Insect Conservation and Diversity (2021) doi: 10.1111/icad.12482

SPECIAL ISSUE ARTICLE

Assessing long-term effects of artificial light at night on insects: what is missing and how to get there

GREGOR KALINKAT,[1] MAJA GRUBISIC,[1] ANDREAS JECHOW,[1] ROY H. A. VAN GRUNSVEN,[2] SIBYLLE SCHROER[1] and FRANZ HÖLKER[1,3]

[1]Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany, [2]Dutch Butterfly Conservation, Wageningen, The Netherlands and [3]Institute of Biology, Freie Universität Berlin, Berlin, Germany

Abstract. 1. Widespread and significant declines of insect population abundances and biomass are currently one of the most pressing issues in entomology, ecology and conservation biology. It has been suggested that artificial light at night is one major driver behind this trend.

2. Recent advances in the gathering and analysis of long-term data sets of insect population and biomass trends, however, have mostly focused on the effects of climate change and agricultural intensification.

3. We posit here that adequate assessment of artificial night at light that would be required to evaluate its role as a driver of insect declines is far from trivial. Currently its implementation into entomological monitoring programmes and long-running ecological experiments is hampered by several challenges that arise due to (i) its relatively late appearance as a biodiversity threat on the research agenda and (ii) the interdisciplinary nature of the research field where biologists, physicists and engineers still need to develop a set of standardised assessment methods that are both biologically meaningful and easy to implement.

4. As more studies that address these challenges are urgently needed, this article aims to provide a short overview of the few existing studies that have attempted to investigate longer-term effects of artificial light at night on insect populations.

5. To improve the quality and relevance of studies addressing artificial light at night and its effect on insects, we present a set of best practise recommendations where this field needs to be heading in the coming years and how to achieve it.

Key words. Artificial light at night, insect declines, light pollution, population trends.

Introduction

Since a major study on biomass declines of flying insects in Germany was published in 2017 (Hallmann *et al*., 2017), a plethora of reports on insect abundance and biomass trends across the globe have been published, entailing an intense debate and discussion about the imminence of insect declines both in the academic as well as in the media and public realms (Didham *et al*., 2020; Saunders *et al*., 2020; Wagner *et al*., 2021). These controversies around how widespread and universal insect declines really are, and how the respective findings are depicted in public debate has sparked a surge of new studies relying on long-term data sets (e.g. Baranov *et al*., 2020; Crossley *et al*., 2020) and meta-analyses of published data (Sanchez-Bayo & Wyckhuys, 2019; van Klink *et al*., 2020; also see critical comments on these meta-studies, e.g. Komonen *et al*., 2019; Thomas *et al*., 2019; Desquilbet *et al*., 2020; Jähnig *et al*., 2021). Overall, the most recent findings of long-term trends for insects currently paint a complex picture where some taxonomic or functional groups of insects show marked declines both in species numbers and overall biomass on local or regional levels (Seibold *et al*., 2019; van Strien *et al*., 2019; Baranov *et al*., 2020; Hallmann, 2021), while other studies and meta-analyses relying on large data sets fail to detect uniform declines in abundances or biomasses (Macgregor *et al*., 2019; Crossley *et al*., 2020; van Klink *et al*., 2020; but see Desquilbet *et al*., 2020; Jähnig *et al*., 2021). One potential cause for these inconsistencies documented in existing data sets could to be

Correspondence: Gregor Kalinkat, Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, 12587 Berlin, Germany. E-mail: kalinkat@igb-berlin.de

grounded in false baseline effects as shown by Fournier and colleagues (2019). There, site selection bias may cause decreasing trends in diversity or abundance as statistical artefacts (i.e. study sites chosen for monitoring are likely to have high abundances of focal taxa in starting years of long-term studies). The resulting 'regression to the mean' effect is likely to affect results regularly but is rarely addressed in the studies of insect declines so far (also see Didham *et al*., 2020; Mentges *et al*., 2020).

Several factors have been suggested as main drivers of insect declines and among them climate change, agricultural intensification with high loads of fertilisers and pesticides, as well as land use change are most often blamed for insect declines, biodiversity loss and community reorganisation (Sanchez-Bayo & Wyckhuys, 2019; Seibold *et al*., 2019; van Strien *et al*., 2019; Baranov *et al*., 2020; Wagner *et al*., 2021). Compared to these factors, the importance of light pollution or artificial light at night (ALAN) as another major driver affecting local or regional declines of insects has received less attention, although a recent analysis of data on insect declines in Germany with remotely sensed night-time light data suggests high overlap (Grubisic *et al*., 2018). Notably, the large majority of these studies analysed biomass and/or abundance trends of particular orders or functional groups of insects due to a lack of data providing sufficient taxonomic resolution (but see Hallmann *et al*., 2021). While these analyses are important on their own (e.g. for their ecosystem level consequences), in order to assess how species diversity of insects are affected by particular drivers, better taxonomic resolution is critically needed as the change among and within many insect groups is often characterised by a 'winners and loser' pattern (e.g. Baranov *et al*., 2020).

While there are numerous valuable studies investigating short-term effects of ALAN on nocturnal insects, showing detrimental effects of ALAN on a physiological or behavioural level (e.g. Elgert *et al*., 2020; also see recent reviews Owens & Lewis, 2018; Desouhant *et al*., 2019; Owens *et al*., 2020), very few studies focus on effects of ALAN on insect populations that rely on data covering more than one or two seasons (e.g. van Langevelde *et al*., 2018; van Grunsven *et al*., 2020). Ideally, long-term studies would include several generations of key species and would preferably last 10 years or more (Gaston *et al*., 2015; Didham *et al*., 2020, also see Daskalova *et al*., 2021). Hence, understanding the long-term effects that ALAN imposes on insect populations requires properly designed studies that combine regular, standardised samplings over such extended time scales with state of the art light at night measurements. The recent surge in publications on insect population trends clearly shows how difficult it can be to find robust and thorough data from long-term studies investigating insect population abundance or biomass trends (e.g. Desquilbet *et al*., 2020; Jähnig *et al*., 2021). For the assessment of the impact of ALAN on long-term insect population trends, such rigorously sampled and standardised continuous time series of insect monitoring need to be complemented with adequate documentation of light at night conditions and change thereof over time, which is particularly lacking. Therefore, it is not surprising that long-term studies looking explicitly at the correlation between insect trends and nocturnal light levels are almost non-existent. To shed light on this developing, yet data-poor field within the research area of ecological light pollution, we provide a short overview of existing studies on long-term effects of ALAN on insects in which standardised sampling of insects has been carried out over at least 2 years or seasons. To ensure that good-quality data are collected in the long term, we provide a checklist for future study design and guidelines for implementing systematic studies that are able to illuminate the long-term effects and ecological mechanisms that light pollution has on insect populations and communities. Only by improving and implementing approaches to properly measure and document ALAN and other anthropogenic factors at the experimental sites, but also in the surroundings, it will become possible to better disentangle the impact of multiple drivers of global change that are simultaneously acting (ALAN, introduced species, land use change, habitat fragmentation, urban climate, soil sealing and more). The checklist we present is meant to provide entomologists and insect conservationists entering the field of light pollution research guidelines to avoid common mistakes and add knowledge where it is most critically needed. As ecologists are only starting to add tools for the characterisation and quantification of illumination to their tool box, we discuss adequacy and limitations of various light measurement approaches and present a set of recommendations how future ways of illumination characterisation and quantification can be standardised. Investigating, assessing and quantifying the extent to which light pollution actually contributes to negative trends in insect populations is urgently needed to mitigate adverse effects and help recovery of insect populations in illuminated landscapes. Overall, our main goal in this article is to present a set of best practise recommendations for long-term studies of the impacts of ALAN on insects to improve and refine the relevant research programmes.

Light pollution and insects

Before laying out our recommendations for future long-term studies on insects and ALAN we provide a short definition and clarification of light pollution: it can be distinguished into direct light pollution that originates from nearby light sources or indirect light pollution from light that is diverted by reflection or scattering. *Skyglow* is a form of indirect light pollution that originates from light radiated upwards that is then scattered back within the atmosphere. It depends on the weather conditions like clouds or snow cover and can reach illuminance levels brighter than full-moon in and nearby urban areas (Jechow & Hölker, 2019a; Jechow *et al*., 2020).

For insects usually the direct light pollution is the one that matters most, particularly for flying insects (Eisenbeis, 2006). However, in some contexts, skyglow can become important when it is masking celestial information used by insects, for example, the Milky Way (Dacke *et al*., 2013) or polarisation patterns (Foster *et al*., 2019).

Overview of existing literature on insect population trends and light pollution

One way to investigate the effects of ALAN on certain insect groups is to use long-term monitoring data (for e.g. moths) and search for differences in population trends for those species that are known to be light-sensitive compared to those species that are less attracted to light when confronted with ALAN. Van Langevelde and colleagues (2018) recently showed with such a study that light-sensitive moths are particularly affected by population declines analysing a data set ranging from 1985 to 2015. In these kind of correlative analyses other factors can be incorporated and separated statistically but ultimately one cannot be sure that there is indeed a causal relationship between light pollution and the declines of the light-attracted species. For instance, these species could also be the ones that are particularly sensitive to other anthropogenic drivers.

For this study, we collected published studies that investigate effects of ALAN based on experimental setting that explicitly sample to investigate population trends in response to light pollution. We were explicitly looking for long-term studies [at least two, but ideally more years (or seasons) of sampling], but we found only a very limited set of publications to meet these criteria. Our literature research revealed only 11 studies that tracked insect population trends in studies with explicit consideration of ALAN over more than one season (Table 1, see Supporting Information for more details). Almost all of these studies were conducted in Europe and North America, with only one study taking place in Africa (Minaar *et al*., 2015). Currently available studies on long-term effects of ALAN on insects are mostly limited in temporal duration or resolution, or both. Moreover, the data sets are dominated by studies on Lepidoptera, although there are few studies investigating the effects of ALAN on other insect groups or species (e.g. see Larsson *et al*., 2020 for a study on Trichoptera). In terms of lighting, the majority of these studies investigated effects of one type of light source (e.g. white LED, high-pressure sodium, mercury vapour lamps) or a change in lighting technology, while fewer studies investigated different light sources and/or colour spectra (e.g. van Grunsven et al. 2020). Few studies that investigated varying levels of light intensities were not included here due to limited experimental samplings (e.g. Sullivan et al. 2019) while most of the studies in Table 1 rely on data sampled in two consecutive years (6 out of 11 studies). The notable exception is one recent study involving seven experimental sites in the Netherlands that were sampled in five consecutive years from 2012 to 2016 (van Grunsven *et al*., 2020; see Spoelstra *et al*., 2015 for details on the experimental setup). Another experimental site where data have been collected since 2012 is located in the nature park Westhavelland in North-Eastern Germany (see Holzhauer *et al*., 2015; Manfrin *et al*., 2017 for details).

Brief overview of light measurement basics

Light measurements are essential to assess the impact of ALAN on species, including insects. While light measurements may appear to be simple, it is particularly the interdisciplinarity of the field that complicates the measurements. Different physical quantities (measurands) in different spectral bands and different units are used across different disciplines. Astronomers, biologists, and lighting researchers have historically established different approaches and measures that sometimes are and sometimes are not convertible. Here, we provide a very short outline about the relevant radiometry, but recommend the book by Johnsen (2012) to biologists new to the field.

There are fundamentally two different radiometric quantities that can be measured relatively easily with broadly available sensors, the radiance or the irradiance. The radiance L (in $W/sr \cdot m^2$), a directional quantity, is the radiant flux emitted per unit solid angle per unit projected area. For an observer, it is the light incident from a specific solid angle. The irradiance E (in W/m^2) is the total radiant flux received by a surface per unit area. It is important to define the irradiance properly, because it can be differentiated between scalar irradiance E_{scalar} (sometimes termed E_0), which is the light incident on a sphere (Smith *et al*., 1972), and vector or plane irradiance E_{plane}, which is the light incident on a plane surface. The latter is most commonly measured in the horizontal plane $E_{horizontal}$.

In the spectral domain, radiance and irradiance are defined according to spectral responsivity of a detector, often referred to as 'band'. Panchromatic sensors measure the radiance in a single spectral band, sometimes due to the sensors own responsivity (e.g. silicon) or by adding spectral (colour) filters to target a specific application. The luminance L_v, for example, is the radiance referenced to the sensitivity of the human eye (in cd/m^2) and illuminance E_v (in lx) would be the irradiance equivalent. Another quantity often used in biology is photosynthetically active radiation (PAR) that weights the incident number of photons equally (not energy) between 400 nm and 700 nm (Thimijan and Heins 1983). PAR is often given in energetic units $W/s \cdot m^2$ or using photon numbers photons/$s \cdot m^2$, sometimes expressed in mol (1 μmol photons), which is occasionally called 'Einstein' – E. If the spectrum is known, a conversion between luminance and radiance in any known spectral band (including PAR) is possible (see supplement of Grubisic *et al*., 2018).

A panchromatic sensor often used in the context of ALAN is the sky quality meter (SQM) that measures the zenith night sky brightness in a spectral band that is only roughly resembling the photopic curve (Hänel *et al*., 2018). Astronomers historically use 'magnitudes', a negative logarithmic scale (the lower the brighter, the higher the darker). The SQM provides a value in units of mags/arcsec^2 that can be roughly approximated to a luminance value (Hänel et al. 2018). The SQM is designed to measure at the zenith and should be used with care in the context of biological studies (Longcore *et al*., 2020). There are attempts to establish more intuitive units for the night sky brightness like the 'natural sky unit' and the 'dark sky unit' (see Kolláth *et al*., 2020), but so far none of them has been standardised.

In biology, spectral information is important and therefore it is highly advised to measure in multiple bands. So called multi-spectral sensors have several discrete bands, typically from 3 to about 20, realised with optical filters. For example, a digital consumer camera with an red, green, blue (RGB) sensor qualifies as multi-spectral sensor and such cameras with wide field optics are used to study ecological light pollution (Jechow et al. 2019). A hyperspectral sensor has many (typically about 100) discrete bands and spans over a continuum of wavelengths measuring either the spectral radiance or the spectral irradiance. A spectrum should ideally be reported in SI unit W/m^2 nm. However, in biological studies often units based on photon numbers are used.

Table 1. Overview of published studies investigating effects of light pollution on insects over extended periods.

Study	Light type	Landscape context	Country	Continent	Insect group(s)	Response variable	Sampling methods	Study duration	Temporal resolution	Sum of sampling events
Studies of relatively high quality with repeated samplings in the same location, over more than 2 years										
van Grunsven *et al*. (2020)	Three colours of LED	Six forest edge sites in unlit areas	Netherlands	Europe	Moths	Abundance	Heath traps	2012–2016	4–8 nights between per season (May-Sept) per location	14–32 per location
van Grunsven *et al*. (2019)	Change in lights	Urban and peri-urban streets	Germany	Europe	Various	Abundances	Flight intercept traps	2011–2013	weekly Jun-Oct	between 33 and 112 per location
Wilson et al. (2018)	Various	Various; large-scale citizen science project	UK	Europe	Moths (100 most common species)	Abundance	Various light traps	1968–2002 (2005–2015)	weekly Mar-Nov	n.a.
Studies with samplings in 2 years or if more than that not repeated in the same location										
Larsson et al. (2020)	Light traps vs passive	Three different field sites along streams	Sweden	Europe	Trichoptera	Abundance	Light traps and different passive traps (malaise, suction, window traps)	1972–73, 1974, 2016	each sampling event at different site, one-time sampling	n.a.
Manfrin et al. (2017)	High-pressure sodium	Agricultural drainage ditch	Germany	Europe	Various (flying and emerging insects, riparian arthropods)	Abundance	Emergence, flight intercept, pitfall	May-Oct 2012–13	weekly May-Aug, monthly Sep-Oct	25
Minnaar *et al*. (2015)	Mercury vapour lamps	Nature reserve	South Africa	Africa	Various	Abundance	Wweep net, omni-directional impaction traps	Feb-Apr 2010–11	11 experimental runs	11
Meyer and Sullivan (2013)	White LED	Suburban streams	USA	N-America	Various (emerging insects and riparian arthropods)	Abundance, biomass, traits	Emergence, floating pan traps	2010–2011	every 2 months	6
Degen *et al*. (2016)	High-pressure sodium	Agricultural drainage ditch	Germany	Europe	Various	Abundances	Flight intercept traps	2012–2013	monthly	n.a.
Nankoo *et al*. (2019)	Bridge illumination	Urban river	Canada	N-America	Various (flying and emerging insects)	Abundance	n.a.	Apr-Aug 2017–18	twice each summer	4
Studies with only two sampling dates										
Plummer *et al*. (2016)	change in street lights	Urban gardens	UK	Europe	Moths	Abundance	Light traps	2011 and 2013	one time each year	2
Firebaugh and Haynes (2020)	12 W LED	Grassland (research station)	USA	N-America	Various	Abundance	Sweep nets	2015–2016	2 single sampling days, one each year	2

n.a. = not available.

Checklist for study design and light measurements

Our recommendations for study design and adequate light measurements fall broadly within three categories that are of course interconnected in various ways, but for the sake of presentation we deem them helpful here. These categories are (I) resolution of insect sampling and analysis, particularly in terms of temporal and taxonomic considerations; (II) adequate and independent control treatments that are designed to take into account co-occurring stressors; and (III) adequate measurement of light at night given its multiple dimensions (see above). We outline the details for all of these categories and how they can be implemented in improved research programmes tackling the problem of declining insect populations and continuously growing levels of light pollution. We are fully aware that lack of implementation of proper replication, control, sampling resolution or taxonomic detail are more often than not primarily a problem of limited funding and expertise rather than intentional. On the other hand, methodological accuracy when measuring and evaluating ALAN is still also a problem of lack of common practical standards in this rapidly developing field. While we acknowledge that fulfilling all listed criteria will rarely be possible from the practical point of view, we want to encourage researchers to find the best possible trade-off between different aspects (e.g. identification of taxa at species level and sampling frequency) given the question they aim to answer. Not fulfilling all of the desirable criteria that we lay out here does not invalidate a study but merely limits the conclusions that can be drawn from it. Therefore, these recommendations should be seen as that, recommendations, rather than a binding list of requirements.

Category I: insect sampling and analysis

A crucial challenge when investigating the long-term effect of ALAN is that many insect populations are fluctuating substantially and often randomly even in the absence of anthropogenic impacts (Gaston & Lawton, 1988). There is often high inter-annual variability and pronounced seasonality in insect abundance patterns and this variation can confound the observed effects and lead to false conclusions if not accounted for in the study design. Particularly site selection bias has been discussed recently as an underappreciated issue in the design of long-term studies (Fournier *et al*., 2019; Didham *et al*., 2020; Mentges *et al*., 2020).

- Conduct long-term studies with repeated samplings: Ecological effects of ALAN might not be visible in short term (van Grunsven *et al*., 2020) and the initial impact of ALAN on insect communities can even be opposite to the long-term effects. Initial attraction to light may result in local increases in insect abundances (Eisenbeis 2006), but in the long term the negative impact on reproduction and survival might result in reduced numbers. In most cases, the long-term impact is of interest and any study should last long enough to be able to measure these. Drawing from recent analyses of insect abundance or biomass trends unrelated to ALAN research (e.g. Macgregor *et al*., 2019, Crossley *et al*., 2020, Baranov *et al*., 2020), one can simply conclude: the longer a time series the better to avoid drawing false conclusions (also see Fournier *et al*., 2019). But in the case of a completely new threat, we necessarily have to start from scratch if we want to establish a long-term experiment with full control over lighting conditions (see below).
- Sample across multiple seasons: Insect population dynamics often have pronounced seasonal patterns. Therefore, it is important to assess them in more than one season, at least if the aim is to achieve representative samples. For insect groups or species, which are active only during short periods in a year, sampling across multiple years is recommended to increase level of replication and robustness of the results (see Fournier *et al*., 2019; Didham *et al*., 2020).
- Aim for a high temporal resolution: If the intention is to quantify an impact on the whole insect community or the whole assemblage of one or more insect orders, the temporal resolution should be relatively high. Many insect species have short flight periods and sampling that coincides with a flight peak or falls in between flight peaks can falsely give the impression that numbers have changed between years. By sampling frequently, this can be avoided. Weekly or biweekly samplings would be desirable, and biweekly samplings have the additional advantage to allow for synchronisation with lunar phases (see below).
- Aim to achieve a high taxonomic resolution in your study: Most entomologists will know that high taxonomic resolution in a long-running monitoring or experimental set-up will be difficult to implement due to lack of resources or taxonomical expertise. We want to highlight here that particularly when setting up a long-term experiment researchers should consider emerging technologies. Automated identification with high- throughput image analyses or molecular methods will likely become more easily available during the coming years as seen by recent methodological advances (e.g. Ärje *et al*., 2020 for automated image based identification or Thomas *et al*., 2018 for automated sampling of environmental DNA; also see Høye *et al*., 2021). Depending on the questions, one wants to answer it can be sufficient to identify specmen to higher taxonomical levels only (e.g. family or order), but identification on species level does give insight in how composition shifts and not merely changes in total numbers or biomass. Notably, highly resolved time series for a larger number of taxonomically well-resolved taxa also helps to avoid the aforementioned issue with false baseline effects (Fournier *et al*., 2019; Didham *et al*., 2020; Mentges *et al*., 2020).
- Diversify sampling methods: Using a set of different trapping and sampling methods (e.g. interception traps, pitfall traps, sweep netting, emergence traps, light traps, etc.) within the same habitat is suitable to give more comprehensive results and cover a broader range of functional and taxonomic groups. Each trapping mechanism has its own benefits and disadvantages. Using one method can be sufficient to establish a trend but comparing trends with different methods should be done carefully.
- Document how traits (e.g. body size, eye size) respond to ALAN: Documenting not only taxonomic identity but also

 Insect Conservation and Diversity, doi: 10.1111/icad.12482

traits like eye size over time would allow to assess adaptive responses on a population level as well functional changes on the level of assemblages and communities. This can give insight in how insect communities change functionally as a result of ALAN.

Category II: providing adequate control treatments that take into account co-occurring stressors

In addition to naturally high levels of fluctuation, insect abundances that are monitored in long-term studies might also be particularly affected by other anthropogenic factors like climate change (e.g. Baranov *et al*., 2020) or land use change and agricultural intensification (Seibold *et al*., 2019). Hence for being able to disentangle the effects of ALAN from other factors affecting population dynamics, it is critical to implement various control schemes in the sampling design of any study that assesses the effects of ALAN on insects.

- Monitor background dynamics of insect populations in adjacent unlit areas: To assess the responses of insects to ALAN, it is essential to have controls that are sampled under very similar conditions (including other anthropogenic stressors) to the experimental (i.e. lit) treatments. Populations of insects can fluctuate strongly and this should not be confounded in the results. To be potentially able to track even subtle changes in abundances of various groups and species of insects, a two-level control is preferable: (i) Monitoring at a local level in relative vicinity (i.e. within a distance of few hundred metres) to the lit sampling area, but also (ii) monitoring insect abundances and biomass at the landscape level to estimate background information which can give insight in natural fluctuations in abundances of the insects studied. In some places it might be possible to complement studies on ALAN with existing long-term monitoring programmes. Moreover, it has been particularly difficult repeatedly to disentangle the effects of ALAN from other associated anthropogenic stressors (Perkin et al. 2011). Experimental approaches can help to exclude confounding factors such as typical urban stressors by e.g. arranging an experiment in previously ALAN-naïve pristine areas (e.g. Manfrin *et al*., 2017). Alternatively, positioning of replicated study sites along urban-to-rural gradients while complementing them with latitudinal and altitudinal gradients has been suggested to improve our understanding of insects' evolutionary responses to climate change (Verheyen *et al*., 2019) and this approach could also be useful for ALAN research.
- Monitor diurnal abundances in the same areas: In addition to keeping track of landscape levels of insect population dynamics, it is also advisable to monitor the background dynamics during the day, although we know that the diurnal insect community is different, affected by other drivers and not necessarily correlated. This is especially useful if passive and/or nocturnal traps are being used because, opportunistic nocturnal species may change their temporal niche (Manfrin *et al*., 2017), resulting in increased diurnal activity and population abundances and a potential decrease in nocturnal samples.
- Independent replicates for both the treatment and the control enhance robustness of results: As trends may differ locally and can be influenced by factors outside of the control of the experiment it is advisable to have multiple independent assessments of the impact of ALAN. In this way, the real impacts of ALAN can be statistically separated from random fluctuations.
- Make sure that control sites provide adequately dark conditions deprived of nocturnal illumination as much as possible: Spill of light into the controls from nearby light sources should be avoided. Ideally, no light sources should be directly visible at the controls e.g. from nearby settlements even if almost no light is detected with standard measures at the site. It might be required to add shielding to lighting near the control sites. In addition, the control should be placed in a location with minimum skyglow, but this might be challenging in or near densely populated places with high levels of ALAN. As a rough orientation for maximum illuminance in controls, the light that natural light sources (e.g. the moon) may provide can be used. However, since outdoor studies should always refer to the lighting context to which the insect communities have already adapted (urban, peri-urban, pristine), an adjustment to these conditions is highly recommended depending on the research questions.

Category III: comprehensive and regular measurements of nocturnal light to accompany long-term studies

Light is key to any ALAN study so a comprehensive monitoring of natural nocturnal light and light pollution is necessary. We are aware that the full assessment of all details of the multi-dimensional light field in terms of spectral, spatial and temporal information is extremely challenging with current commercial equipment. However, a strategy to obtain as much meaningful information as possible can be outlined.

- How to measure? We recommend to mainly use ground-based measurements to monitor changes in nocturnal light during long-term studies of ALAN on insects. The classic single-channel devices such as illuminance meters (luxmeters) or PAR meters should generally be avoided. If these are used, they need to be calibrated for low light levels and should ideally be used in combination with spectral measurements (i.e. of the surrounding major light sources). Combined, a calibrated illuminance meter and a spectroradiometer can provide some estimate of ALAN conditions, however, no spatial information is provided and sensitive spectroradiometers are not available. It is rather recommended to acquire spatially resolved radiance, ideally in multiple bands, with an imaging instrument. Commercial digital cameras with fisheye optics are currently the best instruments for this purpose because they are sensitive down to starlight level, it is possible to cover a large dynamic range and have the colour information in three bands (Jechow *et al*., 2020). Furthermore, the full 4pi light field can be obtained with just two images (Jechow *et al*., 2019). The camera needs to be calibrated and software is developed from the astronomical community (Kolláth & Dömény, 2017; Jechow *et al*., 2019). From the RGB camera measurements, it is possible to infer the light sources and other colours, with some limitations (Garcia et al. 2015). Ideally, a spectral measurement should accompany the camera measurement, particularly to detect whether UV radiation is present. Currently outdoor capable camera systems and cheap DIY alternatives (Walczak *et al.*, 2020) are being developed to enable a continuous monitoring.

- Where to measure? Measurements should be obtained within the habitat at one or multiple representative locations. Depending on subhabitat use, there can be substantial variation where different organisms will experience light levels very differently, e.g. a mayfly flying along a forest edge versus an epigëic ground beetle. When monitoring long-term effects on insects, it is important to also observe the changes in ALAN and of skyglow near the monitoring sites.
- When to measure? Measurements should be performed in parallel with the samplings but ideally obtained on a regular basis and for different weather conditions and moon phases over the course of each monitoring season. If this is not possible, there should be regular measurements at clear sky during new moon conditions at least when skyglow is of interest for the study. Any change in lighting technology should have a before to after comparison under similar conditions. Of course, the potential impact of changes in background lighting depends on the extent of direct and indirect ALAN in the surroundings of experimental sites, which is of particular importance at very dark areas with light sensitive species. Also note that in some ecosystem types, particularly within deciduous forests, seasonal change in vegetation cover will likely have strong effects on effective impacts of ALAN or skyglow on organisms near the ground that needs to be controlled for. Hence, we recommend complementing the night-time measurements we describe with daytime light measurements of photosynthetically active radiation for studies in these ecosystems (Baldocchi *et al.*, 1986).
- What units should be used? In general, it would be desirable to report results in standardised and traceable SI units in Watts and nm. However, the different target groups utilise their own units. Lighting professionals and public authorities are human centric and prefer photometric units (e.g. lx or cd), while biologists tend to use photon numbers as energy unit. If a spectral measurement is obtained, it is possible to convert units. Therefore, a good practise would be to provide multiple units (i.e. lx and Watts and/or photon numbers, nm). Units in the PAR band were developed for photosynthesis and might be only indirectly relevant for entomological or ALAN studies (via impact on host plants) and therefore should be avoided at least during the night.
- Sky brightness monitoring with devices like SQMs has the advantage of high temporal resolution. However, it should be only complementary to other ground-based measurements (ideally with multi-spectral imaging devices) because a zenith night sky brightness value alone is not the ideal parameter for insect studies. Furthermore, the SQM should not be used beyond its scope (Longcore *et al.*, 2020).
- Night-time remote sensing for large-scale monitoring: Long-term changes of ALAN over large areas can be estimated by using night-time light remote sensing (Levin *et al.*, 2020). Currently, the best instrument for monitoring ALAN from space is the day night band (DNB) of the visible infrared imaging radiometer suite (VIIRS) on board of the Suomi NPP satellite. However, there are certain issues with this approach including the spatial resolution of only 750 m, the lack of sensitivity in the blue spectrum (Kyba *et al.*, 2017) but also the unknown ratio of light emitted towards the satellite and light emitted into a certain habitat, particularly for aquatic ones (Jechow & Hölker, 2019b). This is particularly problematic when changing spectral composition from e.g. high pressure sodium to LEDs and/or from unshielded to shielded lamps. Thus, night-time light remote sensing should only accompany ground-based light measurements in insect monitoring.

Concluding remarks and outlook

Despite a limited number of long-term studies on the effects of ALAN on insect population trends, there are already numerous studies that investigate effects of ALAN on insects on shorter time scales (e.g. Perkin *et al.*, 2014; Bolliger *et al.*, 2020; Stewart *et al.*, 2020) and their growing number shows increasing interest in this research topic. Such studies often include single sampling events or short sampling periods within one season, both in newly lit areas and those that already experienced nocturnal illumination for longer times, and the conclusions on the effects of ALAN on insect populations that can be drawn from such studies are limited. These studies do, however, provide valuable insights into effects of a broader range of lighting types and strategies as well as different ALAN intensities and colour spectra on insects (e.g. Pawson & Bader, 2014; Wakefield *et al.*, 2016; Macgregor *et al.*, 2017), as well as data from other ecoregions (Haddock *et al.*, 2019; Pawson & Bader, 2014). This information can be used in a meta-analysis approach to understand a broader picture how ALAN affects insect communities and populations. In this short article, we have given an overview about the current knowledge on long-term impacts of ALAN on insect populations. Direct evidence that artificial light plays a role in reported insect declines is still scarce and we suggest a number of steps how future studies can be improved to address these gaps.

Of course achieving all of our recommendations within a single study is almost impossible given limited resources and limited availability of taxonomic expertise. While (semi-) automated insect identification (and quantification) will likely become more affordable with the use of image recognition software and molecular tools (Ärje *et al.*, 2020; Høye *et al.*, 2021), identifying large numbers of insects, regularly over several years is currently a substantial effort. The fact that most individual studies do not follow all those recommendations, we have laid out here is in itself not problematic. Some of our recommendations are essential to allow for interpretation of the results, such as a comprehensive quantification of the ALAN treatments and ALAN from the surroundings of experimental sites with a proper measurement strategy for nocturnal light. Others such as replication of treatments and controls confine which conclusions can be drawn but data from experiments with low or even non-existent replication can still be used in meta-analyses. If multiple experiments with low replication would all show similar patterns this could still indicate an effect. In this vein, it would be possible to provide additional inside in the long-term impact of ALAN on insect populations based on large numbers of individual experiments that might fulfil only few criteria from our checklist. One should be cautious of a 'file-drawer' bias in the published scientific literature when practising such approach (Lortie *et al*., 2007), and we strongly encourage researchers to publish null results to minimise this issue (Gaston *et al*., 2015).

While we have focused here on the documentation and tracking of insect abundance and biomass trends, there are of course additional topics that can and should be investigated further. For instance, to obtain a better understanding on long-term impacts of ALAN on insect population trends, addressing how species interactions and interaction networks of insects are affected by ALAN is critical to achieve a better understanding of ecosystem level effects. This is particularly relevant as negative effects of ALAN on ecosystem services like pollination have already been documented (Knop *et al*., 2017). Similarly, trophic interactions are altered in a way that might affect energy and biomass fluxes across ecosystem boundaries (Meyer & Sullivan, 2013; Manfrin *et al*., 2017; Manfrin *et al*., 2018).

Finally, we want to reinforce that successful research programmes on ecological light pollution require building – and maintaining – strong inter- and transdisciplinary research networks. Entomological research and insect conservation implementation that are meant to diminish negative effects of ALAN urgently need the inclusion of complementary expertise of physicists, lighting professionals and social scientists covering various aspects of light and lighting. Furthermore, meaningful implementation of findings to future lighting approaches will be impossible without involving industry, legislators, and communities (Hölker *et al*., 2010; Pérez Vega *et al*., 2021).

Although still limited, the information of existing studies should suffice to apply the precautionary principle and to reduce any possible adverse effects of artificial illumination with existing technical solutions. Well-designed long-term experiments will give insight in these adverse effects and to allow for effective mitigation and regulation of the impact of ALAN on insect communities. Hopefully, this will lead to the treatment of light pollution as a pollutant, limiting the exposure of the natural environment to artificial light where and whenever possible.

Acknowledgements

This manuscript was developed as part of the project 'Species protection through environmental friendly lighting' (AuBe) which is funded by the German Federal Agency for Nature Conservation (BfN) within the framework of the Federal Programme for Biological Diversity with funds from the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU; FKZ: 3518685A08). Open access funding enabled and organized by Projekt DEAL.

Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Supporting Information.

References

Ärje, J., Melvad, C., Jeppesen, M.R., Madsen, S.A., Raitoharju, J., Rasmussen, M.S., Iosifidis, A., Tirronen, V., Gabbouj, M., Meissner, K. & Høye, T.T. (2020) Automatic image-based identification and biomass estimation of invertebrates. *Methods in Ecology and Evolution*, **11**, 922–931. https://doi.org/10.1111/2041-210X.13428.

Baldocchi, D., Hutchison, B., Matt, D. & McMillen, R. (1986) Seasonal variation in the statistics of photosynthetically active radiation penetration in an oak-hickory forest. *Agricultural and Forest Meteorology*, **36**, 343–361. https://doi.org/10.1016/0168-1923.

Baranov, V., Jourdan, J., Pilotto, F., Wagner, R. & Haase, P. (2020) Complex and nonlinear climate-driven changes in freshwater insect communities over 42 years. *Conservation Biology*, **34**, 1241–1251. https://doi.org/10.1111/cobi.13477.

Bolliger, J., Hennet, T., Wermelinger, B., Bösch, R., Pazur, R., Blum, S., Haller, J. & Obrist, M.K. (2020) Effects of traffic-regulated street lighting on nocturnal insect abundance and bat activity. *Basic and Applied Ecology*, **47**, 44–56. https://doi.org/10.1016/j.baae.2020.06.003.

Crossley, M.S., Meier, A.R., Baldwin, E.M., Berry, L.L., Crenshaw, L.C., Hartman, G.L., Lagos-Kutz, D., Nichols, D.H., Patel, K., Varriano, S., Snyder, W.E. & Moran, M.D. (2020) No net insect abundance and diversity declines across US Long Term Ecological Research sites. *Nature Ecology & Evolution*, **4**, 1368–1376. https://doi.org/10.1038/s41559-020-1269-4.

Dacke, M., Baird, E., Byrne, M., Scholtz, C.H. & Warrant, E.J. (2013) Dung beetles use the milky way for orientation. *Current Biology*, **23**, 298–300. https://doi.org/10.1016/j.cub.2012.12.034.

Daskalova, G.N., Phillimore, A.B. & Myers-Smith, I.H. (2021) Accounting for year effects and sampling error in temporal analyses of invertebrate population and biodiversity change: a comment on Seibold et al. 2019. *Insect Conservation and Diversity*, **14**, 149–154. https://doi.org/10.1111/icad.12468.

Degen, T., Mitesser, O., Perkin, E.K., Weiß, N.S., Oehlert, M., Mattig, E. & Hölker, F. (2016) Street lighting: sex-independent impacts on moth movement. *Journal of Animal Ecology*, **85**, 1352–1360. https://doi.org/10.1111/1365-2656.12540.

Desouhant, E., Gomes, E., Mondy, N. & Amat, I. (2019) Mechanistic, ecological, and evolutionary consequences of artificial light at night for insects: review and prospective. *Entomologia Experimentalis et Applicata*, **167**, 37–58. https://doi.org/10.1111/eea.12754.

Desquilbet, M., Gaume, L., Grippa, M., Céréghino, R., Humbert, J.-F., Bonmatin, J.-M., Cornillon, P.-A., Maes, D., Van Dyck, H. & Goulson, D. (2020) Comment on "Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances.". *Science*, **370**(6523), eabd8947. https://science.sciencemag.org/content/370/6523/eabd8947.

Didham, R.K., Basset, Y., Collins, C.M., Leather, S.R., Littlewood, N.A., Menz, M.H.M., Müller, J., Packer, L., Saunders, M.E., Schönrogge, K., Stewart, A.J.A., Yanoviak, S.P. & Hassall, C. (2020) Interpreting insect declines: seven challenges and a way forward. *Insect Conservation and Diversity*, **13**, 103–114. https://doi.org/10.1111/icad.12408.

Eisenbeis (2006). Artificial night lighting and insects: Attraction of insects to streetlamps in a rural setting in Germany. *Ecological consequences of artificial night lighting* (edited by Rich, C. & Longcore, T.), pp. 281–304. Island Press, Washington, D.C., USA.

Elgert, C., Hopkins, J., Kaitala, A. & Candolin, U. (2020) Reproduction under light pollution: maladaptive response to spatial variation in artificial light in a glow-worm. *Proceedings of the Royal Society B: Biological Sciences*, **287**, 20200806. https://doi.org/10.1098/rspb.2020.0806.

Firebaugh, A. & Haynes, K.J. (2020) Multi-year experiment shows no impact of artificial light at night on arthropod trophic structure or abundance. *Ecosphere* **11**, e03227. https://doi.org/10.1002/ecs2.3227

Fournier, A.M., White, E.R. & Heard, S.B. (2019) Site-selection bias and apparent population declines in long-term studies. *Conservation Biology*, **33**, 1370–1379. https://doi.org/10.1111/cobi.13371.

Garcia, J.E., Girard, M.B., Kasumovic, M., Petersen, P., Wilksch, P.A. & Dyer, A.G. (2015) Differentiating biological colours with few and many sensors: spectral reconstruction with RGB and hyperspectral cameras. *PLOS One*, **10**, e0125817. https://doi.org/10.1371/journal.pone.0125817.

Gaston, K.J. & Lawton, J.H. (1988) Patterns in the distribution and abundance of insect populations. *Nature*, **331**, 709–712. https://doi.org/10.1038/331709a0.

Gaston, K.J., Visser, M.E. & Hölker, F. (2015) The biological impacts of artificial light at night: the research challenge. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**, 20140133. https://doi.org/10.1098/rstb.2014.0133.

Grubisic, M., van Grunsven, R.H.A., Kyba, C.C.M., Manfrin, A. & Hölker, F. (2018) Insect declines and agroecosystems: does light pollution matter? *Annals of Applied Biology*, **173**, 180–189. https://doi.org/10.1111/aab.12440.

Haddock, J.K., Threlfall, C.G., Law, B. & Hochuli, D.F. (2019) Light pollution at the urban forest edge negatively impacts insectivorous bats. *Biological Conservation*, **236**, 17–28. https://doi.org/10.1016/j.biocon.2019.05.016.

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., Goulson, D. & de Kroon, H. (2017) More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS One*, **12**, e0185809. https://doi.org/10.1371/journal.pone.0185809.

Hallmann, C.A., Ssymank, A., Sorg, M., de Kroon, H. & Jongejans, E. (2021) Insect biomass decline scaled to species diversity: general patterns derived from a hoverfly community. *Proceedings of the National Academy of Sciences of the United States of America*, **118**, e2002554117. https://doi.org/10.1073/pnas.2002554117.

Hänel, A., Posch, T., Ribas, S.J., Aubé, M., Duriscoe, D., Jechow, A., Kollath, Z., Lolkema, D.E., Moore, C., Schmidt, N., Spoelstra, H., Wuchterl, G. & Kyba, C.C.M. (2018) Measuring night sky brightness: methods and challenges. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **205**, 278–290. https://doi.org/10.1016/j.jqsrt.2017.09.008.

Hölker, F., Moss, T., Griefahn, B., Kloas, W., Voigt, C.C., Henckel, D., Hänel, A., Kappeler, P.M., Völker, S., Schwope, A., Franke, S., Uhrlandt, D., Fischer, J., Klenke, R., Wolter, C. & Tockner, K. (2010) The dark side of light: a transdisciplinary research agenda for light pollution policy. *Ecology and Society*, **15**(4), 13. http://www.ecologyandsociety.org/vol15/iss4/art13/.

Holzhauer, S.I.J., Franke, S., Kyba, C.C.M., Manfrin, A., Klenke, R., Voigt, C., Lewanzik, D., Oehlert, M., Monaghan, M., Schneider, S., Heller, S., Kuechly, H., Brüning, A., Honnen, A.C. & Hölker, F. (2015) Out of the dark: establishing a large-scale field experiment to assess the effects of artificial light at night on species and food webs. *Sustainability*, **7**, 15593–15616. https://doi.org/10.3390/su71115593.

Høye, T.T., Ärje, J., Bjerge, K., Hansen, O.L.P., Iosifidis, A., Leese, F., Mann, H.M.R., Meissner, K., Melvad, C. & Raitoharju, J. (2021) Deep learning and computer vision will transform entomology. *Proceedings of the National Academy of Sciences of the United States of America*, **118**, e2002545117. https://doi.org/10.1073/pnas.2002545117.

James, J.F., John, D.K., Basil el, J., Jochen, S., Lana, K., Emily, B., Marcus, J.B., Dan-Eric, N., Sönke, J., & Marie, D. (2019) Orienting to polarized light at night – matching lunar skylight to performance in a nocturnal beetle. *Journal of Experimental Biology* **222**, jeb188532. https://doi.org/10.1242/jeb.188532

Jähnig, S.C., Baranov, V., Altermatt, F., Cranston, P., Friedrichs-Manthey, M., Geist, J., He, F., Heino, J., Hering, D., Hölker, F., Jourdan, J., Kalinkat, G., Kiesel, J., Leese, F., Maasri, A., Monaghan, M.T., Schäfer, R.B., Tockner, K., Tonkin, J.D. & Domisch, S. (2021) Revisiting global trends in freshwater insect biodiversity. *WIREs Water*, **8**, e1506. https://doi.org/10.1002/wat2.1506.

Jechow, A. & Hölker, F. (2019a) Snowglow—The amplification of skyglow by snow and clouds can exceed full moon illuminance in suburban areas. *Journal of Imaging*, **5**, 69. https://doi.org/10.3390/jimaging5080069.

Jechow, A. & Hölker, F. (2019b) How dark is a river? Artificial light at night in aquatic systems and the need for comprehensive night-time light measurements. *Wiley Interdisciplinary Reviews: Water*, **6**, e1388. https://doi.org/10.1002/wat2.1388.

Jechow, A., Kyba, C.C.M. & Hölker, F. (2020) Mapping the brightness and color of urban to rural skyglow with all-sky photometry. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **250**, 106988. https://doi.org/10.1016/j.jqsrt.2020.106988.

Jechow, A., Kyba, C.C.M. & Hölker, F. (2019) Beyond all-sky: assessing ecological light pollution using multi-spectral full-sphere fisheye lens imaging. *Journal of Imaging*, **5**, 46. https://doi.org/10.3390/jimaging5040046.

Johnsen, S. (2012) *The Optics of Life: A Biologist's Guide to Light in Nature*. New Jersey, USA: Princeton University Press.

Knop, E., Zoller, L., Ryser, R., Gerpe, C., Hörler, M. & Fontaine, C. (2017) Artificial light at night as a new threat to pollination. *Nature*, **548**, 206–209. https://doi.org/10.1038/nature23288.

Kolláth, Z., Cool, A., Jechow, A., Kolláth, K., Száz, D. & Tong, K.P. (2020) Introducing the dark sky unit for multi-spectral measurement of the night sky quality with commercial digital cameras. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **253**, 107162. https://doi.org/10.1016/j.jqsrt.2020.107162.

Kolláth, Z. & Dömény, A. (2017) Night sky quality monitoring in existing and planned dark sky parks by digital cameras. *International Journal of Sustainable Lighting*, **19**, 61–68.

Komonen, A., Halme, P. & Kotiaho, J.S. (2019) Alarmist by bad design: strongly popularized unsubstantiated claims undermine credibility of conservation science. *Rethinking Ecology*, **4**, 17–19. https://doi.org/10.3897/rethinkingecology.4.34440.

Kyba, C.C.M., Kuester, T., de Miguel, A.S. *et al*. (2017) Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances*, **3**, e1701528. https://doi.org/10.1126/sciadv.1701528.

Larsson, M., Göthberg, A. & Milberg, P. (2020) Night, light and flight: light attraction in Trichoptera. *Insect Conservation and Diversity*, **13**, 296–302. https://doi.org/10.1111/icad.12379.

Levin, N., Kyba, C.C.M., Zhang, Q., Sánchez de Miguel, A., Román, M. O., Li, X., Portnov, B.A., Molthan, A.L., Jechow, A., Miller, S.D., Wang, Z., Shrestha, R.M. & Elvidge, C.D. (2020) Remote sensing of night lights: a review and an outlook for the future. *Remote Sensing of Environment*, **237**, 111443. https://doi.org/10.1016/j.rse.2019.111443.

Longcore, T., Duriscoe, D., Aubé, M., Jechow, A., Kyba, C.C.M. & Pendoley, K.L. (2020) Commentary: Brightness of the night sky affects loggerhead (Caretta caretta) sea turtle hatchling misorientation but not nest site selection. *Frontiers in Marine Science*, **7**, 706. https://doi.org/10.3389/fmars.2020.00706.

Lortie, C.J., Aarssen, L.W., Budden, A.E., Koricheva, J.K., Leimu, R. & Tregenza, T. (2007) Publication bias and merit in ecology. *Oikos*, **116**, 1247–1253. https://doi.org/10.1111/j.0030-1299.2007.15686.x.

Macgregor, C.J., Evans, D.M., Fox, R. & Pocock, M.J.O. (2017) The dark side of street lighting: impacts on moths and evidence for the disruption of nocturnal pollen transport. *Global Change Biology*, **23**, 697–707. https://doi.org/10.1111/gcb.13371.

Macgregor, C.J., Williams, J.H., Bell, J.R. & Thomas, C.D. (2019) Moth biomass increases and decreases over 50 years in Britain. *Nature Ecology & Evolution*, **3**, 1645–1649. https://doi.org/10.1038/s41559-019-1028-6.

Manfrin, A., Lehmann, D., van Grunsven, R.H.A., Larsen, S., Syväranta, J., Wharton, G., Voigt, C.C., Monaghan, M.T. & Hölker, F. (2018) Dietary changes in predators and scavengers in a nocturnally illuminated riparian ecosystem. *Oikos*, **127**, 960–969. https://doi.org/10.1111/oik.04696.

Manfrin, A., Singer, G., Larsen, S., Weiß, N., van Grunsven, R.H.A., Weiß, N.S., Wohlfahrt, S., Monaghan, M.T. & Hölker, F. (2017) Artificial light at night affects organism flux across ecosystem boundaries and drives community structure in the recipient ecosystem. *Frontiers in Environmental Science*, **5**, 61. https://doi.org/10.3389/fenvs.2017.00061.

Mentges, A., Blowes, S.A., Hodapp, D., Hillebrand, H. & Chase, J.M. (2020) Effects of site-selection bias on estimates of biodiversity change. *Conservation Biology*. https://doi.org/10.1111/cobi.13610.

Meyer, L.A. & Sullivan, S.M.P. (2013) Bright lights, big city: influences of ecological light pollution on reciprocal stream–riparian invertebrate fluxes. *Ecological Applications*, **23**, 1322–1330. https://doi.org/10.1890/12-2007.1.

Minnaar, C., Boyles, J.G., Minnaar, I.A., Sole, C.L. & McKechnie, A.E. (2015) Stacking the odds: light pollution may shift the balance in an ancient predator–prey arms race. *Journal of Applied Ecology*, **52**, 522–531. https://doi.org/10.1111/1365-2664.12381.

Nankoo, S., Raymond, S. & Galvez-Cloutier, R. (2019) The impact of the Jacques Cartier bridge illumination on the food chain: from insects to predators. *Community Ecology*, **20**, 172–180. https://doi.org/10.1556/168.2019.20.2.7.

Owens, A.C.S., Cochard, P., Durrant, J., Farnworth, B., Perkin, E.K. & Seymoure, B. (2020) Light pollution is a driver of insect declines. *Biological Conservation*, **241**, 108259. https://doi.org/10.1016/j.biocon.2019.108259.

Owens, A.C.S. & Lewis, S.M. (2018) The impact of artificial light at night on nocturnal insects: a review and synthesis. *Ecology and Evolution*, **8**, 11337–11358. https://doi.org/10.1002/ece3.4557.

Pawson, S.M. & Bader, M.K.-F. (2014) LED lighting increases the ecological impact of light pollution irrespective of color temperature. *Ecological Applications*, **24**, 1561–1568. https://doi.org/10.1890/14-0468.1.

Pérez Vega, C., Zielinska-Dabkowska, K.M. & Hölker, F. (2021) Urban lighting research transdisciplinary framework—A collaborative process with lighting professionals. *International Journal of Environmental Research and Public Health*, **18**, 624. https://doi.org/10.3390/ijerph18020624.

Perkin, E.K., Hölker, F., Richardson, J.S., Sadler, J.P., Wolter C. & Tockner, K. (2011) The influence of artificial light on stream and riparian ecosystems: questions, challenges, and perspectives. *Ecosphere* **2** (11), 1–16. https://doi.org/10.1890/ES11-00241.1.

Perkin, E.K., Hölker, F. & Tockner, K. (2014) The effects of artificial lighting on adult aquatic and terrestrial insects. *Freshwater Biology*, **59**, 368–377. https://doi.org/10.1111/fwb.12270.

Plummer, K.E., Hale, J.D., O'Callaghan, M.J., Sadler, J.P. & Siriwardena, G.M. (2016) Investigating the impact of street lighting changes on garden moth communities. *Journal of Urban Ecology*, **2**(1), juw004. https://doi.org/10.1093/jue/juw004.

Sánchez-Bayo, F. & Wyckhuys, K.A.G. (2019) Worldwide decline of the entomofauna: a review of its drivers. *Biological Conservation*, **232**, 8–27. https://doi.org/10.1016/j.biocon.2019.01.020.

Saunders, M.E., Janes, J.K. & O'Hanlon, J.C. (2020) Moving on from the insect apocalypse narrative: engaging with evidence-based insect conservation. *BioScience*, **70**, 80–89. https://doi.org/10.1093/biosci/biz143.

Seibold, S., Gossner, M.M., Simons, N.K., Blüthgen, N., Müller, J., Ambarlı, D., Ammer, C., Bauhus, J., Fischer, M., Habel, J.C., Linsenmair, K.E., Nauss, T., Penone, C., Prati, D., Schall, P., Schulze, E.D., Vogt, J., Wöllauer, S. & Weisser, W.W. (2019) Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature*, **574**, 671–674. https://doi.org/10.1038/s41586-019-1684-3.

Smith, R.C. & Wilson, W.H. (1972) Photon scalar irradiance. *Applied Optics*, **11**, 934–938. https://doi.org/10.1364/AO.11.000934.

Spoelstra, K., van Grunsven, R.H.A., Donners, M., Gienapp, P., Huigens, M.E., Slaterus, R., Berendse, F., Visser, M.E. & Veenendaal, E. (2015) Experimental illumination of natural habitat—an experimental set-up to assess the direct and indirect ecological consequences of artificial light of different spectral composition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370**, 20140129. https://doi.org/10.1098/rstb.2014.0129.

Stewart, A.J.A., Perl, C.D. & Niven, J.E. (2020) Artificial lighting impairs mate attraction in a nocturnal capital breeder. *Journal of Experimental Biology*, **223**, jeb229146. https://doi.org/10.1242/jeb.229146.

Sullivan, S.M.P., Hossler, K. & Meyer, L.A. (2019) Artificial lighting at night alters aquatic-riparian invertebrate food webs. *Ecological Applications*, **29**, e01821. https://doi.org/10.1002/eap.1821.

Thimijan, R.W. & Heins, R.D. (1983) Photometric, radiometric, and quantum light units of measure: a review of procedures for interconversion. *HortScience*, **18**(6), 818–822.

Thomas, A.C., Howard, J., Nguyen, P.L., Seimon, T.A. & Goldberg, C. S. (2018) eDNA Sampler: a fully integrated environmental DNA sampling system. *Methods in Ecology and Evolution*, **9**, 1379–1385. https://doi.org/10.1111/2041-210X.12994.

Thomas, C.D., Jones, T.H. & Hartley, S.E. (2019) "Insectageddon": a call for more robust data and rigorous analyses. *Global Change Biology*, **25**, 1891–1892. https://doi.org/10.1111/gcb.14608.

van Grunsven, R.H.A., Becker, J., Peter, S., Heller, S. & Hölker, F. (2019) Long-term comparison of attraction of flying insects to streetlights after the transition from traditional light sources to light-emitting diodes in urban and peri-urban settings. *Sustainability*, **11**, 6198. https://doi.org/10.3390/su11226198.

van Grunsven, R.H.A., van Deijk, J.R., Donners, M., Berendse, F., Visser, M.E., Veenendaal, E. & Spoelstra, K. (2020) Experimental light at night has a negative long-term impact on macro-moth populations. *Current Biology*, **30**, R694–R695. https://doi.org/10.1016/j.cub.2020.04.083.

van Klink, R., Bowler, D.E., Gongalsky, K.B., Swengel, A.B., Gentile, A. & Chase, J.M. (2020) Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science*, **368**, 417–420. https://doi.org/10.1126/science.aax9931.

van Langevelde, F., Braamburg-Annegarn, M., Huigens, M.E., Groendijk, R., Poitevin, O., van Deijk, J.R., Ellis, W.N., van Grunsven, R.H.A., de Vos, R., Vos, R.A., Franzén, M. & WallisDeVries, M.F. (2018) Declines in moth populations stress the need for conserving dark nights. *Global Change Biology*, **24**, 925–932. https://doi.org/10.1111/gcb.14008.

van Strien, A.J., van Swaay, C.A.M., van Strien-van Liempt, W.T.F.H., Poot, M.J.M. & WallisDeVries, M.F. (2019) Over a century of data reveal more than 80% decline in butterflies in The Netherlands. *Biological Conservation*, **234**, 116–122. https://doi.org/10.1016/j.biocon.2019.03.023.

Verheyen, J., Tüzün, N. & Stoks, R. (2019) Using natural laboratories to study evolution to global warming: contrasting altitudinal, latitudinal, and urbanization gradients. *Current Opinion in Insect Science*, **35**, 10–19. https://doi.org/10.1016/j.cois.2019.06.001.

Wagner, D.L., Grames, E.M., Forister, M.L., Berenbaum, M.R. & Stopak, D. (2021) Insect decline in the anthropocene: death by a thousand cuts. *Proceedings of the National Academy of Sciences of the United States of America*, **118**, e2023989118. https://doi.org/10.1073/pnas.2023989118.

Wakefield, A., Broyles, M., Stone, E.L., Jones, G. & Harris, S. (2016) Experimentally comparing the attractiveness of domestic lights to insects: do LEDs attract fewer insects than conventional light types? *Ecology and Evolution*, **6**, 8028–8036. https://doi.org/10.1002/ece3.2527.

Walczak, K., Crim, G., Gesite, T., Habtemichael, S., Morgan, J., Tarr, C., Turkic, L. & Wiedemann, J. (2020) The GONet (Ground Observing Network) camera: an inexpensive light pollution monitoring system. *Researchgate*. https://doi.org/10.13140/RG.2.2.12625.76647.

Wilson, J.F., Baker, D., Cheney, J., Cook, M., Ellis, M., Freestone, R., Gardner, D., Geen, G., Hemming, R., Hodgers, D., Howarth, S., Jupp, A., Lowe, N., Orridge, S., Shaw, M., Smith, B., Turner, A. & Young, H. (2018) A role for artificial night-time lighting in long-term changes in populations of 100 widespread macro-moths in UKand Ireland: a citizen-science study. *Journal of Insect Conservation*, **22**, 189–196. https://doi.org/10.1007/s10841-018-0052-1.

Accepted 11 February 2021

Editor/associate editor: Alan Stewart