; RGB–NIR	–
ISS with Nikon D1-5	Low earth orbit; 400 km; 51.6°	±51.6°	Any	3	40–3,000	4–740	RGB	2003–
Landsat	Polar (98 °); 705 km	Global	–	–	–	8	PAN 500–900	–
CE-SAT-1 with EOSSD	97.45°; 497–517 km	Global	~ 20h00	5	4.8x2.3	1	RGBA	2017–

VIIRS, Visible Infrared Imaging Radiometer Suite; DNB, Day/Night Band; OLS, Operational Linescan System; LLL, low light level; NIR, near infrared; ISS, International Space Station; DMSP, Defense Meteorological Satellite Program; PAN, panchromatic band; RGB, red-green-blue bands.

Figure 1 **Sources of light at night.** Satellite image of artificial light at night. This light can contribute to skyglow (Inset 2). Artificial light sources include gas flares (Inset 1), urban electrification (Inset 3) and fishing boats (Inset 4). Sources of artificial light at night are heterogeneous and linked to different human activities. Map data courtesy Marc Imhoff of NASA GSFC and Christopher Elvidge of NOAA NGDC and image courtesy of Craig Mayhew and Robert Simmon, NASA GSFC. Inset 1: Bloomberg Creative/Getty images, Inset 2: Dneutral Han/Getty images, Inset 3: Wangwukon/Getty images, Inset 4: ZoonarGmbH/Alamy Stock Photo.

Figure 2 **Approaches to measure light at night.** Space-based measurements performed by satellites (red) detect direct and reflected upwards light; however, shading from vegetation can prevent a satellite from detecting some light emissions. Ground-based (blue) techniques include all-sky cameras, which measure light from all directions that has been scattered downwards by clouds and the atmosphere. Direct observations (green), including measurements with a camera or from radiometers attached to animals can measure horizontal light. Therefore, a combination of measurement techniques are required to quantify light exposure.

Figure 3 **Global and local radiance trends.** a) Artificial radiance detected by the Defense Meteorological Satellite Program-Operational Linescan System (DMSP-OLS, blue) and Visible Infrared Imaging Radiometer Suite Day/Night Band (VIIRS DNB, red) satellite radiometers divided by the radiance detected by the DMSP in 1992(ref.²²). The error bars indicate the range of offset values in the intercalibration of the images. b) As in a, but for Europe. c) As in a, but for Spain. d) As in a, but for Madrid. It is unclear whether the decrease in radiance observed for Spain and Madrid is caused by reduced light emissions or by the transition from high-pressure sodium streetlights to light emitting diodes during 2010 to 2016, which produce light outside the spectral range of the sensors^{22,68,69}.

Figure 4 **The direct and indirect effects of light pollution.** Direct impacts of Artificial Light At Night (ALAN, blue) and skyglow caused by ALAN (yellow) on humans and ecology as well as the secondary impacts of light provision (grey). There are many diverse negative impacts of light pollution and new approaches for monitoring light pollution are likely to lead to the identification of additional negative impacts.

Figure 5 **Light emissions as a proxy for human activity.** a) Time series obtained from the radiance lighttrend webtool (see the data availability statement) using the Visible Infrared Imaging Radiometer Suite Day/Night Band (VIIRS DNB) average radiance monthly data with zero point correction product in the city of Sanaa in Yemen following the outbreak of a civil war in 2014²³⁷. b) as in a, but for Tucson, USA during the introduction of shielded streetlights with reduced illuminance¹³². c) as in a, but for the Ischgl ski resort in Austria, highlighting the seasonal trend (red line) with light emissions peaking in winter. d) As in a, but for Wuhan, China, during a period of economic growth²³⁸. Thus, changes in light emissions can provide insight on war and crisis, sustainable lighting development, seasonal changes and economic growth.

Toc Blurb

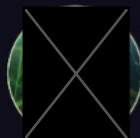
Increasing light emissions threaten human and ecological health. This Review outlines existing measurements and projections of light pollution trends and impacts as well as developments in ground-based and remote sensing techniques that are needed to improve them.

SKY GLOW

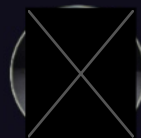
ENVIRONMENTAL IMPACT



PLANT PHENOLOGY



AQUATIC SYSTEMS



REPRODUCTION



MIGRATION

HUMAN IMPACT



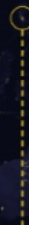
HEALTH



FISHING BOATS



GAS FLARES (Iraq)

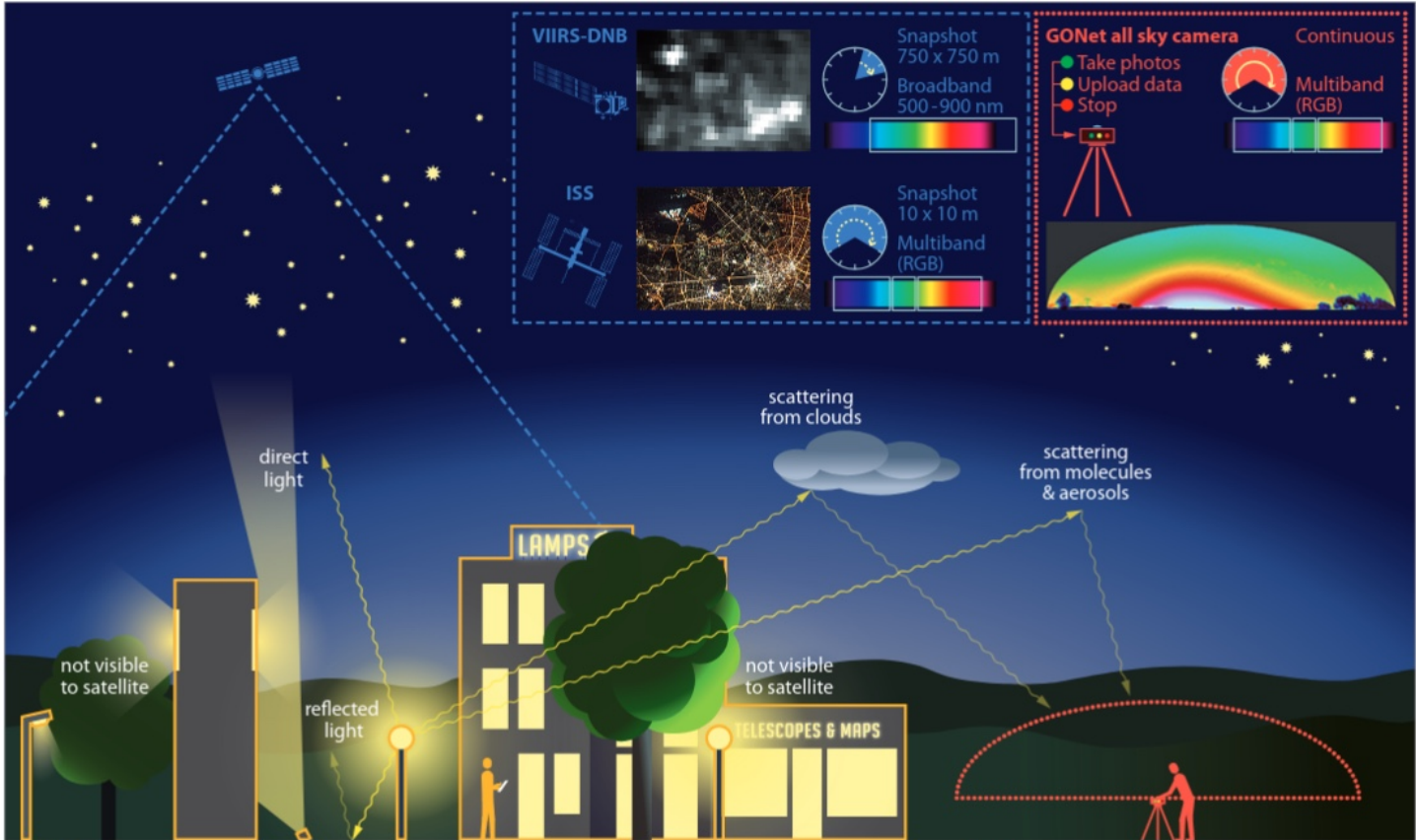


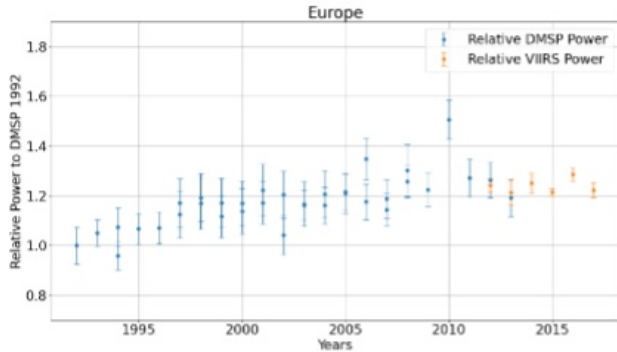
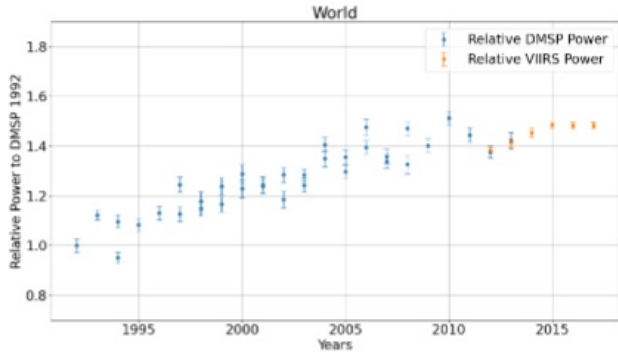
URBAN ELECTRIFICATION (Manila)



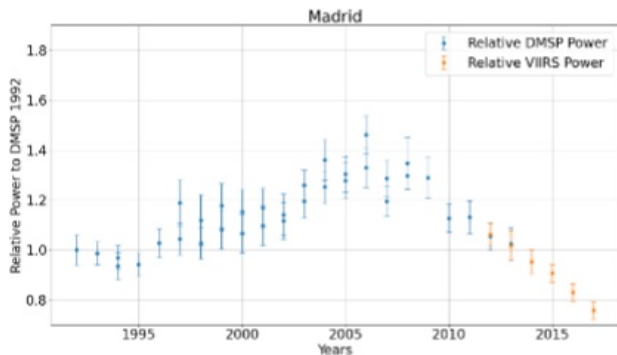
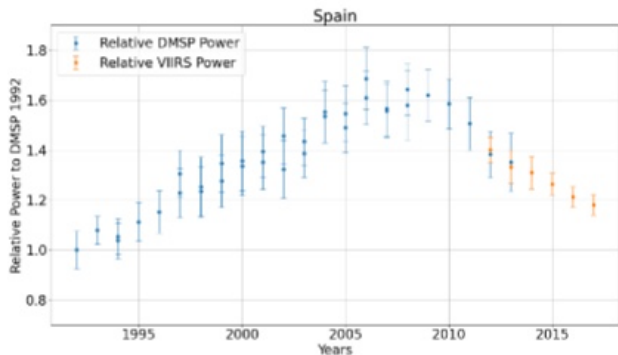
ARTIFICIAL LIGHT AT NIGHT







b)



d)



impacts on humans

impacts on ecology

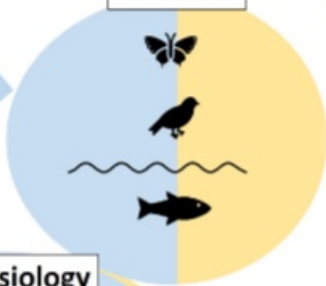
societal



direct light



behavior



secondary aspects



health & well-being



physiology



