Illuminating Changes: The effect of urban light pollution on flying insects

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ABSTRACT

Artificial light at night (ALAN) is a growing ecological problem. Its use has expanded rapidly in recent years in line with urbanisation, introducing light to areas and time periods it is not normally found. Research has identified ALAN as a cause of disruption to the natural behaviours and circadian rhythms of insects, ultimately increasing mortality. Insect biomass has declined by over 75% in the past 30 years, therefore, understanding ways to mitigate further loss is vital. ALAN cannot be eliminated as it allows humans to carry out vital tasks outside of the natural photoperiod; with this in mind, investigation into and limiting its harmful properties is the best way forward. This study aimed to determine the impact of varying artificial light intensities on the abundance, biodiversity, and time of arrival of insects at urban lampposts at six urban sites in the Netherlands. We found that for Dipterans, the most common taxa, attraction/abundance increased with light intensification. Other taxa, including Psocoptera, Hymenoptera, and Hemiptera, were only significantly more attracted to high light intensities. Biodiversity and insect time of arrival were not significantly impacted by intensity but may be linked to a different property of ALAN. These findings suggest that dimming artificial light sources in urban areas could reduce insect attraction to ALAN, mitigating its negative consequences.

Keywords: Artificial light at night (ALAN), Insect behaviour, Urbanisation, Light intensity, Biodiversity, Circadian rhythms, Phototaxis, Conservation

1. Introduction

1.1 Artificial Light at Night

Light pollution, particularly artificial light at night (ALAN), is rapidly increasing due to urbanisation (Bolliger et al., 2020). ALAN is characterized by intentional emission of light across typically dark landscapes, with upwards of 20% of the world's surface now experiencing artificial illumination (Gaston et al., 2015). This widespread illumination occurs not only in urban centres but also in agricultural settings and transportation networks. The ecological effects of this expanding light footprint are only beginning to be understood, with documented alterations to behaviour and physiology identified across diverse organisms (Foster et al., 2021; Thawley & Kolbe, 2020; Sanders et al., 2020). Not only does ALAN introduce light to areas and time periods in which it is not normally found, but it also emits light at a different spectrum to that of the sun and moon (Gaston et al., 2015). This is increasingly broad-spectrum white light from Light-Emitting Diodes (LEDs), which are becoming more prevalent due to their low cost and energy efficiency (Wakefield et al., 2016).

1.2 Effect on Insects

Insect populations have been experiencing drastic declines due to multiple factors including agricultural intensification, habitat loss, climate change, and potentially light pollution. While ALAN may not be the primary driver of global insect decline, it represents an additional stressor that may exacerbate already declining or threatened populations in affected areas. This poses a concern due to the risks to essential ecosystem services provided by insects, including pollination, decomposition, and serving as food sources for higher trophic levels; insect declines could have significant implications for food security, human health, and global biodiversity. Aerial insects are particularly vulnerable to the influence of artificial light sources, due to their observable physical attraction to ALAN. This was previously theorised to be due to various factors, including disruption to navigation using lunar light (Sotthibandhu & Baker,1979), actively seeking heat sources (Callahan, 1965), and predator elusion by escaping dense foliage habitats (Mazokhin-Porshnyakov, 1960).

Recent research (Fabien et al., 2024) has identified that rather than moving directly towards light sources, many insects exhibit a 'dorsal-light-response (DLR)' behaviour, by which the dorsal side of the insect's body remains facing the brightest area in their field of vision. This orientation mechanism evolved to maintain stability during flight under natural celestial light, where the brightest light source (sun or moon) is typically above. However, when artificial light sources are present in the horizontal field of vision, this mechanism creates disrupted orbiting behaviour that encourages attraction to ALAN sources. This phototactic response raises a host of concerns, summarised by Owens & Lewis (2018) into five key issues:

1. Temporal disorientation: most insects follow a circadian rhythm that is dictated by the daily photoperiod (Numata et al., 2015). Changes to this could affect both daily activity patterns and annual phonologies that are triggered by changes to the photoperiod (Saunders, 2012).
2. Spatial disorientation: many species orient themselves using the moon and stars (Ugolini & Chiussi, 1996). Additional influence from artificial light could affect the ability to navigate.
3. Fatal attraction: attraction to light through the DLR draws species away from their natural habitats in which they are adapted to carry out necessary behaviours (van Langevelde et al., 2017). Inability to carry these out, or direct effects, such as overheating (Minnaar et al., 2017), results in the death of 30-40% of insects that collide with ALAN sources.
4. Reduced visual sensitivity: saturation of photoreceptors may cause temporary blindness in some species (Honkanen et al., 2017).
5. Altered foraging activity and species interactions: ALAN may affect the ability to visually identify predators, prey, and foliage, by losing the ability to differentiate colours (Delhey & Peters, 2017)

Long-term consequences of these effects are yet to be fully understood, but show concerning patterns. Laboratory studies have demonstrated reduced reproductive success in moths exposed to artificial light (van Geffen et al., 2015), while field studies have shown altered community composition (abundances of species within communities) around light sources (Davies et al., 2012). At the population level, persistent attraction to light sources can create ecological traps that drain individuals from source habitats, potentially leading to local population declines over time (Eisenbeis, 2006). The ultimate effect this will have on population dynamics remains an area of active research (Sanders et al., 2021).

Collectively, these factors may negatively affect insect populations by emphasising habitat fragmentation, depleting energy, hindering vital behaviours including reproduction and feeding, and directly increasing mortality through predation and light radiation (Hori et al., 2014).

1.3 Light Properties

Several factors related to ALAN have been identified as varying its effect on insect activity. These are most notably light type, wavelength and intensity; however, inconsistencies in conclusions leave uncertainties about what these effects are.

Research on light types has produced variable results. Several studies have identified LEDs as being the least influential bulb on insect activity (Martin et al., 2021; Wakefield et al., 2016), perhaps due to their more energy-efficient reduced heat output, while others found LEDs to have the strongest effect (Fox, 2021). Due to the wide variety in LED properties it is difficult to use a single study as a standard, emphasising the value in an expanding study-base.

Similarly, findings regarding light spectrum have shown varying impacts. Most studies have indicated broad-spectrum white light as being significantly more attractive than single-colour bulbs due to their higher blue content (Stewart, 2021). Yet results by Wakefield et al. (2016) indicated no significant difference between blue-containing 'cool white' bulbs and blue-absent 'warm' bulbs.

As for light intensity, existing evidence suggests that increased ALAN strength is linked to increases in insect attraction; Bolliger et al. (2020), identified the differences between temporarily dimmed street lighting and 'full' light only. This study found that streetlights surrounding urban roads attracted less insects when temporarily dimmed to 35% (in the absence of cars in an urban road system), though this result was heavily dictated by weather conditions, and varied greatly between taxa, with some common orders (Diptera and Coleoptera) showing no effect. ALAN intensity has also been observed as having an increasing effect on changes to insect community composition (Davies et al., 2012), though this is likely a saturating relationship, reaching thresholds where further increases in light intensity may not lead to proportional changes to community composition.

Another area of interest is the impact of ALAN intensity on insect activity patterns; while we know that in general ALAN can impact insect activity peaks (Gaston et al., 2017), it is unknown whether this is related to intensity, or other ALAN properties. At large, it is due to disruption of the circadian rhythm dictated by the sun. For example, peaks of activity may be later due to extension of behaviours such as foraging, beyond their natural limits.

1.4 Objectives

Given that light intensity is a property of ALAN that can be readily manipulated without completely removing illumination in urban settings, we chose to focus our investigation on this parameter. Wavelength and light type do remain important and will be investigated with BioClock, subsequent to this study.

This project aims to take a unique approach by identifying the effect of varying light intensity (consistent throughout a given night) on insect attraction, activity patterns, and community composition across a range of urban environments and comparing these results to the urban insect population in the absence of ALAN, using 'dark' controls. This project will answer the question of how different levels of light intensity compare against darkness in affecting urban insect activity. This will be answered using the following objectives: i) to investigate how light intensity influences the abundance (as a proxy for attraction) and ii) community composition of insects at lamp posts; iii) to analyse how light intensity affects the temporal activity patterns of insects. For objective (iii), we specifically examine time of arrival at light sources as a proxy for altered activity patterns, with the understanding that changes to normal flight and foraging times may impact fitness through suboptimal resource acquisition, increased predation risk, and disrupted mating opportunities (Gaston et al., 2017).

1.5 Project Outline

This project utilised field data collected as part of the BioClock project during September 2023. BioClock is a Dutch-based research consortium investigating light pollution, chronobiology, and the biological clock. Lampposts using LEDs of varying light intensities, across six urban sites in The Hague and Rotterdam, the Netherlands, were used as study points. Both sheet and camera traps were used to collect abundance, community composition, and time-of-arrival data. Additional areas of interest were environmental factors.

1.6 Hypothesis

Based on previous research, it is expected that this study will find that i) increased light intensity will result in increased abundance of insects around lamp posts, but is likely to differ between taxa (Bolliger et al., 2020), ii) increased light intensity will increase changes to community composition, due to varying levels of light attraction between insect species (Davies et al., 2012), iii) increased ALAN intensity will result in earlier times of arrival of insects to the traps, due to increased attraction (Saunders, 2012). Changes in environmental factors may also alter insect behaviour, for example, increased ambient temperature may decrease the clustering effect of ALAN, due to reduced heat gradient between environment and bulb (Bolliger et al., 2020). Determining these impacts on insect activity will help anticipate the future of insect populations within an era of expanding urban environments.

2. Methods and Materials

2.1 Research Group

BioClock aims 'to gain a better understanding of our biological clock, in order to restore the health of this clock, ultimately leading to an increase of human health and of all living creatures on the planet', through research into the impacts of shift work, optimal times for medication administration, and the impacts of light pollution (BioClock, 2024).

2.2 Research Area

Data points were set up in six areas across the cities of The Hague and Rotterdam, the Netherlands (Appendix 1), for collection between 04/09/2023 to 10/09/2023, and 18/09/2023 to 27/09/2023. The study areas were identified as Brasemdael, Laakweg and Groene Zoom (The Hague), and Melanchton Park, John Bruijnzeelpad, and Prinsemolenpad (Rotterdam). The Groene Zoom study site consists of predominantly vegetated borders of a secluded road/car park area in proximity to sports fields and a busy highway system. Laakweg and Brasemdael are both situated on vegetated river banks in residential areas. Melanchton Park, John Bruijnzeelpad, and Prinsemolenpad sites are all moderately vegetated public parks. The maximum distance between study sites is approximately 24.5km (Brasemdael to John Bruijnzeelpad) (Google Maps, 2024), resulting in minimal variance in atmospheric conditions. These locations were selected based on the availability of 4m poles with dimmable lighting (in agreement with municipalities) and their natural features, such as water and more wild vegetation patches, where insects and bats could be expected.

In terms of climate, the Netherlands lies within the global temperate zone, experiencing oceanic weather patterns with its proximity to the Atlantic Ocean. Temperatures reach an average of 18 degrees Celsius in the summer and 4 degrees Celsius in the winter, with an average annual precipitation of 891.0 mm (Time and Date, 2024a).

Like the rest of the world, The Netherlands is experiencing extreme declines in insect populations, of particular concern, with most plants being insect-pollinated. Unfortunately, studies have shown these plants are disappearing at a rate far higher than their wind-pollinated counterparts (Pan et al., 2022), indicating the necessity for insect conservation in this area. The latest figures suggest that there are 19,254 known insect species in the Netherlands (Hallmann et al., 2019). However, with insect biomass estimated to be declining at a worldwide average of 2.5% per year, this number is only growing smaller (Rhodes, 2019). Common orders of nocturnal and diurnal insects have been identified to include Hemiptera (true bugs), Coleoptera (beetles), Lepidoptera (e.g. butterflies and moths), Trichoptera (caddisflies), Diptera (flies) and Hymenoptera (e.g. wasps and bees) (van Wielink & Spijkers, 2013), though data on exact population composition dynamics is presently absent.

2.3 Experimental Set-Up

Each of the six study sites had two active treatment groups/lampposts (Figure 1), with about 25m between each pole. These were set to either high (10lux) or low (2lux) intensity, with the treatment switching each consecutive night. In the Hague, dimming altered between 0% (high intensity) and 70% (low intensity), while in Rotterdam, it was between 20% (high intensity) and 85% (low intensity), with differences based on calculations they made to get the desired lux on average over a 5x5m plot. However, the actual values of low and high intensities varied per pole due to practical constraints. Exact intensities have been logged. This level of dimming was much stronger than in previous studies (a maximum of 35% in Bolliger et al. (2020)). The dark control, unique to this study, was either a third nonfunctional pole or, in two cases, a bare tree, where a pole was vandalized, or placing a pole was impossible. Contrary to the high and low intensities, the dark control treatment pole remained constant throughout the study and was at least 20m away from the nearest light source.

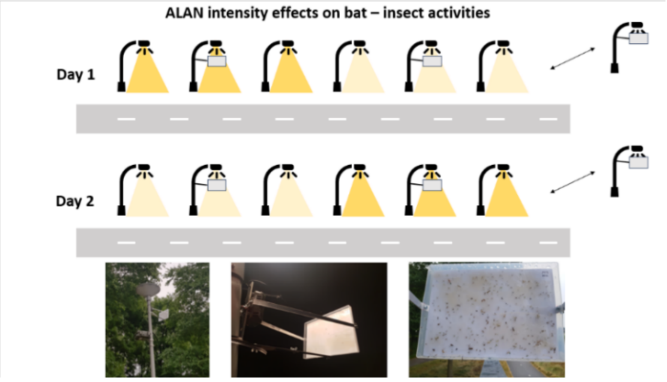


Figure 1: Representation of the alternating dimming regime used for low and high intensity lampposts.

Insect traps were created using laminated A4 paper covered in horsefly glue (Sticky-Trap brand), creating 'sticky sheets'. Bat detectors and sticky sheets hung from the middle of the three selected poles. Sheets were attached 40cm away from the pole, using an aluminium frame to avoid bats being trapped in the glue. The bottom of the sticky sheet frame was placed around 60cm under the bottom of the light fixture. Cameras (Technaxx Mini Nature Wild Cam Tx-117 Wildlife Camera) were also attached to the pole, directed towards the sticky sheet. They were set to take pictures at 5-minute intervals. The sheets were replaced once or twice a week, depending on insect density. Upon collection, they were placed in laminate covers to prevent as much disturbance to the captured insects as possible.

2.4 Data Processing

Camera images taken at 5-minute intervals were chronologically examined for each of the 18 poles, looking only at pictures taken between the hours of 19:30-7:30. This time interval was based on the collection period of September, during which this is the most extreme sunset to sunrise period. When new specimens appeared in an image, the interval time of arrival was noted. Specimens were then identified on the glue trap, marked with an identification number, and microscopically analysed to determine taxa to the order or predetermined family level. The stability of the horsefly glue used for these traps was affected by several factors, including temperature, meaning some insects moved after initial attachment, through glue sliding or movement after failure to be fully immobilised by the glue. These insects were tracked through the images until they settled into a final position or left the sheet completely. Both movement and presence/absence on the sheet were noted; taxa was designated as 'NA' in the case of absence at collection or impossible identification.

2.5 Environmental Variables

Variables of height and distance to water (DTW) for all the traps were measured manually by researchers. Moon phases were retrieved from Time and Date AS (Time and Date, 2024b)

Urbanisation scores were generated using software created by the Image Processing Laboratory at the University of Pannonia (Czúni et al., 2012; Seress et al., 2014; Lipovits et al., 2015). Coordinates for each pole were inputted into the software. Through GoogleMaps, a 1km2 area is taken around each coordinate, calculating the number of cells occupied for vegetation, buildings and paved roads. Using these variables, a principal component analysis (PCA) creates 'urbanisation scores' for each coordinate. These can be seen as relative values in the context of the other scores.

Climatic variables were retrieved from the Koninklijk Nederlands Meteorologisch Instituut (KNMI, 2024), providing historical daily weather data for various weather stations across the Netherlands. Data were sourced from the closest station for each study site: Voorschoten for Laakweg and Groene Zoom, Rotterdam for John Bruijnzeelpad, Melanchton Park and Prinsemolenpad, and Hoek van Holland for Brasemdael. KNMI provides 39 climatic variables, primarily focused on temperature, precipitation, humidity, wind and radiation factors, including means, minima and maxima, giving one value for each variable per day. Due to the large number of variables, only the seven most relevant were selected for this study; these were daily mean windspeed, daily mean temperature, sunshine duration, global radiation, daily precipitation amount, daily mean atmospheric humidity, and potential evapotranspiration. Minimum visibility would also have been included; however, data for this factor were too sparse for use in models.

2.6 Data Analysis

The main aim of the model creation process was to determine the relationship between light intensity, the time of arrival, and the number of insects caught while also accounting for environmental variables. Before model creation, a test for collinearity was carried out on environmental variables and date. Variables with correlation coefficients above 0.7 were considered highly correlated. This resulted in height, DTW, US, daily mean windspeed, daily mean temperature, daily precipitation amount, daily mean atmospheric humidity, and date being the only factors used moving forward (with all others having a high correlation with date).

Abundance – Generalised linear mixed models (GLMMs) were used to determine the effect of light intensity and environmental variables on the number of insects caught in general, and for the five most common taxa. For these, data had to first be aggregated into a data frame that showed number of insects caught at each pole on every night of observation, along with light intensity treatment and environmental variables. GLMMs were created in RStudio, using the packages 'lme4' (Bates et al., 2015) and 'lmerTest' (Kuznetsova et al., 2017). Location and pole were included as random effects and corrected for repeated measures and nesting (three poles within each site, measured for several nights), and models were assigned to the 'poisson' distribution due to the distribution of the count data. Starting from a full model of all environmental variables as fixed effects, a series of simplifications were carried out and best-fit models were selected based on Akaike Information Criterion (AIC) information. Interaction terms were added to simplified models, rather than full, due to the large number of variables of differing scales generating errors on the full models. Only interactions involving light intensity were analysed in the results of this study. Models differed between taxa (see Results). Significance was determined using the summary() and Anova() functions, from the 'car' package (Fox & Weisberg, 2019). Post-hoc contrasts, using the emmeans() function, from the package of the same name (Lenth et al., 2018), were used to further identify significance across different light intensity levels.

Community Composition – Both Simpson and Shannon-Weiner indices were generated for each pole and light intensity to better assess the variations in community composition between treatments, primarily using the package 'vegan' (Oksanen et al., 2017). These indices provide complementary information about community structure, with Shannon-Weiner emphasizing species richness and Simpson emphasizing species evenness or dominance. A full linear mixed model (LMM) was created and simplified to determine the best-fit model. Significance was determined using the summary() and anova() functions (Fox & Weisberg, 2019).

Time of arrival – Linear mixed models (LMMs) were used to determine the impact of light intensity and environmental varibales on the time of arrival of the general insect population, as well as the five most common individual taxa. These used the same packages of 'lme4' and 'lmerTest' and retained the correction for random effects of location and pole number, due to multiple testing. These also followed the same simplification process from the full models, and addition of interaction terms. Again, different species' best-fit models resulted in varying levels of complexity (see Results). Significance was determined using the summary() and anova() functions (Fox & Weisberg, 2019), and emmeans post-hoc contrats (Lenth et al., 2018).

Graphical representations of all factors of interest were created using the package 'ggplot2' (Wickham, 2016).

3. Results

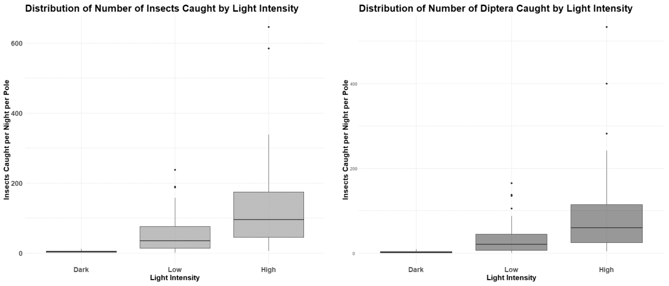
3.1 Abundance of Arthropods Caught

A total of 10,633 individuals were observed, with Diptera being the most abundant, making up 66% of all arthropods, 51% at the dark level, 64% at low light intensity, and 68% at high. Several non-insect arthropods (Araneae (spiders), Collembola (springtails) and Protura) were caught, but due to small numbers, the collective of all individuals will continue to be referred to as 'insects'.

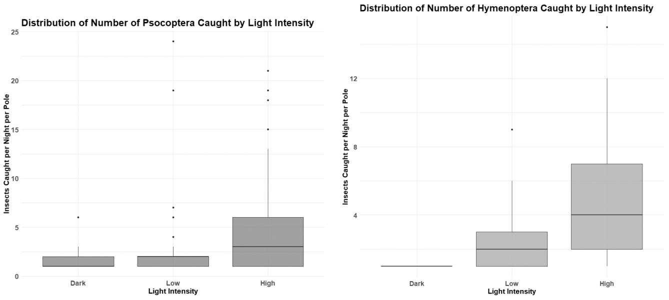
Table 1: Total abundance of arthropods caught by taxon. NA values represent those no longer on sheet at collection and those unable to be identified due to degradation etc. 160 nights-worth of observations; 43 dark, 59 low, 58 high light intensity.

Taxon	**Count**			
	Dark	**Low**	**High**	**Total**
Diptera	91	1913	5061	**7065**
Psocoptera	27	121	236	**384**
Hymenoptera	2	82	221	**305**
Hemiptera	7	86	201	**294**
Coleoptera	8	49	99	**156**
Lepidoptera	2	35	75	**112**
Trichoptera	0	14	43	**57**
Neuroptera	0	15	12	**27**
Thysanoptera	1	0	4	**5**
Araneae	1	2	1	**4**
Collembola	2	0	1	**3**
Ephemeroptera	0	0	1	**1**
Mecoptera	0	1	0	**1**
Protura	0	0	1	**1**
NA	38	690	1489	**2218**
Total	179	3008	7445	**10663**

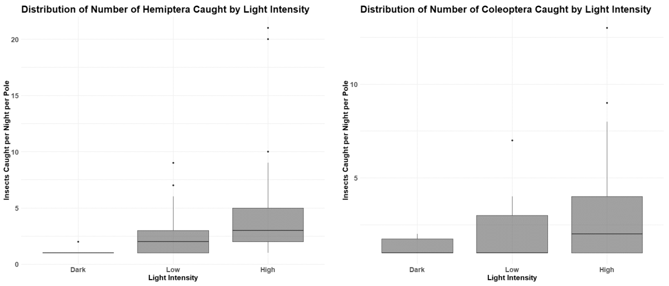
All Insects – A generalised linear mixed model (GLMM) was used to determine the effect of light intensity and environmental variables on the number of insects caught per pole per night for the general insect population. The best-fit model, having the lowest AIC, included the main factor of interest, light intensity, along with daily mean windspeed, daily mean temperature, daily precipitation amount, urbanisation score, and date. This GLMM showed significant differences in insect abundance between different light intensities, as can be seen in Figures 2a and 3. Post-hoc contrasts showed that this effect was observed across all light intensity levels (Dark-Low: z = -10.759, p = <.0001; Dark-High: z = -14.041, p = <.0001; Low-High: z = -34.951, p = <.0001). In terms of environmental variables, windspeed (β = 0.020), temperature (β = 0.018), precipitation (β = 0.006), and data (β = 0.011), showed significant positive effects (Table 2a), meaning that as these factors increased, the number of insects caught also increased. In the case of interactions, windspeed was revealed to have a significantly negative impact on the effect of light intensity (Low x Windspeed: β = -0.010; High x Windspeed: β = -0.017), suggesting that the effect of light intensity on the number of insects caught per night per pole becomes significantly weaker as windspeed increases across all levels.



(a) all insects (b) Diptera



(c) Psocoptera (d) Hymenoptera



(e) Hemiptera (f) Coleoptera

Figure 2: Effect of light intensity on the number of individuals caught for a) all insects, b) Diptera, c) Psocoptera, d) Hymenoptera, e) Hemiptera, f) Coleoptera.

Diptera (true flies) – See Table 2b for fixed effects used in GLMM model. For Diptera, increased light intensity resulted in increased numbers of insects captured (Figure 2b), with post-hoc contrasts showed that this effect was significant across all levels (Dark-Low: z = -7.421, p = <0.001; Dark-High: z = -9.683, p = <0.001; Low-High: z = -20.475, p = <0.001). Windspeed (β = -0.044), temperature (β = -0.00007), and precipitation (β = -0.006) all had significant negative impacts on the number of Diptera caught, meaning as these values increased, the number of Diptera was reduced. Date (β = 0.023) had a significant positive impact; as this value increased, the number of Diptera caught increased. Windspeed and temperature both had significant positive impacts on the effect of light intensity (Low x Windspeed: β = 0.029; High x Windspeed: β = 0.028; Low x Temperature: β = 0.014; High

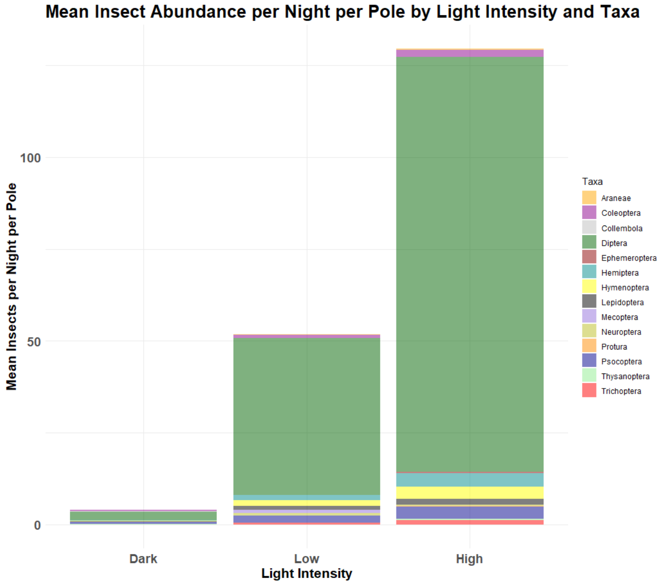


Figure 3: Time of arrival of arthropods caught, separated by taxon.

x Temperature: $\beta = 0.015$), suggesting that the effect of light intensity on the number of Diptera caught becomes significantly stronger as these factors increase.

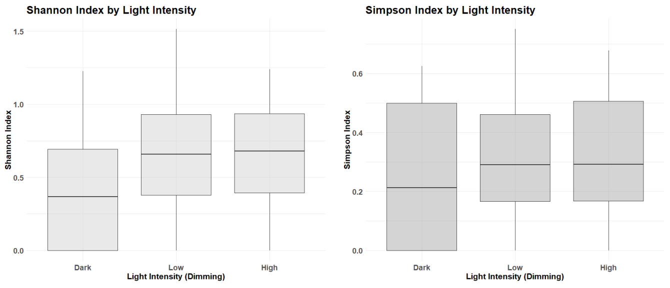
Psocoptera (bark lice) – See Table 2c for fixed effects used in GLMM model. In the case of Psocoptera, the number of insects caught also increased with light intensity (Figure 2c). Post-hoc tests showed that this effect was not significant across all levels, only between dark and high, and low and high (Dark-Low: $z = -1.301$, $p = 0.395$; Dark-High: $z = -2.665$, $p = 0.021$; Low-High: $z = -4.213$, $p = <0.001$). Windspeed ($\beta = -0.390$) and humidity ($\beta = -0.172$) had significant negative effects on the number of Psocoptera caught. Windspeed was revealed to have a significantly positive impact on the effect of light intensity (Low x Windspeed: $\beta = 0.270$; High x Windspeed: $\beta = 0.390$), suggesting that the effect of light intensity on the number of insects caught per night per pole becomes significantly stronger as windspeed increases across all levels.

Hymenoptera (bees, wasps, and ants) – See Table 2d for fixed effects used in GLMM model. The taxa Hymenoptera also followed the pattern of increasing abundance with increased light intensity (Figure 2d). Though the GLMM detected a significant effect of light intensity (Table 2d), only the difference between low and high intensities was identified as significant in post-hoc tests (Dark-Low: $z = -1.339$, $p = 0.373$; Dark-High: $z = -2.190$, $p = 0.073$; Low-High: $z = -4.886$, $p = <0.001$). Daily mean temperature was also identified as having a significant positive effect ($\beta = 0.011$).

Hemiptera (true bugs) – See Table 2e for fixed effects used in GLMM model. The number of Hemiptera caught also increased with light intensity (Figure 2e). The GLMM identified a significant effect of light intensity, but post-hoc contrasts showed this this was a significant difference between only dark and high, and low and high light intensities (Dark-Low: $z = -1.363$, $p = 0.360$; Dark-High: $z = -2.827$, $p = 0.013$; Low-High: $z = -5.197$, $p = <0.001$). Daily mean windspeed ($\beta = 0.010$) and daily mean temperature ($\beta = 0.015$) were also identified as having significant positive effects on the number of Hemiptera caught.

Coleoptera (beetles) – See Table 2f for fixed effects used in GLMM model. Though significant at the GLMM level (Table 4f), post-hoc contrasts showed no significant differences between light intensity levels (Dark-Low: $z = -0.414$, $p = 0.910$; Dark-High: $z = -1.459$, $p = 0.311$; Low-High: $z = -2.328$, $p = 0.052$). In terms of environmental variables, the effect of daily mean temperature ($\beta = 0.017$) on the number of Coleoptera caught was significantly positive ($\beta = 0.017$); a higher temperature resulted in more insects caught.

3.2 Community Composition



(a) (b)

Figure 4: Effect of light intensity on the community composition of insects caught, based on a) Shannon-Weiner Index, b) Simpson Index. Values are based on data per pole per night. NA values have been removed

There is no significant difference in the Shannon-Weiner index based on light intensity, however, there was a non-significant positive trend towards increased changes (Figure 4a) (Dark: $\mu = 0.372$; Low: $\mu = 0.664$; High: $\mu = 0.677$). The Simpson index shows also showed a similar, but weaker non-significant trend of increasing with light intensity (Figure 4b) (Dark: $\mu = 0.242$; Low: $\mu = 0.328$; High: $\mu = 0.326$). For both of these measures, temperature was seen to have a significant positive effect on community composition (Shannon: $\beta = 0.003$; Simpson: $\beta = 0.001$), suggesting greater changes to species richness and dominance at higher temperatures.

Table 2: Anova output for GLMMs for insect abundance. Light intensity = differences between dark, low, and high, windspeed = daily mean windspeed, temperature = daily mean temperature, precipitation = daily precipitation amount. 'x' denotes interaction effect. Statistical levels of significance: $^{***} < 0.001$ $^{**} < 0.01$, $^{*} < 0.05$.

a) All Insects	Analysis of Deviance		
	X^2	DF	Pr(>X^2)
Light Intensity	1586.752	2	<0.001 (***)
Windspeed	87.314	1	<0.001 (***)
Temperature	1587.555	1	<0.001 (***)
Precipitation	48.474	1	<0.001 (***)
Urbanisation Score	2.971	1	0.085
Date	40.416	1	<0.001 (***)
Light Intensity x Windspeed	56.887	2	<0.001 (***)
AIC Performance			*2685.054*

b) Diptera	Analysis of Deviance		
	X^2	DF	Pr(>X^2)
Light Intensity	1160.819	2	<0.001 (***)
Windspeed	37.091	1	<0.001 (***)
Temperature	1056.218	1	<0.001 (***)
Precipitation	73.406	1	<0.001 (***)
Date	120.177	1	<0.001 (***)
Light Intensity x Windspeed	44.717	2	<0.001 (***)
Light Intensity x Temperature	8.260	2	0.016 (*)
AIC Performance			*2267.525*

c) Psocoptera	Analysis of Deviance		
	X^2	DF	Pr(>X^2)
Light Intensity	24.879	2	<0.001 (***)
Windspeed	6.989	1	0.008 (**)
Humidity	53.982	1	<0.001 (***)
Light Intensity x Windspeed	8.903	2	0.012 (*)
Light Intensity x Humidity	4.920		0.085
AIC Performance			*535.6775*

d) Hymenoptera	Analysis of Deviance		
	X^2	DF	Pr(>X^2)
Light Intensity	27.630	646.425	<0.001 (***)
Temperature	30.169	646.381	<0.001 (***)
AIC Performance			*350.3375*

e) Hemiptera	Analysis of Deviance		
	X^2	DF	Pr(>X^2)
Light Intensity	32.334	2	<0.001 (***)
Windspeed	9.464	1	0.002 (**)
Temperature	34.934	1	<0.001 (***)
AIC Performance			*368.8336*

f) Coleoptera	Analysis of Deviance		
	X^2	DF	Pr(>X^2)
Light Intensity	6.710	2	0.035 (*)
Temperature	21.054	1	<0.001 (***)
AIC Performance			*232.0217*

Table 3: Anova output for LMMs for insect community composition as a function of light intensity. Light intensity = differences between dark, low, and high, windspeed = daily mean windspeed, temperature = daily mean temperature, humidity = daily mean atmospheric humidity. 'x' denotes interaction effect. Statistical levels of significance: $^{***} < 0.001$ $^{**} < 0.01$, $^{*} < 0.05$.

a) Shannon-Weiner	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	2	2.587	0.092
Temperature	1	13.1497	<0.001 (***)
AIC Performance			*148.1337*

b) Simpson	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	2	0.432	0.653
Temperature	1	4.282	0.040 (*)
AIC Performance			*-19.156945*

Figure 5 shows preliminary visual results for insect time of arrival, accounting only for differences between taxa, rather than light intensity. The y-axis represents hours after 19:30 (7:30 PM), with values from 0-12 corresponding to 19:30-7:30. Significantly different times of arrival from at least one other taxa were identified for Coleoptera, Diptera, Hemiptera, Hymenoptera, Lepidoptera, Psocoptera, and Trichoptera. Therefore, impacts of light intensity were investigated on a taxa level for the five most abundant of the species (Table 1), to gain further insight into its effect.

All Insects – The linear mixed model used to determine the impact of light intensity and environmental variables on the time of arrival of all insects across all locations showed that the effect of light intensity was not significant (Table 4a). Some environmental variables included in this model did have an impact, identifying a significant positive effect of daily mean temperature ($\beta = 0.0083$) and daily mean windspeed ($\beta = 0.0079$) on time of arrival, i.e., as these factors increased, insect time of arrival was later. The random intercepts explained a variance of 0.389 (SD = 0.6237).

Diptera (true flies) – See Table 4b for fixed effects used in LMM model. A similar linear mixed model was used to determine the effect of light intensity on time of arrival of the most common insect order Diptera; however, in the best-fit model for this taxa, only temperature was shown to have a significant positive effect on time of arrival for Diptera ($\beta = 0.009$) (Table 4b), so as daily mean temperature increases, arrival time becomes later. Diptera were not significantly affected in their arrival time by light intensity (Low: $\beta = 0.416$; High: $\beta = 0.506$), however did show a non-significant positive trend (Figure 6b).

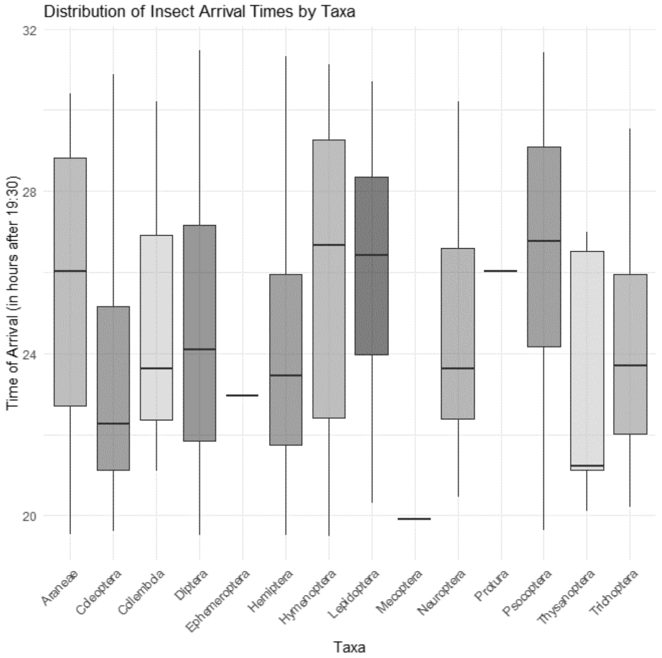
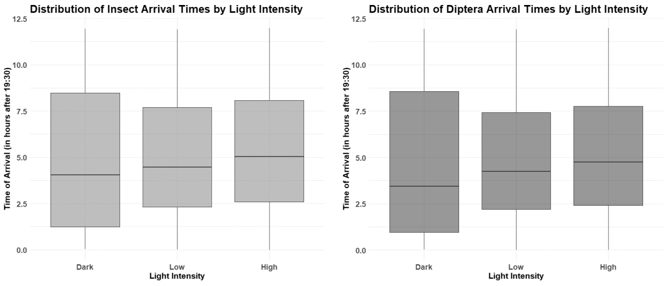


Figure 5: Time of arrival of insects caught, separated by taxon.

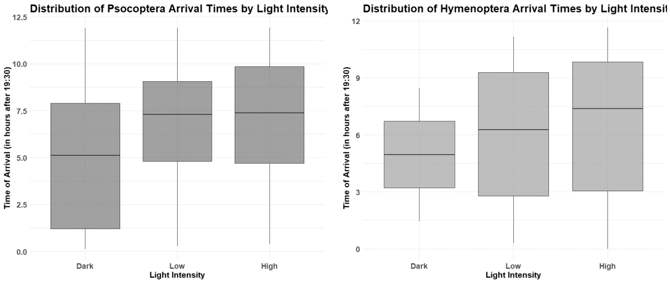
Psocoptera (bark lice) – See Table 4c for fixed effects used in LMM model. The linear mixed model for this species initially showed a significant effect of only high light intensity on this taxon (β = 1.573) (Table 4c) however, this was not seen in post-hoc contrasts (Dark-Low: t = -1.629, p = 0.245; Dark-High: t = -2.147, p = 0.094; Low-High: t = -0.985, p = 0.587), overall not providing enough evidence to define light intensity as having a significant effect on Psocoptera arrival time. Again, a non-significant positive trend was observed. No significant effects of environmental variables were identified in this model.

Hymenoptera (bees, wasps, and ants) – See Table 4d for fixed effects used in LMM model. The effect of light intensity on Hymenoptera time of arrival was not significant (Low: β = 901.212; High: β = 907.507), however also showed a non-significant positive trend. Unique to this taxa, distance to water was identified as having a significant negative effect on time of arrival (β = -0.161) (Table 4d), meaning that poles closer to water saw later arrival times.

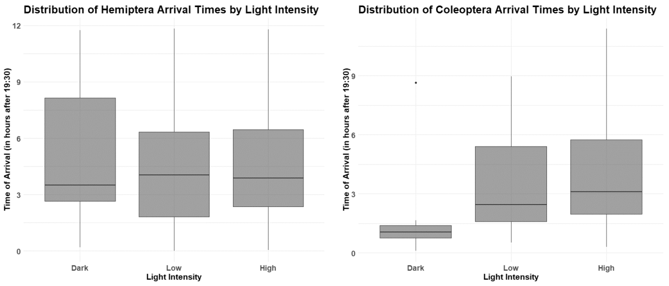
Hemiptera (true bugs) – See Table 4e for fixed effects used in LMM model. No light treatment was identified as having a significant effect on Hemiptera time of arrival (Low: β = -1.610; High: β = -1.557), however daily mean temperature had a significant positive effect (β = 0.023193) (Table 4e). The non-significant trend in arrival times of Hemiptera differed from the general insect population and other individual taxa in that while generally seeing very little difference based on light intensity, the dark control had a wider, later spread, compared to light treatments (Figure 6e).



(a) all insects **(b)** Diptera



(c) Psocoptera **(d)** Hymenoptera



(e) Hemiptera **(f)** Coleoptera

Figure 6: Effect of light intensity on the time of arrival for a) all insects, b) Diptera, c) Psocoptera, d) Hymenoptera, e) Hemiptera, f) Coleoptera.

Coleoptera (beetles) – See Table 4f for fixed effects used in LMM model. The linear mixed model showed that, again, the effect of light intensity on Coleoptera time of arrival was not significant (Low: β = 1.451; High: β = 1.871), but showed non-significant later times of arrival as light intensity increased (Figure 6f). Environmental variables were also not of significance in this model.

4. Discussion

4.1 Summary of Findings

This study examined how varying intensity of artificial light at night (ALAN) affects flying insects in urban environments. The key findings of this study include: (1) increased light intensity significantly increased insect abundance across taxonomic groups, but with differing response

Table 4: Anova output for LMMs for insect time of arrival.. Light intensity = differences between dark, low, and high, windspeed = daily mean windspeed, temperature = daily mean temperature, humidity = daily mean atmospheric humidity. 'x' denotes interaction effect. Statistical levels of significance: $^{***} < 0.001$ $^{**} < 0.01$, $^{*} < 0.05$.

a) All Insects	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	2	2.627	0.081
Windspeed	1	17.379	<0.001 (***)
Temperature	1	40.676	<0.001 (***)
AIC Performance			*54406.94*

b) Diptera	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	2	0.941	0.396
Temperature	1	40.768	<0.001 (***)
AIC Performance			*36097.01*

c) Psocoptera	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	1	2.559	0.087
AIC Performance			*1956.308*

d) Hymenoptera	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	2	1.732	0.179
Height	1	1.848	0.175
Distance to Water	1	15.770	<0.001 (***)
Light Intensity x Height	2	1.595	0.205
AIC Performance			*1581.263*

e) Hemiptera	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	2 0.814	0.446	
Temperature	1	15.215	<0.001 (***)
AIC Performance			*1455.745*

f) Coleoptera	Analysis of Variance		
	Numerator DF	F Value	Pr(>F)
Light Intensity	2	1.517	0.229
AIC Performance			*753.4829*

patterns; (2) Diptera showed increasing abundance at both low and high intensities, while Psocoptera, Hymenoptera, and Hemiptera were only significantly more abundant at high intensities; (3) community composition showed no significant differences between light intensity levels; and (4) time of arrival was not significantly affected by light intensity across all taxa studied, though environmental variables like temperature did influence this parameter.

4.2 Importance of Insects

Insect biomass has been seen to have reduced to by over 75% in the past 30 years, due to multiple anthropogenic factors (Hallman et al., 2017), including habitat fragmentation (Dirzo et al., 2014), climate change (IPCC, 2021), and the focus of this study, light pollution (Gaston et al., 2014). Reduced insect numbers raise a host of issues related to the maintenance of insect biodiversity for conservation and agriculture. Insects play important roles in the food chain as pollinators, decomposers (Hartley & Jones, 2008), and prey, being a primary food source for many threatened urban-dwelling species, such as birds, bats, and other small land mammals (Stanton et al., 2018; Del-Claro et al., 2018). Since 1966, North American insectivorous birds have declined by more than 40%, exceeding than any other avian group in the region (Stanton et al., 2018), revealing the cascading effects of insect declines. In both natural and agricultural floral systems, insects act as both pollinators and biological pest control, meaning dwindling numbers will have cascading effects on natural flora and the food supply – currently both wild and managed bees contribute an estimated $518 billion per annum in pollination services, a provision we cannot afford to lose (IPBES, 2016). Declining insect diversity isn't, however, the only threat of ALAN. Drawing insects away from their natural habitats, towards urban areas, pose threats to human health. Insects act as vectors for many zoonotic diseases and white LEDs have been identified as attracting higher levels of species that are vectors for human illness (Stewart, 2021). Changes to the regular photoperiod, as is natural with changing seasons above and below the tropics, also acts as the main phenological indicator for many species. Changes to this, induced by ALAN, have been seen to delay diapause in several mosquito species (Culex pipiens f. molestus, Aedes albopictus), increasing the biting period, and therefore extending their associated disease seasons (Borges, 2022). As small ectotherms, insects are also vulnerable to temperatures that differ from those they are adapted to (Borges, 2022). Phenological changes are therefore also a threat to insect reproduction and mortality.

4.3 Abundance

We quantified the attraction of insects caught in light traps by looking at the abundance of individuals caught by sticky traps. This was observed across two intensities, 2 lux (low) and 10 lux (high), and compared to a dark control. Light intensity was a significant driver of insect attraction across all levels.

There were differences in the effect of light on attraction between taxonomic groups. This is likely related to their differing evolutionary histories and ecological traits.In this study, Dipterans exhibited a graduated response to light intensity, with attraction increasing with increasing levels of light intensity. Their strong phototactic response may relate to their generally good flight capabilities and predominantly visual navigation. In contrast, Psocoptera, Hymenoptera, and Hemiptera only exhibited significant attraction to high light intensities. As decomposers of vegetation, dark-adapted Psocoptera have been seen to have varying responses to light, with some showing neutral or negative phototaxis, which could explain this result (New & Lienhard, 2007). In the case of Hymenoptera, unlike most nocturnal insects, this order possesses apposition compound eyes, most often seen in diurnal species due to their relative light-insensitivity (Warrant, 2008). With this in mind, it may take a higher light intensity to trigger a phototactic response in Hymenopterans. Coleoptera showed no significant response to either light intensity, possibly due to the diversity ecological niches of the order, having previously been seen to vary in their attraction to light (Kaunath & Eccard, 2022).

This result is in line with other studies that indicated an increased attraction to higher intensities of ALAN, and variations between taxa (Bolliger et al., 2020; Johansen et al., 2011), and confirmed our initial hypothesis of increased attraction with increased light intensity. While Diptera are consistently the dominant group between light treatments, they made up a greater percentage of the catch under ALAN. This was also observed in other studies (Anthony, 2016; Donners et al., 2018), suggesting a stronger phototactism in Dipterans. This result is in direct contrast to Bolliger et al. (2020), which saw no significant changes to attraction in Diptera. This could be due to difference in study sites (our study used a variety of urban green spaces whereas Bolliger et al. studied high-traffic zones), but is more likely a result of the relatively small catchment size observed in Bolliger et al. (2020), with a mean of only 10 insects per night, compared to 66 in this study. Like Bolliger et al. (2020), we also saw no significant attraction from Coleoptera.

General variation in attraction between taxa may be attributed to several factors. Firstly, differences in life stages between taxa; previous studies have identified variances in attraction to light traps between different insect life stages (A'Brook, 1973), which vary based on time of year between taxa. Flight pattern height also influences the abundance of individuals caught in light traps (A'Brook, 1973), and varies between taxa. Though the insects caught in this study all reside within the same urban study sites, occupation of different microhabitats can affect the strength of a species' phototactism due to adaptation to different photoenvironments (Okamoto & Kakui, 2023).

Daily mean temperature and windspeed were also seen to affect the abundance of insects caught, though this differed from a positive effect in the general population, Hymenoptera (temp. only), Hemiptera, and Coleoptera (temp. only), to a negative effect in Diptera and Psocoptera (wind only). As ectotherms, insects are very sensitive to heat; while increase temperatures increase metabolic activity, beyond a turning point (that may differ between taxa), individuals enter periods of heat stress that must be recovered from before flying again (Speights et al., 2017). In terms of wind, the increase in abundance of insects could be a result of increased speeds dispersing individuals in greater numbers to areas they are not normally found (Murlis et al., 1992), such as our traps. On the other hand, taxa containing larger numbers of smaller insects, such as Diptera and Psocoptera (which saw a negative effect of wind), may have flight completely inhibited beyond certain speeds (Riley et al., 1993).

More Diptera were caught at later dates. As date was correlated with moon phase, this variable was excluded from the model, but could be an explanation for this change; a fuller moon, which peaked towards the end of this study (Time and Date, 2024b), results in an increased overall atmospheric lux; as this study has discovered, a higher lux results in more attraction.

Daily mean windspeed was also seen to impact the effect of light intensity on the number of insects caught, resulting in a weaker effect of light intensity on abundance in the general population, and a stronger effect for Diptera. This may be due to individuals being blown into traps indiscriminately, rather than being able to express their attraction as under normal conditions. As for Dipterans, with to fewer individuals being caught under windy conditions, perhaps only stronger light intensities proved an incentive for these individuals to fly under more difficult circumstances. Temperature also strengthened the effect of light intensity on the number of Diptera, potentially for the same reason.

4.4 Community Composition

Our results showed that change to light intensity was not a driver for changes to community composition, meaning we are unable to accept the hypothesis of increasing changes to community composition as a function of light intensity. Our results did show non-significant trends towards increased diversity (Shannon-Wiener) and increased dominance (Simpson). As these trends are in direct conflict with one another this can only be interpreted as indicating complex interactions, by which species richness remains stable but the relative abundance among species changes. Previous literature (Davies et al., 2012) has concluded that increasing ALAN intensity directly impacts invertebrate community, increasing the percentage of predators and scavengers. While Davies et al. (2012) focused on ground-dwelling, rather than aerial invertebrates, it is worth noting that this study followed a much deeper investigation into community structure. Though the use of Simpson and Shannon-Weiner indices provides a valuable overview of changes to community composition, a more in-depth study, perhaps to a species- rather than order-level into this aspect may reveal more drastic changes.

Instead of light intensity, daily mean temperature appeared to be the main driver of changes to community composition, with higher temperatures resulting in significantly higher species richness and dominance. This suggests that despite differences in light attraction between taxa, this does not lower the wide variety of insects affected by light pollution.

4.5 Time of Arrival

Time of arrival at light sources provides insight into potential disruptions of normal activity patterns, which could have ecological consequences for insects. Changes in activity timing may affect foraging success, predator avoidance, and reproductive opportunities. For example, insects active outside their optimal time period may face increased predation risk, reduced access to food resources that are temporally available, or missed mating opportunities with conspecifics that maintain normal activity patterns (Gaston et al., 2017).

We analysed the effect of light intensity on daily insect activity by looking at their time of arrival at light traps the two intensities; approximately 2 lux (low) and 10 lux (high), compared to those caught at a dark control. Our results showed that light intensity did not impact time of arrival for any of the taxa we analysed, meaning our initial hypothesis of differences between light intensities must be rejected. If anything, there was a non-significant trend of later arrival, where it may be expected that insects would arrive earlier, due to the increased attraction to higher light intensities, as observed in this study. While these findings appear counterintuitive, we suggest two possible explanations, though we acknowledge these interpretations are speculative and require further investigation. First, this could be due to the dorsal light response (Fabien et al., 2024); insects are attracted to increasing light sources, but spend a period of time circling them (perhaps more with higher light intensities), before reaching exhaustion and being caught in the traps, causing no difference, or later arrival times. Second, ALAN has been observed to affect navigational ability (Owens & Lewis, 2018; Ugolini & Chiussi, 1996); insects remain attracted to higher light intensities but may take increasingly longer to reach them due to increasing navigational impairment.

As this test appears to be unique to this study, it is difficult to compare to previous literature. What has been established is that individuals in areas long polluted by artificial light sources are much more adapted and less affected than those in newly polluted areas (Altermatt & Ebert, 2016). Location with newer light sources may observe changes to peaks of activity.

We did, however, see that several environmental variables made periods of insect activity occur later in the general insect population, including temperature and windspeed. For individual taxa, temperature (Diptera, Hemiptera) also pushed back time of arrival. As with abundance, wind and high temperatures impact flight through distortion or inhibition of flight patterns (Riley et al., 1993) that may cause later arrival, while high temperatures are likely to induce a period of heat stress recovery that may cause arrival at later, cooler times (Speights et al., 2017). Alternatively, higher temperatures may allow diurnal insects to fly at later time periods, where they may then later become attracted to the artificial light (Lewis & Taylor, 2009).

4.6 Limitations

This study has effectively built upon previous research regarding the impact of light pollution on nocturnal flying insects, in urban environments (Bolliger et al., 2020). Particularly unique to this study is the temporal aspect, identifying activity peaks through time of arrival. Aspects that remained difficult were identifying which variables to use when faced with multi-collinearity; it may have been beneficial to include factors such as moon phase, as the reasons behind the effect of ‘date’ remain speculative. Additionally, while sticky traps were the most suitable for this study, allowing for monitoring of time of arrival and taxon identification, there were still a large number of individuals that managed to escape and were subsequently considered 'NA' regarding their taxon; it may be useful to try alternative glue types. Other limits include the data processing of the sticky sheets for this study, taking up a lot of time. Future studies might benefit from alternative methods such as algorithms for picture recognition or radar. Finally, while this provides a beneficial representation of the impact of ALAN on insects, variations in study season and light-source height may give rise to other results (A'Brook, 1973), emphasising the importance of growing the literature base on the impact of ALAN on insects.

4.7 Conclusion/Implications

Artificial light plays an important role in modern society, allowing us to carry out important functions beyond the natural photoperiod (Boyce, 2019). However, with its expanding usage due to urbanisation, we must identify and mitigate negative consequences it could cause to already fragile ecosystems (Foster et al., 2021; Thawley & Kolbe, 2020; Sanders et al., 2020).

At the individual level, attraction to artificial light can lead to increased energy expenditure, disrupted foraging, and greater predation risk (Owens & Lewis, 2018). At the population level, these effects may translate to reduced reproductive success and fitness, particularly if they affect species already experiencing declines from other anthropogenic stressors (Sanders et al., 2021). Though this study did not provide an empirical measure for these effects on fitness, the attraction patterns observed are likely to cause such disruptions to natural behaviour that they create a pathway for negative consequences on insect populations in urban areas.

By identifying how the impacts of ALAN vary with intensity, this research can help inform urban planning and policy development to reduce ecological impact, whilst keeping in mind the intended human purpose of ALAN. This study saw that for several taxa, including Hymenoptera, Hemiptera, and Psocoptera, lower light intensities did not increase attraction, and for others that were attracted to even low levels, such as Diptera, this attraction was significantly less than at higher light intensities. With this in mind, restricting ALAN to lower intensities, particularly in insect-dense habitats, could reduce its negative impacts on navigation, mortality, sight, foraging, and species interactions (Owens & Lewis, 2018). By identifying this impact on a taxa-level, future management strategies can be targeted based on conservation priorities; for example where light-sensitive species are of concern, ALAN intensity can be more strictly controlled. The reduction of ALAN intensity could also have human benefits, including reduced attraction of insects that carry vector-borne diseases to residential areas. Insects remain a vital part of urban ecosystems, and to this end, fortunately this study revealed that ALAN intensity did not affect the timings of insect activity on the individuals in this study. This has, however, been identified as a general concern related to ALAN (Eisenbeis, 2006; Gaston et a., 2015; Owens & Lewis, 2018), and so may be affected by other factors, such as wavelength.

4.8 Future Directions

BioClock will soon expand on this project by identifying the impact of changes in ALAN wavelength and light type on urban insects. The focus on these parameters complements this study on intensity, as both represent adjustable properties of artificial lighting that could inform mitigation strategies. This will further specify best-practice guidelines for ALAN usage, and potentially reveal the mechanisms behind variation in insect activity peaks, related to ALAN.

To fine-tune this study, future research may benefit from more advanced data processing methods, expansion the study period and varying ALAN-source height. A more in-depth investigation into changes to community composition may also provide useful detail (Davies et al., 2012).

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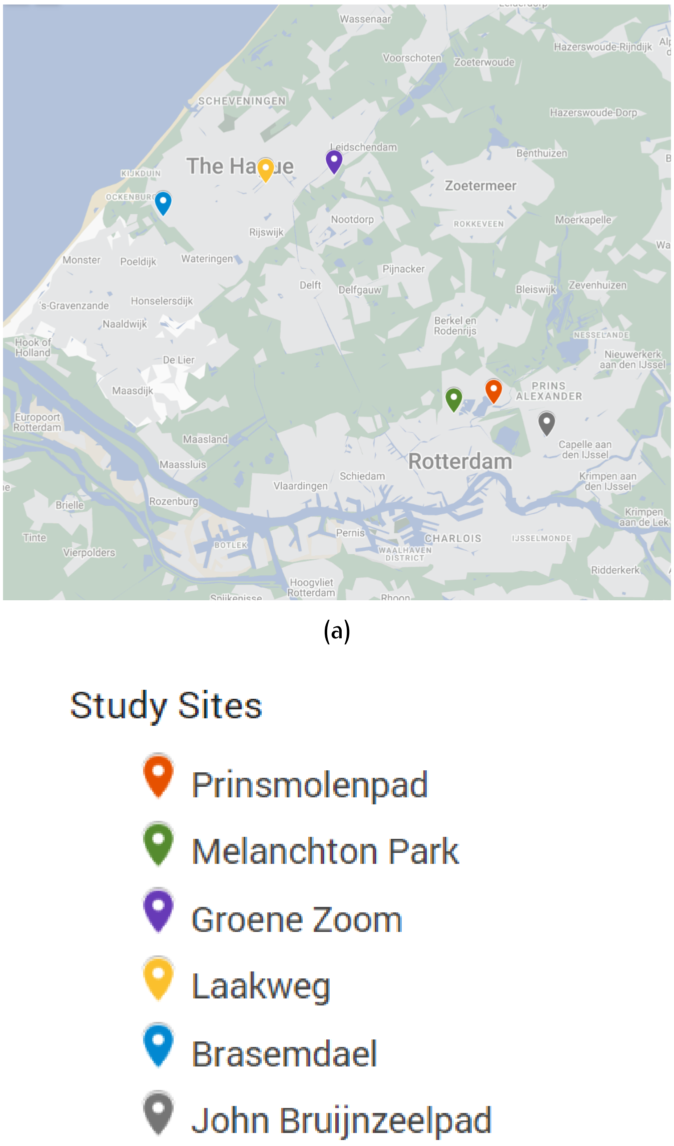
7. Appendix



(a)

(b)

Figure 7: Map of study sites (Created using GoogleMaps)