Artificial Light at Night: State of the Science 2022

International Dark-Sky Association

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This briefing summarizes the current state of knowledge about how the widespread and growing use of artificial light at night interacts with six key topics: the night sky (Section 1); wildlife and ecology (Section 2); human health (Section 3); public safety (Section 4); energy security and climate change (Section 5); and social justice (Section 6). It also includes a discussion of the emerging threat from light pollution caused by objects orbiting the Earth (Section 7). Finally, it concludes with a discussion of the knowledge gaps that exist within these topics and the research questions whose answers can fill the gaps (Section 8). It is intended be useful to those seeking to broaden their understanding of research on the causes and consequences of artificial light at night.

Introduction

Light pollution is surging in both its presence and reach across our planet (1, 2). It is the source of both known and suspected harm to the nighttime environment (3). Scientific studies suggest the over-use of artificial light at night (henceforth, 'ALAN') is the main source of light pollution (4, 5). The main challenge they identify is how to maximize the human benefits of ALAN while limiting its potentially negative social and environmental impacts (6–8).

1 The Night Sky

Light emitted into the night sky makes it difficult to see the stars. On the ground, ALAN makes the nighttime environment brighter. Weather changes like clouds and snow on the ground can make this impact worse. New and inexpensive light sources like white light-emitting diodes (LEDs) have a growing impact on both the night sky and outdoor spaces at night.

The most immediate symptom of light pollution is the phenomenon of "skyglow". It brightens the night sky in and near cities where large installations of outdoor lighting exist. The lower layers of the Earth's atmosphere scatter light emitted near the ground. Some of that light escapes the atmosphere where Earth-orbiting satellites detect it, but many light rays encounter molecules and small particles in the atmosphere. These interactions redirect the paths of some of the light rays back down to the ground. Observers there see light appearing to come from the night sky itself; see Figure 1. Skyglow competes with the faint light of astronomical objects in the night sky. It lowers the contrast between those objects and the background sky, making it difficult to observe them.

A slow but steady rise in skyglow in much of the world leads to gradually degraded visibility of the natural night sky and a transformation of lighted outdoor spaces. Such a situation, changing slowly over decades, may go unnoticed due to a psychological effect know as a "shifting baseline" (9). This applies to various aspects of artificial light on a 'normal' night: the number of visible stars, the amount of artificial light associated with perceptions of safety, and the experience of using non-visual senses such as hearing and balance at night. Along with other effects, the loss of the night sky is barely noticed.

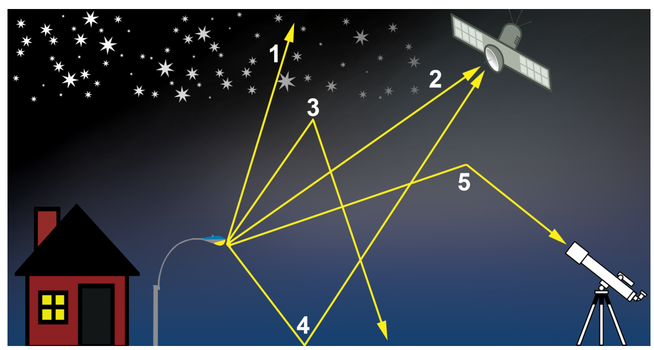

Figure 1. The streetlight at left emits light in many different directions. Some of the light rays (1) travel upward into the sky and pass completely through Earth's atmosphere. Satellites detect some of these rays (2) as they pass over the nighttime side of our planet. In other cases (3), the atmosphere scatters rays back to the ground. This light becomes the familiar "skyglow" seen over cities. Some of the rays traveling downward (4) reflect off the ground into the sky where they are seen by satellites. Lastly, some rays scatter into astronomers' telescopes (5), blocking their view of the universe. Credit: IDA.

Remote sensing of light pollution

"Remote sensing" is a method of measuring the properties of something at a distance without directly sampling it. It is often applied to observations of our planet made by orbiting satellites. When those satellites look at light on the night side of Earth they provide a view of the global scale of the problem of light pollution (1, 10, 11).

Figure 2 shows a global map of night lights made with remote sensing observations (12). This is a composite image composed of observations of Earth made over many nights in one year. It gives the appearance of our planet as if it were simultaneously night everywhere at once. It also ensures that the result does not include clouds or light from the aurora near the Earth's poles.

The camera used to make this map uses a sensitive detector that records faint light in the visible spectrum. It can resolve features on Earth smaller than one kilometer in size. This is smaller than the size of most cities, so the images give detailed information about the number and characteristics of various light sources on the ground. Images like these dating from as early as the 1970s are available to the public and for scientific study.

In recent years, researchers have learned much about the spread of light pollution across the globe by studying remote sensing data. They found that skyglow fouls the night sky for more than 80% of all people and more than 99% of the U.S. and European populations (10).

Both the amount of artificial light seen on Earth at night and the land area that light covers grow by about two percent each year on average.(Figure 3) (1). Yet, both numbers vary across our planet (13). There are only a few countries in which they seem to be either stable or decreasing (1, 14).

Satellite remote sensing used to make studies like these is not perfect. For example, the best available satellite cameras are not sensitive to some colors of light. In particular, they do not see the blue light emitted by white LED lighting. This means that key light pollution indicators are probably underestimated. Combining satellite data with ground-based observations can improve the reliability of results (15), but the need for new, dedicated orbital facilities to address important research questions is urgent (16, 17). This is especially true given that some Earth-observing satellite missions, such as NASA's Terra, are slated to end in coming years.

Environmental conditions change night sky quality

Cloudy conditions tend to make skyglow more intense in urban and suburban areas because overcast nights can increase the intensity of light reflected back down to ground level by up to ten times (18, 19). However in rural areas with few light sources, cloud cover tends to *darken* the night sky (20). This is because clouds efficiently absorb and scatter light from both natural and artificial sources, decreasing the amount reaching the ground. Skyglow is also sensitive to very small particles in the air (21), and it can be increased by air pollution (22).

Ice and snow make skyglow worse because they reflect much more light than darker ground covers. This enhances the apparent nighttime artificial light emissions from cities (23). Snow cover on the ground under clear-sky conditions can increase night sky brightness by up to three times (24). When clouds cover the sky in the winter months, light reflected from both snow and clouds amplifies skyglow. The result can raise the night sky brightness by over 3,500 times compared to overcast conditions with no artificial light (25). Even in clear weather, the tendency of ground covers like asphalt and concrete to reflect light can raise night sky brightness (26, 27).

The rise of solid-state lighting may threaten dark skies

Global light pollution has increased in recent years in part because of the introduction of solid-state lighting (SSL). This kind of lighting uses semiconductor materials to generate light. It differs from earlier technologies that used electric currents in tubes of gases like sodium vapor. Those earlier methods of making light once dominated the global outdoor lighting market.

The most familiar kind of SSL technology is the white LED. This technology now accounts for almost 50% of global lighting sales (28). The lighting market's explosive growth in recent years is due in part to the exceptional energy efficiency of SSL, which is up to ten times higher than earlier technologies like incandescent filament lamps. While one-for-one SSL replacements save energy compared to earlier technologies (with beneficial impacts; see Section 5), the energy efficiency and low cost of SSL can encourage overlighting (with negative impacts; see Sections 2, 3, and 5). In order achieve the full promise of SSL, factors such as the spectrum and distribution of the light source should be carefully designed.

The rapid rush to adopt and install SSL has changed the color of artificial light emitted into the nighttime environment (29, 30). White LED lighting generally emits much more short-wavelength (i.e., blue) light than other technologies. This causes a shift in the color of cities as they transition to SSL (31). It may also make skyglow over cities worse even when the number of lumens – that is, the *amount* of light to which the human eye is sensitive – used is the same (32–34). This may extend the impact of city lights much farther into adjacent, ecologically sensitive areas (35, 36). It also specifically threatens the productivity of ground-based astronomical observatories (37), which rely on sites with dark night skies in order to produce new knowledge about our universe. However, the characteristics of LED lighting can enable its more efficient use, often requiring less light for the same applications than previous technologies (38). When cities plan LED retrofits carefully, they can hold light pollution steady or even reduce it (39–41).

Dark-sky conservation and astrotourism

Meanwhile, the ongoing conversion of world outdoor lighting to SSL, and its potential to increase skyglow, may work against dark-sky landscape conservation goals. Public interest in visiting naturally dark places is increasing (42). This has created a new kind of "astrotourism" (43, 44) with significant revenue-generating potential (45). This may in turn encourage lighting practices and public policies that protect night skies, yet it calls into question what defines a "dark sky" (46) and how it should be quantified (47, 48). It also requires understanding how to measure or describe nighttime

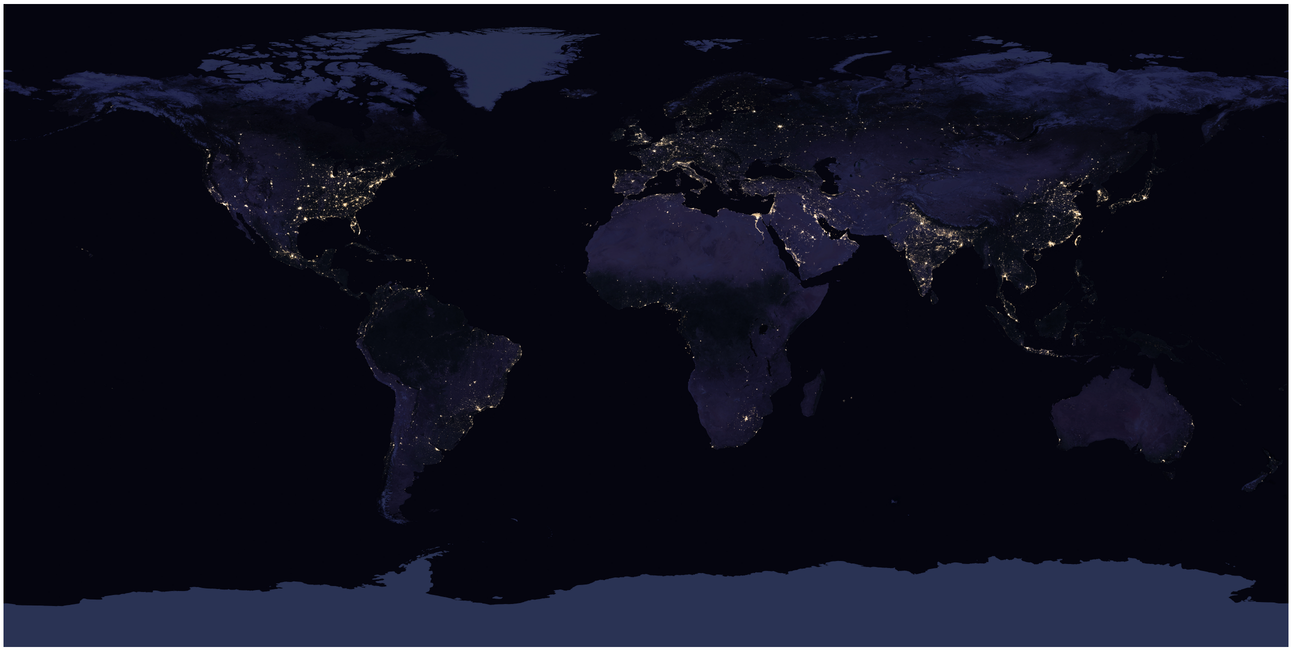

Figure 2. A cloud-free composite image of the Earth at night made using Earth-orbiting satellite data for the year 2016. Credit: NASA Earth Observatory/Goddard Space Flight Center/J. Stevens/M. Román.

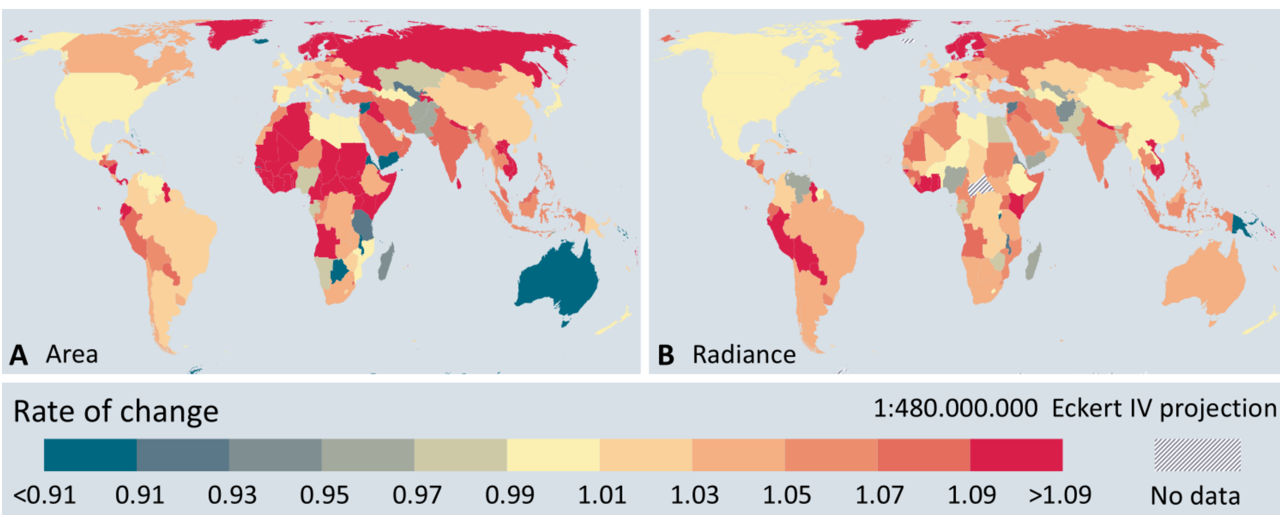

Figure 3. This figure from reference (1) shows how nighttime lights on Earth changed during 2012-2016. The map on the left shows the change in the land area showing indications of artificial light as seen from space, and the map on the right shows how much the brightness of the light changed. Red colors mean increases in lit area and/or brightness during the study period and blue colors mean decreases. Yellow areas were unchanged.

darkness to best preserve it (49, 50). Limited evidence suggests that efforts that recognize the value of dark skies and support their conservation may have positive benefits in reducing skyglow on regional scales (51).

2 Ecological Impacts

ALAN exposure impacts almost every species studied by scientists. It interferes with their biology and changes how they interact with the environment. This harms ecosystems and can make plants and animals less resilient in the face of environmental change.

Organisms at or near the surface of the Earth experience natural levels of light that vary by factors of over one billion times (Figure 4). The rising and setting of the Sun and

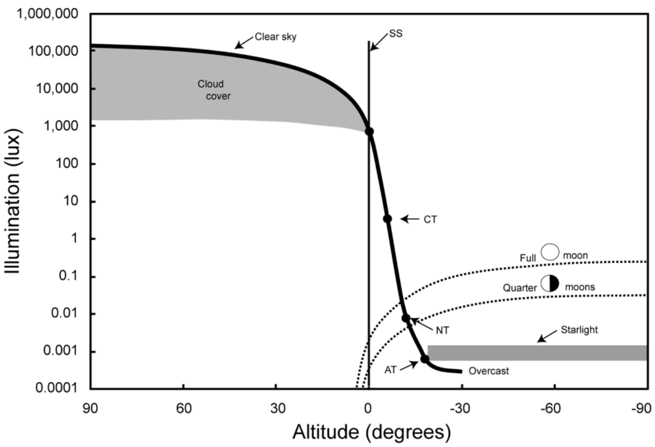

Figure 4. Natural illumination during the day and at night. The solid black line is the amount of light falling on surfaces near the ground. Certain times are indicated: SS = sunset (when the Sun's angle above the horizon reaches $0°$); CT = end of civil twilight (Sun angle = $-6°$); NT = end of nautical twilight (Sun angle = $-12°$); AT = end of astronomical twilight (Sun angle = $-18°$). Note that the increments on the vertical axis increase in powers of ten. The horizontal axis shows the angle above or below the horizon of the moon. Dotted lines show the the illumination by the moon for its full and quarter phases. Cloud cover decreases the ground brightness by the amount in the shaded region at upper left. The shaded region at lower right is the contribution from starlight under clear skies. Adapted from (52); figure courtesy of T. Longcore.

moon set light levels and the timing and duration of light exposure. They are the most important sources of light in the natural environment, and they establish cues that species look for around them. This tells them when to engage in certain behaviors like finding food and mates.

Some species rely on very dim sources of natural light, such as starlight, for orientation and navigation (53–57). Artificial light can disrupt the activities of these species. Their behaviors evolved over billions of years in the presence of only natural sources of light at night.

The scale of ALAN impacts on wildlife

Scientists have studied at least 160 species for effects due to light exposure. They have observed harms at levels from individual plants and animals all the way up to entire populations (58, 59). Nearly all living things react to light. Often these reactions negatively affect both individual organisms and entire populations. Observed effects have been seen among birds (60–62); fishes (63–65); mammals (66–68); reptiles (69–71); amphibians (72–74); insects and other invertebrates (75–78); and plants (79–82). Effects are seen particularly in aquatic environments (83) including the world's oceans (84, 85) to depths of hundreds of meters (86).

Exposure to ALAN disrupts natural light intensity, timing and its color characteristics (87). It increases total light intensity relative to natural levels and shifts the spectrum of ambient light away from its natural condition and toward shorter wavelengths to which many nocturnal species are especially sensitive (88, 89). Poorly timed light exposure interrupts various biological activities in plants and animals (90). These activities rely on the daily and seasonal rhythms of exposure to light in the environment. Examples include finding food (91–93); the time at which certain animals first emerge from their hiding places (94, 95); plant and animal reproduction (66, 96–98); and animal migration (99) and communication (100, 101). All these effects can make it difficult for organisms to survive and reproduce; it may even influence how species evolve (102, 103). This adds to other environmental pressures many species face like habitat loss and climate change (104–106).

Artificial light exposure seems to weaken the immune systems of some organisms (107–109). Parents may pass that weakness to their offspring (110, 111). Light at night exposure may thus leave some species more vulnerable to both predators and parasites (112, 113). Researchers also find that light exposure often occurs alongside noise caused by human activity (114). The combination of artificial light and acoustic noise can further harm some species (115, 116).

How light affects biology

Light has two kinds of effects on plants and animals: internal (through physiology) and external (through interactions with the environment and with other species). Physiological effects of ALAN exposure include disruption of normal chemical signaling in organisms (117, 118). This signaling relates to the circadian rhythm, a roughly 24-hour cycle of activity tied to the length of the day. Exposure to sunlight, followed by many hours of darkness, establishes an environmental cue. This helps 'entrain' the circadian rhythm when the period of the rhythm differs from the day length. Artificial light exposure at times that conflict with these natural cues is an environmental effect that can interfere with this entrainment.

In addition, some species show sensitivity to the *polarization* of light (119, 120). Polarization refers to the plane in which light waves travel. Light can become polarized by reflection from surfaces such as water, which presents a special challenge to aquatic species near sources of ALAN (121, 122). The example of polarization effects shows that when evaluating the impact of ALAN on wildlife, we must look at factors in addition to the intensity, spectrum, duration and timing of light exposure (123).

Modifying the outdoor spaces at night by exposing species to artificial light causes environmental effects. There are few sources of natural light in the nocturnal environment besides the moon and stars. This light dominated the landscape for billions of years until the invention of electric light. ALAN can therefore be a disadvantage to species that evolved in a world without it.

The sweeping changes brought about by ALAN have many observed effects on ecosystems (Figure 6). For instance, ALAN exposure can change the interaction between predatory species and their prey (126–128). This weakens food webs (129, 130) and can make wildlife suscepti-

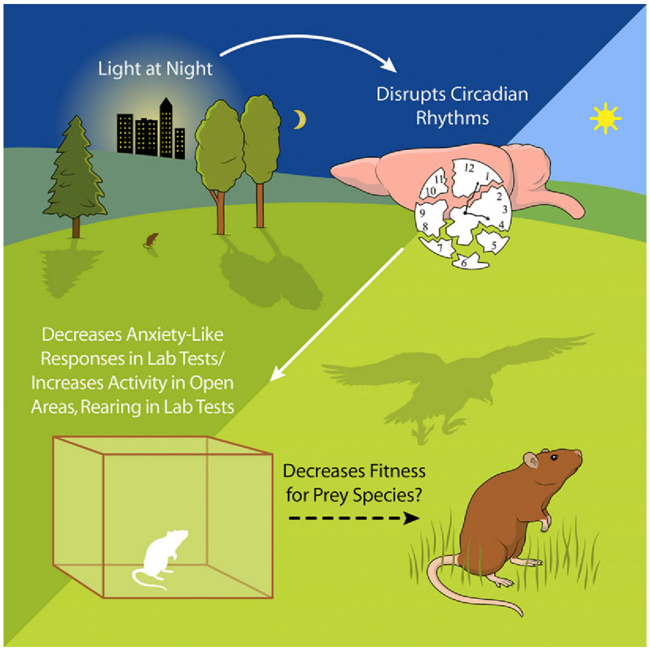

Figure 5. A cartoon representation showing how ALAN exposure can make prey species more vulnerable to predators in the wild. In lab tests of rodents, ALAN interferes with signaling processes beginning in the brain's pineal gland. This interference apparently decreases anxiety responses, such as activity in open areas and behaviors like standing up on the hind legs, that could increase their visibility to predators. Figure 1 from Russart and Nelson 2018 (124).

ble to other environmental harms (131–133). Other ways ALAN causes environmental harms to species are by reducing options for finding food (91, 92, 134); altering how species find mates and reproduce (135–138); and interfering with organisms' abilities to orient themselves and move about (56, 62, 139–141). ALAN also alters the competition for resources between species by either including species in, or excluding them from, their habitats based on their exposure tolerance (142–144).

ALAN can create an effective barrier in the environment to the movement of organisms. They sometimes avoid lit areas in preference to darker ones, and ALAN can disguise barriers that can injure or kill individuals (145, 146). It can also cause *phototaxis*, a condition in which organisms tend to move either toward light (positive phototaxis; e.g., 133, 147, 148) or away from light (negative phototaxis; e.g., 149, 150). Phototaxis is a cause of injury and death among both birds and insects (151–153).

ALAN is one of the most pressing and imminent threats to global biodiversity (154, 155). Studies suggest clear impacts on wildlife populations due to artificial light, even from indirect exposures (156). In particular, certain types of outdoor lighting adversely affect wildlife biology (157). In some cases it may convey advantages to invasive species (158), helping them out-compete native species. Yet biological impacts of artificial light sources are still mainly referenced to human vision. Our understanding of the impact of artificial light on species beyond our own is therefore hindered by the convention of measuring light in reference to human vision. Scientists stress the need to take into account the different visual systems of animals in comparison to humans (89, 159).

ALAN is likely responsible for the death of millions of birds and insects each year. In the following subsections, we focus on these two classes of animals.

Migratory birds

Although most migrating birds navigate by sensing the Earth's magnetic field (160), many species also rely on light cues in the environment. Some use these cues to 'calibrate' their magnetic sensitivity (161, 162). Artificial light exposure interferes with this behavior (163).

Positive phototaxis is of particular concern for the conservation of migrating birds. Bright lighting in cities can become a beacon to some species, drawing them away from their migratory routes (164, 165). Fixtures emitting light vertically seem to have the strongest effect (140), but even 'dark sky friendly' lighting attracts birds at night (166). The attraction to light can become lethal as it promotes collisions between birds and windows (167).

ALAN can negatively affect the distribution of birds at points along migratory routes where birds stop to rest and feed (168). The presence of lit cities along those routes causes birds to fly higher than in more rural areas (169). Very bright installations can attract so many birds that weather radar installations can detect them (165). This fact is now used to measure the extent of attraction of birds to bright light sources on landscape scales. Researchers find that periodically switching powerful light sources off during the night can reduce this effect by providing opportunities for birds 'trapped' by positive phototaxis to escape (170).

Pollinating insects

Ecologists have studied the role that various species play in providing what are now called 'ecosystem services'. These are the benefits that humans receive from the natural environment. An example of an ecosystem service that is critical to human wellbeing is the pollination of food crops by insects. Many of these insects are only active at night. Some species seem to pollinate only under conditions of dim, natural light such as moonlight (171).

ALAN appears to harm at least some nocturnal pollinator species (101, 172–174). This could reduce crop yields and threaten food supplies in some instances (175). It may even contribute to significant population declines among pollinators that some have called the 'insect apocalypse' (176–178).

Researchers find effects from many types of outdoor lighting, including common applications such as street lighting (179), and in at least some cases, light color may disrupt nocturnal pollination (180). While some pollinators may simply seek out darker places, they may find conditions there less suitable (181). Further work is needed to firmly establish

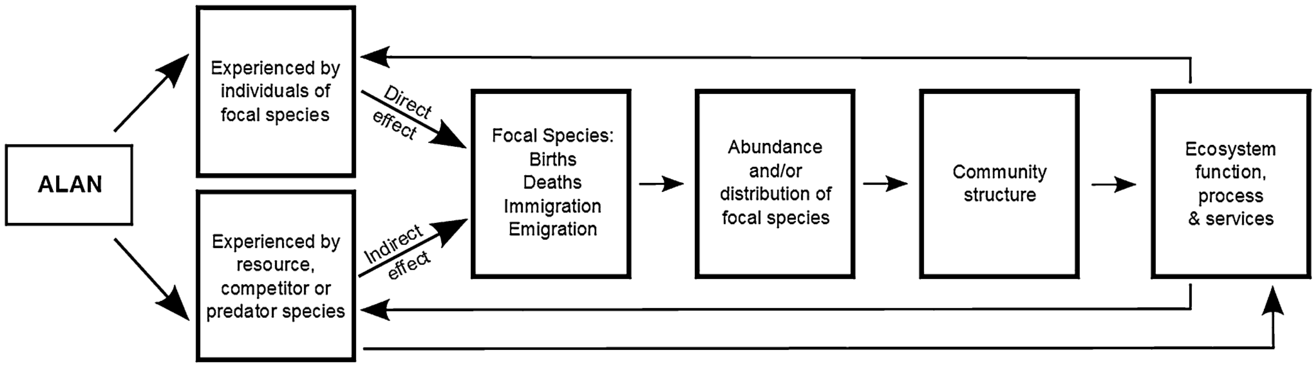

Figure 6. Routes by which ALAN exposure can influence interactions between different species. The figure shows some of the ecological consequences of those interactions. Figure 7 in Gaston *et al.*. 2014 (125), licensed under CC-BY-3.0.

importance of the threat and which lighting changes make the greatest improvements for pollinators.

3 Human Health

Scientific evidence establishes a link between ALAN exposure and adverse human health consequences. These include disruptions in chemical signaling in the body, certain kinds of changes at the genetic level, and shifts in sleep/wake cycles set by natural light sources. These effects may contribute to the incidence of certain chronic diseases in some people. These conclusions are largely drawn from controlled studies of exposures to indoor lighting, suggesting caution in interpreting the influence of outdoor lighting on health.

The light-melatonin connection

The relationship between outdoor ALAN exposure and human health and wellbeing is controversial. Replicating urban environments and using human participants is difficult to achieve in practice. This leads researchers to rely on lab studies carried out on certain animals, such as mice and rats, which serve as well-understood models of biology in mammals generally. In these studies, ALAN exposure seems to have effects on the entire life cycle, from childhood (182, 183) and adolescence (184, 185) to old age (186, 187). In particular, these effects seem to result from short-wavelength ("blue") light. While exposure to blue light during the day is important for healthy circadian functioning (188), exposure to this light at night can disrupt the human circadian rhythm. This can affect everything from the timing of hormone release in the body to the duration and quality of our sleep (189). The significance of these effects depend on the intensity of blue light and and the timing and duration of the exposure.

Exposure to light at inappropriate times during the 24-hour day delays or prevents the secretion of melatonin (190). This powerful antioxidant is a hormone that interacts with the immune system (109, 191). Low-intensity artificial light can suppress melatonin production (192). As little as 5 lux of light can yield this effect in some particularly sensitive people (193, 194); that is about 50 times brighter than full moonlight and 100 times less intense than the amount of light in a bright indoor office environment. The long-term effects of this kind of light exposure are unknown.

The production of melatonin varies over the 24-hour day. Researchers guessed that there must be some way by which the body senses light in the environment. They suspected that it might not relate to our image-forming sense of sight. In 2001, Professor George Brainard and his co-workers discovered the missing piece of the puzzle. They found evidence for the chemical machinery in light-sensitive cells in the retina of the eye that couples light exposure to the system regulating the circadian rhythm (195). This machinery involves a substance called melanopsin that is very sensitive to blue light (196).

ipRGCs exposed to blue light send signals to the master circadian "clock" in the brain. This establishes a timing reference for other such 'clocks' in various organs and systems of the body. Those clocks in turn govern various biological activities (197, 198). Exposure to ALAN can cause the master clock to go out of sync with the natural light pattern of the 24-hour day (199). The consequences of such resets are still not fully understood. And some of the peripheral clocks seem to be sensitive to light on their own, independent of the brain (200).

Further, it is now recognized that light exposure makes changes at the level of our genetic code. While it is not known to alter our DNA, the molecule that spells out that code, light can cause "epigenetic" changes in humans (201, 202). These changes can switch genes "on" or "off", altering their normal roles. Some of those genes relate to the function of our circadian clocks. Epigenetic changes to those genes appear to increase the risks of certain cancers (203), particularly breast cancer (204, 205).

The consequences of frequent ALAN exposure

Frequent exposure to excessive light at night may be an emerging lifestyle risk along with other factors associated with shiftwork, contributing to various health problems. These include obesity (206–208), diabetes (209, 210), and certain cancers (211–213) such as that of the breast (214–216) and prostate (217–220). ALAN exposure also seems to promote the more aggressive spread of some types of cancer (221). It can make cancer resistant to even the best available drug therapies (222) and weaken the body's self-repair mechanisms (223).

Some epidemiological studies find strong correlations between indications of ALAN from satellite data and the incidence of breast and prostate cancers, suggesting that outdoor light exposure is an influence (224, 225). At the same time, critics point out the reliance on the use of satellite data to predict disease-related ALAN exposures (226). This may make the results of some studies less reliable because satellite measurements are only crude estimates of the actual doses of ALAN from outdoor sources that most people receive.

A more common way that ALAN exposure triggers effects in humans is by causing insomnia (227, 228). Melatonin production and cycles of sleep and wakefulness follow each other. Chronic light exposure at night associated with night shift work can cause these two cycles to decouple (229).The result is often poor quality sleep and low sleep duration (230). Many social and health consequences associate with frequent insomnia (231, 232), posing a threat to both public health and worker safety and productivity (233, 234).

Influences on health outcomes

Health practitioners now recognize the roles that light and darkness play in healing from disease and medical procedures. ALAN exposure delays or prevents recovery from stroke (235, 236), hardening of the arteries (237), skin wounds (238), and whole-body inflammation (239). Controlling ALAN exposures in places like hospitals results in better health outcomes (240, 241). The growth of outdoor lighting may be encouraging the spread of communicable diseases (242). It may also create conditions for new and devastating diseases, such as COVID-19, to emerge (243, 244).

Other studies identify ALAN as an influence on the process of normal aging (245). Nighttime light exposure and frequent disruption of the circadian rhythm relate to mental illness (246–249), improper signaling between nerves (250), and the onset of dementia (251), and it may play a role in the the incidence of autism (252). Babies born to some pregnant women exposed to ALAN suffer from certain developmental defects (253, 254). On the other hand, limiting nighttime light exposure — especially blue light — helps maintain a normal circadian rhythm. It can ward off some abnormalities that may lead to disease (255).

We now understand much about how ALAN interacts with our health. However, our knowledge is incomplete. It is not possible now to directly connect *outdoor* light at night exposure to the incidence of disease in individual people. The interplay between the timing and duration of ALAN exposure, along with the brightness and color of the light, are key factors; however, whether outdoor light pollution influences human health and wellbeing awaits further research. Part of the challenge is telling the influence of ALAN apart from that of other types of pollution, such as noise and air, alongside other environmental stressors.

4 Public Safety

The belief that outdoor lighting improves traffic safety and discourages or prevents crime is common. It may explain in part the rapid growth in the use of outdoor light at night in recent years and decades. There are cases where the careful application of outdoor lighting may improve nighttime safety, but there is no general benefit supported by scientific evidence.

Traffic safety and crime

There are many conflicting research results on this topic. Some studies find that adding lighting to outdoor spaces reduces crime and road collisions (256, 257), and even recommend particular illumination levels based on the results of field experiments (258). Others find either a negative effect (259), no effect at all (260–262), or unclear results (263, 264). Some researchers ask whether *reducing* outdoor lighting in areas prone to either crime or traffic accidents leads to poorer outcomes. Little evidence has emerged to support this hypothesis (265).

Both traffic and crime studies are notoriously challenging to design. In particular, it is difficult to properly account for all the variables that might alter the results. For example, a road safety study about lighting might fail to account for changing traffic volume throughout the night. Some variables may have a stronger influence on the observations than lighting changes.

Sometimes these variables are subtle effects that add up to important results. It can be easy to assign responsibility to lighting even though it actually contributed very little. As a result, many of the claims about outdoor lighting and its impact on crime and traffic safety – for better or worse – may be fundamentally wrong (266, 267).

Researchers have not been able to predictively model the way outdoor lighting might affect safety and security. This is one reason why it is difficult to establish the significance of lighting in studies. There is no clear known "dose-response" relationship that may predict appropriate lighting levels (268). In other words, even if lighting influences outcomes, scientists can't determine how much light is required.

International lighting standards often do not clearly establish benchmarks for the amount of light at night that drivers and pedestrians need on the basis of scientific evidence (269).

There are only a few instances in which the issue has been rigorously studied, e.g., (38), and it is unclear whether the results are universally applicable. Decision makers, from elected officials to lighting designers, often substitute their intuition when guidance is lacking. In a belief that more of something is always better, they often specify too much light relative to actual needs.

The amount of light used in outdoor spaces at night may not reflect public expectations for feelings of safety and comfort (270), and artificial light itself may influence the human perception of fear (271). In some cases, over-lighting can itself become the source of safety hazards (272). However, properly designed lighting can reduce light pollution and save energy without compromising on public feelings of safety in outdoor spaces at night (273).

Automotive and roadway lighting

No one doubts that automotive lighting has clear public safety benefits, but this kind of lighting may itself be the source of objectionable light pollution. There is little evidence to date on the contribution of automobile lights to light pollution. Some early work suggests that the impact is not small (274–276). Many expect autonomous (self-driving) vehicles to become common in coming decades. Researchers are only beginning to study what this means in terms of reducing the need for roadway lighting in the future (277).

The hazards of glare

Glare from bright artificial light sources is a particular concern for nighttime safety. It results from intense light rays entering the eye directly from a source. Some of that light scatters inside the observer's eye, reducing the contrast between foreground and background. This effect makes it difficult to see objects as distinct from what surrounds them. In addition, the pupil of the observer's eye contracts, reducing visibility by dimming the appearance of the entire scene.

Glare reduces the visibility of objects at night for motorists, pedestrians and bicyclists. Although some older observers report stronger sensations of glare from certain sources, it seems to affect people of all ages (278). Some modern lighting sources, like LED, can make glare worse by emitting considerable light at very shallow downward angles (9) and also by using non-uniform light sources with insufficient optical diffusion (279).

The perception of glare seems to vary with the wavelength of light involved. In general short-wavelength ('cool') light causes stronger glare than long-wavelength ('warm') light (280). Observers report that it takes about the same amount of time to recover from glare exposure no matter the color of light (281). The severity of glare appears to relate more to the 'dose' (light intensity times exposure duration) rather than to the color (280). If the background surrounding a glare source is higher in luminance, its perceived intensity is lower. Warmer light backgrounds reduce perceived glare more than cooler backgrounds (282).

5 Energy Use and Climate Change

Wasted outdoor light at night is wasted energy. The world remains highly dependent on fossil fuels to generate electricity. Since light pollution represents a waste of energy, it also contributes directly to climate change.

Light and global energy demand

Electricity used to power outdoor lighting once accounted for about 1.5% of global power consumption (283–285). Researchers hypothesized that the introduction of energy-efficient solid-state lighting would reduce this consumption. Many governments rushed to deploy the new technology in the past decade. As the price of SSL products declined, the adoption rate increased. The motivations for this included reduced cost of operation and meeting the requirements of "green" policies.

At first glance, the high energy efficiency of SSL seems to be good for the environment. For example, the United Nations Environment Programme estimates that a transition to energy efficient lighting would reduce global electricity demand for lighting by 30–40% by 2030 (286). The rapid adoption of SSL may, however, unintentionally worsen the problem of light pollution. SSL makes outdoor light less expensive and more convenient to consume. In turn, cheaper light may cause the use of more and brighter light at night where it is not needed.

The "greenwashing" of solid-state lighting

As ALAN has become cheaper to produce, the world has consumed more of it. In fact, humans now consume thousands of times more lumens of light than they did in the historic past (287). There are now signs of what economists call a "rebound effect" in lighting. This is thought to result from the improved energy efficiency and long lifetime of SSL products. In such conditions, increased consumption of light at night erodes away the expected savings in energy use and reduction of greenhouse gas emissions. Some researchers now question whether SSL is truly "sustainable" lighting (288).

By the mid-2010s, the average country's annual economic output was changing at a rate that matched that country's increase in light at night consumption (1), although large variations among countries existed. That observation suggests that the cost savings from the switch to SSL went into deploying new outdoor lighting. If true, it means that SSL has not to date brought a reduction in world energy use. The authors of the landmark 2017 study that made these findings wrote that their results are "inconsistent with the hypothesis of large reductions in global energy consumption for outdoor lighting because of the introduction of solid-state lighting."

Claims about the environmental benefits of SSL may be, at best, overstated. Some researchers conclude from this that a new definition of 'efficiency' is needed (9). It would consider the total cost of outdoor light at night over the full life cycle of outdoor lighting products and include factors beyond just the cost of electricity, such as harm to the environment. Redefining efficiency in this way may help governments make better decisions about outdoor lighting in the future. It is furthermore unclear whether the root of the problem is in the technology itself or how it is applied, and hence whether a shift in the ways in which SSL is deployed might result in a different outcome.

The total cost of outdoor lighting

Solid-state lighting may not provide any meaningful environmental benefits in terms of reducing carbon emissions. Realizing the promise of SSL requires rethinking how governments regulate outdoor lighting. Otherwise, SSL may well make the problem of light pollution worse. Its impacts have costs to the environment that can't be measured in currency alone.

The social and financial benefits of SSL seems to fade if one considers the total environmental cost of lighting. For example, one study of a SSL retrofit program in the United States found a ten-year rate of return of +118.2% based solely on savings due to reduced electricity consumption. Researchers then adjusted the return for externalities such as the social costs of poor health outcomes that may be related to ALAN exposure and the benefit of avoided carbon emissions. The resulting rate of return dropped to –146.2% (289).

SSL programs become less attractive when the negative consequences of ALAN are included in return-on-investment calculations. The jury remains out on the question of whether SSL can deliver its promised environmental benefits without a reduction in outdoor light consumption.

6 Light and Social Justice

We know very little about how ALAN affects people in social contexts. Light at night may be used in ways that affect neighborhoods according to the race of the people who live in them. That may make light at night use a matter of social and environmental justice.

We know little about the social implications of using outdoor light at night. Remote sensing of light at night from space can show certain patterns of light use. These observations may reveal social inequities in other variables otherwise unnoticed (290). Poor social outcomes may follow from the application of outdoor light. Considerations include equity, health outcomes, mobility barriers, and community cohesion (291). The only comprehensive study to date on this topic looked at the social aspects of lighting in the U.S. only (292). Researchers found that Americans of Asian, Hispanic and Black descent tend to live in brighter neighborhoods (Figure 7). In these areas, skyglow is about twice as high as in predominantly white neighborhoods. They further note that lower socioeconomic status is also associated with higher nighttime light exposures. These conditions can add to other social and environmental stressors such as poverty and exposure to air and water pollution, affecting quality of life.

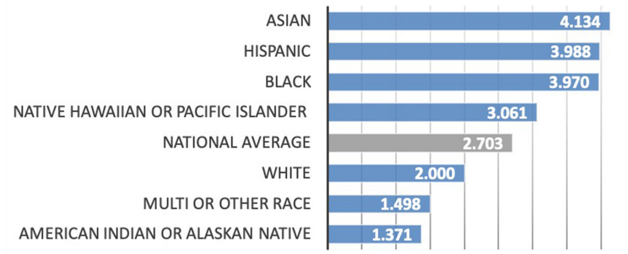

Figure 7. Average exposure to light pollution in the continental United States by racial/ethnic group. The bars show population-weighted average zenith night sky brightness levels in units of millicandelas per square meter. Figure 4 in Nadybal, Collins and Grineski, 2020 (292).

Other approaches link light at night exposure to specific health outcomes that may harm certain groups more than others (293, 294). There are also limited results from established fields such as environmental psychology (295, 296). For instance, feelings of "safety" can lead people to accept lower lighting levels (297). Biased perceptions may drive the punitive installation of lighting in certain neighborhoods.

Lastly, some scholars have criticized framing the idea of "darkness" in terms how outdoor light at night use can affect marginalized people (298, 299). They argue that failing to learn from the lessons of environmental history may result in simply repeating mistakes of the past. Closely related to this is the idea that light pollution is harmful to people whose religious or cultural practices rely on access to the night sky. The erasure of the stars from view due to skyglow separates people from this resource. Some argue that, in particular, it threatens Indigenous traditions and knowledge systems based on accessibility of the natural night sky (300).

7 Space Light Pollution

The number of artificial satellites surrounding the Earth is increasing rapidly. Satellites reflect sunlight to the ground and change the appearance of the night sky. Because they raise night sky brightness, they are a new kind of light pollution threat.

Artificial satellites have orbited the Earth since the late 1950s. Until recently, they were not considered a source of light pollution. That perception changed in May 2019, when the launch of 60 satellites in the SpaceX "Starlink" project ushered in a new era in the use of outer space (301). Private commercial space companies have since announced plans to launch about 100,000 new satellites. They intend the satellites to expand broadband internet access around the world. Yet, some researchers question whether satellites are necessary to achieve this goal (302).

Satellites are increasingly considered an emerging form of light pollution (303–305). They impact the night sky in two key ways. First, they reflect sunlight to the night side of Earth. Illuminated satellites appear as bright, moving points of light. They can affect activities of both amateur and professional astronomers (306–309). Second, satellites can

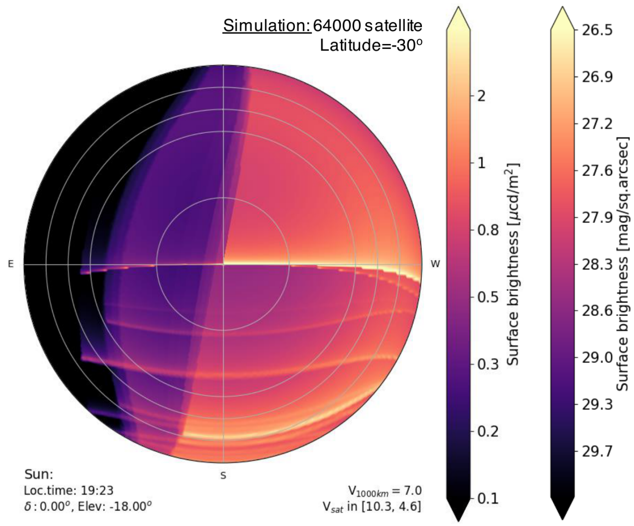

Figure 8. A simulated view of the night sky showing the brightness attributable to a population of 64,000 Earth-orbiting satellites. The view is centered on the zenith, with the horizon running around the outer edge; circles centered on the zenith mark lines of constant elevation above the horizon at 10°, 20°, 30° and 60°. Warmer colors indicate brighter parts of the sky. Unpublished results adapted from Bassa, Hainaut and Galadí-Enríquez, 2021 (309).

make the night sky itself brighter (Figure 8). This may be true even when observers do not see the individual satellites. As a form of light pollution, it adds to the observed brightness of the night sky along with skyglow caused by cities. Researchers estimate that satellites already raise night sky brightness above natural light sources by ten percent (310). It may rival the influence of "terrestrial" light pollution by 2030. Observers at high latitudes are thought to be affected more than those in the tropics (311).

Astronomers and space industry officials began consultations soon after the first Starlink launch. Scientists suggested reducing satellite brightnesses to reduce harm to their observations. Design changes dimmed the Starlink satellites, but they still exceed the target (312–316). Other recommendations included limiting the altitude at which satellites may orbit the Earth.

Recent efforts emphasized the need to engage industry and regulators with stakeholders beyond astronomy (317). They also called for funding to study the problem more and to create a central clearinghouse for information (318). Ensuring reasonable access to space for commercial development is important, but we do not understand yet how to do so while protecting the night sky from the effects of satellites.

8 Knowledge Gaps and Research Needs

While we have learned much about the effects and costs of ALAN, there is also much we still do not know. Here we summarize key research questions in the coming decade.

Interest in ALAN among researchers in all fields has grown by leaps and bounds (319). The average number of scientific papers published each year has increased by over 1000% since 2000. Methods required to answer particular questions increasingly span many different disciplines (320), and the emergence of 'night studies' as its own research field prove that the subject is rapidly maturing (321).

The state of the science summarized in this report leads to identifying important topics for future research:

The Night Sky

- What drives increasing ALAN emissions around the world?
- How is night sky brightness changing on global scales?
- How bright is the night sky worldwide on cloudy nights?

Ecological Impacts

- What are the sensitivity thresholds and spectral contents at which different ALAN impacts occur for different species?
- Does skyglow in particular affect many or most plant and animal species? Does it impact entire ecosystems?
- What are the long-term ecological consequences of light pollution?
- How does ALAN contribute to species population decline or extinction?
- To what extent is ALAN responsible for insect population declines?

Human Health

- Does exposure to ALAN in specifically outdoor spaces affect human health in any way?
- Does outdoor light at night entering indoor spaces affect sleep and health?
- Are the observed relationships between outdoor light at night and health the result of cause and effect?

Public Safety

- How does outdoor light at night relate to traffic safety?
- How does it relate to both violent crime and property crime?
- Can we design better experiments to answer these questions definitively?
- What are the characteristics of lights, such as intensity, color, and other design features, that achieve desired safety results?
- How can the directionality, uniformity, controllability and spectral tuning of LED lighting support actual and perceived safety with minimally disruptive light levels?
- How far down can roadway, street and area lighting be dimmed during low-traffic times of the night in a safe and legally defensible manner?

Energy Use and Climate Change

- Has the ongoing global transition to solid-state lighting had a net positive effect in terms of reducing electricity consumption and the emission of greenhouse gases?
- What social, financial and environmental tradeoffs have resulted from the LED lighting revolution?
- By how much does good lighting design lower electric power consumption?
- How effective are adaptive controls at reducing light at night use?
- Can we better quantify the amount of carbon emissions associated with outdoor lighting?
- Which lighting technologies, design practices and policies can reduce light pollution and electricity usage to minimum safe levels?

Light and Social Justice

- How well does ALAN use match with indicators of public health along racial and economic lines? If consistent disparities in the application of ALAN are found, why do they exist?
- Which public policies are effective in reducing ALAN disparities across different communities?

Space Light Pollution

- Are predictions about the contribution of satellites to night sky brightness correct?
- How do night sky impacts vary according to the numbers of satellites, their orbital heights, and spatial distributions?
- Is there a particular "carrying capacity" of satellites in Low Earth Orbit?
- Are any satellite designs effective at reducing or eliminating their impacts on the visibility of the night sky?

We also consider questions and topics that span more than one field of ALAN research as well as the application of that research itself:

Synthetic Research

- How are various lighting metrics related? For example, can we model Sky Glow based on broad collections of luminance?
- How does air pollution interface with ALAN?
- How are some measures of ALAN such as skyglow specifically related to a suite of undesired outcomes (e.g., adverse ecological, health, or astronomical outcomes)?

Applications of ALAN Research

- How effective are outdoor lighting public policies at reducing aspects of ALAN?
- What interventions besides public policy are available to mitigate the undesired consequences of ALAN?
- What specific economic benefits does astrotourism bring to communities?
- What measurable benefits do dark sky places receive? What costs do they incur in managing their dark-sky status?
- Which communities seek and obtain dark-sky designations and why?

Methodology

This report was compiled using as its main source the Artificial Light at Night Research Literature Database (ALANDB; https://alandb.darksky.org/), a database of scientific literature citations curated by experts in different fields of ALAN research. We supplemented ALANDB with other online resources such as Google Scholar (https://scholar.google.com/) and PubMed (https://pubmed.ncbi.nlm.nih.gov/).

We defined "scientific literature" as results subjected to at least single-blind, external peer review and published in what we believed to be reputable outlets. Both open-access and non-open-access papers were considered. Where available, we considered post-publication metrics like citations in deciding which sources to use. We state caveats and shortcomings about sources where we know of them.

Generally we did not consider technical reports, white papers, theses and other sources that are sometimes collectively referred to as "grey literature". Future editions of the report may be extended to include grey literature when there is sufficient evidence of rigorous review, especially in cases where there is very little or no information on a topic otherwise available.

The resulting report was externally reviewed by subject matter experts, whom we thank for their comments that helped improve the result. We consider this report a "living document" that will be updated in the future to account for further developments in the various fields of ALAN research.

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