Rewilding the night sky: Mitigating the costs of light pollution for bats and insects

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Abstract Altering the LED street lighting regime in Colter Bay, Grand Teton National Park from warm white to red, in short-term blocks (3-7 days per color) substantially reduces attraction of nocturnal arthropods but has little influence on bat space use. We recommend research on long-term application of this mitigation approach and investigation of lower intensity levels.

Introduction

Dramatic increases in light at night have altered nocturnal light levels across the planet (Falchi et al., 2016). Light pollution has changed the natural light regimes of ecosystems (Longcore and Rich, 2004) and has been shown to influence bird behavior (Russ et al., 2015), habitat use (McLaren et al., 2018), and physiology (Dominoni et al., 2013); sea turtle hatchling orientation (Truscott et al., 2017) and nest abundance (Brei et al., 2016); mammal reproductive timing (Le Tallec et al., 2016; Robert et al., 2015); and nighttime pollinator activity (Knop et al., 2017) among other effects (Gaston et al., 2017). Critically, few studies have aimed to develop mitigation techniques for wildlife habitat chronically exposed to artificial light. As the human footprint continues to grow, it is imperative that we fully understand the effects of light pollution and how these costs can be alleviated to conserve at-risk taxa (Dominoni and Nelson, 2018).

Insects provide valuable ecological services (i.e., pollination, crop pest removal, supporting terrestrial trophic webs; Losey and Vaughan, 2006; Scudder, 2017), many insects are strongly attracted to lights (Desouhant et al., 2019), and insects may suffer population declines from this attraction (Owens et al., 2019). Several factors are likely driving insect declines (habitat loss, climate change, and pesticides; Wagner, 2020) and recent evidence indicates that light pollution is likely an important causal agent (Owens et al., 2019). For example, nocturnal moths, attracted to artificial light, appear to be declining much more quickly than diurnal moths and butterflies, at the same locations (van Langevelde et al., 2018). The spectral characteristics of the light insects are exposed to influences the magnitude of their response, presenting a potential avenue for mitigation. Blue, short-wavelength light attracts more insects than lights with longer wavelength, such as yellow or red lights (van Langevelde et al., 2011; Wakefield et al., 2016). Research done in the Netherlands in which green, red, and white streetlights were placed in previously dark areas showed that fewer insects were captured under red lights than other light colors, effectively showing that red light can mitigate artificial light's impact on insects (Spoelstra et al., 2017).

Bats are inextricably linked to insects. Some species of insectivorous bats, particularly in Europe, have been shown to respond strongly to artificial lights (Rowse et al., 2016; Stone et al., 2012, 2015), either avoiding lit areas or opportunistically exploiting insects at lights (Rowse et al., 2016). In a unique study conducted in the Netherlands, some bats, like insects, exhibited activity levels closer to those seen at unlit sites when exposed to red streetlights compared to white or green (Spoelstra et al., 2017). Understanding light's effects on bats may prove to be crucial for bat conservation, as bat numbers across North America have fallen dramatically due to the white-nose syndrome epidemic sweeping across the continent. In 2012, it was estimated that between 5.7 million and 6.7 million bats had been killed by white-nose syndrome since its discovery in in 2006 (Coleman, 2012). The disease has since been confirmed in 33 US States and 7 Canadian provinces (White-nose Syndrome Response Team, 2020). Our knowledge of bat responses to artificial light, and mitigation techniques to encourage natural bat habitat use may be key to recovering bat populations across the continent.

Here we test two key mitigation strategies to rewild the night sky for insects and bats: light color and light intensity. Using proprietary LED luminaires containing both red and white LEDs that are dimmable, we conducted research in the largest visitor center in Grand Teton National Park, Colter Bay. Over two summer field seasons, we turned 32 streetlights from red to white in either 3-night blocks (2019) or 7-night blocks (2020). We monitored bats using both passive acoustic monitoring and telemetry while simultaneously tracking nocturnal insect abundance.

Methods

Study area

We conducted this work in the parking lot of Grand Teton National Park's largest visitor center, Colter Bay. This T-shaped parking lot is surrounded by dense coniferous forest and multiple buildings including the visitor center, the general store, and the marina office. While these buildings have some light sources including small high-pressure sodium, incandescent, and LED bulbs, the primary light source in the parking lot is an array of 32 pole-mounted streetlights. At three lit sites and four adjacent unlit (dark) sites throughout the Colter Bay area (Figure 1), we monitored bats and insects. We selected dark sites with similar habitat characteristics to lit sites - dense forest surrounding clearings of both paved and natural substrates.

An experimental lightscape

In 2019, we replaced the existing 32 streetlights in the Colter Bay parking lot (previously a mixture of high-pressure sodium vapor lamps and ~4000K white LEDs) with proprietary LED luminaires. These luminaires project a nearly pure red light (Signify Fortimo ClearField™) in addition to a ~3400 Kelvin white light, and have wireless controls (Nedap Luxon™) that enable dimming and switching between the two light sources. Throughout the summers of 2019 and 2020, we experimentally manipulated the Colter Bay lightscape from red to white in either 3-night blocks (2019) or 7-night blocks (2020) while altering the brightness of the lights every six nights during the 2019 field season. After examining preliminary analyses of the 2019 dataset, we concluded that there may be a latency in bat responses to treatment changes (i.e., bats may continue to exhibit behavior associated with the previous treatment into the next treatment period), and that light brightness range we presented had no to little effect on bat or insect activity. Thus, we extended the treatment periods in 2020 to 7 days and maintained a constant luminaire brightness (95% of maximum wattage).

Bat monitoring

We monitored bat activity at our 7 sites using ultrasonic acoustic recording units (Wildlife Acoustics SM4BAT) that we mounted on ten-foot lengths of ½" EMT conduit, placed in the center of natural clearings or parking lots, and oriented microphones toward the center of the open space. We programmed units to record bat echolocation from 30 minutes before sunset until sunrise. In 2019, we also monitored bat habitat use with radio telemetry. We used mist nets to capture bats and fitted males and non-pregnant/non-lactating females (48 *Myotis lucifugus* in total) with

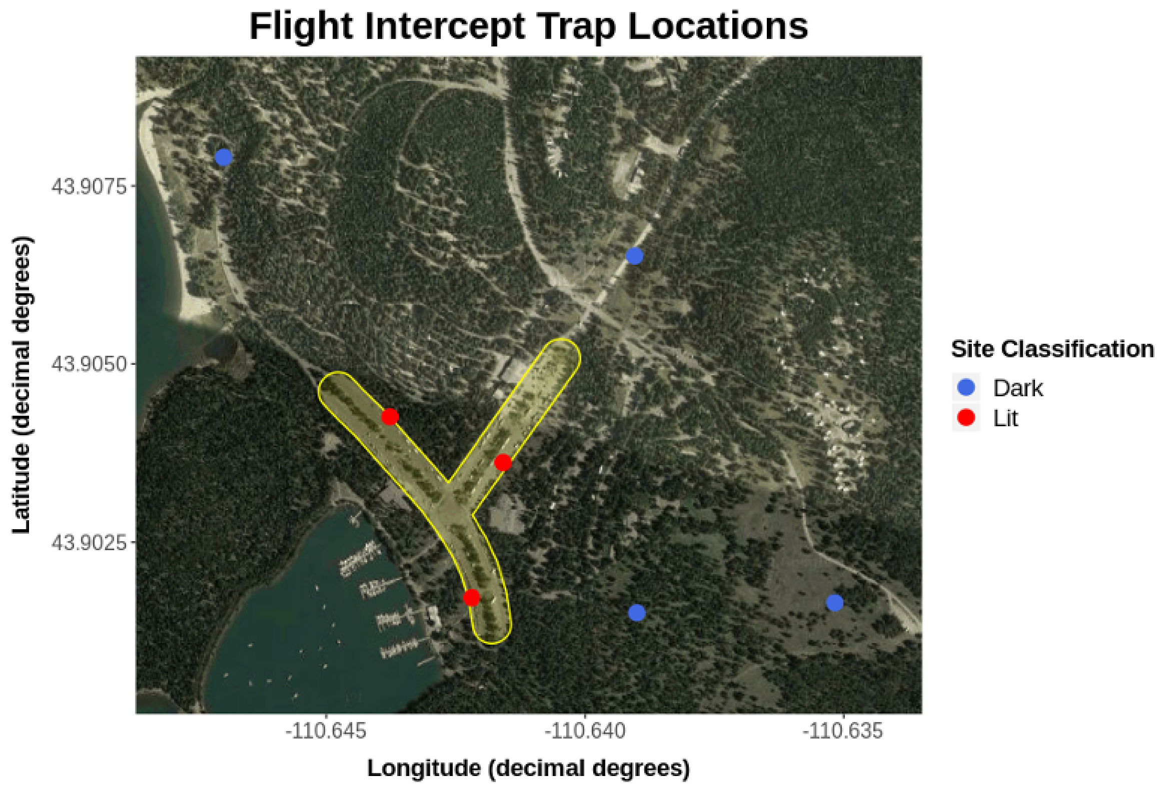

Figure 1. Bat and insect monitoring site locations in Colter Bay, Grand Teton National Park, WY.

radiotags (Lotek coded Nanotags; signaling interval: 5 sec). At each of our seven monitoring sites we deployed a Lotek SRX-800 paired with a four-element Yagi antenna. Any time a tagged bat passed close enough to a telemetry logger and antenna, its presence was logged with an associated date and time.

Insect monitoring

We monitored insects in 2019 and 2020. In 2019, we deployed a flight-intercept trap (2' plastic veins; collection container with dry poison, No-pest® Strip2) at each site, nightly (Figure 2). At lit sites, we suspended traps directly below streetlights using a pulley and cord, and at dark sites we suspended traps between trees (10+ m apart) using cord. As this approach collected few insects (with the exception of Diptera) we used UV bucket traps (BioQuip) in 2020. We deployed UV bucket traps with dry poison for 3 consecutive nights (nights 4-6 of each block) at each site. Each trap was paired with a timer switch that turned the UV light on for 2 hours, starting 30 minutes after sunset.

Data preparation

Following data collection, we processed all acoustic recordings with SonoBat 4.3.0 using the Sonobat Western Wyoming call library. We used an acceptable call quality value of 0.80, a sequence decision threshold of 0.90, and a maximum of 32 calls to consider per call sequence. We aggregated the resultant tabulations of species identifications by site-night for each species. Similarly, we aggregated all telemetry detections by site-night and tag ID. All insects composing insect samples were identified to Order.

Analysis

The entirety of our analytical process was carried out using the statistical program R (R Core Team, 2020). Our analytical framework followed the protocol outlined in the EcoCountHelper R package (Cole et al.,

Figure 2. Flight intercept trap design. Traps consisted of two 24”x18” acrylic sheets cut half way up their longitudinal axis and slid together, a wooden top support, and a tarp funnel below with a collection container. Collection containers were filled with cut pieces of No-pest® Strip2.

2022). This framework (outlined below) was executed for each species of bat detected using acoustic monitoring, aggregated telemetry detections, and each insect Order present in insect samples.

We first determined a general conditional model structure that would be used to build models for a given data set (acoustic recordings, telemetry, or insect sampling). We also constructed a general zero-inflated formula to be used in the model selection process. Following our determination of general conditional model structure and zero-inflated formula structure, we constructed multiple models for each taxonomic group using all combinations of frequently used count-data error-distribution families (negative-binomial with a linear parameterization, negative-binomial with a quadratic parameterization, and Poisson) and zero-inflation formula presence (zero-inflated formula included or not). AIC values were generated for each of the resultant models, and mean-variance plots were generated for each group-level and error-distribution family combination. AIC values and mean-variance plots were corroborated to determine the most appropriate error distribution for each taxonomic group. It was determined *a priori* that, in the case of any conflicts between AIC values and mean-variance plots, the model using the best error-distribution family as suggested by the mean-variance plots would be selected. Following taxonomic-group-level model selection, we examined residual diagnostic plots to check for goodness-of-fit via residual dispersion, outliers, and uniformity. At this point we also checked VIF values for each model to ensure that there were no instances of multicollinearity. In total, we constructed models for four data sets: acoustic monitoring data, telemetry data, flight-intercept trap data, and UV-bucket trap data. The general conditional model structure for all candidate models is shown below:

Acoustic monitoring

Calls/Night = Ordinal Date + Year + Moon Illumination + Site Classification + Light Color + Light Brightness + Latency Days + Site Classification:Light Color + Light Brightness:Light Color + Site Classification:Light Color:Latency Days + (1|Site)

Telemetry

Detections/Night = Ordinal Date + Moon Illumination + Site Classification + Light Color + Latency Days + Site Classification:Light Color + Site Classification:Light Color:Latency Days + (1|Site) + (1|Tag ID)

Flight-intercept traps

Arthropods/Night = Ordinal Date + Year + Moon Illumination + Site Classification + Light Color + Light Brightness + Latency Days + Site Classification:Light Color + Light Brightness:Light Color + Site Classification:Light Color:Latency Days + (1|Site)

UV-bucket traps

Arthropods/Night = Ordinal Date + Moon Illumination + Site Classification + Light Color + Site Classification:Light Color + (1|Site)

Models including zero-inflated formulas had the same general structure as shown below.

Acoustic monitoring

Calls/Night = Ordinal Date + Site

Telemetry

Detections/Night = Ordinal Date + Bat ID + Site

Flight intercept traps & UV bucket traps

Arthropods/Night = Ordinal Date + Site

Preliminary results

Bat acoustic monitoring

For the 6 species of bats for which we created candidate models (*Eptesicus fuscus*, *Lasiurus cinereus*, *Lasionycteris noctivagans*, *Myotis evotis*, *Myotis lucifugus*, and *Myotis volans*), there were no conflicts between AIC values and error-distribution plots. All top models were zero-inflated and implemented a quadratic error distribution excluding the top *M. volans* model which implemented linear error distribution. Residual diagnostic plots showed exceptional model fit with regards to dispersion, outliers, and uniformity. All models had low VIF values, with the highest VIF being 3.97.

All modelled species (Figure 3), excluding *E. fuscus*, exhibited significantly different activity levels between dark and lit sites when not considering light color, with *L. cinereus*, *L. noctivagans*, and *M. lucifugus* showing increased activity in lit areas, and *M. evotis* and *M. volans* showing decreased activity in lit areas. Additionally, 95% confidence intervals for predicted activity in both dark and lit areas during red light treatments overlapped for both *L. cinereus* and *L. noctivagans*. Model results for both *E. fuscus* and *M. lucifugus* contained a significant and negative interaction term for site classification and light color treatment, indicating a decreased difference in activity levels between dark and lit areas during white lighting, and not red lighting, treatments for these species. Only *L. cinereus* exhibited a significant response to light intensity, with species-level activity increasing with light intensity irrespective of site classification.

Bat telemetry

When corroborating the AIC values and error-distribution plots for *M. lucifugus* candidate models from radio tag data, we observed conflicting results and selected the model implementing a quadratic negative-binomial error distribution and omitting a zero-inflated formula as suggested by AIC values. Residual diagnostic plots indicated good model fit with regards to dispersion, outliers, and uniformity. All model parameters exhibited low VIFs, with the highest VIF being 2.38.

As was also shown in passive acoustic monitoring model results, 48 radiotagged *M. lucifugus* individuals showed increased activity levels in lit areas compared to dark areas irrespective of light color (Figure 4). Model results for radiotagged *M. lucifugus* individuals also showed a negative and significant interaction term for site classification and color, indicating that disparities in *M. lucifugus* activity between dark and lit sites are lessened under white light.

Insects: Flight-intercept traps

There were no conflicts between AIC values and the error distribution plots for any of the four arthropod Orders we constructed candidate models for (Figure 5), with both model selection methods suggesting that a Poisson error distribution best fit Araneae and Coleoptera data, and a quadratic error distribution best fit Diptera and Hemiptera data. Additionally, AIC results suggested that zero inflated models best fit the Coleoptera data. All residual diagnostic plots suggested adequate goodness of fit. Two terms in the Hemiptera model, light color and the interaction between site classification and color, had moderate VIFs ($>$5), while all other models had no VIFs greater than 4.41.

Model results for Dipterans and Hemipterans indicate that these Orders are more active in lit areas compared to dark areas irrespective of lighting treatment. Additionally, our Diptera model showed a positive and significant interaction between site classi-

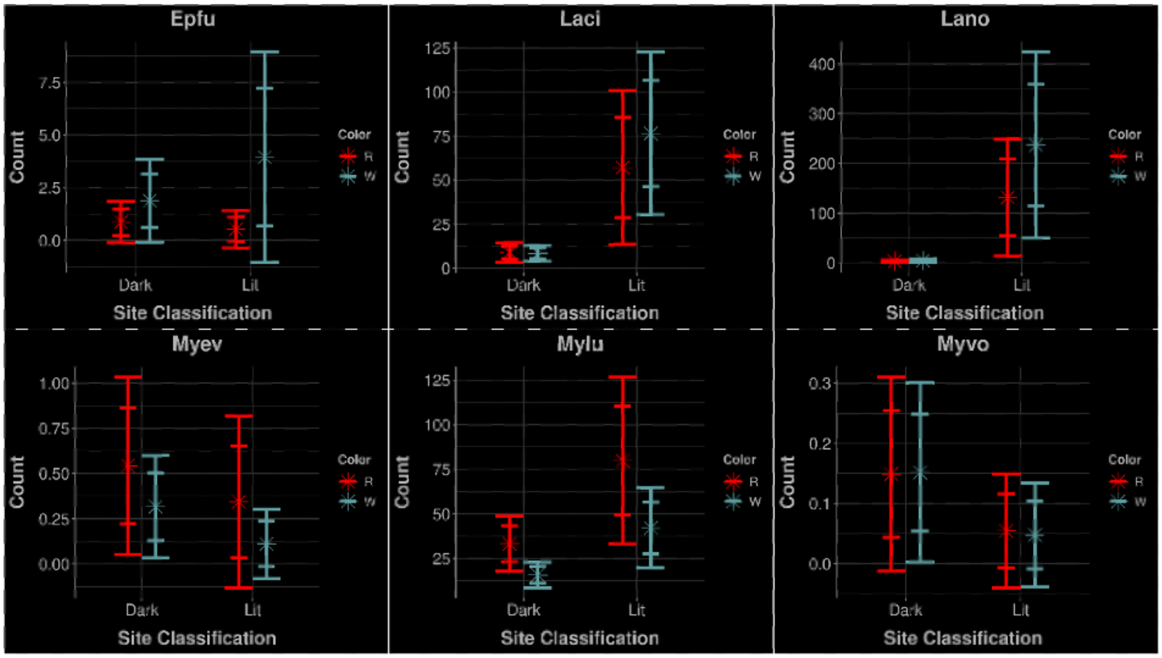

Figure 3. Passive acoustic monitoring prediction plot. All model parameters were held at their median values except light color and site classification, and model-based predictions were made for all combinations of light color and site classification. Inner and outer error bars represent 80% and 95% confidence intervals, respectively.

fication and light color, indicating that disparities in activity between dark and lit areas are exacerbated under white light conditions compared to red light conditions. Model predictions with varying lighting conditions and site classifications showed overlapping 95% confidence intervals for Dipterans under red lighting conditions but non-overlapping 95% confidence intervals under white lighting conditions, effectively indicating that Dipterans exhibit more natural behavior under red lighting conditions.

Insects: UV-bucket traps

There were no conflicts between AIC values and the error distribution plots for any of the eight arthropod Orders for which we constructed models (Acari, Coleoptera, Diptera, Ephemeroptera, Hemiptera, Hymenoptera, Lepidoptera, and Tricoptera; Figure 6). All top models implemented glmmTMB's quadratic error distribution aside from the top Hymenoptera model which used a linear error distribution. Additionally, AIC values suggested that zero-inflated negative-binomial models best fit the Acari and Ephemeroptera data. All residual diagnostic plots suggested adequate goodness of fit. No model terms had a VIF greater than 4.54.

For all Orders modelled, white light led to higher nightly counts than red lighting conditions. Coleoptera and Trichoptera also showed higher counts in lit areas irrespective of lighting treatment. Only Diptera and Hemiptera models exhibited a significant interaction between site classification and light color treatment with Diptera showing a smaller difference between dark and lit site counts under white light conditions in comparison to red light, and Hemiptera showing a larger difference between dark and lit site counts under white light conditions in comparison to red light. Model predictions holding all predictor values constant at their medians and varying both lighting treatment and site classification showed decreased counts at lit sites during red lighting treatments compared to white lighting treatments for Hemipterans, Hymenopterans, Lepidopterans, and Trichopterans. These predictions also showed no difference in counts between dark and lit sites during red light treatments for Acari, Coleopterans, Dipterans, Ephemeropterans, Hemipterans,

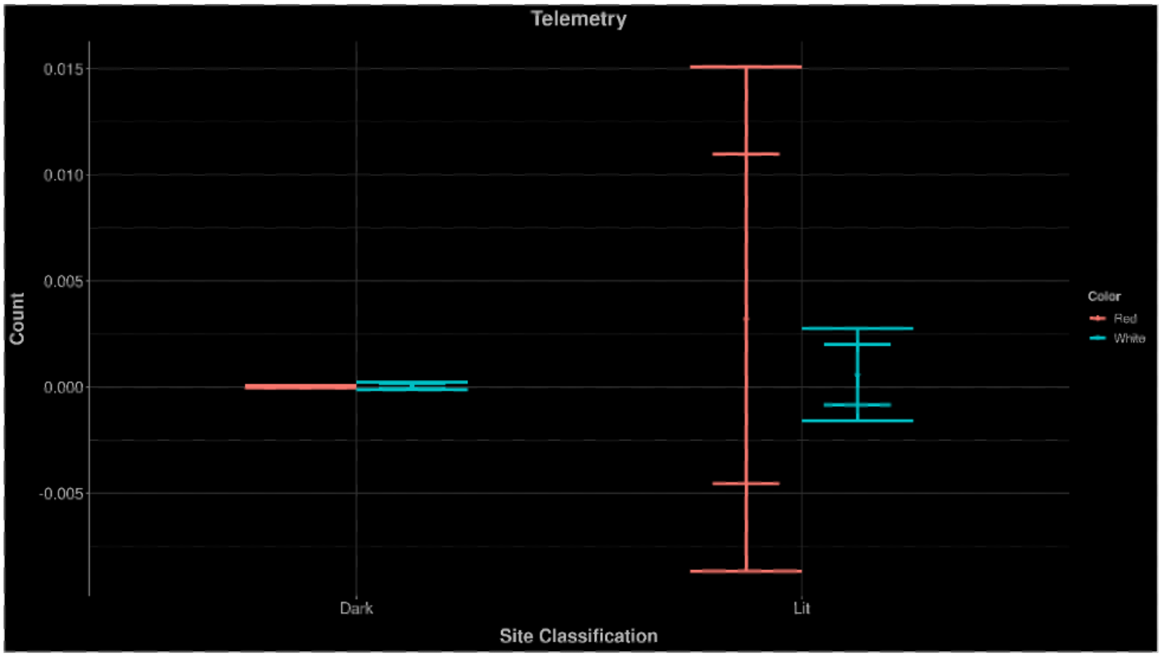

Figure 4. Telemetry prediction plot. All model parameters were held at their median values except light color and site classification, and model-based predictions were made for all combinations of light color and site classification. Inner and outer error bars represent 80% and 95% confidence intervals, respectively.

Hymenopterans, and Lepidopterans.

Conclusions

Our findings show strong evidence for the short-term (3-7 days) application of red light being an effective mitigation technique for reducing artificial light's impacts on nocturnal arthropods, and limited evidence for red light's efficacy as a mitigation technique for bats. Our results for UV bucket traps indicate that red lights not only provide reduced arthropod attraction to light fixtures, but also that red lit areas have similar activity levels to dark areas. Our flight intercept trap results are less supportive of red light's efficacy as a mitigation technique, however there are multiple caveats pertaining to these results that inform the implications of our findings. While deploying flight intercept traps, we observed a strong effect of wind on trap movement. Even slight breezes caused the traps to spin at a high speed, which likely increased the trap's detectability to aerial arthropods, perhaps contributing to the cause of problematically low sample resolutions (individuals per site-night) for all Orders but Diptera included in this analysis.

Additionally, while our flight intercept trap results suggest that red light may be an effective mitigation technique for Diptera, our UV bucket trap results do not show any strong evidence for red light reducing the impacts of artificial light on nocturnal arthropods. This difference in results may be driven by a discrepancy in the spatial scale of response measurement in combination with potential implications of Dipteran physiology. While flight intercept traps were hung from light fixtures, effectively sampling insects that were in the immediate vicinity of a single light, bucket traps were placed in the median of the parking lot (or center of a site) and sampled individuals that were within the entirety of the lit area. Relevantly, recent research indicates that *Drosophila* photoreceptors are more sensitive to long-wavelength red light than previously assumed (Sharkey et al., 2020).

These results suggest that, for many arthropod Orders, the use of red lights in lieu of more traditionally used light colors may be an effective means of mitigating potential negative effects of insect attraction to artificial light (Owens and Lewis, 2018). Given trends of declining arthropod populations globally (Sánchez-

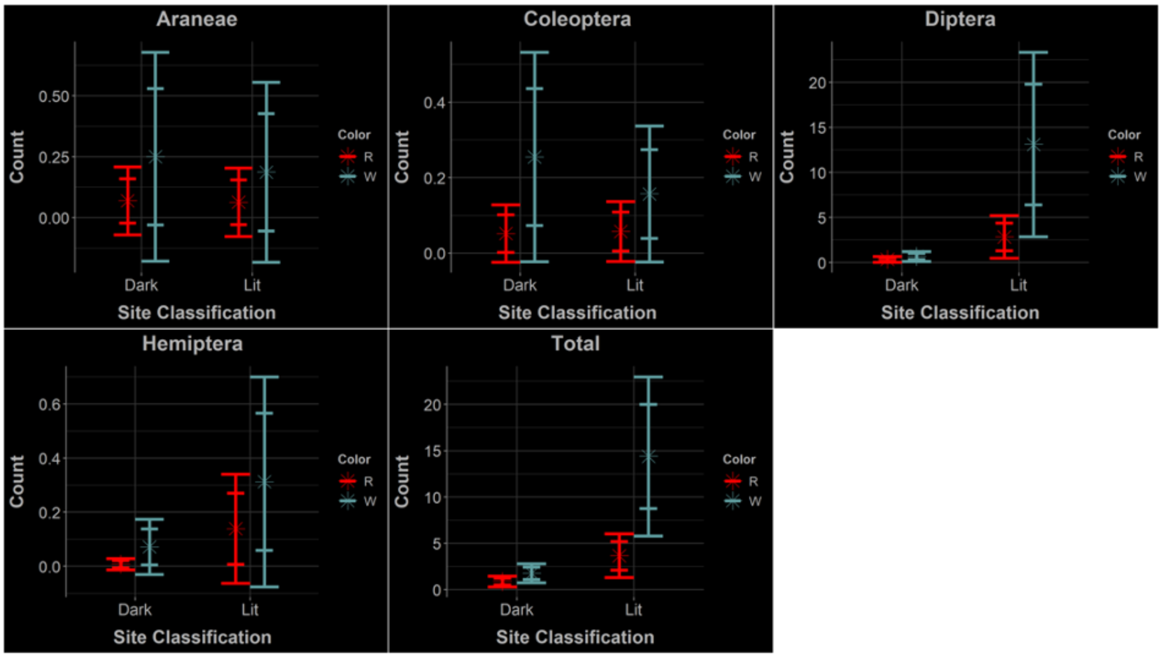

Figure 5. Flight intercept trap prediction plots. All model parameters were held at their median values except light color and site classification, and model-based predictions were made for all combinations of light color and site classification. Inner and outer error bars represent 80% and 95% confidence intervals, respectively.

Bayo and Wyckhuys, 2019) and their importance to socioecological systems (Losey and Vaughan, 2006), taking action to reduce artificial light's impacts on arthropod populations through implementation of red is prudent.

In contrast to our finding surrounding arthropods, we found little evidence of red light being an effective means of mitigating artificial light's influence on the bats of Grand Teton, with only one species (*L. cinereus*) showing similar activity at both dark and lit sites during red light treatments. It is critical to place these results in context: our experimental design presented red light in short term blocks (3- and 7-day), time intervals that may not have been extensive enough for these long-lived animals to learn new hunting behaviors. Further, we were altering the lighting regime in a parking lot (Colter Bay) that has been lit for decades and the high site fidelity of bats may have been further resistance against a change to their foraging patterns. While our results deviate from those of Spoelstra et al. (2017), these workers applied red light to previous dark areas for 5 years and found substantial re-structuring of the bat community.

Reducing light intensity also appeared to be an ineffective means of mitigating artificial light's impacts on bats, again with the important caveat of the short-term light application in our experiment. Only *L. cinereus* showing a significantly positive relationship with light intensity. Despite our largely negative findings surrounding decreased light intensity as a light pollution mitigation technique for bats, the presence of any artificial light within the range of intensities that we implemented significantly impacted activity for five of the six bat species for which we constructed models. Our findings highlight that further research is necessary to identify lighting practices that reduce light pollution's impacts on bats.

Future work

Our results should be expanded upon in future research to better our understanding of the long-term effects of artificial light mitigation efforts. Due to our limited number of sample sites and the constraints of working in a National Park, our treatment periods

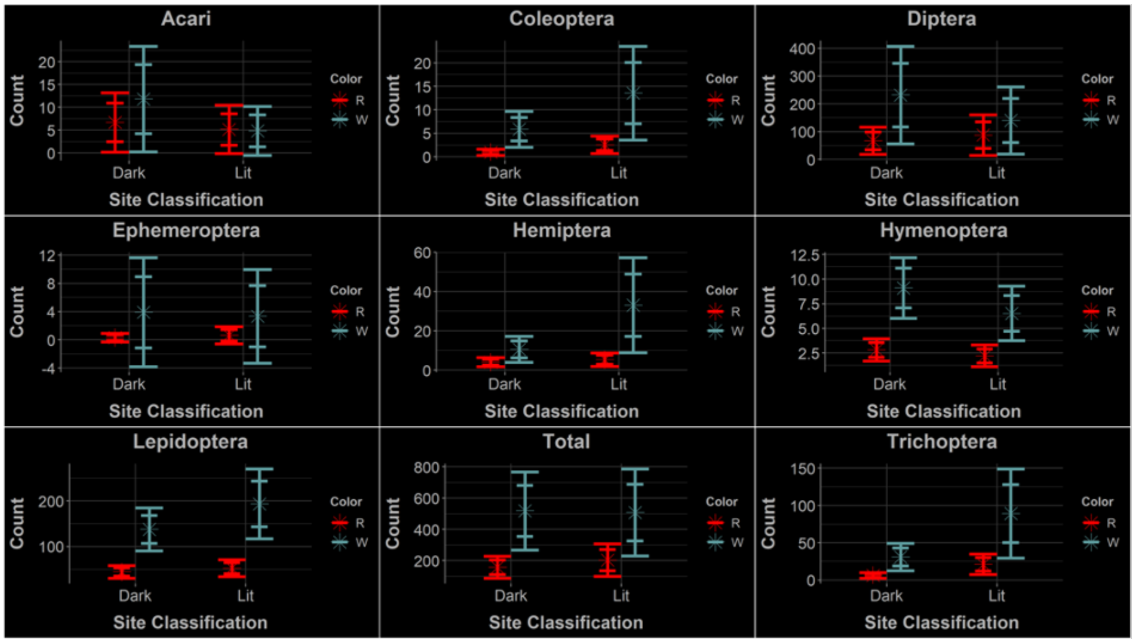

Figure 6. UV bucket trap prediction plots. All model parameters were held at their median values except light color and site classification, and model-based predictions were made for all combinations of light color and site classification. Inner and outer error bars represent 80% and 95% confidence intervals, respectively.

were necessarily short term (3 days in 2019, and 7 days in 2020). Seven days does not give bat (and perhaps even some arthropod) populations sufficient time to respond, and therefore our research cannot address the long-term effects of a permanent change from white streetlights to red streetlights. Future work surrounding red light as a mitigation technique should aim to quantify long-term responses associated with a change in light color. In addition, future research should explore lower light intensity levels than we tested here.

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