Artificial Light at Night(ALAN): Impacts on Carabid Beetle Movement

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ABSTRACT

Geophysical cycles of light and darkness have remained constant for all of life's evolutionary history. Correspondingly, mechanisms for perceiving and responding to light are ubiquitous in nature. In the past few centuries, Artificial light at night(ALAN) has acted as a novel environmental change across much of the earth's surface, with disruptive effects from the molecular to community levels that are just starting to be uncovered. Particularly sensitive to light are nocturnal insects with supposition eye structures that can perceive extremely low levels of light. In this study, I conducted laboratory experiments to test how two species of Carabid beetles respond to ALAN in terms of their activity output when under a stimulated light-dark cycle. Beetles under ALAN experienced continuous lighting over a 24-hour period, while those treated with a control experienced a natural cycle with darkness during the nighttime hours. In *Pterostichs californicus*, I found that ALAN increases the frequency of nighttime activity events, with a significant effect in females but not males. I found no significant effects of ALAN on the duration and frequency of *Calathus ruficollis*. These results show that ALAN can alter movement behaviors, with certain species and sexes more sensitive to changes. Management practices that reduce the extent, intensity, and spectra of ALAN are likely to be effective means of reducing the disruptive effects of ALAN on beetles and other affected species.

KEYWORDS

light pollution, portable locomotion activity monitor(pLAM), photosensitivity, raspberry pi, movement

INTRODUCTION

For four billion years, life on Earth has evolved under consistent cycles of light and darkness as determined by daily, annual, and lunar cycles governed by the sun(Gaston et al. 2014). Because of its reliability as an environmental cue, nearly all living things possess mechanisms for perceiving and responding to light, with timekeeping acting as a sort of 'sixth' sense(Kumar 2017). Over the past few centuries, the invention and expansion of electric lighting have dramatically altered the nighttime environment across much of the earth's surface, with many places deprived of dark nights(Longcore and Rich 2004). Artificial light at night(ALAN) presents one of the fastest-growing global changes, with lit area and brightness each expanding at a rate of 2.2% per year (Kyba et al. 2017). Unlike other anthropogenic changes (e.g. temperature, atmospheric CO2) which have historical analogs, ALAN presents an entirely unprecedented challenge for life on Earth. The effects of ALAN are expected to be widespread across nearly all levels of biological organization and ecosystem types (Swaddle et al. 2015).

A growing body of research characterizing the impacts of ALAN has developed over the past few centuries, with studies showing effects that span from the molecular to community levels and across wide taxonomic groups. Some of the key findings include the disruption and alteration of clock gene expression(Honnen et al. 2019, Chen et al. 2021, Levy et al. 2022), physiological processes(Brüning et al. 2011, Abiusi et al. 2014), behavior(van Geffen et al. 2015, Thompson et al. 2019), the timing of life history events(van Geffen et al. 2014, Robert et al. 2015, Smith et al. 2021), community composition(Hölker et al. 2015, Davies et al. 2017) and species interactions(Frank 2009, Shivanna 2022). Effected taxa span from bacteria to primary producers, arthropods, birds, mammals, fish, and more. Some species exhibit responses that are maladaptive, such as a moth's fatal attraction to light, while others experience shifts that increase their fitness(Haynes and Robertson 2021).

Of particular concern is the effect that ALAN may be having on insects, which are experiencing striking population declines from a combination of anthropogenic sources (Owens et al. 2020, Boyes et al. 2021). Over sixty percent of insects are nocturnal, occupying temporal niches with light intensities up to eleven magnitudes lower than daytime levels (Tierney et al. 2017). Key to the success of many nocturnal species amidst low levels of light is their supposition compound eye structure, which allows hundreds of facet lenses to trigger a single photoreceptor, allowing light to be detected at extremely low levels(Warrant 2017). Coleoptera is largely nocturnal, with evidence of early transitions to dim environments. Dung beetles have been shown to have highly refined temporal niche partitioning, even within diurnal, crepuscular, and nocturnal periods(Tocco et al. 2021). Despite all this, the impacts of ALAN on beetle behavior have not been well described.

The aim of my study was to characterize how artificial light at night affects the activity of two nocturnal Carabid beetles. I asked whether ALAN impacts *Pterosichus californicus* and *Calathus ruficollis* in terms of the (1) duration and (2) frequency of activity and whether these effects were (3) sex-specific. I defined duration as the sum of time an individual spent actively moving and hypothesized that those under ALAN beetles would engage in a shorter duration of activity. I defined frequency as the number of unique activity events an individual started and stopped and hypothesized that ALAN would decrease the number of activities. My rationale behind these hypotheses was that light might throw off their endogenous clocks by communicating that it is the wrong time of day, signaling them to shift behaviors. Such shifts in activity levels could have impacts on an individual's ability to mate, forage, and migrate which could have individual fitness effects and could scale up to higher levels in the ecosystem.

METHODS

To test how artificial light at night impacts beetle activity, I ran controlled laboratory experiments on two species of ground beetle, *Pterostichus californicus* and *Calathus ruficollis*. They were treated with 24-hour light-dark cycles, with the treatment group experiencing dim warm white light, and the control receiving darkness during the nighttime period.

Study species

P. californichus and *C. ruficollis* were collected from the University of California, Berkeley campus in early March. Both species are predatory and nocturnal, belonging to the family Carabidae. I had them separated by species and sex and maintained in a refrigerator before starting experiments.

Experimental setup

I built two experimental boxes of dimensions 15in x 15in x 15in out of cardboard and corrugated plastic sheets. I configured two motion-detecting cameras using raspberry pi 3s, Arducam Day-Night Cameras, and open source code (Sondhi et al. 2022, Yash Sondhi 2022). I attached the cameras to box lids, with the lenses facing downward at a height of 15in(Figure 1a). I then soldered Adafruit Neopixel RGBW LED Strips into groups of three and arranged them in a ring at the top of each box for eighteen neopixels per box. I set the lights as a “warm white” (RGBW: 255,128,15,0), varying intensities depending on the time of day. I turned the lights on and off using the raspberry pi3. I diffused light using angled plastic directed towards the top of the box. I individually housed beetles in closed plastic containers with a damp paper towel(Figure 1c).

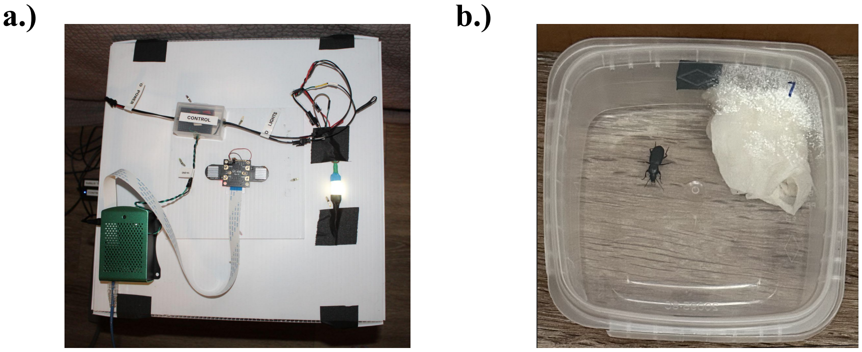

Figure 1. Experimental setup. (a) angle of the top of experimental box with the camera and LED lights attached to raspberry pi3. (b) Individually housed beetle with a damp paper towel.

Running experiments

I ran overnight experiments starting on April 13th and April 18th for *P. californicus* and *C. ruficollis*, respectively. I randomly assigned four males and four females to each treatment, for a total of eight beetles per treatment. I entrained them for 24 hours with the light-dark cycle assigned to the control before giving each treatment their unique light-dark cycle. Both the ALAN treatment and control received high-intensity light during the day between sunrise and sunset and moderate-intensity light for thirty minutes between sunset and night. During the night, I exposed the ALAN treatment to low-intensity light, while the control had lights turned off. After the experiments were done, I viewed the videos captured and recorded which individuals were moving, how long they were moving, and when they were moving. I chose three-hour periods during the day and during the night to compare. The daytime period I selected was from 16:00-19:00 and the nighttime period was from 00:00-03:00.

Data Analysis

I tested if my data fit assumptions of normality with Shipero-Wilk tests and quantile-quantile plots. I used ANOVA for *P. californicus* data and obtained p-values from Dunn-Bonferroni tests. For *C. ruficollis* data, I used Kruskow Wallace tests and obtained p-values with Dunn-Bonferroni tests.

RESULTS

Pterostichus californicus

Duration

P. californicus beetles treated with ALAN were active for an average duration of 107.13 seconds during the day period and 3528 seconds during the night period. Beetles treated with the control were active for an average duration of 339.5 seconds during the day period and 3951 seconds during the night period. I found no significant differences in duration of activity across ALAN and control treatments for the day period or the night period(Figure 2). I did find significant differences in the duration of activity across day and night of the ALAN treatment, with average nighttime activity over 30x greater than daytime activity(Figure 2). The control treatment likewise was significantly different between day and night durations of activity, with the average duration of nighttime activity being over 11x greater than the average daytime duration of activity(Table 1).

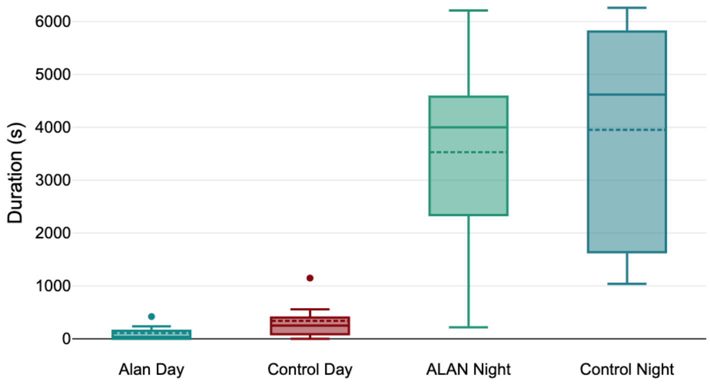

Figure 2. Duration of activity under ALAN and control in *P. californicus.* Box-and-whisker plots, with boxes representing interquartile ranges and whiskers representing the data points within 1.5x of the interquartile range. Male and female beetles exposed to ALAN(N)=8, Control(N)=8 for 24 hour light-dark cycles. Significant differences observed between ALAN day and ALAN night(P< .001) and between control day and control night(P< .001).

Frequency

Beetles treated with ALAN were active for an average of 7.63 activity events during the day period and 73.88 activity events during the night period. Beetles treated with the control were active for an average of 17.5 activity events during the day period and 34.5 activity events during the night period. There were no significant differences in the frequency of activity events across ALAN and control treatments for the day period, but there were significant differences across the night period(Figure 3, Table 1). There were significant differences in the frequency of activity across day and night of the ALAN treatment, with the average number of activities during the night almost 10x greater than during the daytime(Figure 3, Table 1). Differences in the control treatment were non-significant across day and night(Figure 3).

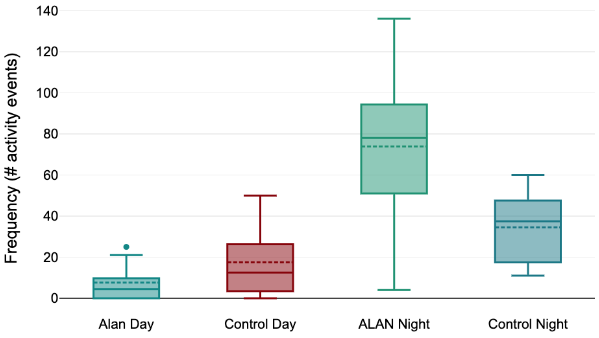

Figure 3. Frequency of activity under ALAN and control in *P. californicus.* Box-and-whisker plots, with boxes representing interquartile ranges and whiskers representing the data points within 1.5x of the interquartile range. Beetles exposed to ALAN(N)=8, Control(N)=8 for 24 hour light-dark cycles. Significant differences observed between ALAN day and ALAN night(P< .001).

Sex

Female Data. Female duration in *P. californicus* is significant across day and night for both ALAN and the control, with the duration of activity greater during the night period for both.(Figure 4a). There are nonsignificant differences between the duration of the treatments for day and for night(Table 1, Figure 4a). Frequency is significant between day and night for the ALAN treatment, but not the control(Figure 4b). ALAN frequency is significantly higher for the nighttime than the control during the night(Figure 4b, Table 1).

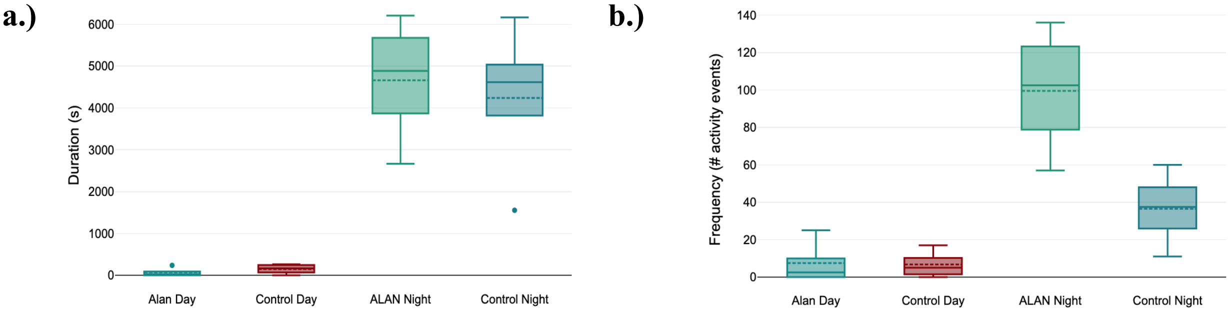

Figure 4. Female duration and frequency under ALAN and control in *P. californicus.* Box-and-whisker plots for: (a) duration of activity, and (b) frequency of activity. Boxes represent interquartile ranges and whiskers represent the data points within 1.5x of the interquartile range. For (a), N(ALAN)=4, N(Control)=4. Significant differences observed between ALAN day and ALAN night(P< .05) and between control day

and control night (P<.05).For (b), N(ALAN)=4, N(Control)=4. Significant differences exist between ALAN night and Control night(P< .05) and ALAN day and ALAN night (P<.001).

Male data. For male *P. californicus*, duration is nonsignificant across all treatments and time periods (Figure 5a) Frequency likewise exhibits nonsignificant differences between all treatments and time periods(Figure 5b).

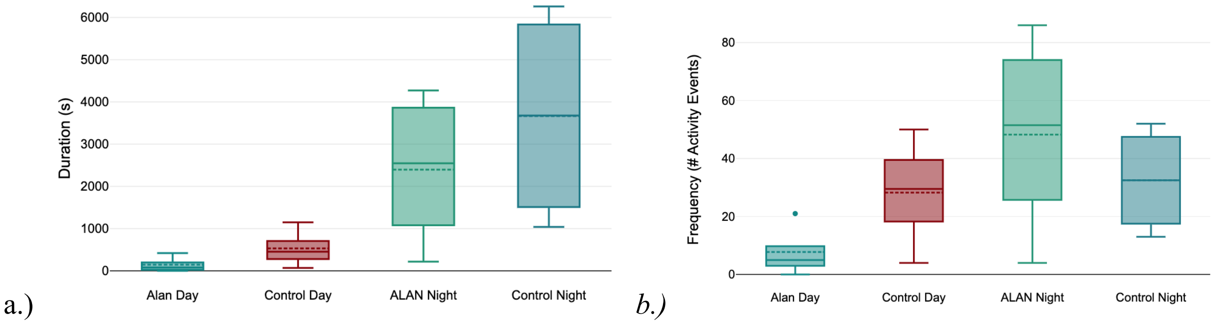

Figure 5. Male duration and frequency under ALAN and control in *P. californicus.* Box-and-whisker plots for: (a) duration of activity, and (b) frequency of activity. Boxes represent interquartile ranges and whiskers represent the data points within 1.5x of the interquartile range. For (a), N(ALAN)=4, N(Control)=4. No significant differences were observed. For (b), N(ALAN)=4, N(Control)=4. No significant differences were observed.

Calathus ruficollis

Duration

C. ruficollis beetles treated with ALAN were active for an average duration of 37.88 seconds during the day period and 7.88 seconds during the night period. Beetles treated with the control were active for an average duration of 20.63 seconds during the day period and 31.25 seconds during the night period. I found no significant differences in the duration of activity across ALAN and control treatments for the day period or the night period (Table 1, Figure 6). There were also no differences within treatments across day and night for both ALAN and the control.

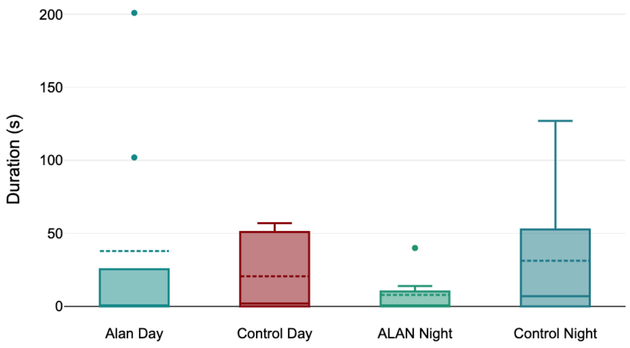

Figure 6. Duration of activity under ALAN and control in *C. ruficollis.* Box-and-whisker plots, with boxes representing interquartile ranges and whiskers representing the data points within 1.5x of the interquartile range. Male and female beetles exposed to ALAN(N)=8, Control(N)=8 for 24 hour light-dark cycles. Significant differences between ALAN night and control night durations (P< .1).

Frequency

C. ruficollis beetles treated with ALAN were active for an average of 3.38 activity events during the day period and 1.88 activity events during the night period. Beetles treated with the control were active for an average of 3.25 activity events during the day period and 8.13 activity events during the night period. There were no significant differences in the frequency of activity events across ALAN and control treatments for the day period or the night period(Table 1, Figure 7).

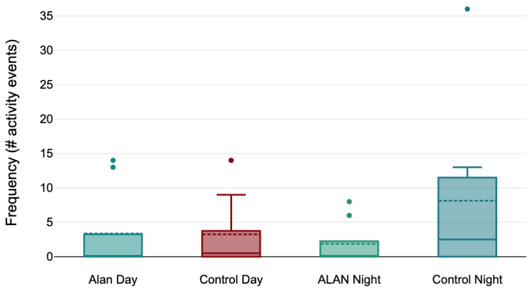

Figure 7. Frequency of activity under ALAN and control in *C. ruficollis.* Box-and-whisker plots, with boxes representing interquartile ranges and whiskers representing the data points within 1.5x of the interquartile range. Male and female beetles exposed to ALAN(N)=8, Control(N)=8 for 24 hour light-dark cycles. No statistically significant differences were observed.

Sex:

Female Data. There are no significant differences in the duration or frequency of female C. ruficollis activity events between day and night or treatment type(Figure 8ab, Table 1).

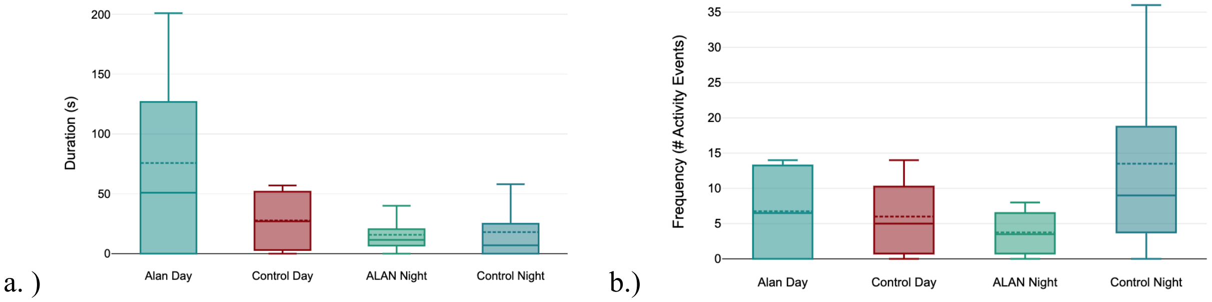

Figure 8. Female duration and frequency under ALAN and control in *C. ruficollis.* Box-and-whisker plots for: (a) duration of activity, and (b) frequency of activity. Boxes represent interquartile ranges and whiskers represent the data points within 1.5x of the interquartile range. For (a), N(ALAN)=4, N(Control)=4. No significant differences observed. For (b), N(ALAN)=4, N(Control)=4. No significant differences were observed.

Male Data. There are no significant differences in the duration or frequency of male *C. ruficollis* activity events between day and night or treatment type(Figure 9ab, Table 1).

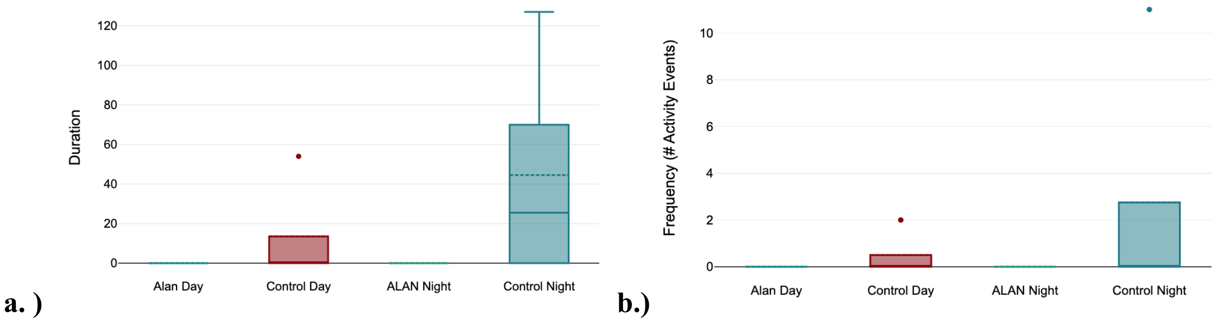

Figure 9. Male duration and frequency under ALAN and control in *C. ruficollis.* Box-and-whisker plots for: (a) duration of activity, and (b) frequency of activity. Boxes represent interquartile ranges and whiskers represent the data points within 1.5x of the interquartile range. For (a), N(ALAN)=4, N(Control)=4. No significant differences were observed. For (b), N(ALAN)=4, N(Control)=4. No significant differences were observed.

Table 1. Duration and frequency of nighttime activity under ALAN and a control for *P. californicus* and *C. ruficollis.* N(ALAN)= 8, N(control)= 8, N(ALAN female)=4, N(ALAN male)=4. *= P< .1, **= P< .05, ***=P<.001.

Treatment	**Average Duration Nighttime Activity (seconds)**	**Average Duration Female Nighttime Activity (seconds)**	**Average Duration Male Nighttime Activity (seconds)**	**Average Frequency Nighttime Activity (# activities)**	**Average Frequency Female Nighttime Activity (# activities)**	**Average Frequency Male nighttime Activity (# activities)**
P. Californicus						
ALAN	3528	4661.25	2394.75	73.88	99.5	48.25

Control	3951	4239	3663	34.5	36.5	32.5
P-values	1	1	1	0.028 **	.008**	1
Statistical Tests	ANOVA, Bonferroni Post-hoc-Tests	ANOVA, Bonferroni Post-hoc-Tests	ANOVA, Bonferroni Post-hoc-Tests	ANOVA, Bonferroni Post-hoc-Tests	ANOVA, Bonferroni Post-hoc-Tests	ANOVA, Bonferroni Post-hoc-Tests
C. ruficollis						
ALAN	7.88	15.75	0	1.88	3.75	0
Control	31.25	18	44.5	8.13	13.5	2.75
P-values	0.353	0.909	0.081*	0.353	0.11	0.272
Statistical Tests	Kruskal-Wallis Test, Dunn-Bonferroni-Tests	Kruskal-Wallis Test, Dunn-Bonferroni-Tests	Kruskal-Wallis Test, Dunn-Bonferroni-Tests	Kruskal-Wallis Test, Dunn-Bonferroni-Tests	Kruskal-Wallis Test, Dunn-Bonferroni-Tests	Kruskal-Wallis Test, Dunn-Bonferroni-Tests

DISCUSSION

In recent years, concerns have grown over the commonly neglected role of artificial light at night as a contributing factor in global insect delines (Boyes et al. 2021). Studies are increasingly pointing to the pervasive impact that ALAN is having on insects from gene expression to community composition and trophic relationships. Though a diverse and ecologically important group with highly sensitive visual perception, few studies look at how ALAN impacts beetles. A handful of studies examine how beetle community composition shifts in response to ALAN(Davies et al. 2012, Lockett et al. 2021), and one study examines orientation behavior (Foster et al. 2021)induced by ALAN. In this study, I show how ALAN shifts certain characteristics of beetle movement, with species and sex-specific differences.

I found that *P. californicus* engaged in more activity events when under ALAN. This result is contrary to my hypothesis that ALAN would reduce the frequency of activity. Much of the current research on ALAN emphasizes how ALAN is suppressing fitness-related activities of nocturnal species such as foraging(Shier et al. 2020) and courtship and mating behaviors (Botha et al. 2017). The suppression of beneficial behaviors is one form of responding to ALAN maladaptively. Another way organisms can respond maladaptively is by engaging in activities beyond the point where the costs and benefits of an activity are balanced (Haynes and Robertson 2021). In my study, the number of activity events significantly increased, with no change to duration. *P. californicus* Beetles thus engaged in more short bursts of activity, which is likely to have negative energetic consequences.

My results show these Carabid beetles have sex-specific and species-specific behavioral responses to ALAN. I found that the frequency of nighttime activity changed for *P. californicus* in a sex-specific manner, with females increasing the number of activities, but not males. This shows differential responses to ALAN, which can cause challenges for male-female interactions such as mating, scaling up to changes in population dynamics. Other studies have found sex-specific responses to ALAN, such as with mosquito clock gene expression, and cardiac hypertrophy in zebra finches(Honnen et al. 2016, Alaasam et al. 2021). In this study, I tested two species of beetles but only saw significant changes in *P. californicus.* Research continually points to the variety of responses to ALAN, even amidst taxonomically similar groups(Bauer et al. 2022). These two species, though both in the family Carabidae and occupying physically similar environments, had different behavioral responses to ALAN.

While my study provides insight into the sex-specific and species-specific behavioral responses of Carabid beetles to ALAN, there are a number of limitations that make it difficult to know whether these trends hold significant external validity. First off, experiments were only run for 24 hours, with ALAN-treated beetles only experiencing one night of ALAN. In reality, organisms exposed to ALAN are likely to experience persistent, long-term exposure for which they might adapt to over time. I only test the acute response of beetles to ALAN, which has been shown to vary significantly from the long-term effects. Another limitation of my study is that I ran experiments for *C. ruficollis* a week after they were collected from their natural habitat. In the time between collecting them and starting entertainment, I kept beetles in a cooling bag that blocked out light. I entrained them for 24 hours before the experiment with the control light-dark cycle, but this may not have been sufficient for their daily rhythms to become completely resynchronized.

Reducing the effects of light pollution can take on many forms from adjusting the spectral composition of light to decreasing the range and intensity of light to turning lights off completely. Of course, the most effective option is to simply turn lights off, but living in a world of second-best policies, we know that this may not be realistic as human societies rely heavily on

ALAN. In this study, I used LED light with components in the red, green, and blue spectra, mirroring typical artificial lighting. Because of their energy efficiency and cost-effectiveness, LED lights are increasingly replacing other forms of artificial lighting, such as narrow-spectrum HPS lamps. LEDs are shown to be particularly disruptive to insects due to the wide spectrum of light they emit(Grubisic et al. 2018). While many LED lights currently emit broad spectrums of light, including particularly disruptive blue light, they are adjustable with the ability to easily engineer which spectrums of light are emitted(Longcore et al. 2015). Other management decisions commonly used to reduce light pollution include adding structures to limit the reach of ALAN to the area it is directed for. Unlike other pollutants which persist in the environment, light pollution can be immediately removed. Implementing management techniques for ALAN are both important and relatively simple.

There are a number of future directions that could add to my study. First, someone could run a long-term experiment to test whether acute responses observed in this study hold up over the long term. Testing how beetles respond to specific wavelengths of light is another important relationship to characterize, especially if we want to tune the spectrum of lights to be least disruptive to local wildlife. Finally, seeing how diurnal, crepuscular and nocturnal beetles compare in regard to behavioral responses to ALAN is another much-needed question to solve.

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