11 Pressing Research Questions on How Light Pollution Affects Biodiversity

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Artificial light at night (ALAN) is closely associated with modern societies and is rapidly increasing worldwide. A dynamically growing body of literature shows that ALAN poses a serious threat to all levels of biodiversity—from genes to ecosystems. Many "unknowns" remain to be addressed however, before we fully understand the impact of ALAN on biodiversity and can design effective mitigation measures. Here, we distilled the findings of a workshop on the effects of ALAN on biodiversity at the first World Biodiversity Forum in Davos attended by several major research groups in the field from across the globe. We argue that 11 pressing research questions have to be answered to find ways to reduce the impact of ALAN on biodiversity. The questions address fundamental knowledge gaps, ranging from basic challenges on how to standardize light measurements, through the multi-level impacts on biodiversity, to opportunities and challenges for more sustainable use.

Keywords: ecological light pollution, biodiversity loss, thresholds, traits, populations, ecosystems, interdisciplinary, mitigation

INTRODUCTION

Our planet faces numerous challenges, many of which have direct and indirect connections to biodiversity (Díaz et al., 2020). One such challenge is artificial light at night (ALAN) leading to a fundamental change in the light environment over half of the Earth's surface—the Earth at night. ALAN has been growing exponentially since the nineteenth century and currently increases by 2–6% per year worldwide (Hölker et al., 2010a; Kyba et al., 2017). ALAN has been introduced in places, at times, spectra and intensities that do not occur naturally (Gaston et al., 2015). Ecosystems are largely organized by natural light-dark cycles, i.e., diurnal, yearly and lunar cycles, which have been stable over geological and hence evolutionary time scales. ALAN-induced disruptions of those cycles affect the structure and function of multiple levels of biodiversity that are again strongly interconnected (Longcore and Rich, 2004; Hölker et al., 2010b; Gaston et al., 2013). Given the growing global pervasiveness of ALAN (Kyba et al., 2017; Gaston et al., 2021), it is important to understand how multiple levels of biodiversity respond to it directly and indirectly (**Figure 1**).

Research into the ecological impacts of ALAN has exploded in recent years, mostly focusing on changes in species behavior and physiology (Gaston et al., 2015; Grubisic et al., 2019; Sanders et al., 2021). Yet, many "unknowns" remain that need to be addressed before we can understand and predict the impact of ALAN on multiple levels of biodiversity (genes and cells, individuals, populations, communities, ecosystems and landscapes, **Figure 1**), and develop effective mitigation measures. Here, we address these "unknowns" by synthesizing the results of a special session and follow-up discussions at the first World Biodiversity Forum in Davos, Switzerland, in 2020, where experts from across the world convened to discuss the impacts of ALAN on multiple levels of biodiversity over a broad spectrum of taxa in multiple biomes (aerial, aquatic, and terrestrial). We capture the complexity of the problem as broadly as possible by considering that different natural light cycles (**Figure 2A**) are affected by multiple forms of ALAN (e.g., streetlights, advertising lighting, skyglow, **Figure 2B**) with multiple effects (e.g., lethal attraction of organisms, disruption of circadian rhythms and erosion of ecosystem functions) at multiple levels of biodiversity in multiple realms (**Figure 2C**). Already at the World Biodiversity Forum it became clear that a transition toward the more sustainable use of ALAN is extremely challenging and requires answers to questions that can only be tackled by broadening the disciplinary perspective to strengthen transdisciplinary approaches.
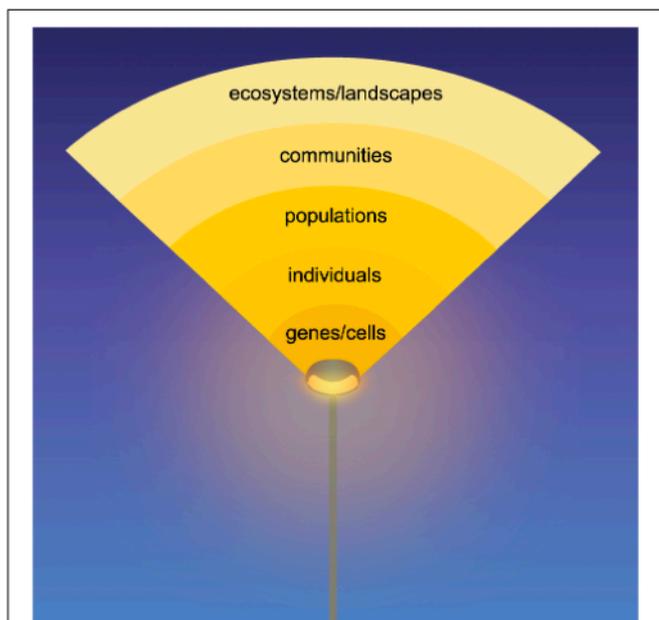

FIGURE 1 | Impact of artificial light at night (ALAN) on multiple levels of biodiversity. The multiple levels of biodiversity are interlinked, i.e., one level of biodiversity may respond to ALAN and modify processes at other biodiversity levels. For example, ALAN may impact the gene expression of certain clock genes, which results in a reduced fitness of individuals and a population decrease due to a phenological mismatch with other species and finally a changed community composition. This may impact ecosystem processes and nocturnal lightscapes (e.g., forests, coral reefs), which in turn influences all other levels.
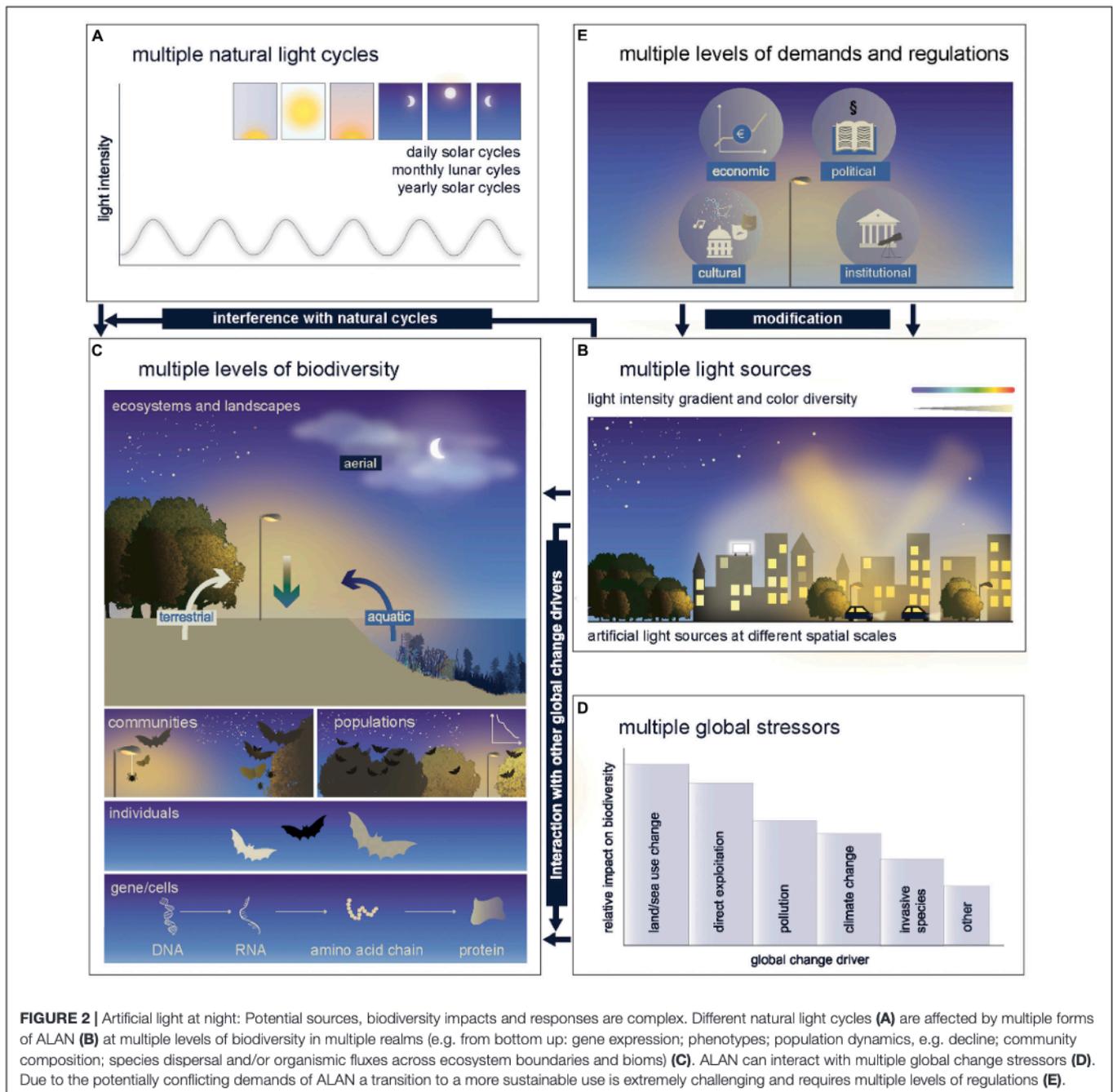
11 PRESSING RESEARCH QUESTIONS

We identify 11 research questions that can be clustered into three main themes. We first outline questions linked to the diverse nature of natural and ALAN. Second, we outline questions related to the effects of ALAN on multiple levels of biodiversity. Finally, we formulate research needs on how to bend the curve of ALAN-induced biodiversity loss.

Interdisciplinary Barriers to Measuring Nocturnal Light

ALAN research is inherently interdisciplinary, with knowledge of the nighttime being fragmented across multiple subject areas including astronomy, physics, ecology, chronobiology, psychology, and engineering. Each field has different motivations for conducting ALAN research, and draws upon different instrumentation, measurement conventions, and experimental frameworks. Multiple units of measurement for light are encountered across the sciences, and many have little biological relevance. The absence of instruments capable of performing light at night measurements with the required level of detail, and insufficient training of biologists in radiometry and light propagation further compound this problem.
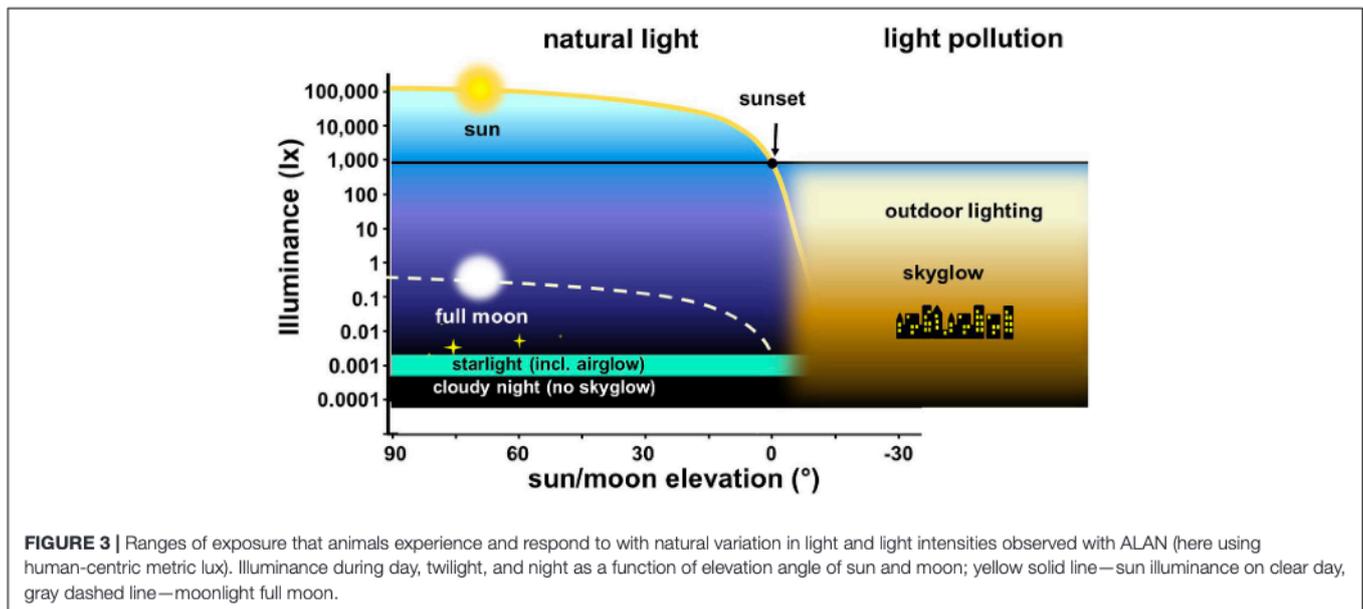
Q1 How to harmonize light measurement methods across disciplinary boundaries?

The interdisciplinary nature of ALAN research has resulted in different measurement approaches, procedures, and the use of various light units (Hänel et al., 2018), which complicates comparison of results (Kalinkat et al., 2021). Lighting engineers measure mainly in human-centric photometric SI units (mostly horizontal illuminance in lx, **Figure 3**), which some ALAN researchers have adapted for their studies to better facilitate the translation of results into lighting policy (see Q11). Astronomers mainly measure the radiance of the night sky (mostly at zenith) in units of magnitudes/arcsec[2] in different astronomical bands (see e.g., Patat, 2008). Some ALAN researchers have adapted the use of a simple radiometer, the Sky Quality Meter (SQM) that has its own spectral band (Hänel et al., 2018), which can be extended to multiple color channels (Kyba et al., 2012; Sánchez de Miguel et al., 2017). The meaningfulness of single point SQM measurements for biodiversity is, however, questionable and can be used in the wrong context (Longcore et al., 2020). Biologists tend to measure either irradiance or radiance in different spectral bands (e.g., photosynthetically active radiation—PAR) and sometimes report W (Watts) in micromole photons per seconds (μmol/s). Visual ecologists prefer wavelength resolved "hyperspectral" measurements, requiring high sensitivity spectrometers to resolve at low nighttime light levels (see Spitschan et al., 2016). Moreover, even within biodiversity research there are large disciplinary differences in the state of the art for measuring light. For example, while an array of measurement systems exists for terrestrial habitats, the attenuation of light in water makes hyperspectral light measurements even more challenging in aquatic ecosystems (Jechow and Hölker, 2019a; Tidau et al., 2021).

FIGURE 2 | Artificial light at night: Potential sources, biodiversity impacts and responses are complex. Different natural light cycles **(A)** are affected by multiple forms of ALAN **(B)** at multiple levels of biodiversity in multiple realms (e.g. from bottom up: gene expression; phenotypes; population dynamics, e.g. decline; community composition; species dispersal and/or organismic fluxes across ecosystem boundaries and bioms) **(C)**. ALAN can interact with multiple global change stressors **(D)**. Due to the potentially conflicting demands of ALAN a transition to a more sustainable use is extremely challenging and requires multiple levels of regulations **(E)**.

For biodiversity studies, nocturnal light ideally would be measured in biologically relevant ways, based on thresholds and spectral sensitivities of the species under question (see Q2 and Q5), because different light sources interfere differently with the large diversity of sensory systems in nature (Davies et al., 2013; see Q3). Furthermore, it is important to perform and provide ALAN-free natural light reference measurements for different habitats, seasons and weather conditions (Jechow and Hölker, 2019b). One challenge is to break disciplinary boundaries by, for example, connecting photometry of anthropogenic light sources (performed by lighting engineers) and night-sky or night-time radiometry (see e.g., Foster et al., 2021) to visual ecology and species responses (van Grunsven et al., 2014; Longcore et al., 2018; Seymoure et al., 2019). Thus, standardized light measurements that allow comparison across ALAN disciplines are desperately needed. Recent proposals favor spatially resolved multi-spectral night-time radiance measurements of the full light field (not just the upper hemisphere or at zenith) with digital cameras with fisheye lenses in the RGB bands (Jechow et al., 2019; Nilsson and Smolka, 2021), which is further supported by new calibration strategies (Fiorentin et al., 2020; Cardiel et al., 2021) and the proposal of a dark sky unit (Kolláth et al., 2020). This method has radiance and irradiance information in three spectral bands in one image. Additional hyperspectral measurements

FIGURE 3 | Ranges of exposure that animals experience and respond to with natural variation in light and light intensities observed with ALAN (here using human-centric metric lux). Illuminance during day, twilight, and night as a function of elevation angle of sun and moon; yellow solid line—sun illuminance on clear day, gray dashed line—moonlight full moon.

or species-specific bands, however, are required for visual ecologists, and a translation to photometric units is essential for policy making and the connection to lighting professionals. Thus, a wider and more interdisciplinary harmonization of different needs for a broad application is required to help to establish standardized protocols that are currently lacking. These protocols should match the ecological and biological responses being investigated in terms of spectral band and resolution, directionality (radiance vs. irradiance; scalar vs. planar) and time scale (see Q2). Such consistent and cross-disciplinary standards for measurement are also necessary to formulate thresholds for mitigation and management (Jechow and Hölker, 2019b; Davies et al., 2020; see Q11).

Q2 What are biodiversity-relevant light-measurements and methods?

The multiple realms and levels of biodiversity all have specific photic properties and measurement requirements. At the same time, quantifying ALAN is rather a complex task that requires method development and training. Commercial, off-the-shelf measurement equipment is rarely appropriate because it lacks sensitivity and sufficient spatial and/or spectral resolution. This becomes particularly challenging in aquatic or aerial environments (Jechow and Hölker, 2019a). Furthermore, ecologists often lack sufficient understanding of radiometry in terms of units and measurement approaches, making it hard for ecologists to interpret measurements obtained outside of their field and translate them for their research (see Q1).

In ecological studies, information on ALAN is in most cases derived from single point ground-based measurements with limited spatial, temporal and spectral resolution, very often using human centric devices like lux meters. To be able to understand what an organism perceives, it is important to have the full spatial and spectral information of the light field. This could be acquired either with a spectroradiometer mounted on a rotational head that scans the radiance over the whole sphere (Kocifaj et al., 2018)

or with a full-sphere hyperspectral camera that works at night-time, which is not available yet (but see Alamús et al., 2017 for night-time measurements and Shiwen et al., 2021 for full-sphere hyperspectral imaging in a forest during day). Both solutions are not technically mature, and the best current approximation is full-sphere imaging with a fisheye lens digital camera system with limited spectral resolution in the RGB bands (Jechow et al., 2019). Further technological development toward a hyperspectral solution are necessary and interim steps could be adding additional spectral bands to such imaging systems like in the ASTMON system (Aceituno et al., 2011) or by tailoring camera systems to achieve hypercolorimetric multispectral imaging (Colantonio et al., 2018). Ideally, the measurement strategy should also cover temporal variations in light on short time scales but also seasonal variations (**Figure 2A**). Remaining obstacles of such a holistic approach are the complexity of data and handling as well as potential high costs of a sophisticated device. A combination of multiple measurement devices (multispectral camera, hyperspectral single point, photometric single point) might be a more practical compromise.

Another pressing issue is the extrapolation of single point ground-based measurements to larger areas, which is relevant, for example, for migratory species. Here, challenges are posed by remote sensing approaches that are almost always only proxies for the ecological variable of interest. Night-time satellite data are limited in spatial, spectral and temporal resolution, but color imaging from the international space station ISS, airborne measurements, and particularly UAVs have the potential to fill the existing gaps in ALAN related biodiversity research (Bouroussis and Topalis, 2020; Levin et al., 2020; Sánchez de Miguel et al., 2021). A key component to improving the utility of these data would be research efforts that can translate what remotely sensed values could represent for conditions at ground level, where first steps have been taken but uncertainties remain high (Simons et al., 2020). Furthermore, there is an urgent need for stand-alone