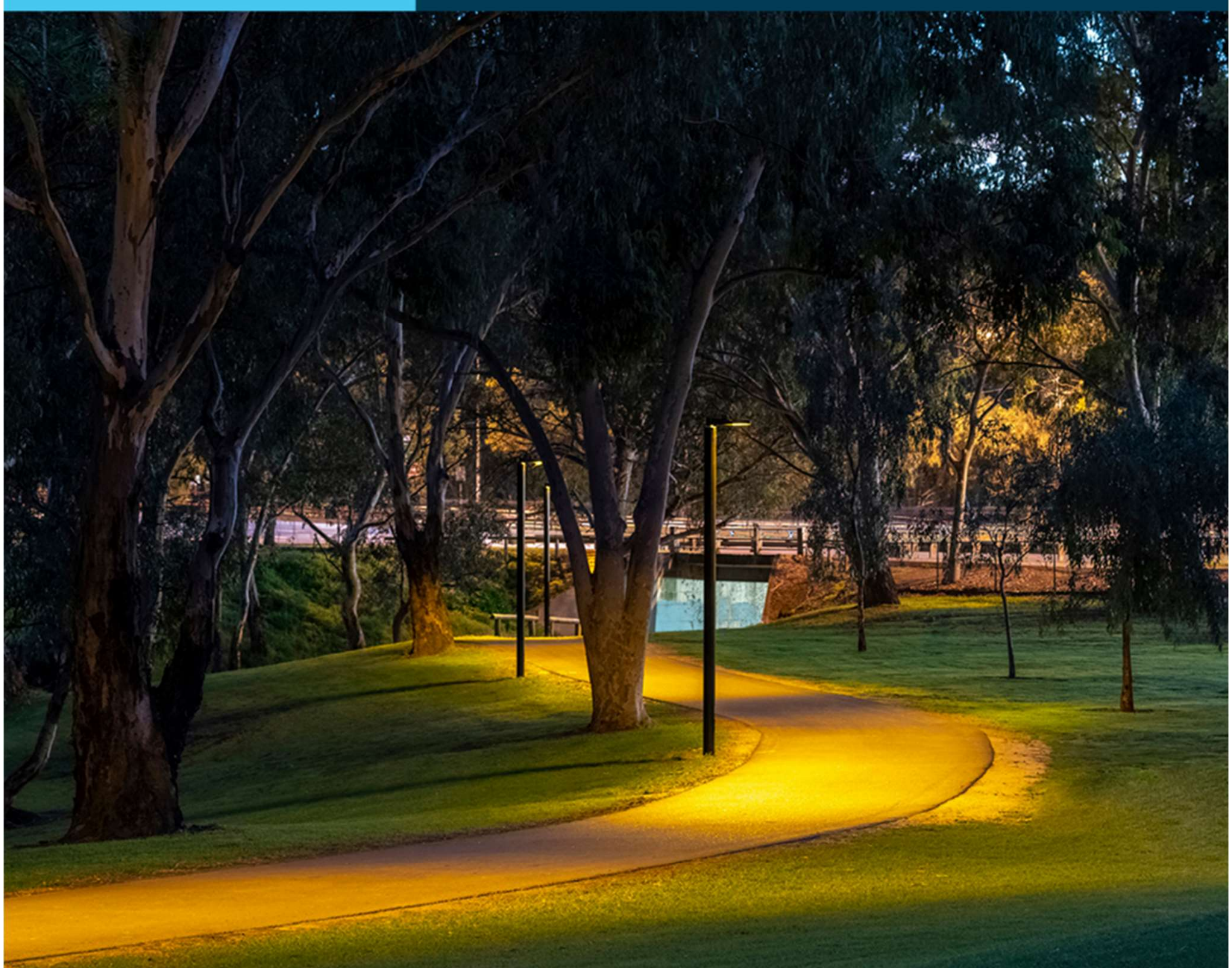
THE UNIVERSITY OF MELBOURNE

Faculty of Science

Using Acoustic Monitoring to Assess Wildlife Sensitive Lighting: A Case Study from South Australia



Report Commissioned by WE-EF

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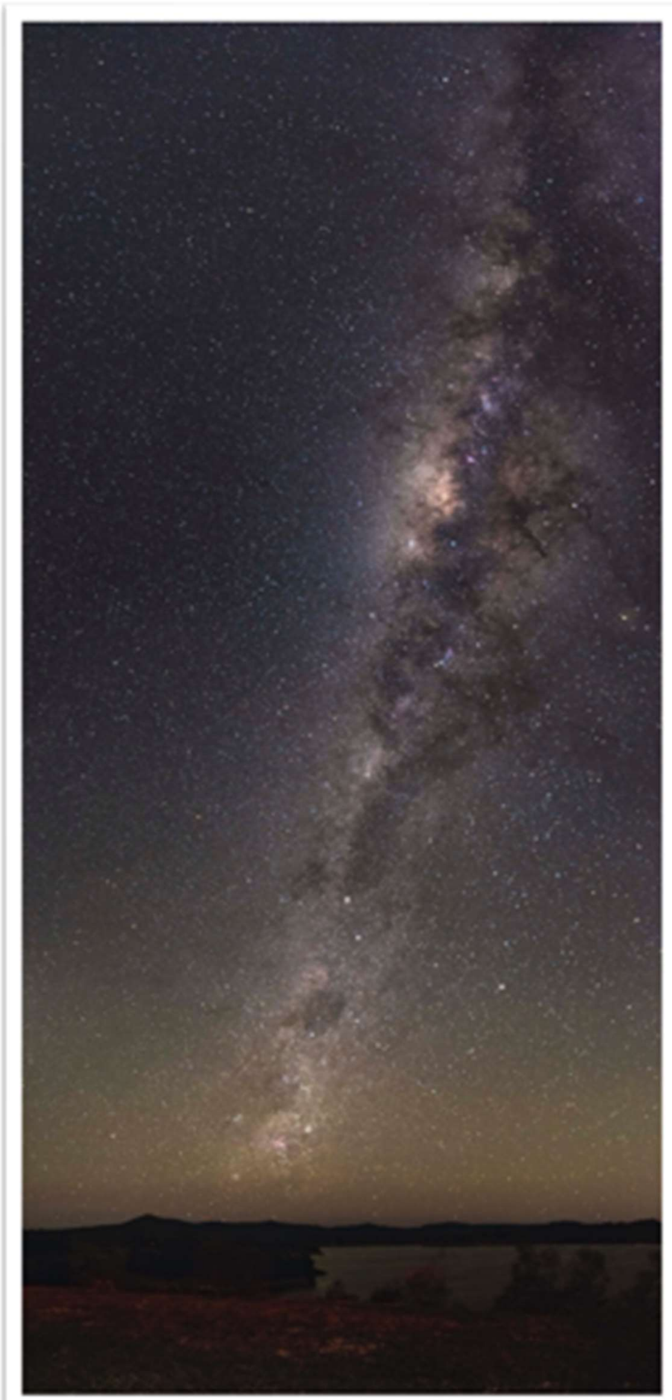
Acknowledgment of country

We acknowledge the Traditional Owners of the land where this work was carried out, the Wurundjeri and Boon wurrung people of the Kulin Nations (Victoria) and the Kaurna people of the Adelaide Plains (South Australia) and their deep connection to this land. We pay our respects to their Elders both past and present.



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1. EXECUTIVE SUMMARY

1.1 Background

Artificial light at night enhances the visual environment for humans but nocturnal lighting is a significant environmental pollutant that has negative ecological impacts. Wildlife sensitive lighting approaches and technologies have been proposed to reduce ecological impact. Typically, these fulfil the physical requirements of wildlife sensitive lighting including (allowing flexibility in the timing, intensity and colour temperature of the lights used. However, there remains a critical knowledge gap: few studies have demonstrated that wildlife sensitive lighting reduces ecological impact.

1.2 Addressing the knowledge gap

The Urban Light Lab (The University of Melbourne) partnered with WE-EF LIGHTING Australia Pty Ltd and The City of Salisbury (South Australia) to undertake a pilot study that explored variation in the wildlife responses to the presence and colour temperature of nocturnal lighting. We used an automated monitoring approach to gather acoustic data over a five-month period across three sites that varied in the presence (yes v no) and type (PC Amber v 3000k LED) of lighting. We then assessed how biodiversity and anthropogenic noise varied at the three locations using three standard ecological acoustic indices that measured biodiversity, with a particular focus on birds (ACI), loudness of the biological environment, with a particular focus on frog and insect chorusing (M) and anthropogenic noise, a proxy for traffic noise (RMS).

1.3 Project Aims

We had three specific aims: (i) Develop a protocol for monitoring the ecological impact of lighting using an automated audio recording approach; (ii) Develop a protocol for assessing the ecological impact of lighting using acoustic diversity indices to assess directly the impact of lighting on biodiversity; (iii) Use the acoustic monitoring and assessment protocols to provide a preliminary exploration of the impact of the presence and colour (PC Amber v 3000k LED) of lighting on biodiversity responses.

1.4 Methods

We deployed 13 automated recording devices (Audiomoths) at Little Para Trail (PC Amber lighting - 5 moths deployed); Dry Creek (No lighting currently – 3 moths deployed) and Mawson Lakes (3000k LED lighting – 5 moths deployed). We recorded for 13 hours/day for up to 14 days at a time between December 2023 and April 2024. Recording data and associated climate data per site were extracted using automated extraction and collection protocols. We also obtained a preliminary summary of LIDAR data for human movement through Little Para that aligned with the monitoring period.

1.5 Results

We collected 4759 hr worth of data (range = 60-144hr/device/recording period, N = 12 devices – one device vandalised). The three sites differed significantly in average radiance levels (Dry Creek = Little Para < Mawson Lakes) and overall biodiversity (Little Para > Dry Creek > Mawson Lakes).

Acoustic Biodiversity (ACI) - declined after sunset (the end of the dusk chorus) and after sunrise (the end of the dawn chorus) at all sites and, at Little Para (PC Amber site), was significantly related to variation in the natural moon cycle.

Frog and insect chorusing (M) - was highest at Mawsons Lakes suggesting that it may have a greater presence of these taxa. Overall, M declined over each daily time-period and was positively related to temperature (likely because insect and frog activity is temperature-related). M appeared to vary across the moonlight cycle, but the response was less clear compared to ACI.

Traffic Noise (RMS) – was significantly higher at Mawson Lakes than at the other two locations indicative of higher traffic and other anthropogenic noise. RMS varied with respect to moon and cloud cover which requires further explanation, but it was unrelated to temperature which is expected as it is an assay that measures anthropogenic, rather than Bioacoustic, noise.

LIDAR data (Little Para) - The LIDAR data from Little Para suggests that human movement aligns broadly with the RMS values and is significantly reduced during the central part of the night. This offers potential to introduce further approaches such as lighting curfews (adaptive lighting control between 10pm-4am for example) to reduce ecological impact.

1.6 Project Summary

This pilot study provides initial evidence to suggest that, at Little Para Trail, the use of PC Amber lighting is not totally masking natural variation in the moon cycle and thus may be sensitive to some of the needs of wildlife. A broader study across more sites, with differing light schedules (timing) and lighting intensities is required to confirm these outcomes and assess formally the efficacy of a Wildlife Sensitive Lighting Approach on ecological outcome.

1.7 Best Practice Approaches for Wildlife Sensitive Lighting

In the interim, it is suggested that all future lighting projects adopt a conservative approach to lighting. While there is a need to be aligned with the existing national lighting and design standards, conserving the ecological values of a particular area may require a degree of discretionary application. At a minimum, areas not used by humans, or that do not require lighting for safe use, should not be lit. Where lighting is required, wildlife sensitive lighting technologies and approaches should be incorporated in the decision-making process as they offer the best potential to reduce the ecological impact of lighting and are highly unlikely to be worse than current lighting. With this in mind, all park lighting should (where possible):

- be at the minimum intensity required;
- be directed only where intended;
- have adaptive light controls with flexible sensor capability to manage timing (ensuring only on when required), intensity (minimum for the location and dimmable to zero when not required) and colour temperature (2500-2700k should be sufficient for most parks);
- only be used during peak hours of human use only (sunset-10pm; 4am-sunrise). At all other times, adaptive lighting should (where possible) be employed to minimise light emissions;
- In areas where vehicles and pedestrians interact (carparks and crossing points), lighting should comply with Australian Standards, but the minimum (or close to minimum) specifications should be employed to reduce ecological impact.

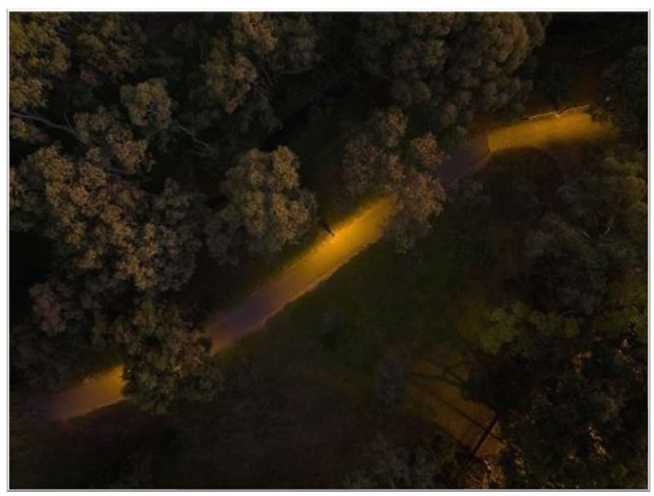
2. BACKGROUND

The use of artificial light at night (ALAN) during hours of darkness enhances the visual environment for humans; increases perceptions of safety and personal security and, as a consequence, facilitates human activities including commuting, sport, recreation and exercise (Davies and Farrington 2020, Svechkina, Trop and Portnov 2020). However, the presence of artificial light at night changes the nocturnal environment for all species, not just humans (Sanders, Frago et al. 2021).

ALAN is now recognised (albeit currently not legislated) as a significant environmental pollutant, that affects the physiology and behaviour of individual organisms (Longcore and Rich 2004, Holker, Moss et al. 2010). It can also significantly alter ecological communities and ecosystems because (rather like deforestation) its presence cuts an illuminated swath through natural habitat. This reduces connectivity between sites, affects the structure of biological communities and ultimately reduces ecosystem function and biodiversity (Korpach, Garroway et al. 2022).

The conflict between the human need for artificial light and wildlife's need for natural darkness demands a holistic lighting strategy that reduces disruption for wildlife, while allowing equitable access to night-time activities. This approach is often referred to as a 'wildlife sensitive lighting strategy' (or incorrectly as 'wildlife friendly lighting strategy') (Schroer, Austen et al. 2021, Owens, Dressler and Lewis 2022). In response to these needs, *Wildlife Sensitive* lighting technology (including timers, dimmers sensors, and amber and PC Amber LEDs) has been developed and is now increasingly cost-neutral. However, uptake remains patchy and has, until recently, been limited to high-profile ecologically sensitive locations.

Wildlife sensitive lighting technology is often physically sensitive to the presumed needs of wildlife: colour temperatures are as warm as possible, minimising blue light content; lights are placed only where they are required for wayfinding and glare is minimised; upward light spill is eliminated; lights are controlled and, where possible, on sensors ensuring lights are only on when needed; intensity is as low as affordable for the given area; and, the minimum number of lights installed. However, there remains a critical knowledge gap: *few studies have demonstrated that wildlife sensitive lighting reduces ecological impact*.



3. ADDRESSING THE KNOWLEDGE GAP

To redress this imbalance, The Urban Light Lab (University of Melbourne) partnered with WE-EF LIGHTING Australia Pty Ltd and The City of Salisbury (South Australia) to conduct a pilot study to explore variation in the wildlife responses to the presence of nocturnal lighting. We chose three sites that varied in the presence (yes v no) and type (PC Amber v 3000k LED; see the **Appendix** for differences in spectral output) of lighting. We used an automated monitoring approach to gather acoustic data over a five-month period and then assessed how biodiversity and anthropogenic noise varied at the three locations using ecological acoustic indices. We note that the nature of the study means these pilot data should be used as indicative rather than definitive of outcomes. Specifically, while there is within-site replication (multiple recorders deployed at each site), the project lacks replication in terms of lighting (one site per lighting treatment). This reduces interpretation of the results, but it does provide preliminary data to inform next steps.

3.1 Soundscapes as a means to measure biodiversity

Acoustic soundscapes, or Bioacoustics, are increasingly recognised as effective tools for measuring biodiversity (Kotian, Biniwale et al. 2024, Qiu, Tong et al. 2024, Santos, Wiederhecker et al. 2024, Turlington, Suárez-Castro et al. 2024). Recent technological developments in automated sound collection and processing offer significant potential for rapid and cost-effective monitoring of biodiversity, an essential task in the face of global land-use change. There are several advantages to monitoring using automated recording of soundscapes that include: they are

(i) non-invasive, which reduces disturbance to the habitat or the organisms within and is thus particularly beneficial for studying sensitive or endangered species.

(ii) able to operate continuously over long periods, providing extensive temporal data that would otherwise be impossible to collect. Moreover, data can be captured both day and night allowing for exploration of diurnal, seasonal, and annual patterns in biodiversity.

(iii) able to capture the sounds of a wide range of organisms, including birds, amphibians, mammals, and insects allowing a comprehensive assessment of biodiversity in an area.

(iv) relatively affordable and easy to deploy. This makes them accessible for widespread use, even in remote, difficult-to-access or potentially vulnerable areas.

(v) if appropriately used, able to act as indicators of ecosystem health allowing assessment of variation in habitat quality, species interactions, and environmental stressors.

4. AIMS

Capitalising on the recent instalment of PC Amber lights at Little Para Trail, the pre-existing 3000k led lighting on the Park Way Mawson Lakes Trail; and the proposed 2024 installation of amber lights into a previously unlit area (Dry Creek Trail) we assessed the degree to which wildlife sensitive amber lights influenced temporal and geographic biodiversity. We use the acoustic soundscape as our measure of biodiversity. We had specific three aims:

Aim 1. Develop a protocol for monitoring the ecological impact of lighting using an automated audio recording approach;

Aim 2. Develop a protocol for assessing the ecological impact of lighting using acoustic diversity indices to assess directly the impact of lighting on biodiversity;

Aim 3. Use the acoustic monitoring and assessment protocols to provide a preliminary exploration of the impact of the presence and particularly type of lighting (plus other abiotic variables) on biodiversity.

5. Methods

5.1 Site Selection

Sites were identified based on their current or proposed lighting technologies as well as their availability. Given the nature of the pilot study, we were restricted in the number of sites that could be monitored resulting in two already lit sites (Little Para Trail and Mawson Lakes) and one currently unlit, but proposed to be lit site, (Dry Creek) (see **Figure 1** for locations and **Table 2** for an overview of the sites). The three sites were proposed by the City of Salisbury and collectively agreed upon as appropriate for the pilot study by all parties.

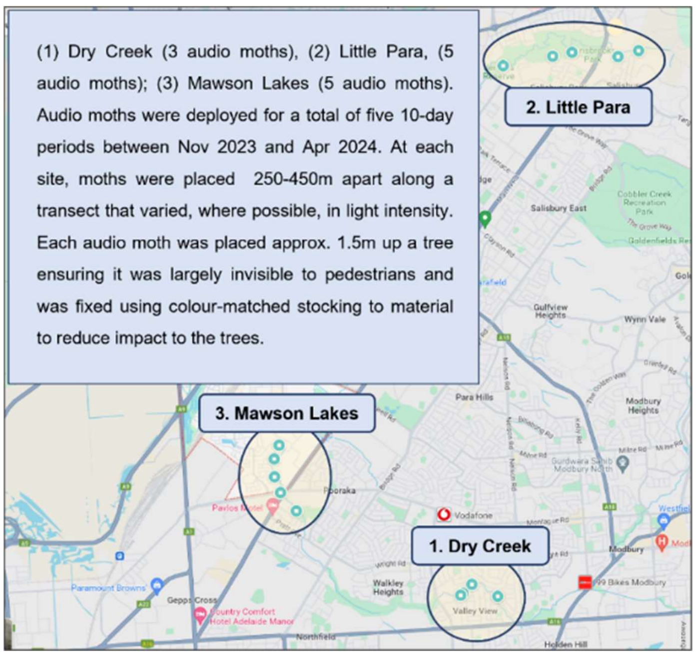


Figure 1. Location of the 13 Audiomoths deployed across the City of Salisbury between Nov 2023 to Apr 2024 (each audio moth is represented by a blue circle with a central square). See Table 2 for full details.

5.2 Audio moths - Location and Scheduling

A total of 13 Audiomoths were deployed between December 2023 and April 2024 (see **Table 2** for exact co-ordinates). Each device was installed on a single tree secured (at approx. breast height) using stocking material. Where possible, we ensured the device was not visible from the track (see **Figure 2** for examples). Due to the nature of the chosen sites, most devices were deployed within audible distance of a road or heavily used pathway/trail.

We set the recording schedule of the Audiomoths to record every minute from approximately two hours before sunset until approximately two hours after sunrise for up to 12 days (batteries and SD cards limited recording duration). This schedule allowed us to partition the day into three time-periods for analysis – sunset (two hours prior and after sunset), night (between 10pm and 4am), and sunrise (two hours prior and after sunrise). These time partitions were chosen as they are ecologically relevant both in terms of biodiversity (sunset – dusk chorus and crepuscular species active, night – true nocturnal species active, sunrise – dawn chorus) but also in terms of anthropogenic impacts of human and vehicular traffic.

We changed the batteries and SD cards approximately monthly. A full change of all three sites took two experienced researchers approximately five hours.

Table 1. Site descriptions for Dry Creek Trail, Little Para Trail, Mawson Lakes.

Site	Description
Dry Creek Trail (No trail lighting present during the trial period)	Three Audiomoths were deployed spanning along an 800 m stretch of path bordering Dry Creek to provide background diversity measures. This path is proposed as a location for future lighting installation. The Dry Creek site is already heavily lit by white LED street lighting on one or both sides of the proposed path and there is a road intersection running through the middle of the site.
Little Para Trail (PC Amber lighting was introduced to this site in 2022; prior to this there was no lighting)	Five Audiomoths were deployed along a 2.5km stretch of the trail. We deployed two devices in the centre of the trail, and then 1-2 moths at approximately 500m distances from the centre. This configuration allowed testing of within-site differences between the lightest (centre moth bounded by trail lights either side) and darkest areas (end moths which had less or no trail lighting). The trail runs through grassland and there are multiple large native trees and bushes bordering as well as a creek that runs alongside. At the eastern side of the trail the installed lighting ends but above the trail there is an urban area with street lighting.
Mawson Lakes (3000k LED white lighting already present on the trial; currently being viewed for replacement)	Five Audiomoths were deployed along a 1.4km stretch of the trail. We placed one audio-moth at the centre and 2 moths either side. This trail runs alongside a heavily industrialised area and is bordered at several locations by houses. At several locations there are bright streetlights that spill over into the trail area. The trail borders a creek for much of its length and passes through a substantial sports area at the southern end.

5.3 Acoustic Indices

To quantify and compare acoustic diversity across the locations we used three acoustic indicators: the Acoustic Complexity Index (ACI), the Median Amplitude Envelope (M) and the Root-Mean Squared amplitude (RMS) (see **Table 3** for a description of the acoustic assays used). These three measures provide two direct assessments of Bioacoustics related to biodiversity: ACI is a good proxy for bird diversity and M responds well to the continuous sounds commonly produced in anuran and orthopteran chorusing. These two measures are uncorrelated and thus distinct in their output. We combined these with an acoustic assessment that is targeted at lower frequency continuous sound production typical of anthropogenic noise (RMS).

Table 2. Audio-moth locations and radiance values for 2022 and (2023) over a 500m radius for each deployed Audio-moth (1-13) at Dry Creek (DC), Little Para (LP) and Mawson Lakes (ML). The 500m radius is dictated by the Light pollution map but is an ecologically relevant distance for activity and movement patterns of animals (both invertebrates and vertebrates).

Site/Audio-Moth	Audio-moth Co-ordinates	Radiance 10^{-9} W/cm^2 * sr Mean	SD	Min	Max
Dry Creek (DC)		12.6 (13.2)	2.11 (2.31)	10.0 (10.7)	15.5 (16.6)
1	-34.840771868436609, 138.6582393056703	12.1 (12.9)	1.88 (1.87)	10.0 (10.7)	14.0 (15.0)
2	-34.83887427490089, 138.65327997179165	11.7 (13.9)	1.32 (2.92)	10.0 (10.7)	13.7 (18.7)
3	-34.84059382336485, 138.65110224321242	13.8 (12.7)	3.12 (1.84)	10.0 (10.7)	18.7 (15.4)
Little Para (LP)		10.1 (10.8)	3.27 (2.96)	5.76 (6.82)	14.8 (14.9)
4	-34.75485876981883, 138.68511121443942	7.36 (8.24)	3.57 (3.56)	3.20 (4.00)	12.4 (13.4)
5	-34.755807542707565, 138.68132204197664	11.4 (12.0)	4.22 (3.56)	5.20 (6.70)	17.0 (16.5)
6	-34.75518491172892, 138.67258890163382	11.4 (12.0)	4.22 (3.13)	5.20 (7.80)	17.0 (16.5)
7	-34.755688946692636, 138.6686553797439	9.38 (9.80)	2.02 (2.10)	7.60 (7.80)	12.8 (12.7)
8	-34.75728997852225, 138.65945310376287	11.3 (11.8)	2.31 (2.45)	7.60 (7.80)	14.6 (15.4)
Mawson Lakes (ML)		34.8 (35.3)	6.93 (7.16)	25.1 (25.3)	42.8 (43.8)
9	-34.81696971465492, 138.61632024351738	31.2 (31.1)	5.50 (5.98)	23.7 (22.7)	39.0 (39.6)
10	-34.81910653144941, 138.61532505645508	33.4 (32.0)	7.46 (8.19)	23.1 (22.7)	41.8 (43.2)
11	-34.8219607713957, 138.61536333291923	38.1 (39.7)	4.67 (4.80)	29.6 (30.7)	42.8 (44.3)
12	-34.82440119902024, 138.61655628143586	40.0 (41.2)	5.73 (5.70)	30.3 (31.5)	45.1 (45.9)
13	-34.827318095988936, 138.61958649847915	31.1 (32.3)	11.3 (11.4)	18.6 (17.9)	45.1 (45.9)

Table 3. The three acoustic assays used as proxy measures for assessment of diversity

Acoustic Index	Definition (Reference)	Proxy measure
The Acoustic Complexity Index (ACI)	The Acoustic Complexity Index is an algorithm created to quantify the variability of the intensities registered in audio-recordings to estimate complex biotic sounds (Pieretti, Farina and Morri 2011). The index measures the Bioacoustics in the presence of constant anthropogenic noise – making it ideal for our study. The formula for ACI makes use of the fact that wildlife acoustics are typically characterised by a variability of intensities, while anthropogenic noise (e.g., traffic noise) typically occurs at very constant intensity values. ACI typically increases with the number of different vocalisations in a soundscape.	Number of different individuals or species calling (good proxy measure for bird biodiversity)
Median Amplitude Envelope (M)	The Median Amplitude Envelope (M) reflects the median amplitude of a recording. It describes the overall sound intensity of an environment, capturing both the loudness and the presence of various sound sources. As species compete for acoustic space there should be variation in frequency and temporal patterns that minimise the overlap of songs. This index therefore relies on the assumption that more species in a community corresponds to a more heterogenous acoustic environment. Higher mean amplitude values thus typically reflect noisier soundscapes, but this could be due to natural sounds like variation in animal calls or anthropogenic noise.	Loudness of the environment (good proxy measure for chorusing species and thus for insect and frog presence and calling behaviour)
Root-Mean Squared (RMS)	The Root-Mean Squared amplitude (RMS) is an acoustic metric which provides an estimation of the amplitude average for any given sound wave (Sueur, Krause and Farina 2021). Effectively it measures the average sound level of a recording – i.e. where there is an increase in sound intensity RMS will increase. It is commonly used to measure changes in continuous sound (characteristic of many human-generated noises) and has previously been used to measure changes in shipping noises to evaluate their effects on fish communities (Popper and Hawkins 2018, Slabbekoorn, Dooling and Popper 2018). Here, we used it as a proxy for traffic noise.	Anthropogenic noise (Traffic/human)

Figure 2. Audiomoth deployment. A) Equipment and housing for Audiomoths; B) An audiomoth; C) stocking attachment; D & E) Deployed audiomoth in a tree.

5.4 Extraction of abiotic climatic variables

Climatic factors were extracted automatically from the visual crossing website (https://www.visualcrossing.com). We extracted sunrise, sunset, ambient temperature, humidity, windspeed, cloud-cover, and percent illumination of the moon. Data were extracted for the central co-ordinate at each of the three sites for every minute of recording. Light data at each of the Audiomoths was also extracted using the light pollution map (https://www.lightpollutionmap.info/). We used the VIIRS 2023 overlay and the area tool (circle) to extract radiance values for 2021 and 2023 (prior to and after deployment of the PC Amber lighting at the Little Para Trail). Means, Standard Deviations, Maximum and Minimum values were extracted in a 500m radius about each device (**Table 2**). While the 500m radius is dictated by the online program it is ecologically relevant in terms of wildlife movement and the detection distance (approx. 300m) of the Audiomoths.

5.5 Summary LIDAR data (Little Para only)

In addition to the audio and climatic data The City of Salisbury were using an automated collecting data on human traffic (pedestrian, bicycle and scooter) – LIDAR (Light Detection and Ranging). LIDAR is highly effective for monitoring human movement due to its:

1. **High spatial resolution** that facilitates 3D maps of environments, capturing the exact location and movement of individuals within a space. This high spatial resolution allows for precise tracking of human movement, distinguishing between different individuals and their specific actions.
2. **Accuracy and precision** that provides accurate distance measurements by using laser pulses to determine the distance between the sensor and objects (or people) in its path.
3. **Ability to collect data under various lighting conditions** that facilitates effective operation in both daylight and darkness, allowing 24/7 monitoring in varying lighting conditions.

4. **Non-Intrusive and Privacy-Friendly** meaning it generates 3D point clouds rather than detailed images and is thus more privacy-friendly, making it suitable for monitoring in public spaces where privacy concerns are paramount.

Here, we utilise the summarised data from the monitoring time period only (5pm-8am) to provide an indication of the alignment between RMS values (in particular) and detected human movement - through the park. These data also provide an indication of the specific times period that the park is being utilised by pedestrians, bicycles and scooters.

5.6 Processing of Data and Statistical Approach

To simplify interpretation, prior to data analysis, we averaged the one-minute recordings into 15-minute blocks and partitioned data into the three time-periods (sunset, night, sunrise). We added all climatic variables, and time in all analyses. Initially, we compared variation in responses between all three locations, but we also explored within site variation for each location individually and specifically compared the two sites with lighting (i.e. excluding Dry Creek as these data were preliminary and essentially unrelated to lighting on the path).

6. RESULTS

6.1 Data collected and audiomoth recovery

In total, we collected 4759 hr worth of data over four complete time-periods. Three Audiomoths failed to record, were water-damaged or were physically removed and one audio-moth recorded interference during the collection period. This resulted in us discarding data from two Audiomoths (Little Para = device 5, Mawson Lakes = device 13) and a significantly reduced data set from a further device (Dry Creek = device 3). In addition, some issues with SD cards (cheaper cards were less effective) meant that not all moths recorded for the duration of their allocated recording period (Range = 60-144hr, Mean = 107 hr, Standard Deviation = 30hr, N = 12 devices). In addition, while only a single device was physically lost during the study, a further two were damaged beyond functionality suggesting that the extended time-period and exposed sites of deployment may require further thought for future studies.

6.2 Irradiance levels at the three sites of audiomoth deployment

An analysis of the intensity of nocturnal lighting across the three sites encapsulating the time before and after PC Amber lighting was installed into Little Para reveals significant differences in average radiance levels between sites (for all metrics; Dry Creek = Little Para < Mawson Lakes; all $P < 0.001$). There was little difference between years (overall, lighting increased by approximately 3% between 2021 and 2023). There was a small but consistent increase in the average irradiance levels at Little Para after the new PC Amber lighting was installed in 2022 (6% increase) but light levels remained comparable to Dry Creek and significantly less than Mawson Lakes. This suggests that the presumed advantage of the WE-EF VFL520s used in the installation holds true and that the PC Amber lighting is largely directed to where it is needed (i.e. onto the path) with limited ground or upward light spill.

However, the averages indicate that there was little difference in irradiance light levels within each site suggesting that any variation observed between moths at the centre and edges was unlikely to be related to light levels. A preliminary analysis of the data revealed that while there was variation in acoustic responses across the Audiomoths this was not related to light levels.

6.3 ACI – biodiversity (targetted at bird song)

ACI (a proxy measure for bird activity and biodiversity) was significantly lower at Mawson Lakes compared to either Dry Creek or Little Para. For all locations, ACI declined temporally over the dusk chorus (sunset) and again following the dawn chorus (sunrise). At all sites, ACI was significantly lower during the true night (10pm-4am). At Little Para and Dry Creek, there was a significant decline from 10pm through to 4pm, but Mawson Lakes remained consistently low and static over this time-period (**Figure 3**).

ACI was also significantly influenced by the natural moon cycle but again this was most significant at Dry Creek Little Para with the Mawson Lakes site revealing little variability (**Figure 3**). On average, ACI increased with Moon brightness during the sunset and sunrise periods at both Dry Creek and Little Para. In contrast, during true night (10pm-4am), ACI was positively related to moon brightness at Little Para (declining only on the brightest nights). This suggests that the PC Amber lighting is not masking natural moon cycles. A similar pattern was absent at Dry Creek during the night and for Mawson Lakes there was largely no variability in ACI levels over the three time-periods suggesting that the soundscape is not responding to shifts in natural moon phases. The temporal relationship (time of recording) between ACI and moonlight reveals comparable outcomes and emphasises the relatively static response of ACI at Mawson Lakes (**Figure 3**).

Finally, ACI was positively related to temperature during dusk and dawn choruses but negatively related to temperature during the true night which likely reflects reduced bird activity and calling behaviours.

6.4 M – chorusing (targetted at insect and frog chorusing)

M (a proxy measure for insect and frog chousing) varied significantly across the three locations (**Figure 4**): Mawsons Lakes had the highest values throughout suggesting that it may have a greater presence of frogs and/or insects; Dry Creek and Little Para were lower, but broadly similar to one another. Overall, M declined across all time-periods and, as for ACI, was significantly lower during the true night (10pm-4am) where it was also positively related to temperature. This latter result is unsurprising given M is a proxy for ectothermic insect and frog species whose nocturnal activity is related to (often reliant on) nighttime temperature thresholds. M appears to vary across the moonlight cycle, but the response is less clear compared to ACI (**Figure 4**). This may be because frogs and insects inhabit the more sheltered canopy or ground areas and thus may not experience the direct effects of variation in moonlight as frequently.

6.5 RMS – anthropogenic noise (targetted at traffic and human noise)

RMS values varied over time and across the three locations (**Figure 5**). The data suggest that RMS is significantly higher at Mawson Lakes than at the other two locations indicative of higher traffic and other anthropogenic noise but at all sites RMS declines over each time-period. There is some variation in RMS with respect to the moon and cloud cover which requires further explanation, but it was unrelated to temperature which is predicted for an assay that measures anthropogenic, rather than Bioacoustic, noise.

6.6 Variation across the recording period and in Audiomoths – random terms

There was significant variation across the entire recording period (significant effect of the random term date in all models). There was also significant variation in all parameters with respect to the individual Audiomoths.

Recording period (**Figure 6**) - With respect to ACI, there was significantly more activity during the middle of the summer (Jan-Feb) at Little Para which would be predicted by seasonal bioactivity patterns, however this pattern was less clear at Dry Creek and largely non-existent at Mawson Lakes. We also see variation in M across all sites, but this was less seasonal, although there is a notable peak at Dry Creek on 25/12/23 which may reflect less disturbance and more insect activity in the area. Finally, RMS is consistently highest at Mawson Lakes with some notable increased variability during the school holiday period at Little Para and Dry Creek.

Audiomoth locations (**Figure 7**) – we deployed Audiomoths at specific locations along the trail which we predicted would vary in the amount of surrounding light. We found significant within site locational variation (i.e. the Audiomoths differed), but these were not consistent with the predicted light environment suggesting a range of other (unmeasured) habitat variables (including ground cover, number of established trees, grass cover and distance to nearest streams etc) likely impacted on the recording and further exploration is required.

6.7 Summary LIDAR data from Little Para

The summary LIDAR data for Little Para are in broad alignment with the RMS data (a proxy for traffic and thus human activity) in as much as when human movement is high so are the values for RMS. It is also interesting to note that human movement and wayfaring is significantly reduced after 10pm which may introduce opportunities for a more adaptive lighting regime in this park that minimised lights when not required for human use/wayfinding.

7. SUMMARY

In relation to our three kay aims:

Aim 1. We have developed a protocol that can be used for monitoring the ecological impact of lighting using an automated audio recording approach. The protocol worked well for acquisition of data and was relatively easy to deploy across multiple sites. There were some technical difficulties that require adjustment if the study were to be repeated on a larger sample sise. Replacement of batteries and SD cards took approximately five hours for 13 devices across the three sites. Staggering deployment over time would be required if a larger number of devices were deployed over a larger area. To reduce replacement times, a reduced recording schedule that encompassed the sunset and sunrise windows plus a 4- rather than 6-hour block during the middle of true night would save 30% recording time and allow for an extended duration of recording per block. This would depend on the question being addressed but would be appropriate in most cases. We also note that a reduction in recording duration would reduce extraction and processing times – each recording time-block of 10-12 days took approximately 10 days (x a full 24hr) to extract data for the three assays used. High quality SD cards and batteries should also be used to ensure maximum recording duration. Finally, data and time were lost due to vandalism so where devices are placed is important and may limit chosen sites.

Aim 2. We have developed a protocol for assessing the ecological impact of lighting using acoustic diversity indices to assess directly the impact of lighting on biodiversity We combined our recording data with automated extraction of climatic data using R-code, websites and the light pollution map. The acoustic assays and associated code are readily available, although processing of the data took considerable time even with a high-power computer using the majority of its processing cores. However, time-aside, the three metrics used (ACI, M, RMS) appeared to provide a solid overview of variation in Bioacoustic and anthropogenic noise and were appropriate to explore how noise was affected by external variables at the three sites. More species-specific analyses are possible – specific sounds from target species may be extractable using an acoustic template approach - but these were outside the scope of the current project

Aim 3. We used an acoustic monitoring and assessment protocols to provide a preliminary exploration of the impact of the presence and type of lighting (plus other abiotic variables) on biodiversity responses. Emphasising that these data are preliminary, there are some key take-home messages from the study:

(i) Biodiversity (as measured by ACI) was significantly greater at Little Para and Dry Creek compared to Mawson Lakes. This likely reflects habitat differences as well as variation in the lighting environment but confirmation of this requires further investigation.

(ii) Insect and frog activity (M) was higher at Mawson Lakes. This likely reflects more individuals of particular species calling (i.e. increasing the loudness in the environment) rather than an increase in biodiversity but again this requires confirmation. There was less evidence that M responded to the moonlight cycle at any of the three sites lower moonlight levels were typically associated with reduced loudness (M). This may be because frogs and insects inhabit the more sheltered canopy or ground areas and thus may not experience the direct effects of variation in moonlight as frequently. It is possible that individual species calling behaviours would provide the required detail.

(iii) Light levels at all sites were more than 300 times the intensity of a full moon (0.03 – 0.1 lux) but light levels and anthropogenic activity were significantly higher at Mawson Lakes than either Dry Creek or Little Para. This reflects that the trail runs through a highly industrialised area and major roads run alongside the device deployment locations. Changing the lighting at this site may improve localised biodiversity.

(iv) Compared to Mawson Lakes, biological activity (as measured by ACI) at Little Para and Dry Creek varied significantly with natural variation in the moon cycle, for at least part of the recorded period. This pattern is most pronounced at Little Para suggesting that the PC Amber lighting is not totally masking natural variation in levels of moonlight and was at least comparable to a site that currently has no lighting.

(v) The recordings detected significant seasonal variation (over the duration of the recording period) which was most pronounced (and aligned with biological prediction) at the Little Para site. The degree to which this reflects natural variation in light levels (daily, monthly or annual), or other variables (within site biodiversity, habitat differences) is unclear.

(vi) There was significant variation within the sites (between the Audiomoths) although this did not appear to be directly related to light levels or their placement. It is noted that device placement was constrained and thus the design was not balanced – in particular, it was challenging to find dark spots and even the darkest area in all parks was likely brighter than natural light levels due to the amount of light pollution in the region.

(vii) Finally, the LIDAR data from Little Para aligns with the RMS data and suggests that human movement through the park also varies across a night. This introduces the possibility that additional measures could be introduced such as lighting curfews to reduce ecological impact. Under a curfew scenario, lighting should be on only when required for wayfinding and (where possible) should be restricted to peak hours of human use only (e.g. sunset - 10pm; 4am - sunrise). At all other times, adaptive lighting could (where possible) be employed to minimise light emissions when there is no human movement or requirement for lighting.

8. NEXT STEPS

The study provides a protocol and pilot data to assess the impact of one aspect (colour temperature – PC Amber v 3000k LED) of Wildlife Sensitive Lighting using the acoustic soundscape as a proxy for Biodiversity. To gain a fuller understanding of how other aspects of Wildlife Sensitive Lighting technologies (timing and intensity) may improve ecological outcome we suggest the following modifications:

8.1 Site selection and audiomoth deployment

(i) Replication – there should be a minimum of three replicated sites per lighting treatment each with five pairs of Audiomoths (N = 10 Audiomoths per site to reduce data loss at any given recording period).

(ii) Habitat variation – Where possible, habitat variation should be fully quantified using standardised ecological monitoring methods (and/or online data bases including Google Earth) and habitats should be replicated across all lighting treatments.

(iii) Acoustic recording timing – Using four-hour windows during sunset, sunrise and true night will likely provide high confidence as a proxy for biodiversity. Consideration could also be given to adding daytime assessment as it is known that nocturnal shifts in ecology can spill into the diurnal space (i.e. day). This could be a fourth four-hour block that spans the middle of the day.

(iv) Sampling schedule – Depending on the question, it might be appropriate to sample each site four times per year (total of 8 weeks per site) but the timing of sampling need not be identical for each site. If all lighting treatments are represented at each sampling block this may be sufficient.

8.2 Data analysis and additional variables of interest

(i) Developing an automated throughput for data analysis and reporting – this could save significant processing time.

(ii) Manual assessment of Biodiversity – Where possible, a pilot or preliminary data of actual biodiversity would be beneficial as a proxy measure to compare against the automated data.

(iii) Templates for targeted species – if particular species were identified and considered of interest, it would be advantageous to combine the biodiversity data with specific targeted species.

(iv) Additional variables for consideration - Pairing this approach with more detail traffic or human activity data would further enhance interpretation of the automated data.

9. BEST PRACTICE APPROACHES FOR LIGHTING TO REDUCE ECOLOGICAL IMPACT

Regardless of the monitoring and assessment approaches outlined above, there are a number of strategies and best practice approaches to potentially mitigate the presence of lighting for wildlife. The following recommendations align with the *National Light Pollution Guidelines for Wildlife (www.agriculture.gov.au/sites/default/files/documents/national-light-pollution-guidelineswildlife.pdf)* and findings from the *Wildlife Sensitive Tools Report* (Lockett and Jones 2022) (link can be found here: https://urbanlightlab.com/useful-resources/).

9.1 Alignment with existing standards

There is a clear need to be aligned with the existing national lighting and design standards (in particular, AS/NZS 1158.3.2:2020 - Lighting for roads and public spaces pedestrian area (Category P) lighting; AS/NZ AS/NZS 4282:2023 - Control of the obtrusive effects of outdoor lighting; and AS 2560.2.2021 - Sports Lighting). However, conserving the ecological values of a particular area may require a degree of discretionary application. This is within the boundaries of the guidelines - AS/NZS 1158.3.2:2020 acknowledges potential for ecological impact (albeit provides little guidance on delivery) and also explicitly states that “determining the applicable lighting category and subcategory each separate element needs to be assessed by considering its own particular operational characteristic”.

9.2 Guiding principles for wildlife sensitive lighting

At a minimum, areas not used by humans, or that do not require lighting for safe use, should not be lit (see *Wildlife Sensitive Tools Report*, *Design Guide – Part I*). Where lighting is required, wildlife sensitive lighting technologies and approaches should be incorporated in the decision-making process as they likely offer the best means to reduce the ecological impact of lighting and will be highly unlikely to do more harm than current lighting practices (see *Wildlife Sensitive Tools Report*, *Design Guide – Parts 2-4*). With this in mind:

(i) Lighting intensity should be reduced to a minimum wherever possible. Illuminance levels should not exceed the amount required by AS/NZ 4282 (control of the obtrusive effects of outdoor lighting), AS/NZS 1158 (paths, carparks), AS/NZS 2560 (sports ground) by more than 50% at any point.

(ii) Lights should be directed only where intended (lights should be close to the ground, directed and shielded to avoid light spill other than where light is required).

(iii) Have adaptive light controls with sensor capability to manage (i) light timing (ensuring only on when required), (ii) intensity (minimum for the location and dimmable to zero when not required) and (iii) colour temperature (<2700k should always be sufficient and <2500k should be initially considered and adopted where possible).

(iv) Adopt lighting curfews - if lighting is required this should (where possible) be during peak hours of human use only (sunset-10pm; 4am-sunrise). At all other times, adaptive lighting should be used to minimise light emissions. The data from Little Para suggest that this could be a viable future opportunity.

(v) In areas where vehicles and pedestrians interact (carparks and crossing points), lighting should comply with Australian Standards, but the minimum (or close to minimum) specifications should be employed (where possible) to reduce ecological impact.

Table 3. Model outcomes for full model analysis of ACI, RMS and M acoustic indices (data centred prior to analyses). Factors explaining significant variation denoted by P < 0.05 or below.

		Location	Time	% Moon	Location * Time	Location * % Moon	Time * % Moon	Temperature	% Cloud	%Cloud * % Moon
ACI – proxy measure for birdsong	Sunset	$F_{2,5694}=30.3$ $P<0.0001$	$F_{1,5694}=199$ $P<0.0001$ $\beta=-2e^{-2}(1e^{-3})$	$F_{3,5694}=0.85$ $P=0.47$	$F_{2,5694}=13.8$ $P<0.0001$	$F_{6,5694}=18.39$ $P<0.0001$	$F_{3,5694}=9.63$ $P<0.0001$	$F_{1,5694}=15.7$ $P<0.0001$ $\beta=0.13(0.03)$	$F_{1,5694}=8.11$ $P<0.0001$ $\beta=0.013(0.004)$	
	Night	$F_{2,9271}=354.4$ $P<0.0001$	$F_{1,9271}=33.72$ $P<0.0001$ $\beta=-2e^{-3}(3e^{-4})$	$F_{3,9271}=1.97$ $P=0.12$	$F_{3,9271}=8.22$ $P<0.0001$		$F_{6,9271}=26.6$ $P<0.0001$	$F_{1,9271}=7.44$ $P=0.007$ $\beta=-5e^{-2}(2e^{-2})$		
	Sunrise	$F_{2,5696}=22.75$ $P<0.0001$	$F_{1,5696}=62.99$ $P<0.0001$ $\beta=-1e^{-2}(2e^{-3})$	$F_{3,5696}=1.04$ $P=0.38$	$F_{2,5696}=13.54$ $P<0.0001$	$F_{6,5696}=18.35$ $P=<0.0001$	$F_{3,5696}=9.59$ $P<0.0001$	$F_{1,5696}=11.87$ $P=0.0008$ $\beta=11e^{-2}(3e^{-2})$		
M – proxy measure for chorusing insects/Frogs	Sunset	$F_{2,5734}=123$ $P<0.0001$	$F_{1,5734}=502$ $P<0.0001$ $\beta=-4e^{-5}(2e^{-6})$	$F_{3,5734}=0.91$ $P=0.44$	$F_{2,5734}=33.7$ $P<0.0001$	$F_{6,5734}=6.75$ $P<0.0001$	$F_{3,5734}=4.58$ $P=0.003$		$F_{1,5734}=11.6$ $P=0.0007$ $\beta=2.9e^{-5}(8e^{-6})$	
	Night	$F_{2,9262}=94.2$ $P<0.0001$		$F_{3,9262}=15.6$ $P<0.0001$		$F_{6,9262}=5.43$ $P<0.0001$		$F_{1,9262}=44.9$ $P<0.0001$ $\beta=2.e^{-5}(3e^{-5})$	$F_{1,9262}=0.18$ $P=0.67$	$F_{3,9262}=4.94$ $P=0.002$
	Sunrise	$F_{2,5725}=84.4$ $P<0.0001$	$F_{1,5725}=109$ $P<0.0001$ $\beta=-3e^{-5}(3e^{-6})$	$F_{3,5725}=0.90$ $P=0.45$	$F_{2,5725}=34.4$ $P<0.0001$	$F_{6,5725}=6.75$ $P<0.0001$	$F_{3,5725}=5.10$ $P=0.002$			
RMS – proxy measure for anthropogenic noise	Sunset	$F_{2,5729}=98.0$ $P<0.0001$	$F_{1,5729}=524$ $P<0.0001$ $\beta=-2.41,0.11$	$F_{3,5729}=0.88$ $P=0.46$	$F_{2,5729}=23.0$ $P<0.0001$	$F_{6,5729}=6.34$ $P<0.0001$	$F_{3,5729}=3.48$ $P=0.015$		$F_{1,5729}=14.3$ $P<0.001$ $\beta=1.95(0.52)$	
	Night	$F_{2,9270}=29.5$ $P<0.0001$	$F_{1,9270}=186$ $P<0.0001$ $\beta=-0.6(0.04)$	$F_{3,9270}=3.09$ $P=0.03$	$F_{2,9270}=25.81$ $P<0.0001$	$F_{6,9270}=8.68$ $P<0.0001$	$F_{3,9270}=4.84$ $P=0.002$		$F_{1,9270}=0.04$ $P=0.83$	$F_{3,9270}=3.43$ $P=0.016$
	Sunrise	$F_{2,5725}=72.8$ $P<0.0001$	$F_{1,5725}=126$ $P<0.0001$ $\beta=-1.9(0.2)$	$F_{3,5725}=0.85$ $P=0.47$	$F_{2,5725}=23.55$ $P<0.0001$	$F_{6,5725}=6.33$ $P<0.0001$	$F_{3,5725}=4.02$ $P=0.007$			

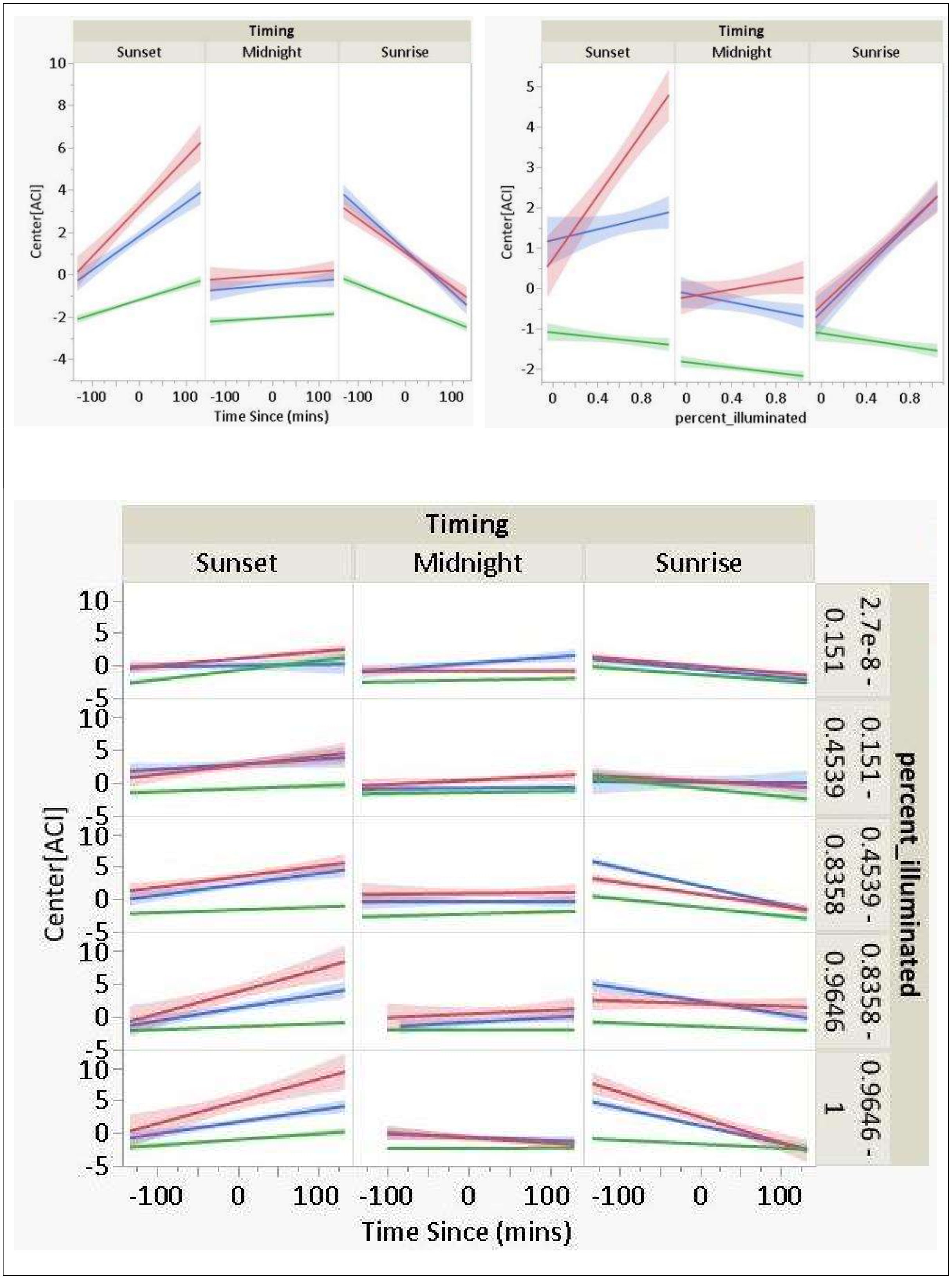


Figure 3. Variation in ACI at Little Para, Dry Creek and Mawson Lake throughout the night (top left); with the percentage visibility of the full moon (top right); and as an interaction between time and % moon (bottom). Little Para = Red; Dry Creek = Blue; Mawson Lakes = Green.

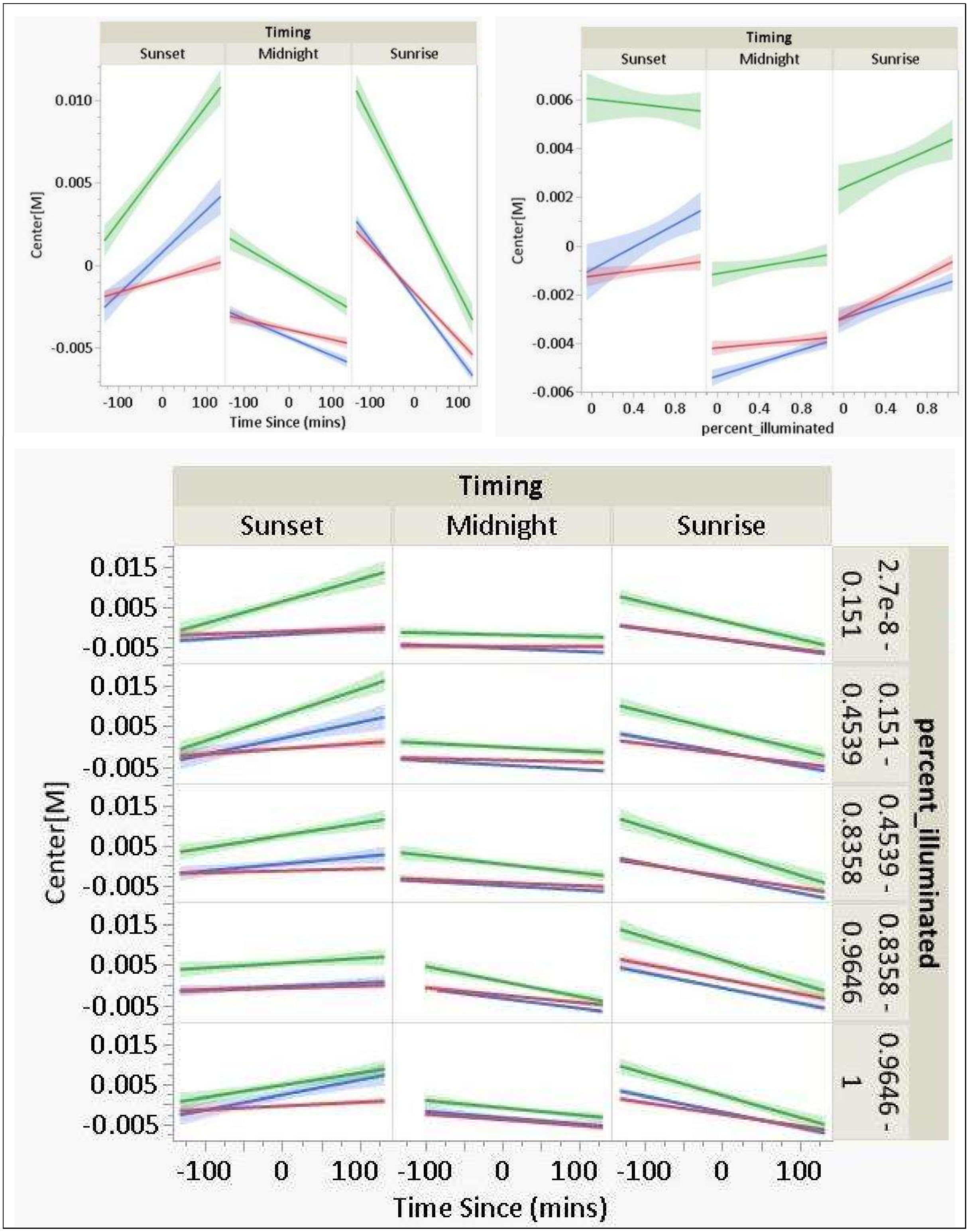


Figure 4. Variation in M at Little Para, Dry Creek and Mawson Lake throughout the night (top left); with the percentage visibility of the full moon (top right); and as an interaction between time and % moon (bottom). Little Para = Red; Dry Creek = Blue; Mawson Lakes = Green.

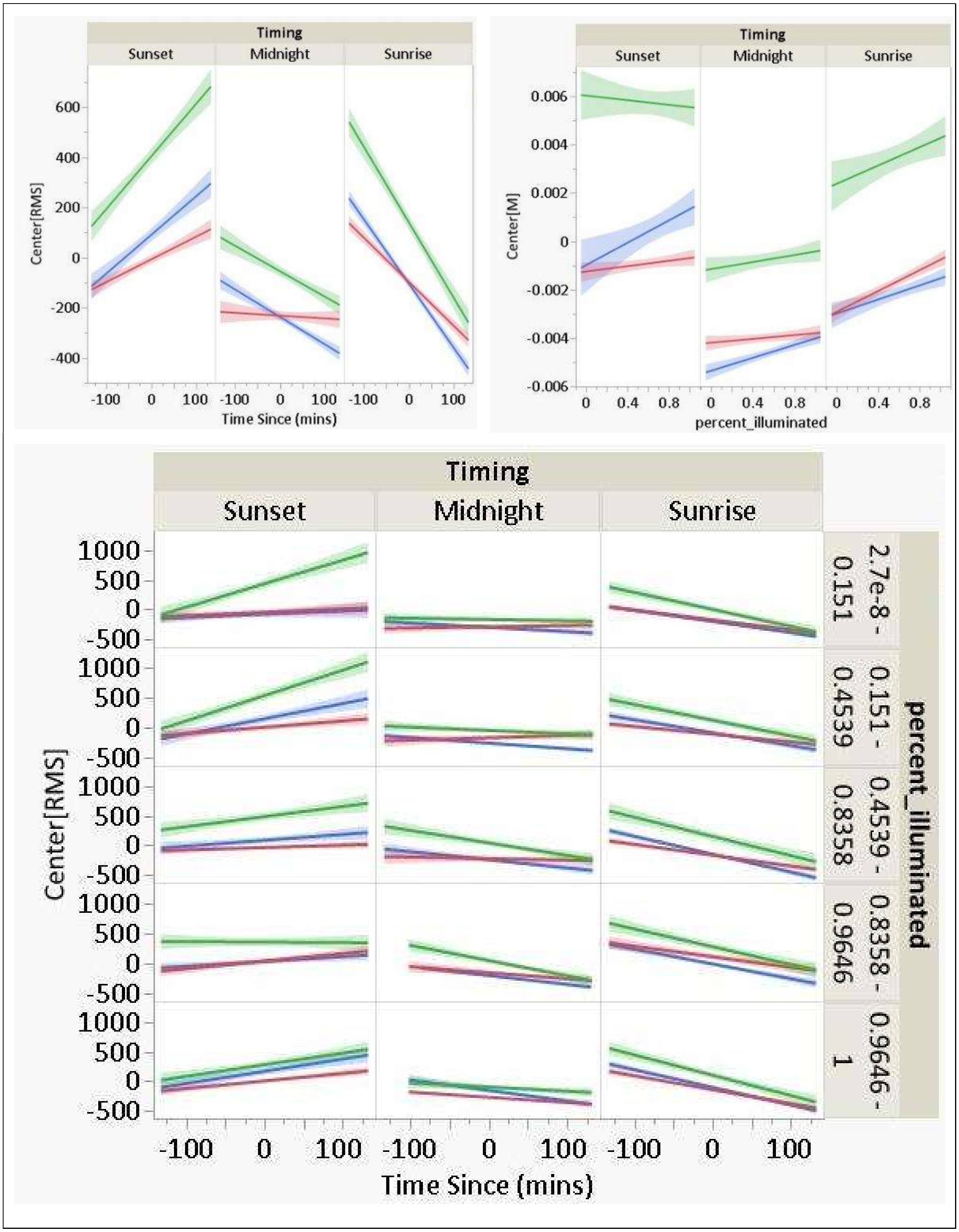


Figure 5. Variation in RMS at Little Para, Dry Creek and Mawson Lake throughout the night (top left); with the percentage visibility of the full moon (top right); and as an interaction between time and % moon (bottom). Little Para = Red; Dry Creek = Blue; Mawson Lakes = Green.

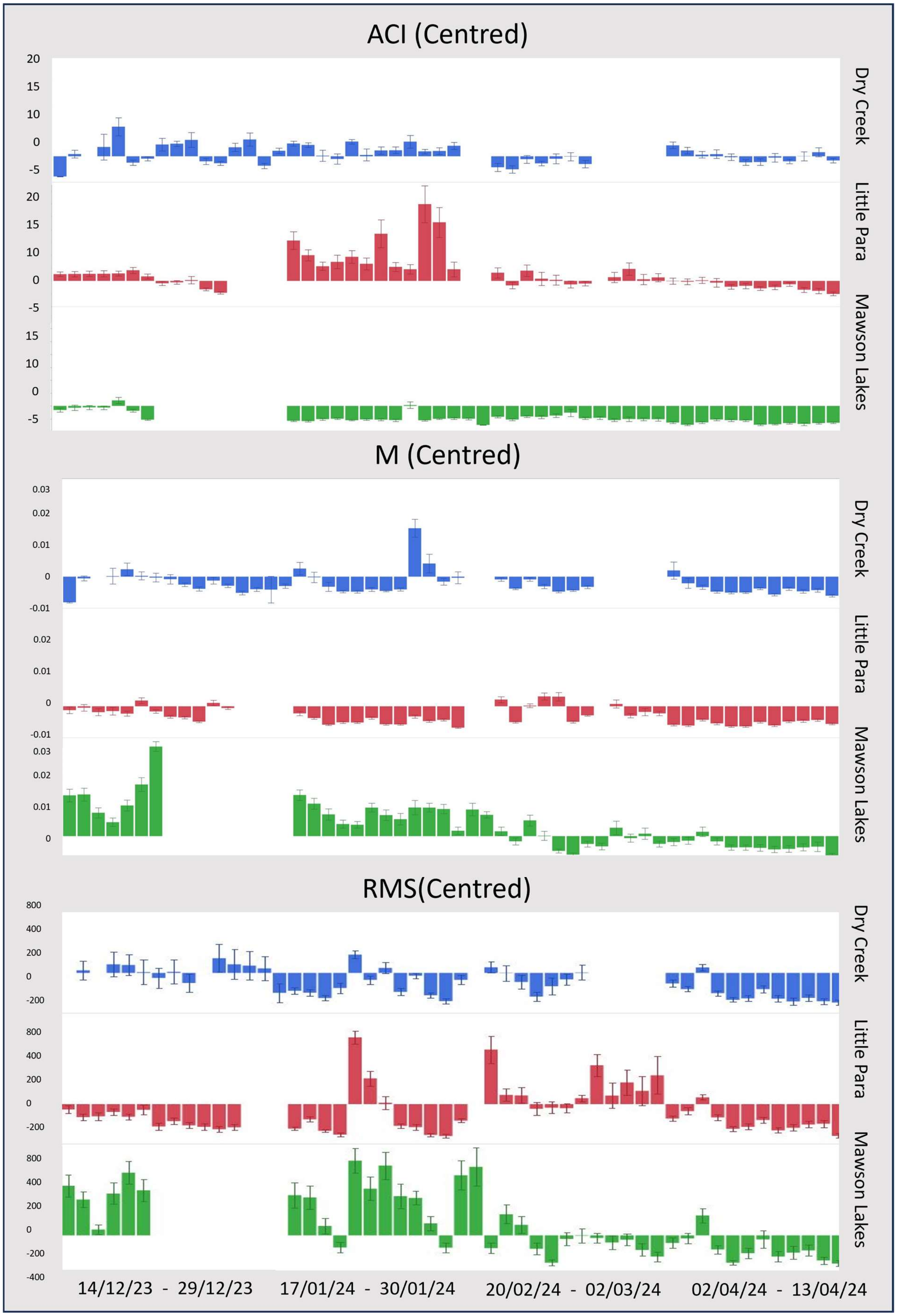


Figure 6. Variation in ACI, M and RMS at each of the three sites over the entire deployment period (14/12/23-13/4/24). Little Para = Red; Dry Creek = Blue; Mawson Lakes = Green.

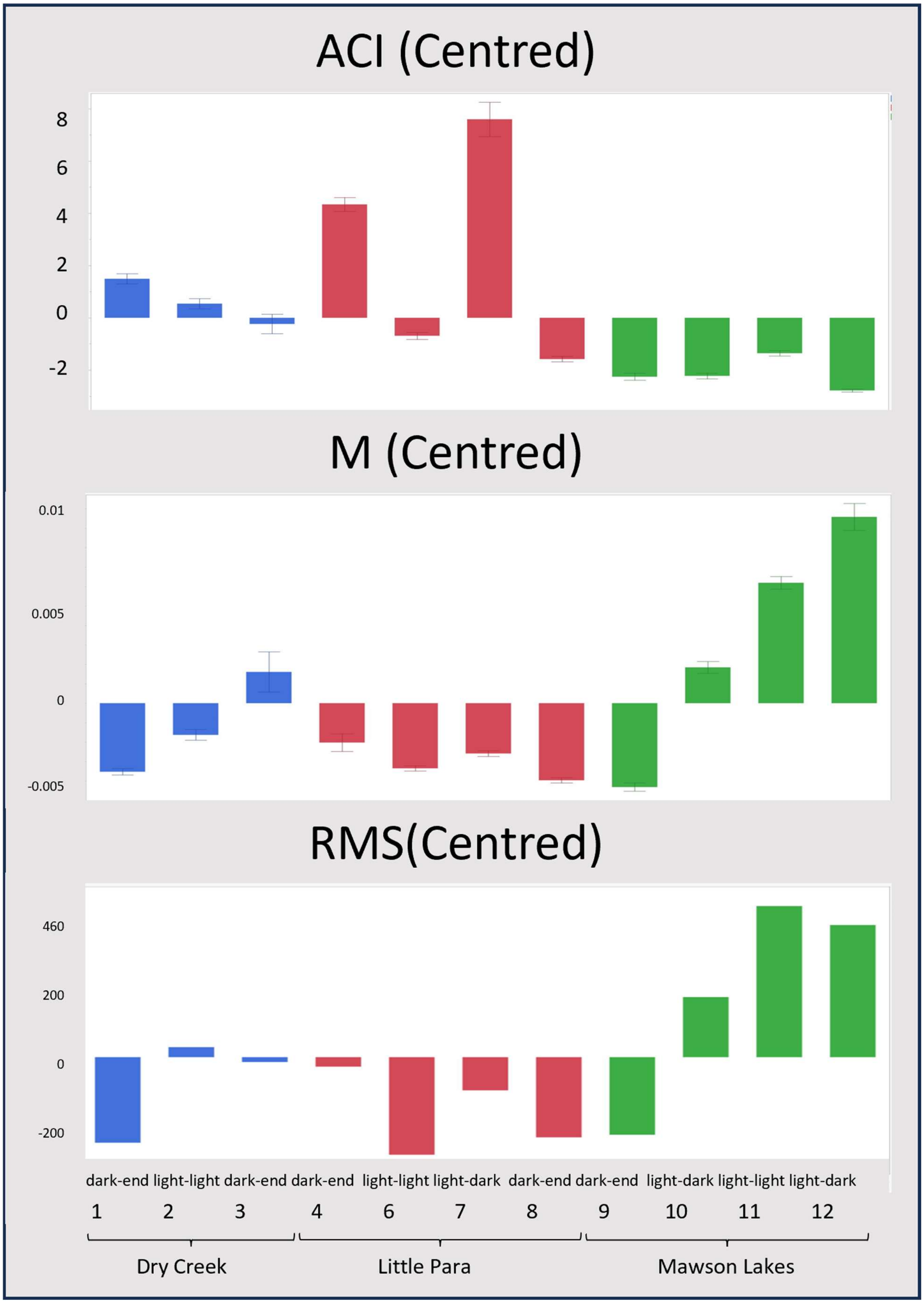


Figure 7. Variation in ACI, M and RMS for each of the Audiomoths (1-13) and light conditions (dark-end, light-dark, light light) across the three sites. Little Para = Red; Dry Creek = Blue; Mawson Lakes = Green.

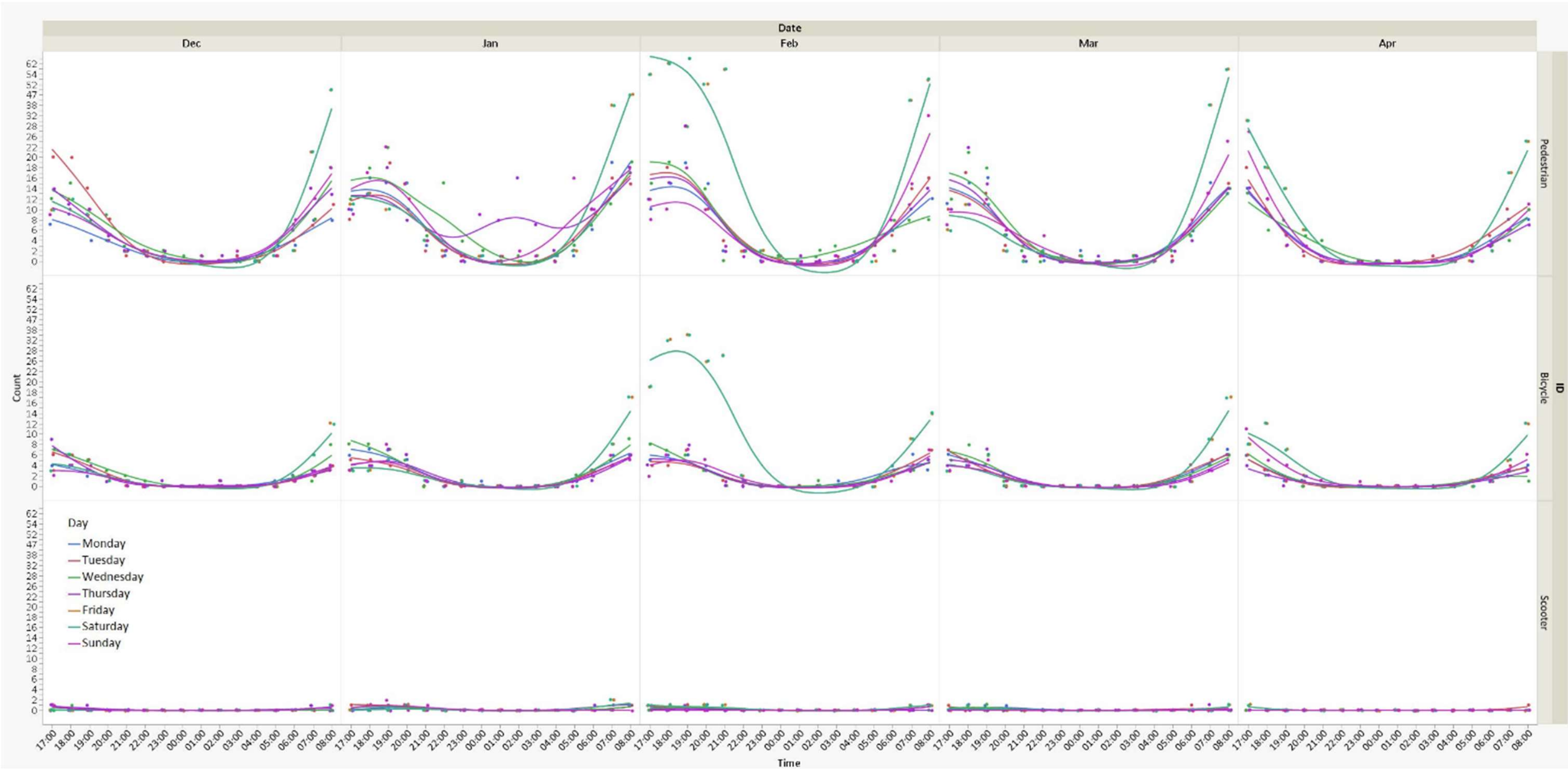


Figure 8. Summary daily LIDAR data (December 2023 and April 2024) aligning with the 15hr audio recording period (approx. 5pm-8am) for pedestrians, bicycles and scooters.

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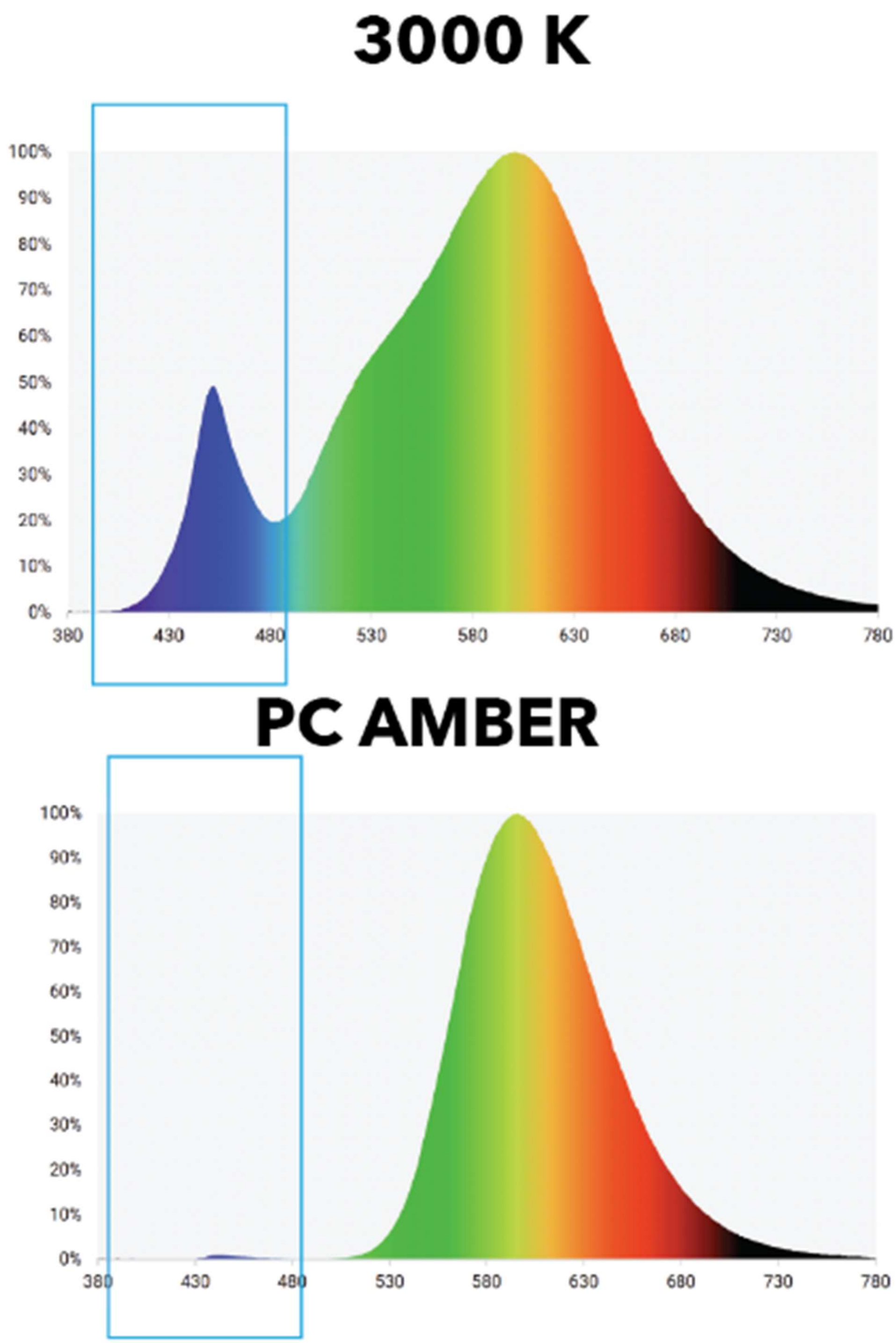
11. Appendix

Spectral output for 3000k and PC amber lights – noting the blue rich peak for the 3000k LED lights



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