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2019 Artificial Light at Night Research Year in Review

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Abstract: Interest in the transdisciplinary topic of the effects of artificial light at night (ALAN) is on the rise, and the number of scientific papers about ALAN grew each year during the preceding decade at an annualized rate of more than 10 percent. Results published in 2019 strengthened previous conclusions and explored new ideas, prompting some authors to call for the recognition of 'night studies' as its own scholarly discipline. Highlights from ALAN research published in in the past year are reviewed here in five broad subject areas: biology, human health, skyglow, social concerns, and advances in the sensing, measurement and modeling of ALAN. The review concludes with speculations about important elements for the research agenda of the 2020s.

Keywords: artificial light at night; biology; human health; skyglow; society; remote sensing

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1. Introduction

Artificial light at night (ALAN) is a novel challenge to the nocturnal environment and one of the key indicators of an epoch in the history of our planet that scholars have called the Anthropocene. [1] While ALAN confers a number of social benefits to humans in both indoor and outdoor settings, it is known to cause harm to wildlife, [2] human health, [3] public safety, [4] and the visibility of the night sky. [5] Strategies for confronting and solving this problem are rooted in humanity's understanding of it, and research results are important to inform everything from the technical design parameters of outdoor lighting products to the public policy approaches that regulate their use.

[1] 2019 closed a decade during which the number of published papers about ALAN increased by a factor of almost three; in this time the number of papers published each year grew at a steady annual rate of about 13 percent. Figure 1 shows the number of recent citations by publication year in the International Dark-Sky Association/Loss of the Night Network (IDA-LoNNe) Artificial Light At Night Research Literature Database, a curated online resource. This publication rate mirrors the rising research interest in the subject of ALAN and its effects. As the year ended, two papers by Acuto [6] and Kyba *et al.* [7] argued that the broader field of 'night studies' is quickly coming into its own as a field of transdisciplinary research and should be recognized as an academic discipline. Kyba and coworkers wrote that when it does, "the field will consider questions that disciplinary researchers haven't yet thought to ask." They even suggest a name for this field: *nyctology*.[2]

For the analysis reported here, we looked at 388 papers listed in the International Dark-Sky Association/Loss of the Night Network (IDA-LoNNe) Artificial Light At Night Research Literature Database

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[1] http://alandb.darksky.org.
[2] From the Greek $\nu\acute{\upsilon}\xi$, $\nu\upsilon\kappa\tau\acute{o}\varsigma$ ('night'); so, "the study of the night".

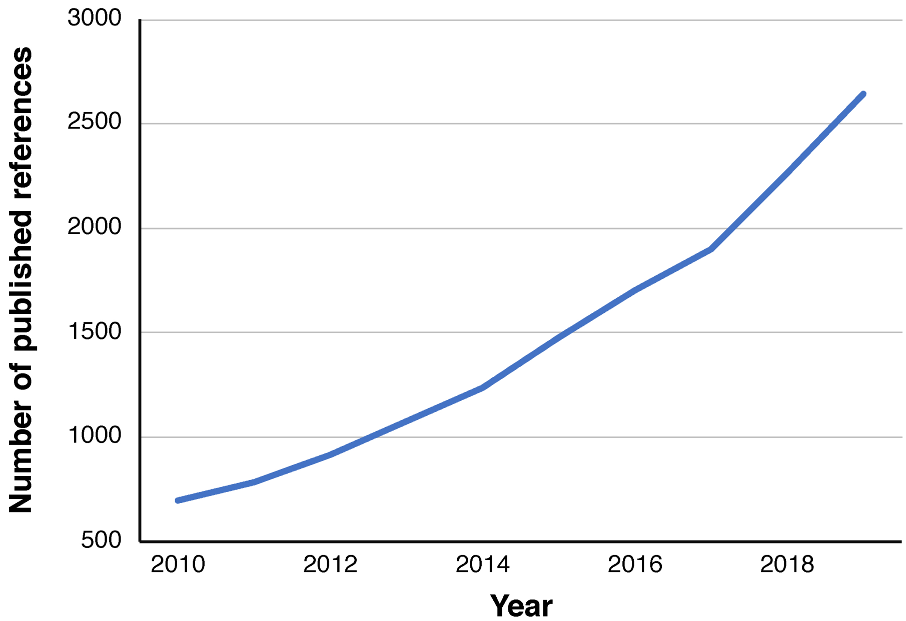

Figure 1. The cumulative number of papers in the IDA-LoNNe Artificial Light At Night Research Literature Database published by year during the period of 2010-2019.

published in 2019.[3] From this list we selected 34 papers representing what we feel are the highlights of the year in ALAN research. The papers chosen span five subjects: biology, human health, skyglow, social concerns, and advances in the sensing, measurement and modeling of ALAN. The choice of subjects broadly mirrors their frequency among 2019 papers (Figure 2).[4]

2. Biology

By the end of the 2010s it was clearly established that ALAN exposure produces measurable effects in essentially every species studied to date, and that many of those effects relate to the disruption of endogenous biological rhythms set by the timing of exposure to sources of natural light such as the Sun and Moon. ALAN is a novel challenge to the biology of organisms that evolved in conditions modulated only by the signal from these natural light sources; how biological systems respond to this challenge, from the level of the individual organism to entire populations, is now the focus of much research interest. Furthermore, it is increasingly evident that ALAN represents an ecosystem-scale threat with a host of biological and ecological consequences.

In 2019 Grubisic *et al.* published an extensive systematic review of studies under typical light-polluted conditions in fishes, amphibians, reptiles, birds, and mammals, including humans. [8] They found that many vertebrate species are more sensitive to ALAN than previously understood, and that the effect of chronic, low-intensity exposure remain unknown. Various studies show that the natural production of

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[3] The complete list is available from the database on http://bit.ly/35Vw79Y. Papers were considered 'published' in 2019 if they were distributed after peer review before the end of the calendar year. For this reason, some papers listed here have publication dates in 2018 or 2020.

[4] Frequency is determined from the occurrence of top-level keywords among database records. Each paper added to the database receives at least one of 21 possible top-level keywords describing the main subject of the paper. Instances where papers received more than one top-level keyword count as separate occurrences for the purpose of this analysis.

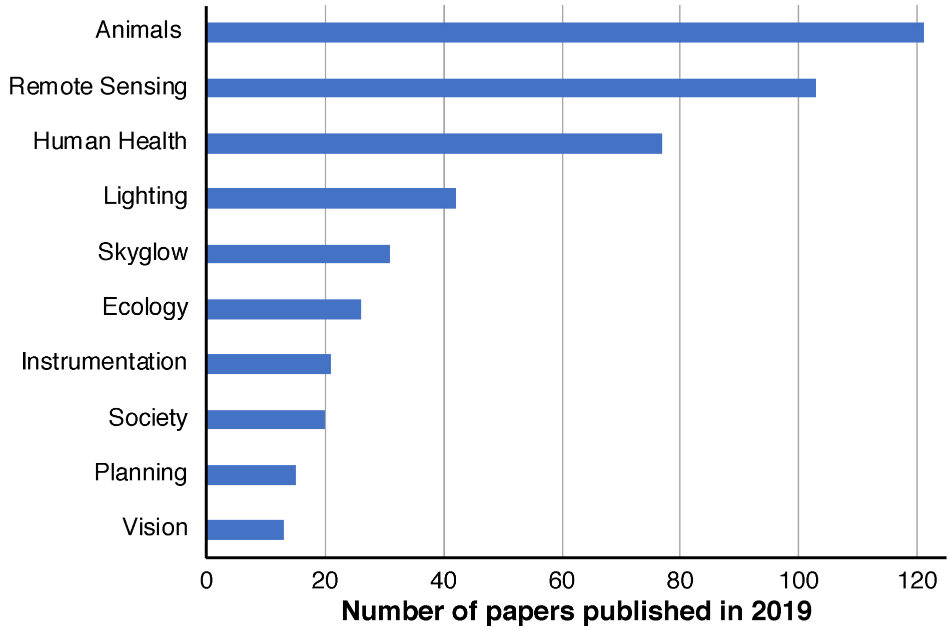

Figure 2. The most frequent top-level keywords characterizing ALAN papers published in 2019 as represented in the IDA-LoNNe Artificial Light At Night Research Literature Database.

melatonin, a hormone that regulates the sleep-wake cycle in animals and protects against oxidative stress in plants, is suppressed by extremely low levels of light at night, from as little as 0.01 lux in certain fish species. However, the authors note that "even lower, wavelength-dependent intensities are implied by some studies."

We are beginning to understand how ALAN exposure, and the harms known to result from it, are influenced and amplified by other environmental stressors; this is not usually taken into account when assessing the threat. To illustrate the point about interacting influences, May *et al.* studied wood frogs (*Lithobates sylvaticus*) from embryos to adults in groups both exposed and not exposed to ALAN. [9] ALAN exposure reduced the hatching success of embryos, produced larger individuals when the frogs underwent metamorphosis, and yielded more susceptibility to hazards such as road salt and parasite infection. The work "underscores the importance of considering not only the direct effects of light on fitness metrics but also the indirect effects of light with other abiotic and biotic stressors."

Interest in whether the effects of ALAN are magnified by global climate change is rising. In a recent review, Walkerargued that a previously unappreciated effect of ALAN has to do with the timing of organism behaviors to properly match availability of resources in the environment, something already under pressure from climate change. [10] Since many species time their reproductive cycles to coincide with optimal food availability, misalignments between the apparent length of the day due to ALAN exposure and food availability can harm fitness among animals. By itself this would disadvantage affected species, but it is further intensified by climate change, which "has provoked changes in the availability of insects and plants which shifts the timing of optimal reproduction." The authors argue that climate change represents an "extreme evolutionary pressure" on species with severe consequences for both reproduction and survival.

Similarly, ALAN is now more firmly established as an influence not limited strictly to the taxa that are directly affected. Sullivan, Hossley and Meyer looked at the length of food chains in linked aquatic-terrestrial ecosystems, determining that ALAN exposure at moderate to high levels alters the makeup of the invertebrate community, particular favoring both predators and detritivores. [11] The result means that

ALAN "can alter the flows of energy between aquatic and terrestrial systems, thereby representing an environmental perturbation that can cross ecosystem boundaries."

Seymoure, Linares and White argued that attention to the spectral content of ALAN is more important than ever. [12] They studied five representative visual systems in species ranging from birds to humans and insects, specifically including non-image-forming photoreceptors known to control circadian rhythms in vertebrates. They found that the nature of color perception is highly diverse; for example, although most visual systems would distinguish different types of artificial light sources, mammalian visual systems would perceive many different sources as the same color. The authors concluded that there is equal importance in "understanding not only the brightness of artificial light types, but also the spectral composition of light types, as most organisms have different visual systems from humans."

3. Human Health

As part of the biological world, people are not immune to the effects of ALAN exposure. However, the exact causal relationship between ALAN exposure and human health and wellbeing remains an unsettled subject. The dominant hypothesis holds that disruption of the circadian rhythm by ALAN triggers a cascade of effects beginning at the molecular and genetic levels. [3] These changes can culminate in a host of metabolic and 'lifestyle' disorders, including obesity, diabetes, and certain cancers. [13,14]

There is now enough evidence in the health research literature to support the contention that 'light desynchronosis' represents a syndrome, or collection of symptoms occurring together, manifested by circadian arrhythmicity resulting from exposure to inappropriately timed ALAN. Anisimov reviewed this evidence in 2019 and argued that "an urgent task is to develop recommendations for optimizing the illumination of workplaces and residential premises, of cities and towns as a prevention measure for premature aging and age-related pathology, which, ultimately, will contribute to the long-term maintaining of performance and improving the quality of life." [15]

The long-term health impacts of low-level ALAN exposure are still unknown, but it is suspected that chronic exposure to dim ALAN has cumulative effects comparable to those from short doses at higher intensities. Prayag, Najjar and Gronfier showed data suggesting that ALAN is effective at suppressing melatonin production and disrupting circadian rhythms in humans at light levels as low 1.5 lux for certain light wavelengths. [16] Melatonin suppression by monochromatic lighting can therefore "be initiated at extremely low melanopic lux levels in experimental conditions." Low-intensity ALAN also appears to promote the development of some human morbidities. Walker *et al.* looked for effects of low-intensity ALAN exposure on neurological function in a mouse model, exposing mice to a cycle of either light days and dark nights, or light days and low-level (5 lux) ALAN. [17] The ALAN-exposed group experienced physiological changes in the brain and led to increased depressive-like responses compared to the control group. "Altogether," the authors wrote, "this study demonstrates that acute exposure to LAN alters brain physiology and can be detrimental to well-being in otherwise healthy individuals."

Obayashi *et al.* presented results from ongoing longitudinal studies of the 'HEIJO-KYO cohort', a group of 1,127 community-dwelling Japanese individuals aged over 60 previously shown to have a significantly higher clinical depression risk when exposed to moderate levels of ALAN in sleeping rooms. [18] The new work by Obayashi and coworkers shows that exposure to persistent, low levels of ALAN (< 3 lux) in sleeping rooms increases progression of carotid atherosclerosis, even controlling for other known risk factors. [19] Rumanova *et al.* studied dim ALAN exposure in a rat model, finding that it raised systolic blood pressure and raised both plasma insulin and hepatic triglyceride levels compared to a control group not exposed to ALAN. [20] While admitting that the observed effect is not specifically proven in humans, the authors wrote that low-intensity ALAN may nevertheless "represent a serious risk factor for cardiometabolic diseases."

Chronic inflammation is important to heart health because it plays a crucial role in the progress of atherosclerosis that can lead to heart attack and death. Mindel *et al.* recently showed that by contributing to systemic inflammation, exposure to moderate ALAN intensities could have an overall negative impact on health beyond metabolic and hormonal disorders. [21] Study subjects were exposed to either darkness or 40 lux of light during sleep at home for seven nights, after which tests showed that ALAN exposure "significantly increased hsCRP [high-sensitivity C-reactive protein] levels and modestly increased depression scores in humans." Patients with elevated hsCRP are known to be at higher risk of major adverse cardiovascular events. Fonken *et al.* observed that exposure to dim (5 lux) ALAN led to increased overall brain inflammation, neuronal damage, and mortality in mice, which may well impair recovery from injury. [22] The work by both groups suggests that the management of cardiovascular disease risk should include consideration of light in patients' sleeping rooms at night. Fonken and colleagues submit that "replacing broad-spectrum nighttime light with specific circadian-inert wavelengths could be protective."

2019 saw the publication of more evidence for epigenetic changes resulting from ALAN exposure. Yonis, Haim and Elsalam reported results in a rat model that provide more clarity on the interacting roles of ALAN-mediated melatonin suppression and epigenetic changes brought about through DNA methylation in certain body tissues. [23] They studied the effects of ALAN on body mass, food and water intake, daily rhythms of body temperature, serum glucose and insulin in male rats, concluding that although the signaling pathway eliciting metabolism and endocrine responses due to ALAN exposure is still unclear, ALAN-induced alteration in metabolic and hormonal responses may well be mediated by melatonin via epigenetic modifications. The authors describe this phenomenon as one of "crosstalk between melatonin and both epigenetics and metabolic levels expressed as body temperature rhythm."

Furthermore, changes at the epigenetic level do not seem to be confined to the 'central' timing system in the brain. Instead, researchers are discovering that exposure to ALAN can cause damage in peripheral systems in the human body in part by disrupting the expression of local clock genes. As an example, Dong *et al.* recently showed that epidermal skin cells sense light directly and control their own clock gene expression, which "triggers cells to 'think' it is daytime even at nighttime." [24] Skin cells exposed to blue light in different doses and at different times in their study exhibited an increase in radical oxygen species production, DNA damage, and inflammatory mediators versus cells kept in full darkness.

Lastly, the influence of ALAN exposure appears to play specific roles during both the beginning and end of life. Torres-Farfan *et al.* reviewed studies in the literature on the effects of circadian disruption in pregnant women on their offspring, finding that gestational chronodisruption induces major changes in fetal development, and these changes have an impact in the adult phase of life at several physiological levels. [25] It alters the consistency of melatonin signaling, explained by 'phenotypic plasticity' in which a particular genotype can result in different physiological or morphological outcomes depending on the dominant environmental influences during development. The result is unsettling of the fetal circadian system, "potentially inducing long-term effects in the offspring." Shen and Tower reviewed the literature on ALAN exposure as it appears to affect the regulation of aging and longevity, identifying the relevant routes as "controlling circadian rhythms, inducing oxidative stress, and acting through the retina to affect neuronal circuits and systems." [26]

4. Skyglow

The most the most immediate environmental manifestation of ALAN is 'skyglow,' a brightening of the night sky resulting from the atmospheric scattering of light emitted on the ground. In addition to diminishing the contrast between astronomical objects and the sky, making it more difficult to see those objects, skyglow increases ground illuminance both in and beyond urban spaces. The impacts of ALAN are therefore not strictly confined to areas near sources of light; rather, they can be measured up to hundreds of kilometers away.

Garrett, Donald and Gaston showed the extent to which skyglow now affects key biodiversity areas globally and significant protected spaces locally. [27] Using the the 2016 New World Atlas of Artificial Night Sky Brightness dataset [28] and the Atlas definition of ‘pristine’ darkness (up to one percent above the natural background level), the authors compared the spatial extent of pristine darkness against Important Bird and Biodiversity Areas.[5] Less than a third of the world’s Key Biodiversity Areas (KBAs)[6] have completely pristine night-time skies; about a half lie entirely under artificially bright skies; and only about a fifth contain no area in which night-time skies are not polluted at the zenith. They further examined night sky quality in KBAs as a function of regional gross domestic product, human population density and protected area coverage, finding that “likelihood of a KBA having pristine skies decreased with increasing GDP and population density, and the interaction between the two, and increased with proportional coverage by protected areas.”

On smaller spatial scales, new investigations are providing input to urban planners on how to reduce skyglow impacts in urban protected areas. Schirmer *et al.* combined field and laboratory techniques, applying observed light level impacts from lab studies in a mouse model to measured intensities in the field in order to identify behaviorally relevant ALAN levels and mapping the extent of those levels across the city of Chicago, U.S. [29] Their results indicate that over one-third of urban greenspace in Chicago is illuminated at night to levels higher than that required to cause animal behavioral changes. The technique can be used to better delineate regions of particular ALAN sensitivity as an input to developing better urban habitat plans.

In 2019 we learned more about the susceptibility of cities to changes in skyglow caused by climatic and air quality events. Jechow and Hölker identified the amplification of skyglow by snow with and without clouds — christened ‘snowglow’ — that represents an increase of night sky brightness in (sub)urban areas by a factor of as much as 3500 times over that of a natural night sky. [30] On clear nights with snow on the ground, the amplification is still up to 33 times the sky brightness without snow. Other factors influencing skyglow are caused by humans. Liu *et al.* examined weather data and night sky brightness measurements over Dalian, China, taken by ground-based sensors in 2016-17, finding “a significant correlation among the air quality index, the ground illumination ratio of moon, the atmospheric visibility and the sky brightness.” [31] They identified the culprit as small particulates in air pollution, primarily PM2.5, which can increase the brightness of the night sky over a polluted city by factors ranging from three to ten. Moonlight, tracking the lunar cycle, has the least impact on sky brightness under clear conditions, accounting for an increase of only two to three times under a full moon as compared to a new moon.

As the snowglow phenomenon suggests, it is increasingly clear that the albedo of ground surfaces is important in determining night sky brightness. This is especially true as newer, fully shielded light-emitting diode (LED) lighting gradually replaces older, partially shielded technologies like sodium vapor. Kocifaj lately showed through radiative transfer modeling that the artificial brightness of the night sky correlates with ground albedo, but the effect is dependent on angle and amplitudes are higher toward shorter wavelengths. [32] Skyglow exhibits a positive correlation with ground albedo, but Kocifaj found no linear relationship between ground albedo and night sky brightness. Noting that the effects of seasonally changing ground albedo are observable in time-series night sky brightness measurements, Wallner and Kocifaj simulated skyglow using as inputs spatially detailed albedo information. [33] Their results indicate that the averaged surface albedo value over a city does not provide accurate predictions of zenithal brightness in

[5] See https://www.birdlife.org/worldwide/programme-additional-info/important-bird-and-biodiversity-areas-ibas.
[6] See https://www.iucn.org/resources/conservation-tools/world-database-on-key-biodiversity-areas.

simulations, and they note that “there is a major difference in simulation results if either conducting city parts with various surface albedos or using only one averaged value over the whole city.”

5. Society

Research on the “society” of artificial light at night, light pollution and dark skies takes place in the overlap of diverse disciplines in the humanities and the social sciences. It is also one of the least explored spaces in the broad subject areas represented by the references listed in the ALAN Research Literature Database. In her review of two recent books about social scientific aspects of ALAN, Schulte-Römer describes the nature of the ALAN research field as a “promising test bed for exploding the social dimension of human-environment interactions . . . perfectly suited to challenging the persistent dichotomous notions of nature and culture and add to a better understanding go how our sense making relates to our senses.” [34]

Some of these scholarly efforts turn a figurative mirror on the world of light pollution research and activism, exploring the motives and outcomes of these efforts. Two papers published in 2019 examine the interactions of outdoor lighting advocates, experts and design professionals in reaching consensus on the issues of light pollution mitigation methods and standards. As part of a larger research project, Schulte-Römer *et al.* surveyed over 200 world experts described under the group headings “lighting professionals” and “light pollution experts.” [35] Their analysis of survey responses suggests that although members of these two groups agree that light pollution is a problem and that there are some obvious ways to approach solving it, they often disagree in the details. “Despite seemingly conflicting interests, lighting professionals and light pollution experts largely agree on the problem definition and problem-solving approaches,” the authors wrote. “However, we see diverging views regarding potential obstacles to light pollution mitigation and associated governance challenges.”

Ebbensgaard, drawing from interviews with lighting designers involved in a recent mixed-use redevelopment project in east London, U.K., finds that although standards and regulations can establish frameworks for improving outdoor lighting and simultaneously reducing light pollution, lighting designers should actively question how standards and regulations are measured, defined and maintained. [36] The London case was used to explore how designers often confront and manage the challenge posed by various industry standards and legal regulations in such projects, arguing that these professionals can and should play more of a direct role in the definition of the parameters that bound their work by challenging such standards. Ebbensgaard noted that while both scholars and lighting practitioners “unite in their disapproval of uniform and homogenous lighting that follows from standardised lighting technologies and design principles,” outdoor lighting standards and regulations are useful tools. The author urges urban scholars to be more involved in ‘foregrounding’ the process by which standards and regulations are measured, defined and maintained.

Light trespass, in which light emitted on one property falls on another property, remains an urgent matter in issues of lighting design. Communities are increasingly aware of it as a problem, but designers still lack a proper methodology and tools to measure it especially as pertains to dynamic and color-changing sources such as non-static, self-luminous LED displays. Zielińska-Dąbkowska and Xavia considered both a literature review and survey results in this area to confirm the significance of the problem and highlight "the need to better measure, apply, and manage this new technology." [37]

Even as the “professional” ALAN world continues to grow and mature, increasing emphasis is placed on the importance of recognizing nighttime darkness as a valuable natural resource that calls for the protection of dark sites. Pressure in this direction comes from the burgeoning ‘astrotourism’ business, which is now shown to have the potential to realize significant financial gains, particularly in depressed rural economies suffering the wind-down of traditional extractive industries. Mitchell and Gallaway reported the results of the first study attempting to value the environmental amenity of dark skies under such circumstances in the Colorado Plateau region of the western U.S. [38] "Using a 10-year forecast of visitors to the national parks and using standard input-output modeling," the authors found that "non-local tourists who value dark skies will spend $5.8 billion over the next 10 years in the Colorado Plateau." They further predict that astrotourism will generate $2.4 billion in higher wages and create over 10,000 additional jobs for the region annually in the coming decade. The projected economic benefits are made more impactful to local economies because "they have the ability to increase visitor counts to national parks year-round and lead to a more efficient use of local community and tourism-related resources throughout the year."

6. Remote Sensing

Understanding a problem and devising solutions often starts with quantifying the underlying effect. Researchers now have access to a variety of platforms with which to sense and measure ALAN from Earth-orbiting satellites to uncrewed aerial vehicles, or drones, flying close to the ground. Developments in hardware, software and analysis methods are growing the utility of these observations, and remote sensing data are both improving our understanding of the science of ALAN as well as providing the means to assess the efficacy of various outdoor lighting treatments and interventions. The recent, comprehensive review by Levin *et al.* conveys a sense of the remarkable current capabilities of the remote sensing of night lights as well as future opportunities and challenges. [39]

2019 saw the publication of the most granular data yet available on ALAN as it relates to population density and economic output. Falchi *et al.* applied the the New World Atlas of Artificial Sky Brightness data set to sub-national regional divisions to correlate upward radiance with population and gross domestic product (GDP). [40] The authors found large disparities in the consumption of artificial light per capita and per dollar of GDP in both the U.S. and Europe, noting that "a direct correlation between the wealth of a country or a state and the light it uses at night does not exist." Wang, Sutton and Qi showed that latest civilian satellite remote sensing data for night lights can yield accurate subnational GDP data products uniformly across the globe. They used Day-Night Band radiance data from the Visible Infrared Imaging Radiometer Suite (VIIRS-DNB) aboard the Suomi NPP satellite, World Bank data on GDP at purchasing power parity, and machine learning techniques to to map GDP at 1 km2 resolution. The authors then used the data products to derive inequality indexes (e.g., Gini coefficients) at nationally aggregate levels. [41]

The application of orbital remote sensing data strongly suggests that the growth of cities is fueling the observed global average increase in light pollution. An analysis of U.S. Defense Meteorological Satellite Program (DMSP) data from India during the twenty years between 1993 and 2013 by Kumar *et al.* indicates that the main drivers behind observed changes in upward radiance detected on orbit are "urban expansion, industrial development and air pollution." [42] The study found a "strong correlation ... between light pollution and digital numbers (DN) values at regional scale." Even with known DMSP calibration issues, the authors conclude that nighttime lights data can be effectively utilized for the purposes of land management and conservation planning.

Although new DMSP observations have not been routinely available to the public since 2013, the lengthy DMSP time series is still being mined to draw new inferences about the nature and impacts of ALAN. Leng, He and Jiang published a study last year based on DMSP observations in the Beijing-Tianjin-Hebei region of China essentially confirming that urbanization is the main driver of observed time-series changes in upward radiance. [43] The authors applied the Mann-Kendall non-parametric test, the standard deviation method, and nighttime light indices to DMSP data, finding urban radiance increases as high as 334 percent over the 1992 to 2012 study period. "Urban expansion, transportation hubs, and industries were the major reasons for the significant change in nighttime light," they wrote, identifying "a trend of overuse" of light in cities as the proximate cause of the increase.

At the same time, new results urge caution in applying satellite remote sensing data to epidemiological studies, suggesting that upward radiance measurements of ALAN from space may not correlate with human exposures on the ground. Huss *et al.* attempted to correlate satellite measurements of upward radiance with the reported personal exposure to outdoor ALAN in a limited geographic sample, finding only a very weak dependence. [44] They found that although "outdoor satellite-assessed outdoor LAN exposure levels were correlated with urban environmental exposures, ... they were not a good proxy for indoor evening or nighttime personal exposure." While it does not discount the reliability of studies depending on radiance as an indicator of total human nighttime light exposure, the results of this work imply that the "moderate-to-strong correlation of outdoor LAN with other environmental exposures should be accounted for in epidemiological investigations."

7. ALAN Research in the 2020s

A number of technological and social changes are expected in the coming decade that will influence trends in research. For instance, the color of the world at night continues to change with the ongoing transition away from conventional lighting technologies such as high-intensity discharge lamps and toward solid-state lighting (SSL) sources like white LED. The last major manufacturer of low-pressure sodium (LPS) lamps phased out their production in 2019 as global demand for LPS continued to decline. While the demand for high-pressure sodium (HPS) lighting products remains strong, it too is under downward pressure brought on by the rapid adoption of SSL. As light sources change, so too does the spectral power distribution of their light, with implications for the measurement and modeling of light pollution to biological impacts.

Research into the biological and ecological consequences of ALAN is expected to dominate published results in the 2020s as evidence mounts that many species are sensitive to light at night with illuminances comparable to moonlight ($\leq$0.3 lux; [45]). For instance, we anticipate a more definitive answer about the degree to which ALAN is related to the global insect biodiversity loss. [46,47] ALAN may influence the population dynamics of human communicable disease vectors such as mosquitoes, which is of heightened interest as the effects of climate change are felt more acutely. Given that some species appear to orient and navigate by the stars at night, [48], it is currently an open question whether the proliferation of large constellations of satellites in low-Earth orbit pose a novel ecological threat. [49] A need persists for the holistic integration of existing knowledge about the interactions between ALAN and biology to better understand impacts of the former at the ecosystems level; from this we are optimistic that effective methods and best practices can be developed to remediate ecological light pollution and reliably monitor the efficacy of interventions.

The results of studies aiming to identify the human health effects of ALAN exposure progressively make a stronger case associating ALAN with specific morbidities, but many unknowns remain in terms of the intensity, duration, timing and spectral content of ALAN that promote or inhibit the incidence of disease. The full range of visual and non-visual mechanisms through which light interacts with and regulates human physiology is not known. The relative risks of human exposure to ALAN in indoor versus outdoor contexts are not well quantified, and the relevance of ALAN in the overall human exposome [50] has yet to be demonstrated. The coming decade may see advances in the direction of defining dose-response relationships that may yield something like safe exposure thresholds; this in turn has implications for occupational safety as well as the design of lighting in public indoor and outdoor spaces. We foresee both new epidemiological studies about ALAN, and investigations into lighting technological innovations that actively promote human health and wellbeing.

Our understanding of skyglow and its impacts on the environment still depends on a better contextual definition of "darkness" based on field measurement techniques and limits imposed by terrestrial atmospheric and astrophysical light sources, particularly for non-human visual systems. By the end of the decade, we speculate that researchers will understand the relative contributions of different light sources to both upward radiance and skyglow. There will be better and more consistent tracking of how skyglow is changing around the world, including spectral information, through approaches such as citizen science; among the outputs of these efforts we expect the emerging capability to forecast night sky brightness over large areal regions. Controlled experiments will demonstrate a clearer connection between specific outdoor lighting interventions and resulting changes in night sky brightness, specifically with regard to the continuing adoption of solid-state lighting for roadway applications. New sensor and passband combinations will improve sky brightness measurements while better accounting for the changing color of the night sky attributable to the proliferation of LED lighting, and more reliable methods will be devised for extracting night sky brightness from diffuse light observations with existing remote sensing platforms.

Meanwhile, we envision a decade of bigger and more extensive data sets from remote sensing platforms along with the large-scale deployment of new devices for sensing and monitoring ALAN. Drone aircraft will make important observations of ALAN at low altitudes and with unprecedented spatial resolution, while instrumentation for new small satellites and cubesat missions will make routine the collection of multispectral night lights data with regular temporal cadence. By the end of the 2020s, we hope to see the launch of a years-long, dedicated "NightSat" mission with nightly global overpasses, high radiance sensitivity, imaging in multiple spectral bands, and spatial resolution better than 100 meters per pixel. [51]

Robust empirical evidence is still lacking in decisions about how much light to use in different applications in order to ensure adequate public safety. [4] At least in the West, the price of electricity delivered at night may well rise due to the proliferation of electric cars recharged during overnight hours and the gradual shift away from fossil fuels and toward more renewable sources of energy; this may result in a reduction in the demand for ALAN measurable through remote sensing. Autonomous vehicles will constitute an increasing share of automobiles on the world's roads, and in some economies may come to dominate traffic by decade's end; their prevalence may eventually obviate the need for continuous roadway lighting in many circumstances, offering an opportunity to reduce ALAN reliance in their designs. [52] And even as the nature of the interplay between ALAN and the incidence of both property and violent crime remains fundamentally unknown, evidence suggests that widely held beliefs about lighting and crime may simply be wrong. [53] This subject needs more funding, better experimental design, and more thoughtful statistical analysis to bring the problems to solution. And although the popularity of astrotourism will likely increase in the 2020s, it remains to be shown empirically that assumptions about the economic benefit to local communities are correct.

Lastly, the social scientific scrutiny of the ALAN phenomenon will only intensify in coming years, and scholars in the humanities will increasingly hold a mirror up to the nature of the academic discipline itself. Methods and approaches in this field have already drawn critical attention, [54,55] challenging ideas about 'sustainability' [56] and confronting social justice issues. We cannot yet tell whether various conservation and regulatory frameworks designed to preserve natural darkness in protected areas yield meaningful results, [57,58] but we are hopeful that research in the next decade will reveal the most effective strategies and guide the creation of public policies that prioritize the control of light pollution as highly as existing policies value control of other forms of environmental pollution such as air and water pollution. Once enacted, these policies will require robust enforcement regimes in order to be effective. In the meantime, researchers and conservation practitioners alike will continue to focus on quantifying the impacts of policy and and technology changes on lightscapes through further development of light pollution monitoring systems.

Public attention to the issue of ALAN, and the problem is presents, is higher than ever, and interest on the part of the research community mirrors this upward trend. As an environmental issue, light pollution may be to the dawning decade what plastic pollution was to the previous decade: a problem that attracts intense public concern and drives demand for a solution.

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