Reducing the blue spectrum of artificial light at night minimises insect attraction in a tropical lowland forest

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Abstract. 1. New infrastructure development in previously natural environments is introducing light pollution to habitats at an unprecedented rate, which has the potential to be devastating for native insect assemblages.

2. We evaluated insect attraction to three lamp types emitting different spectra of light (white, yellow-filtered and amber-filtered ∼3000 K LED lights) and an unlit control in a lowland forest site in the northern Peruvian Amazon previously naïve to artificial illumination.

3. Lamp type was the only variable included in the most parsimonious models explaining morphospecies richness and abundance for all insects combined and for eight different insect orders. White lamps (3200 K) attracted far more insects, both morphospecies and individuals, including groups containing important vectors of pathogens, bacteria or parasites, than either yellow (2700 K) or amber (2200 K) lamps.

4. Amber lamps attracted the fewest morphospecies and individuals overall but were the most attractive for a limited group of insects, including elaterid beetles (click beetles) and mycetophilid flies (fungus flies).

5. While period of night was not a significant predictor of morphospecies richness or abundance, different assemblages of insects were collected during two different sampling periods (18:00–20:00 and 03:00–05:00).

6. We strongly recommend that new infrastructure development projects introducing ALAN to light-naïve tropical forests use filtered amber LED lamps with no blue and minimal green light content in outdoor lighted areas. Similarly, operators should develop outdoor lighting plans that include overall reduction of nocturnal lighting and impact mitigation measures. These recommendations should also be used to retrofit existing infrastructure including roads and human settlements.

Abstract en español. 1. El desarrollo de nuevas infraestructuras en entornos previamente naturales está introduciendo contaminación lumínica en esos hábitats a una tasa sin precedentes, la cual tiene el potencial de ser particularmente devastadora para las comunidades de insectos nativos.

2. Evaluamos la atracción de insectos a tres tipos de lámparas que emiten diferentes espectros de luz (lámparas LED blancas de ∼3000K sin filtro, con un filtro amarillo y con un filtro ámbar para limitar o eliminar los espectros azules de luz emitidos) y un control sin luz en un sitio de bosque bajo en el norte de la Amazonía peruana, previamente sin iluminación artificial.
3. El tipo de lámpara fue la única variable incluida en los modelos más parsimónicos que explican la riqueza y abundancia de morfoespecies para todos los insectos combinados y para ocho órdenes diferentes de insectos. Las lámparas blancas (3200K) atrajeron muchos más insectos, morfoespecies e individuos, incluyendo grupos conocidos por contener vectores importantes de patógenos, bacterias o parásitos, que las lámparas de color amarillo (2700K) o ámbar (2200K).

4. Las lámparas ámbar atrajeron la menor cantidad de morfoespecies e individuos en general, pero fueron las luces más atractivas para un grupo limitado de insectos, incluyendo a los escarabajos elatéridos (escarabajos clic) y las moscas micetofílidas (moscas de los hongos).

5. Si bien el período de la noche no fue un predictor significativo de la riqueza o abundancia de morfoespecies, se colectaron diferentes ensambajes de insectos durante los dos períodos de muestreo (18:00-20:00 y 03:00-05:00).

6. Recomendamos enéfáticamente que los nuevos proyectos de desarrollo de infraestructura que introduzcan ALAN a bosques sin luces artificiales utilicen luces LED con filtro ámbar sin espectro azul y muy poco espectro verde en áreas iluminadas al aire libre. Del mismo modo, los operadores deben desarrollar un plan de iluminación al aire libre que incluya la reducción general de la iluminación nocturna y métodos de mitigación de impactos. Estas recomendaciones también deben usarse para modernizar la infraestructura existente, incluidas las carreteras y los asentamientos humanos.

**Key words.** ALAN, blue light, dark skies, impact evaluation, insect attraction, insect decline, LED, light pollution.

**Introduction**

Artificial light at night (ALAN) can be particularly devastating for flying insects, which can in turn disrupt natural ecological processes. Insects may be directly affected by lights when they suffer mortality from collisions with hot lamps, exhaustion, or increased predation due to the attraction of predators and/or increased visibility. Alternatively, insects affected by artificial lighting may also become disoriented or inactive, leading to a failure to reproduce (Owens & Lewis, 2018; Boyes et al., 2021), and consequently, a reduction of gene flow in the population (Eisenbeis, 2006). Insects provide important ecosystem services including nutrient cycling, pest control and pollination – these services in the United States alone have been valued at $57 billion annually (Losey & Vaughan, 2006) – and ALAN has recently been identified as a specific threat to pollination (Knop et al., 2017; Giavi et al., 2020; but see Macgregor et al., 2019). Conversely, the rise in electrification in developing countries has been associated with increased incidence rates of insect-transmitted diseases including leishmaniasis, Chagas disease (Barghini & de Medeiros, 2010; Pacheco-Tucuch et al., 2012) and malaria (Pellegrini & Tasciotti, 2016; Tasciotti, 2016, 2017). While general land use change certainly plays a role (Guo et al., 2019), increased insect-born disease transmission is likely linked to both human and insect behaviour changes resulting from the introduction of ALAN (Barghini & de Medeiros, 2010). Artificial lighting can put insect and human populations in jeopardy, potentially leading to drastic and costly consequences.

ALAN is an unavoidable consequence of many types of infrastructure development and urbanisation. Inhabitants, workers and surveillance systems require illumination to varying degrees. New lighting is particularly problematic as infrastructure is developed in natural areas, extending deep into naïve ecosystems including in and around protected areas in the tropics (Guetté et al., 2018; Andrade-Núñez & Aide, 2020). Selective pressure likely erodes flight-to-light behaviour in some insects over time (Altermatt et al., 2009) and phototaxis is greatest when contrast is highest between the light and its surroundings (Robinson & Robinson, 1950; Frank, 2006). New lighting in naïve habitats therefore represents a worst-case scenario for environmental impacts from lamps, which for insects includes high levels of mortality and behavioural disruption (Owens & Lewis, 2018). Pre-construction planners, regulators, and businesses need validated knowledge about the attractiveness of lamps to insects to develop standards for lighting in new (and to retrofit existing) developments in high-biodiversity habitats, such as those in the Amazon Basin.

The degree to which insects are attracted to light is influenced by its intensity, polarisation (Horvath et al., 2014; Robertson et al., 2017) and the spectral composition of the light (Clevé, 1964; Donners et al., 2018; Eisenbeis & Eick, 2011; van Langevelde et al., 2011). The visual sensitivity of many insect groups (Diptera, Lepidoptera, Hymenoptera, Coleoptera) extends into the ultraviolet range (Briscoe & Chittka, 2001; Davies et al., 2013), which has been exploited by insect collectors since the 1950s (Frost, 1957). Flies also exhibit phototaxis to the green and red portions of the spectrum (Green, 1985). Previously, the spectral output of lamps was an intrinsic characteristic of different technologies. Mercury vapour, high-pressure sodium, low-pressure sodium, metal halide, xenon, fluorescent,
and incandescent lamps are inflexible in their spectral power distribution unless filtered. As a result, the attractiveness of these lamps to insects was different and predictable (Longcore et al., 2018). For example, mercury lamps have been shown to attract more than twice the number of insects attracted by high-pressure sodium (HPS) lamps (Eisenbeis & Hassel, 2000; Eisenbeis & Eick, 2011; Boyes et al., 2021). Likewise, metal halide lamps attract substantially more insects than either HPS or light-emitting diode (LED) lamps (Wakefield et al., 2018). In turn, low-pressure sodium lamps attract fewer insects than HPS lamps (Boyes et al., 2021). LED-based lamps, in contrast, have a wide range of spectral power distributions. Although commercially viable LEDs for outdoor lighting were originally based on a blue LED with a white phosphor that created a distinctive spectral power distribution (SPD; a blue spike with a wide spread of longer wavelengths), subsequent innovations have minimised the blue peak, spreading more light at longer wavelengths. Durable and stable lamps have also been developed, allowing for the development of LEDs with a range of colour combinations with different attractiveness to wildlife (Longcore et al., 2018).

The challenge for specifying ALAN mitigation measures for infrastructure development is to evaluate what lighting guidelines would minimise the adverse impacts to sensitive species. Donners et al. (2018) developed a generalised insect attraction model by spectral wavelength, which was constructed and tested with field data gathered in Germany and California. Spectral response curves are also available for moths (Cleve, 1964) and bees (Menzel & Greggers, 1985). Longcore et al. (2018) formulated an approach to predict the comparative influence of any lighting source, given its spectral power distribution, on species, given knowledge of the response of the target organism. They used this approach to predict successfully the relative attractiveness of different lamp types to a species of seabird (Longcore et al., 2018) but neither their approach nor the Donners et al. (2018) insect attractiveness curve have been tested further.

Another trend in mitigating light pollution is the use of part-night lighting, where lights are shut off during certain times during the night (Azam et al., 2015; Day et al., 2015; Gaston et al., 2012; Longcore & Rich, 2016, 2017). Effectiveness of part-night lighting at reducing impacts on bats at a study site in France shows benefits for some species but fewer than the majority (Azam et al., 2015). Another example indicates that lights would need to be shut off by midnight to allow half of the foraging time of a photophobic bat to be light-free (Day et al., 2015). We are unaware of studies on the efficacy of part-night lighting to reduce impacts on insects, important prey for bats. Such measures would be most effective by limiting lighting to times when insect activity is lowest.

Given the importance of developing validated techniques to reduce the adverse effects of infrastructure development in otherwise undisturbed landscapes, we set out to address key questions around the efficacy of ALAN mitigation measures in a soon to be developed light-naive setting in the Peruvian Amazon. We tested three different LED lamps with different spectra during two different periods of the night to evaluate (i) which light types are most effective at reducing overall insect abundance attracted to the light source, (ii) whether different light types attract different compositions of insects, and (iii) whether the time of night influences the abundance and/or composition of insect taxa attracted to lights. Based on previous research on the influence of light spectra on insect attraction (Longcore et al., 2015; Longcore et al., 2018), we predicted that lamps with lower correlated colour temperature (CCT) and longer wavelength spectra would attract fewer insects than lamps with shorter wavelength spectra and that the quantified attraction metrics developed by Longcore et al. (2018) would best predict the attractiveness of different lamp types. With a diverse rainforest arthropod fauna, we expected to detect between-order differences in attraction that are attributable to variations in behavioural responses to light (Cleve, 1964; Menzel & Greggers, 1985). Furthermore, like most living things, insects exhibit circadian rhythms in locomotion, reproduction and feeding that have a genetic basis and are closely tied to light, temperature and chemical cues (Dreisig, 1976; Meireles-Filho & Kyriacou, 2013; Lam & Chiu, 2019). The composition of temperate insect families active during diurnal, nocturnal and crepuscular hours has been shown to vary (McMunn & Hernandez, 2018) and both temperate and tropical insects exhibit size differences in diel activity (Guevara & Avilés, 2013; McMunn & Hernandez, 2018). For these reasons, we also hypothesised that a different assemblage of insects would be captured in the earlier part of the night compared to later hours.

Materials and methods

Study site

The study was conducted in lowland rainforest in northern Peru (Morona District, Datem del Marañón Province, Loreto Department) inside a hydrocarbon (oil and gas) concession operated by GeoPark Perú. The forest is a matrix of aguaje swamps (dominated by several palm species, predominantly by the aguaje, Mauritia flexuosa), seasonally flooded forest, transitional seasonally flooded terra firme forests and terra firme (upland) forest (Encarnación, 1993; RLP unpublished data). Traps were established only in terra firme forest sites.

Sampling

Between 30 July and 19 August 2018, we used light traps with three different lamps (~3000 K LED, ~3000 K LED with CW8 filter yielding 2700 K, ~3000 K LED with CW9 filter yielding 2200 K [C&W Energy, http://cweneryusa.com] and a control (no light) to evaluate the number and composition of insects attracted to the lamps during two different time periods at night. The baseline white (~3000 K) LED lamp is already known to reduce the attraction of insects (Eisenbeis & Eick, 2011; Poiani et al., 2015; Wakefield et al., 2018; Boyes et al., 2021) based on a reduction in blue light content relative to metal halide, fluorescent and other higher CCT (“cooler”) lamps. We compared this to two additional ~3000 K base LED lamps, each with a filter that eliminated different degrees of shorter wavelengths and...
hence altered the CCT (Table 1). These commercial filters are coded CW8 and CW9, the former filtering out most of the blue wavelengths but preserving some green, while the latter contained no blue and less green light content than the CW8 filter (Table 1; Fig. 1). These will be hereafter referred to as ‘yellow’ (CW8) and ‘amber’ (CW9) lamps. We also operated traps with no lamp to determine how many insects might fall in the traps in the absence of light (control).

Each sampling structure consisted of a PVC stand approximately 1.6 m high that supported an LED lamp, a backstop that acted as an intercept for insects flying towards the lamp and a pitfall trap (Fig. 2). A 12 V 20 AH lithium battery housed in a custom-made waterproof box that included a timer and a port allowing the battery to be connected to the light externally (Solar Traffic Controls, LLC) powered each LED lamp. We placed plastic containers, ~40 cm × 60 cm, on a platform ~10 cm beneath each lamp to form the pitfall trap. Each container was half filled with water and a small amount of detergent to reduce water surface tension and to temporarily preserve insects that fell into the traps.

Sampling structures were set up in 12 locations, each a minimum of 100 m apart (Supporting Information Fig. S1) and not visible to one another. Each night, the four treatments (three lamp types and the control) were randomly assigned to eight of the 12 sites (two sites per treatment); the other four sites remained inactive with no lamps and no traps. Each of the four treatments was installed at each of the 12 sites for three nights. Lamps were rotated among the sites so that there was a dark night between light sampling nights in order to reduce the possibility of insects attracted to, but not captured by, the previous sampling period B took place primarily before astronomical twilight (approximately 19:08), while sampling period A took place both during and after Sunrise and sunset occurred at approximately 06:00 and 18:00, respectively. Sampling period A took place during a waning gibbous moon and ended with a first quarter moon. All traps were placed under a closed tropical forest canopy. The research team collected the contents of each trap from the eight active sites (the six sites with lamps and two randomly selected control sites with no light) within 1 h after each sampling period. Sampling was postponed in the event of a downpour event strong enough to inhibit flying insect activity and/or cause pitfall traps to overflow. In total, we sampled over 18 nights, resulting in a total of 144 trap nights, with 36 trap nights per treatment, and with two sampling periods per treatment per night. We collected 288 samples (8 samples/night × 18 nights × 2 sampling periods). Insects were preserved in 96% alcohol. Specimens were examined under a stereo microscope, identified to the level of family or genus, and then further separated into distinct morphospecies based on similar phenotypes by one of the authors (J.M.A.). Specimens were deposited at the Museo de Entomología Klaus Raven Buller, Entomology Department, Universidad Agraria La Molina, Lima, Peru.

Data analysis

To test a priori predictions for lamp attractiveness (Longcore et al., 2018), we plotted the abundance of insects attracted to lamps in this study against the predicted attractiveness of the lamps used. Attractiveness is calculated relative to an equivalent illuminance in lux of daylight, as estimated by the CIE D65 standard illuminant (see Longcore et al., 2018).

To understand the attraction of different insects to the treatments tested, we used a generalised linear model using a Poisson distribution and log-link function (Bolker et al., 2009) with sampling period, site, night and lamp type as explanatory factors, and using Firth bias-adjusted estimates to modify the likelihood function to reduce bias in parameter estimates. We developed generalised linear models using the following response variables: total number of morphospecies, total number of individuals, and number of morphospecies and number of individuals intercepted for insects

![Fig 1. Spectral power distributions of the three lamps used in the study.](wileyonlinelibrary.com)](Image 312x255 to 535x395)

| Light    | Base          | Filter | CCT (K) | CRI | S/P | BLC (%) | BGLC (%) |
|----------|---------------|--------|---------|-----|-----|---------|----------|
| Amber    | 3000 K LED    | CW9    | 2254    | 50  | 0.41| 0       | 12       |
| Yellow   | 3000 K LED    | CW8    | 2759    | 53  | 0.52| 0       | 17       |
| White    | 3000 K LED    | None   | 3223    | 74  | 1.14| 13      | 29       |

CCT = correlated colour temperature, CRI = colour rendering index, S/P = Scotopic/Photopic ratio, BLC = blue light content, BGLC = blue green light content.

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by order for orders with 10 or more morphospecies and >200 individuals (Diptera, Coleoptera, Hymenoptera, Hemiptera, Lepidoptera, Orthoptera, Ephemeroptera, Isoptera, Trichoptera). We tested for and adjusted for overdispersion of the counts by estimating the overdispersion factor and adjusting the likelihood functions and confidence intervals accordingly. We used backward stepwise selection to limit the total number of models compared in each test (Murtaugh, 2009). We also used canonical correspondence analysis (CCA) to investigate whether morphospecies composition and abundances changed with the explanatory variables listed above, using 99% confidence intervals to determine significance. All analyses were carried out using RStudio 1.1.383 (RStudio Team, 2020), R 3.5.1 (R Core Team, 2020) or JMP statistical software (SAS, Cary, NC).

Results

We identified 763 unique morphospecies among the >15,000 insects captured across all samples, belonging to 18 different orders. Overall, significantly more morphospecies were captured on average in the white LED light traps than in either the yellow or amber-filtered traps or the control (Fig. 3a; $F_{3,284} = 78.99$, $P < 0.005$): 1.6 times that at yellow lamps, 1.8 times that at amber lamps, and 15.3 times that at the control. Likewise, significantly more individual insects were captured on average in the white LED traps ($F_{3,284} = 20.01$, $P < 0.005$): 1.7 times the number at yellow lamps, 2.5 times that at amber lamps, and 53.6 times that at the unit control (Fig. 3b). The two filtered lamps did not capture significantly different total numbers of morphospecies ($P = 0.432$) or individuals ($P = 0.570$) overall.

A priori calculations for lamp attractiveness (Longcore et al., 2018) correctly predicted the ranking of attractiveness of the lamps and the decrease in number of insects attracted from the white lamp to the two filtered lamps (Fig. 4). Diptera (flies, 167 morphospecies), Hymenoptera (wasps, bees and ants, 155) and Coleoptera (beetles, 146) were the orders with the most morphospecies captured in light traps. Hymenoptera (6833 individuals), Trichoptera (caddisflies, 1931), Diptera (1586) and Lepidoptera (butterflies and moths, 1549) were the most frequently captured orders across all light types in terms of number of individuals (Fig. 5).

White LED lamps attracted more morphospecies of all orders except Isoptera (termites) and Trichoptera, among which one and two more morphospecies respectively were attracted to the amber lamps than to white lamps (Fig. 5). While abundance of Isoptera was also greatest at amber lamps, the overall abundance

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(number of individuals) of Trichoptera was more than three times greater at white lamps. Note that the abundance of Isoptera seems to be driven by a nuptial flight (alate emergence) event on day 5 of sampling that probably occurred close to sites 7 and 9 (accounting for 193 of 249 individuals across all samples). Among the remaining orders, more morphospecies and individuals were attracted to yellow lamps than amber lamps, with one exception, Lepidoptera, which had more species but fewer individuals at amber lamps. Orthoptera (katydids and crickets) were most abundant at yellow lamps. At the family level, 30 out of 130 families had more morphospecies (range = 1 to 4, median = 1) attracted to amber than to white lamps and 31 families had more individuals (range = 1–127, median = 4) attracted to amber than white lamps.

The composition of morphospecies varied by treatment and by period of night (Fig. 6). There was a distinct and more heterogeneous insect assemblage attracted to amber lamps than all other treatments (Fig. 6a). In addition, different insect morphospecies assemblages were captured during the two sampling periods each night (18:00–20:00 and 03:00–05:00; Fig. 6b). Overwhelmingly more individuals of Trichoptera (95% of the total), Ephemeroptera (84%) and Orthoptera (71%), and more morphospecies of Blattodea (53% more than period B), Coleoptera (36%) and Ephemeroptera (33%) were captured during period A. Individual dipterans were captured nearly equally in both periods (51% in period A, 49% in period B), but 10% more morphospecies were captured during period B. Hymenopterans were captured in greater numbers during period B (67%), although richness was nearly equal during the two periods. For Isoptera, morphospecies richness was equal, but 90% of all individuals were captured during period B.

Among captured insect families known to contain important vectors of pathogens, bacteria or parasites (Diptera: Calliphoridae, Ceratopogonidae, Chloropidae, Culicidae, Muscidae, Psychodidae, Sarcophagidae, Tabanidae; Hemiptera: Reduviidae), 45% of all individuals were captured at white lamps, 41% at yellow lamps and just 13% were found in amber lamp traps.

For total morphospecies richness, the most parsimonious model included only lamp type treatment; the same was true
for all orders analysed separately except Trichoptera, for which
the best model also included ‘period’ and ‘day’ (Table 2). Similarly,
the most parsimonious models explaining total abundance of
insects attracted to lights only included lamp type (Table 3).
This was true for each order as well, with the exception of
Orthoptera, for which “period” was included along with lamp
type in the best model (more than twice as many individuals were
captured during period A as during period B). When we consid-
ered “period” alone across all nine orders combined, more mor-
phospecies (mean 10.3 vs. 9.4) and more individuals (mean 61 vs. 47 specimens) were collected per sample during the first
collecting period, but this difference was not significant once
overdispersion of the data was considered.

Discussion
To our knowledge, this is the first study to investigate the poten-
tial impacts and mitigation methods for ALAN in tropical forest.

This is timely and important given that the hyper-diverse and
largely unstudied assemblage of insects inhabiting Amazonian
rain forests (Stork, 2007; Novotny & Miller, 2014) is under
threat by expanding infrastructure development bringing land
use change and nocturnal lighting to previously undisturbed
areas (Ribeirão de Freitas et al., 2017; Andrade-Núñez &
Aide, 2020). Insects respond relatively rapidly to human
disturbance, making them potentially vulnerable to site extirpa-
tion (Basset et al., 2004) or to changes in dominance structure,
in particular when insect species are introduced to new
habitats (Mikheyev et al., 2008). If left unchecked, ALAN will
negatively impact light-naïve rain forest insect communities.

Fortunately, negative impacts of ALAN on flying insects in
tropical forests can be reduced by improving lighting practices
(Owens et al., 2020). Here we show that by using CW9 lamps
(amber-filtered low CCT LEDs), the number of morphospecies
attracted to the light was reduced by 34% and individual insects
were reduced by nearly 60% as compared to white (~3000 K)
LED lamps with reduced blue light content. Among the lamps

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tested, amber-filtered light that comprised no blue and less green light content than the yellow (CWS) filter is the best of the tested options for reducing overall insect attraction to illuminated areas of operations and thereby minimising the impact of this activity on biodiversity. Lamp attractiveness was accurately predicted by rankings produced previously (Longcore et al., 2018), supporting the utility of these predictive curves for assessing the impact of different lamp types (spectra of lighting) introduced to a system.

Because of the high level of attraction of these groups to light in general, artificial lighting in our study area is most likely to negatively affect insects belonging to the following orders: Hymenoptera, Lepidoptera, Coleoptera, Diptera, Hemiptera, and Trichoptera (Fig. 5). For each of these groups, lamp type was the most important predictor of morphospecies (along with day and period for Trichoptera) and individual attraction, highlighting the importance of impact mitigation through lamp selection. While we captured over 15 000 individual insects in our traps across 288 sampling events, it is important to note that this reflects an underestimation of the actual number of insects attracted to the lamps. We used a modified intercept/pitfall trap, but the use of mixed trapping combining additional methods such as sticky, malaise or electrical traps would provide more comprehensive data on flying insects attracted to light. Furthermore, future studies should consider how ALAN may impact life stages other than adults (Boyes et al., 2021) and use sampling methodologies appropriate for these.

Human safety issues are of primary concern when choosing the type of light used to illuminate industrial areas and human settlements. One primary safety concern is visibility. Visibility includes brightness and colour rendering. The filters slightly reduce brightness (~13%, Table 1) by removing the blue peak in the spectrum, but perhaps more importantly, the filters alter the colour rendering index (Table 1). While it is more difficult for humans to distinguish colour under ‘orange’ relative to ‘white’ light, the yellow and amber-filtered LED lamps provide better colour rendering (Table 1) than high pressure sodium lamps (~30 CRI), which have been used traditionally in outdoor operations and should not impede safety or efficiency. Another concern is health and disease transmission. The introduction of ALAN initiates behaviour changes in both insects and humans, increasing the probability of insect vectors and humans co-occurring in a space (Barghini & de Medeiros, 2010). Our evaluation of known insect disease vectors showed a substantial reduction of potential vectors at amber lamps. This result aligns with a recent review that found higher spectral sensitivity and attraction to shorter wavelengths among biting flies (Wilson et al., 2021). Across all samples, we found just a single individual of Lutzomyia sp., known to transmit Leishmaniasis, at a white LED. This is not surprising given that phlebotomines are known to be attracted to lighted areas, but not directly to lamps (Barghini & de Medeiros, 2010). Multiple species of triatomine bugs, vectors of Chagas disease, are also attracted to lights (Barghini & de Medeiros, 2010) and one study showed that adult Triatoma dimidiata displayed a significant decrease in attraction with increasing wavelength light (Pacheco-Tucuch et al., 2012). This evidence further supports the use of filtered LEDs with little or no blue light in areas that must be illuminated at night.

While the fewest total number of morphospecies and individual insects were captured at amber lamps, some insect groups...
were preferentially attracted to them. Two such groups are the elaterid beetles, also known as click beetles, and the mycetophilid flies, or fungus flies. Interestingly, these groups contain species with bioluminescent adults (Sivinski, 1998). One species of click beetle has been shown to have a broad green visual receptor, perhaps explaining attraction in this group to light with green spectral content and not to the light with blue spectral content (Lall et al., 2000). Likewise, in a larval fungus fly, male glowworms have been shown to prefer artificial light the colour of female glow signals (Owens & Lewis, 2018). By reducing the blue spectra of light in ALAN, impacts on the majority of species can be mitigated; however, we strongly caution that taking the pressure off many species will likely increase the pressure on a select few and potentially bioluminescent species in particular.

ALAN has previously been shown to reduce reproductive success through different mechanisms in some species of flies (Owens & Lewis, 2018; Firebaugh & Haynes, 2019), and further studies are needed to understand long term repercussions of lighting impacts on insects as well as other taxa.

It has been suggested that the impacts of ALAN on nocturnal animals can be categorised by temporal disorientation, spatial disorientation, attraction, desensitisation and recognition.

Table 2. The top two generalised linear model (Poisson distribution; log-link function) results for morphospecies richness across all individuals and by order. Alternative models were constructed by removing the non-treatment variable contributing least to the model. Response values with 95% confidence intervals provided for treatment categories.

| Model                  | Response – number of morphospecies per night (95% confidence intervals) |
|------------------------|---------------------------------------------------------------------------|
|                        | White (3000 K) | Yellow (CW8) | Amber (CW9) | Control |
| Total Treatment        | 336.06         | 3            | 530.85      | 16.37   | 9.89    | 9.10    | 0.75    |
|                        | 14.65–18.29    | 8.57–11.41   | 7.84–10.56  | 0.45–1.27 |
| Treatment, day Coleoptera | 564.64         | 20           | 663.57      | 2.99    | 1.71    | 1.93    | 0.25    |
| Treatment              | 116.61         | 3            | 575.39      | 2.51–3.56 | 1.36–2.16 | 1.55–2.41 | 0.14–0.47 |
| Treatment, Period      | 167.58         | 4            | 588.17      | 4.50–6.02 | 2.61–3.79 | 2.28–3.40 | 0.13–0.49 |
| Treatment, day Ephemeroptera | 193.57        | 3            | 579.73      | 5.20    | 3.14    | 2.78    | 0.25    |
| Treatment              | 45.52          | 3            | 323.04      | 0.59    | 0.25    | 0.27    | 0.02    |
| Treatment, Period      | 100.22         | 4            | 384.97      | 0.43–0.81 | 0.16–0.41 | 0.17–0.44 | 0.00–0.11 |
| Treatment, day Hemiptera | 179.08        | 3            | 600.40      | 2.60    | 1.79    | 1.56    | 0.03    |
| Treatment              | 285.45         | 20           | 730.99      | 2.20–3.08 | 1.47–2.20 | 1.26–1.94 | 0.01–0.15 |
| Treatment, day Hymenoptera | 192.86        | 3            | 813.07      | 4.15    | 3.30    | 2.19    | 0.53    |
| Treatment              | 295.48         | 20           | 933.75      | 3.64–4.72 | 2.85–3.81 | 1.83–2.61 | 0.37–0.76 |
| Treatment, day Isoptera | 15.72          | 3            | 172.58      | 0.10    | 0.10    | 0.19    | 0.0      |
| Treatment              | 168.50         | 20           | 404.50      | 0.05–0.22 | 0.05–0.22 | 0.11–0.32 | 0.00–0.12 |
| Treatment, day Lepidoptera | 190.41        | 3            | 620.78      | 3.65    | 1.78    | 1.63    | 0.15    |
| Treatment              | 316.79         | 21           | 691.11      | 3.14–4.23 | 1.44–2.21 | 1.31–2.04 | 0.08–0.33 |
| Treatment, day, period Orthoptera | 66.27 | 3 | 452.52      | 0.87    | 0.88    | 0.51    | 0.05    |
| Treatment              | 113.06         | 21           | 492.59      | 0.66–1.14 | 0.67–1.15 | 0.35–0.72 | 0.02–0.15 |
| Treatment, period Trichoptera | 61.21        | 21           | 222.96      | 0.41    | 0.26    | 0.27    | 0.02    |
| Treatment, period      | 54.29          | 4            | 297.20      | 0.29–0.57 | 0.16–0.39 | 0.17–0.41 | 0.00–0.09 |

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(Longcore & Rich, 2004; Gaston et al., 2013; Owens & Lewis, 2018). Our study design allowed us to investigate one of these – attraction – and on one broad taxonomic group – insects. Insects are key elements of complex tropical food webs, hence the cascading impacts of ALAN on various plant and animal taxa in this ecosystem are likely considerable. Nevertheless, use of a restricted spectrum (such as amber-filtered LED lamps) will inevitably reduce, but not eliminate, all impacts on wildlife. These impacts can be further minimised by employing additional mitigation measures including the use of full cutoff fixtures, motion activators and dimmers to ensure light is used only where and when it is needed.

Studies in temperate systems have shown that in addition to changing the spectrum of lighting, dimming lights and using partial night lighting (turning off lights for part of the night) can reduce negative impacts of ALAN on insects and plants (Davies et al., 2017; Macgregor et al., 2019). In this study, more individuals and morphospecies overall were captured during the early evening (period A) than in the early morning (period B) and the composition of species differed between the two sampling periods, suggesting that timing of light at night is an important factor to consider in designing broad mitigation strategies.

Table 3. The top two generalised linear model (Poisson distribution; log-link function) results for abundance of all morphospecies combined and by order. Alternative models were constructed by removing the non-treatment variable contributing least to the model. Response values with 95% confidence intervals provided for treatment categories.

| Model                     | Chi-Square | Df | AICc | White (3000 K) | Yellow (CW8) | Amber (CW9) | Control |
|---------------------------|------------|----|------|----------------|--------------|-------------|---------|
| Total                     | 111.27     | 3  | 216.19 | 108.3          | 62.1         | 44.2        | 2.0     |
| Treatment, day            | 267.77     | 20 | 280.89 | 87.9–133.5     | 47.2–81.8    | 31.8–61.2   | 0.4–9.2 |
| Coleoptera                | 83.47      | 3  | 287.87 | 9.5            | 4.5          | 4.4         | 0.5     |
| Treatment                 | 163.88     | 20 | 357.28 | 7.6–11.9       | 3.2–6.2      | 3.1–6.1     | 0.1–1.2 |
| Diptera                   | 157.93     | 3  | 390.15 | 10.23          | 6.58         | 4.79        | 0.27    |
| Treatment, day            | 268.56     | 20 | 456.53 | 8.62–12.14     | 5.31–8.14    | 3.90–6.37   | 0.09–0.78|
| Ephemeroptera             | 48.86      | 3  | 230.99 | 1.77           | 0.54         | 0.63        | 0.02    |
| Treatment, period         | 105.69     | 4  | 264.17 | 1.27–2.45      | 0.30–0.99    | 0.36–1.10   | 0.00–0.43|
| Hemiptera                 | 87.74      | 3  | 272.86 | 9.44           | 6.94         | 4.02        | 0.07    |
| Treatment, day            | 228.08     | 20 | 359.96 | 7.37–12.09     | 5.19–9.26    | 2.75–5.88   | 0.00–1.20|
| Hymenoptera               | 38.95      | 3  | 161.70 | 43.2           | 33.5         | 17.2        | 0.95    |
| Treatment, day            | 182.29     | 20 | 250.93 | 30.1–62.2      | 22.2–50.7    | 9.7–30.6    | 0.08–11.02|
| Isoptera                  | 9.06       | 3  | 65.69  | 1.01           | 0.37         | 2.71        | 0.01    |
| Treatment, day, period    | 194.88     | 21 | 137.27 | 0.25–3.99      | 0.03–3.59    | 1.17–6.28   | 0–110944|
| Lepidoptera               | 87.71      | 3  | 182.75 | 14.31          | 3.77         | 3.26        | 0.2     |
| Treatment, day, period    | 547.52     | 21 | 401.22 | 11.03–18.58    | 2.27–6.27    | 1.88–5.62   | 0.02–1.81|
| Orthoptera                | 81.24      | 4  | 320.94 | 1.73           | 1.98         | 1.34        | 0.05    |
| Treatment, period         | 57.63      | 3  | 327.68 | 1.25–2.38      | 1.47–2.67    | 0.93–1.93   | 0.01–0.32|
| Trichoptera               | 32.65      | 3  | 150.10 | 17.18          | 3.96         | 5.67        | 0.02    |
| Treatment, period         | 94.45      | 4  | 168.89 | 11.26–26.22    | 1.64–9.56    | 2.72–11.83  | 0.00–3882|

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temperate site (McMunn & Hernandez, 2018) and demonstrate that the use of partial night lighting may reduce impacts on a subset of the insect community, we were only able to sample four hours of the night, leaving a large portion of the nighttime unsampled. Tropical insects have high diversity and specificity of terrestrial assemblages – some species are strictly associated with one species of tree, for example (Erwin, 1982) – so it is likely that there are additional differences in insect activity that should be considered when designing lighting plans to mitigate impacts on insects.

Electric lighting at night brings advantages to workers as well as to local populations; however, it is essential that the benefits of light at night outweigh the risks, which include a reduction in ecosystem services provided by insects and an increased potential for disease transmission. The current study suggests one way to achieve this is to select spectra of light that minimise attraction of insect vectors to light. These same spectra will minimise attraction of flying insects in general, thereby reducing overall impacts on insect biodiversity. Therefore, we highly recommend that new infrastructure development projects introducing ALAN to light-naive forests (as well as other habitats) use filtered amber LED lamps (similar to CW9 lamps, 0% blue and 12% green light) in outdoor lighted areas. Filtered LED lamps are currently available commercially by a limited number of lighting companies, so incorporation of these lamps must be considered early in project planning. Because windows and screens may not be in use, indoor lighting should also be of low CCT (Longcore et al., 2015). We also recommend that operators develop a lighting plan for all areas to be illuminated (camps, wells, temporary construction areas, etc.) that includes the following considerations: turn off lights when not in use; put motion activators on lights so they turn on only when people are present; if lights must be kept on through the night, use dimmers to reduce brightness when people are not present. These recommendations are not only relevant for new infrastructure projects but should be used to retrofit existing infrastructure including roads and human settlements. In the future, monitoring studies should be carried out in this and other recently electrified areas to compare results and recommendations presented here and the realised impact of ALAN, including possible impacts of changes in insect composition and abundances on pollination services and how this may cascade to changes in forest composition.

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Authors’ Contributions

J.L.D., A.A. and T.L. conceived of the study. C.A.G. and J.M.A. collected the data. J.L.D., R.L.P. and T.L. analysed the data. J.L.D. and T.L. led manuscript writing. All authors contributed critically to the draft and gave final approval for publication.

Data Availability Statement

Data will be made available in FigShare upon publication.

Supporting information

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

Fig. S1 Arrangement of sampling sites (L01-L12) around the future pipeline route (in purple). CV1 = temporary field camp

References

Altermatt, F., Baumeyer, A. & Ebert, D. (2009) Experimental evidence for male biased flight-to-light behavior in two moth species. *Entomologia Experimentalis et Applicata*, **130**, 259–265.
Andrade-Núñez, M.J. & Aide, T.M. (2020) Using nighttime lights to assess infrastructure expansion within and around protected areas in South America. *Environmental Research Communications*, **2**, 021002.
Azam, C., Kerbiriou, C., Vernet, A., Julien, J.-F., Bas, Y., Plichard, L., Maratrat, J. & Le Viol, I. (2015) Is part-night lighting an effective measure to limit the impacts of artificial lighting on bats? *Global Change Biology*, **21**, 4333–4341.
Barghini, A. & de Medeiros, B.A.S. (2010) Artificial lighting as a vector attractant and cause of disease diffusion. *Environmental Health Perspectives*, **118**, 1503–1506.
Basset, Y., Mavoungou, J.F., Mikissa, J.B., Missa, O., Miller, S.E., Kitching, R.L. & Alonso, A. (2004) Discriminatory power of different arthropod data sets for the biological monitoring of anthropogenic disturbance in tropical forests. *Biodiversity & Conservation*, **13**, 709–732.
Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H. & White, J.-S.S. (2009) Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology & Evolution*, **24**, 127–135.
Boyes, D.H., Evans, D.M., Fox, R., Parsons, M.S. & Pocock, M.J.O. (2021) Is light pollution driving moth population declines? A review of causal mechanisms across the life cycle. *Insect Conservation and Diversity*, **14**, 167–187.
by the Chagas disease vector *Triatoma dimidiata*. *PLOS ONE, 7*, 521–535.

Pellegrini, L. & Tasciotti, L. (2016) The electrification-Malaria Nexus: the Case of Rural Uganda. *The European Journal of Development Research, 28*, 521–535.

Poiini, S., Dietrich, C., Barroso, A. & Costa-Leonardo, A. (2015) Effects of residential energy-saving lamps on the attraction of nocturnal insects. *Lighting Research & Technology, 47*, 338–348.

RStudio Team (2020) *RStudio: Integrated Development for R*. Boston, MA: RStudio, PBC. 10.1515/9781429846776. http://www.rstudio.com/.

R Core Team (2020) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. 10.1515/9781429846776. https://www.R-project.org/.

Ribeirão de Freitas, J., Bennie, J., Mantovani, W. & Gaston, K.J. (2017) Exposure of tropical ecosystems to artificial light at night: Brazil as a case study. *PLOS One, 12*, e0171655.

Robertson, B.A., Campbell, D.-R., Durovich, C., Hetterich, I., Les, J. & Horváth, G. (2017) The interface of ecological novelty and behavioral context in the formation of ecological traps. *Behavioral Ecology, 28*, 1166–1175.

Robinson, H.S. & Robinson, P.J.M. (1950) Some notes on the observed behaviour of Lepidoptera in flight in the vicinity of light-sources together with a description of a light-trap designed to take entomological samples. *Entomologist’s Gazette, 1*, 3–15.

Sivinski, J.M. (1998) Phototropism, bioluminescence, and the Diptera. *Florida Entomologist, 81*, 282–292.

Stork, N.E. (2007) World of insects. *Nature, 448*, 657–658.

Tasciotti, L. (2016) The electrification malaria nexus. *Travel Medicine and Infectious Disease, 14*, 281–282.

Tasciotti, L. (2017) Use of electricity and malaria occurrence: is there a link? The case of Malawi. *Energy Policy, 101*, 310–316.

van Langevelde, F., Ettema, J.A., Domers, M., WallisDeVries, M.F. & Groenendijk, D. (2011) Effect of spectral composition of artificial light on the attraction of moths. *Biological Conservation, 144*, 2274–2281.

Wakefield, A., Broyles, M., Stone, E.L., Harris, S. & Jones, G. (2018) Quantifying the attractiveness of broad-spectrum street lights to aerial nocturnal insects. *Journal of Applied Ecology, 55*, 714–722.

Wilson, R., Wakefield, A., Roberts, N. & Jones, G. (2021) Artificial light and biting flies: the parallel development of attractive light traps and unattractive domestic lights. *Parasites Vectors, 14*, 1–11.

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