Development of a Moon Metric to Characterize Roadway Lighting Impact on Flora and Fauna

Dr. Ronald Gibbons, Virginia Tech Transportation Institute
Dr. Travis Longcore, UCLA

Research Problem

- A metric must be developed to allow for the assessment of the ecological impact of outdoor lighting
  - Allows for comparisons across designs
  - Allows for comparison to a natural condition
- The impact of a lighting system on flora and fauna is based on two aspects
  - the spectrum of the light source
  - the intensity of the light source (Longcore et al.(2018b)).
- These aspects can be considered as a dosage; thus:
  - a higher intensity but a less reactive spectrum may be better than a dim lighting system with a more invasive spectrum.

Metric Development

- Proposed metric is the ratio of the impact of a lighting system on a given species to the impact from the moon on the same species.
    - Based on the work shown in (Longcore et al., 2018a)
  - The effective dosage of the light source on the species is calculated based apparent response of the species and the spectrum of the light source
  - Compared to the effective dosage of the moon, where the spectrum of the moon is used to calculated the impact on the same species
  - Metric is based on a given latitude, longitude, date, and time.

Model Development

-
- $$M_{Species} = \frac{E \int P(\lambda) A_{Species}(\lambda) d\lambda}{E_{Moon,Lat,Long,DateTime} \int Moon(\lambda) A_{Species}(\lambda) d\lambda}$$
- Where
- $M_{Species}$ is the calculated moon metric for a given species
- $P(\lambda)$ = Spectral Power Distribution of the light source chosen for the design (could be normalized)
- E = Illuminance on or in the species under consideration (used if the Spectral Power Distribution is normalized)
- $A_{Species}(\lambda)$ = Actinic curve for the species under consideration
- $E_{Moon,\ Lat,\ Long,\ Date,\ Time}$ = Illuminance from the Moon for a given Latitude, Longitude, Date, and Time
- $Moon(\lambda)$ = The standard spectrum of the moon

Development Impact Factor

$$IF_{Species} = \frac{\int P(\lambda)A_{Species}(\lambda)d\lambda}{\int Moon(\lambda)A_{Species}(\lambda)d\lambda}$$

- This impact factor uses the spectral impact of the moon but does not include the moon illuminance

$$M_{Species} = \frac{E}{E_{Moon,Lat,Long,DateTime}} * IF$$

- A generalized moon metric can be considered, which would be the maximum moon impact for a given latitude and longitude.

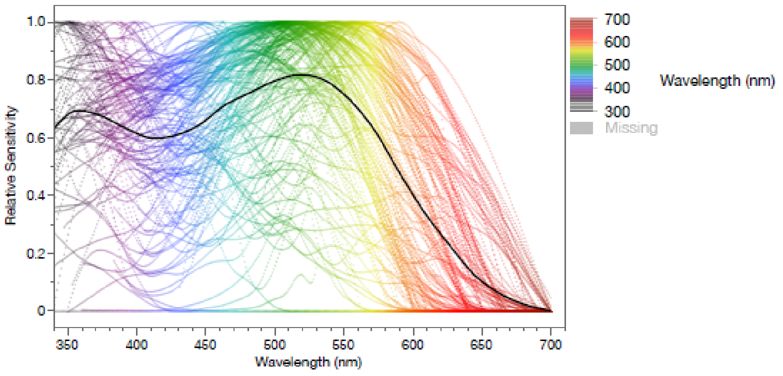
Calculation Requirements

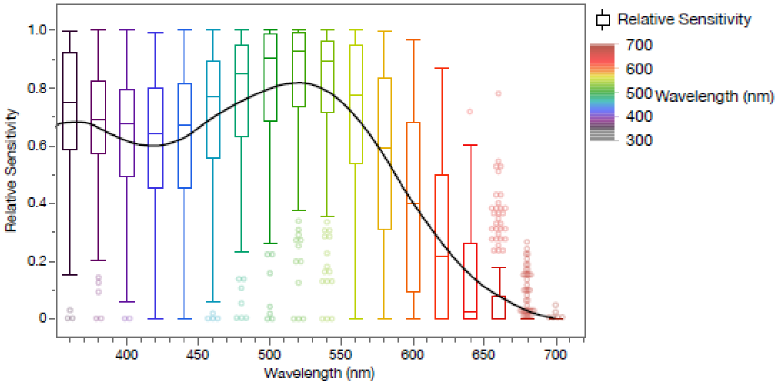
- Actinic curves for a variety of species as well as a generalized sensitivity curve.
- A standard moon illuminance calculation
  - Illuminance can be calculated for a given date, time, latitude, and longitude
  - Maximum illuminance for a given latitude and longitude.

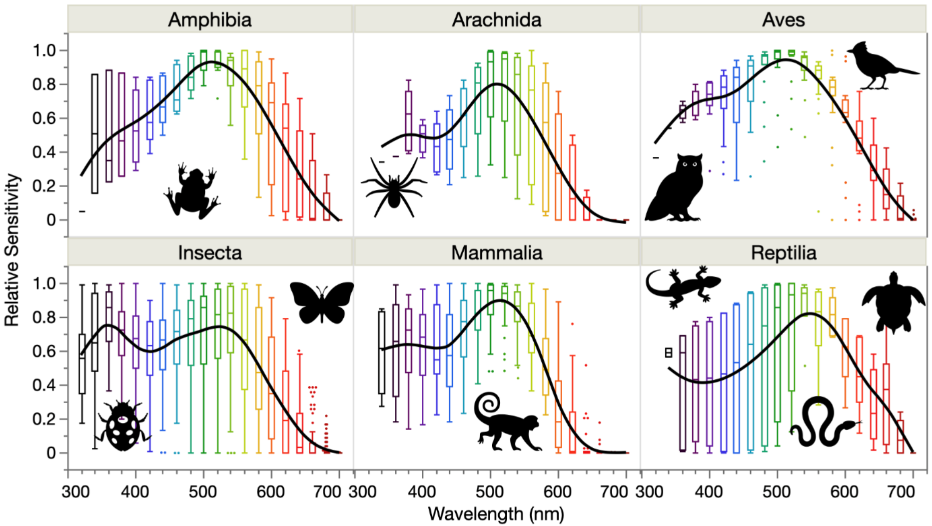
Actinic Curve Cataloging

- Longcore, under contract with the California Department of Transportation, compiled and digitized spectral response curves for as many (Longcore, 2023).
- 175 spectral responses were digitized and standardized to a 0–1 range
  - Light and dark testing conditions for some species.
  - The peak sensitivity for mammals was the longest (508 nm), followed by birds (503 nm), amphibians (499 nm), and insects (460 nm)
- Note this spectral response analysis does not consider any secondary effects where an impact on one species affects another species.

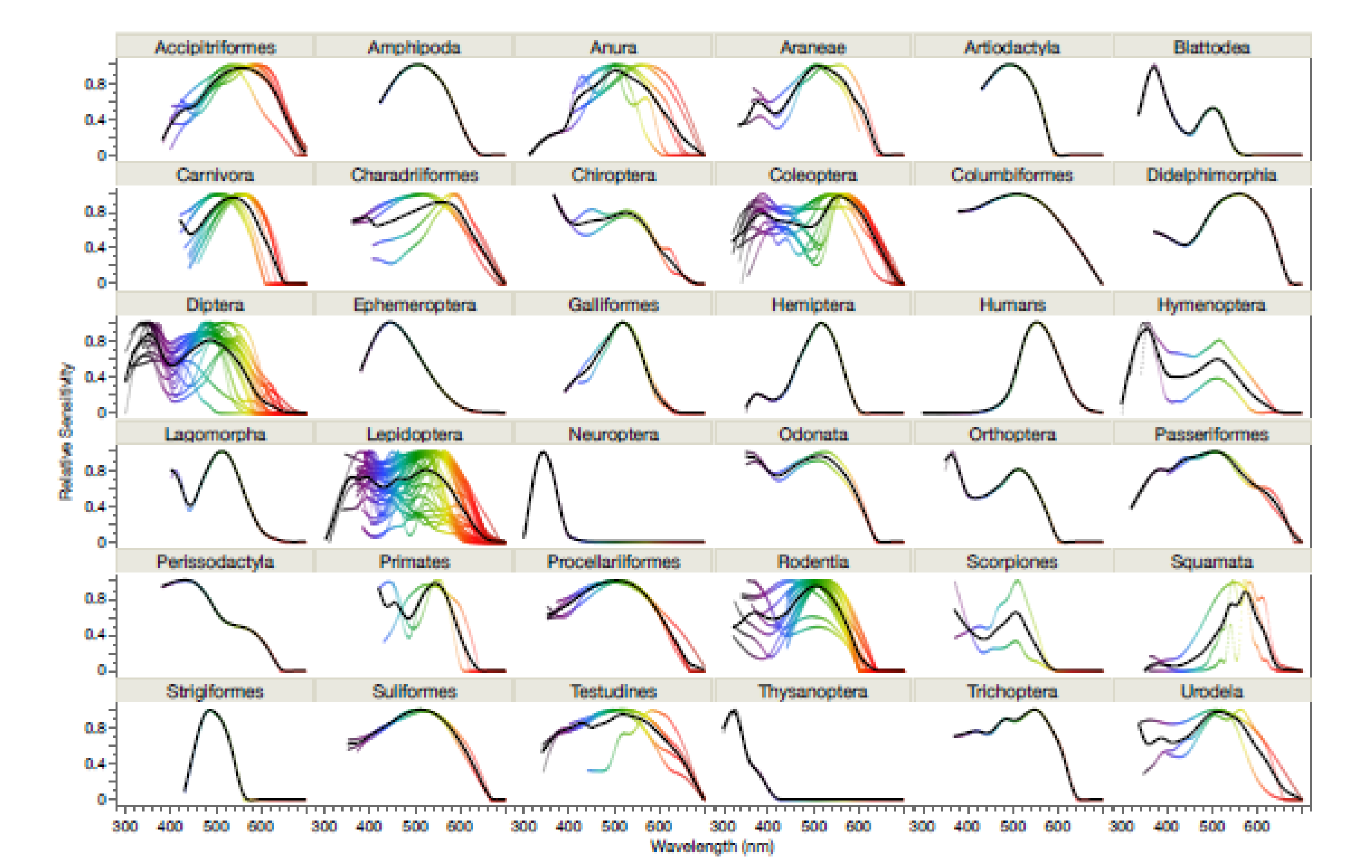
Actinic Curve Cataloging







More Actinic Curves

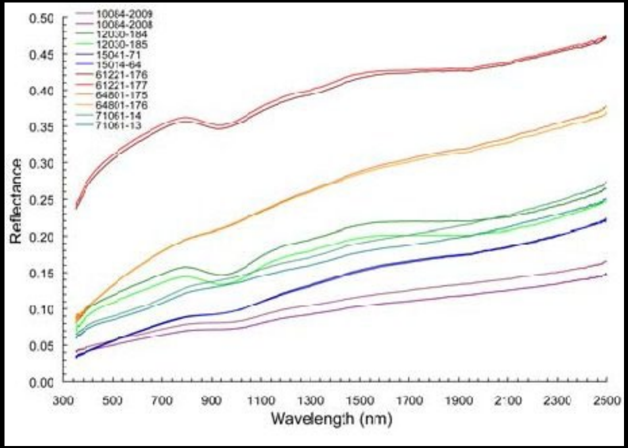


Development of a Standard Moon

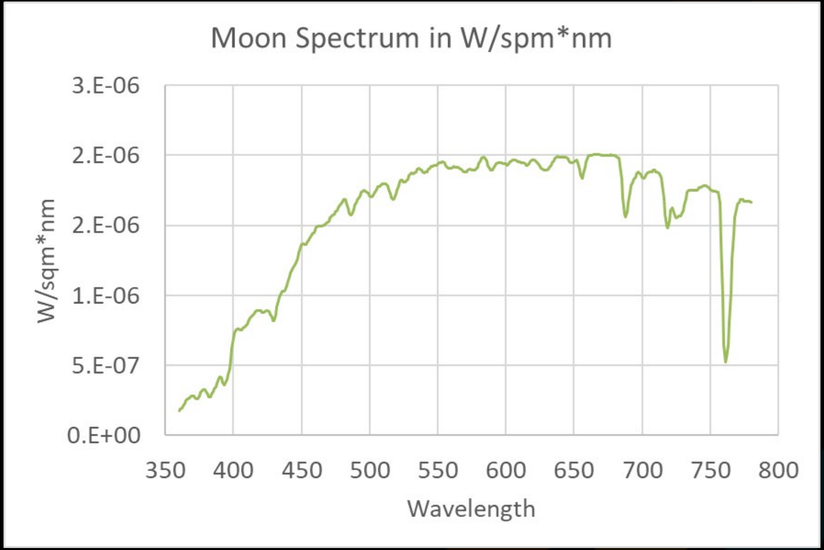
- Two components are required:
  - Moon Spectrum
    - Based on sunlight reflected from the regolith
  - Illuminance from the moon
    - Varies by date, time, and location on the earth

Moon Spectrum

Moon Reflectivity (Apollo Missions)



Resulting Spectrum



Moon Illuminance

- The maximum illuminance from the moon has been found to be approximately 0.4 lux (Brown, 1952; Krisciunas & Schaefer, 1991)
  - under most circumstances it does not exceed 0.1 lux (Kyba et al., 2017
  - The moon's brightness depends both on the angle of altitude and the phase of the moon.
  - The impact of the weather and the cloud layers which reduce the light reaching the Earth however this is not included in the design metric as these are transient conditions.

Moon Illuminance Calculation

- Following the methodology presented in (Austin et al., 1976) the following steps are undertaken to calculate the light from the moon:
  - Determine the position of the moon in the sky in terms of the angle of elevation and the angle from due north
    - Several mathematical models of the moon location in the sky have been developed for the model presented here, and the moon's characteristics have been developed based on the method in (Jean, 2005; Lawrence, 2018; Reingold & Dershowitz, 2018).
  - Calculate the phase of the moon based on the date of interest. If no specific date is used, a standard level of illuminance for a full moon at parallax is used (0.251 lux).
  - Calculate the change in the illuminance due to distance from the moon to the Earth.
    - As the moon's orbit is elliptical, the distance from the moon to the Earth will vary from 226,000 mi (363,300 km) at perigee to 251,000 mi (405,500 km) at apogee.
  - Calculate an adjustment for the attenuation of the moon's radiation due to the atmosphere
    - Rayleigh And Mei Scattering impacts the illuminance due to scattering
  - Calculate the vertical and horizontal components of the illumination based on the moon's angle of elevation.

  - E_{Moon}=0.251*Phase Factor* Distance Factor*Attenuation*Cos (90-Moon Elevation)

Sample Calculation

Location: Blacksburg Virginia, Latitude and Longitude (37.22653, -80.4139)

GMT Adjustment: -4 (This represents the number of hours from Greenwich Mean Time)

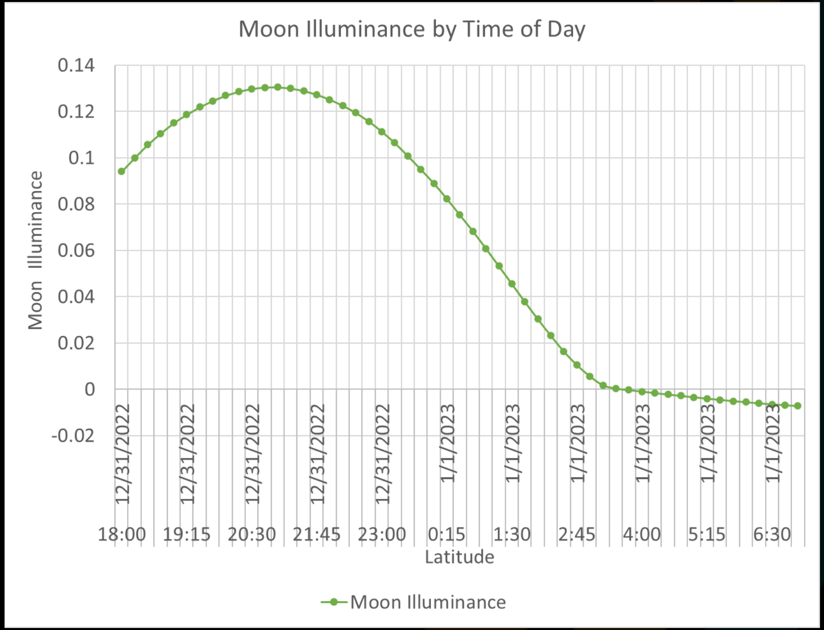
Date of Interest: January 1, 2023, midnight

The results of the calculation for the sun and moon position as well as the irradiance and illuminance are:

Moon Elevation (Degrees)	41.4
Moon Elongation	115.3
Distance (km)	390292
%Illumination	71.5
Diameter	30.94
Moon Azimuth (Degrees)	252.2
Sun Elevation (Degrees)	-66.9
Sun Azimuth (Degrees)	301.9

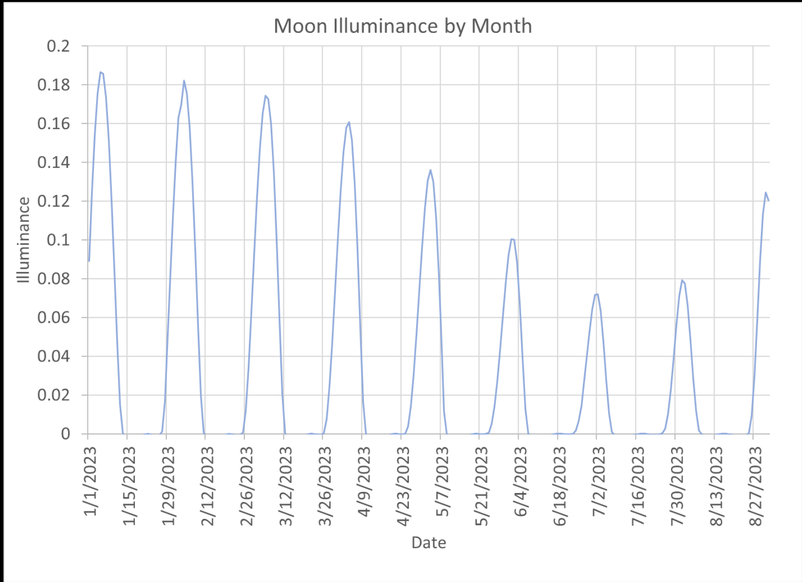
	Maximum	Time-Based
Irradiance	0.00118	0.00044
Illuminance	0.238	0.089

- A negative elevation angle indicates that the sun or the moon are below the horizon.

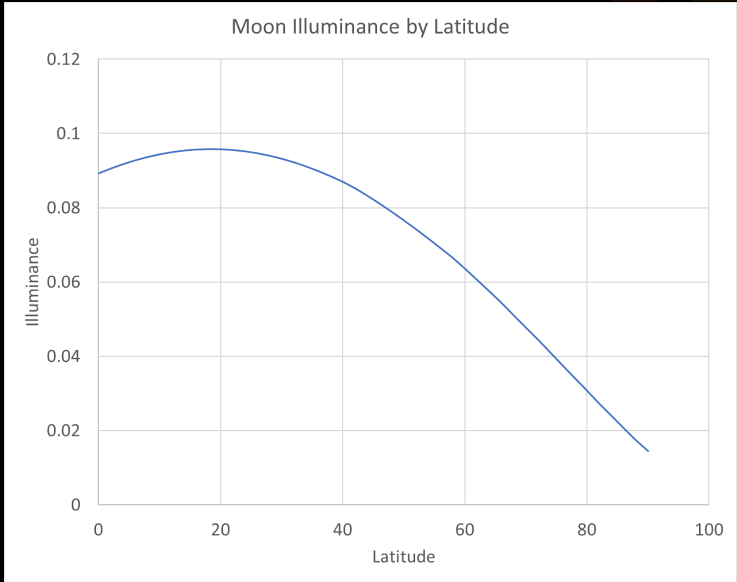


Moon Illuminance

By Month

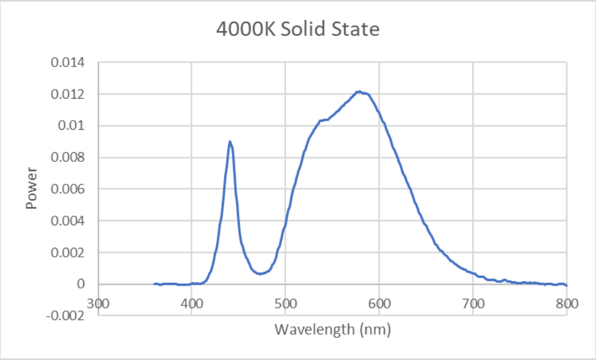


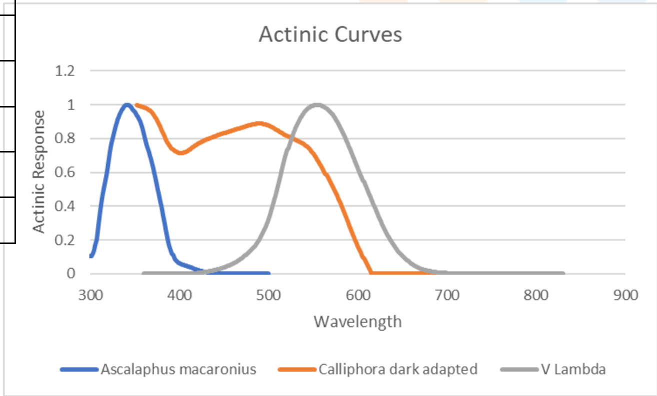
By Latitude



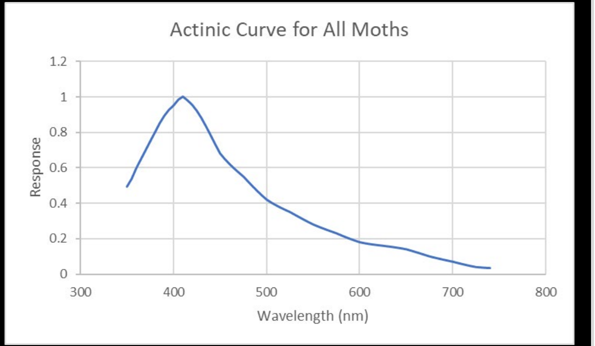
4000K Example – 5 Lux Design

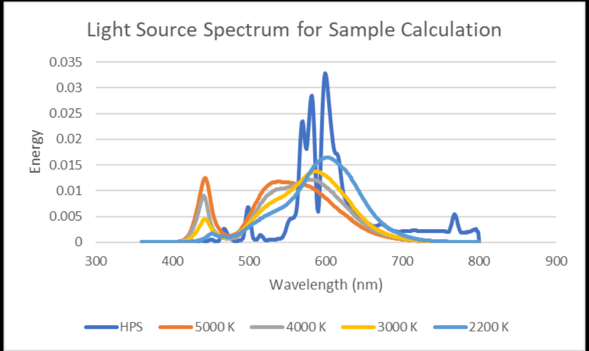
Actinic Curve	*Ascalaphus macaronius*	*Calliphora* (dark adapted)	V Lambda
Response Under Test	0.00104	0.81042	0.99762
Response Scaled to Lighting Design	0.00001	0.00595	0.00073
Maximum			
Moon Response	0.00001	0.00041	0.00035
Moon Metric	1	14.512	20.914
Time Based			
Moon Response	0.00001	0.00015	0.00013
Moon Metric	1	39.667	56.308

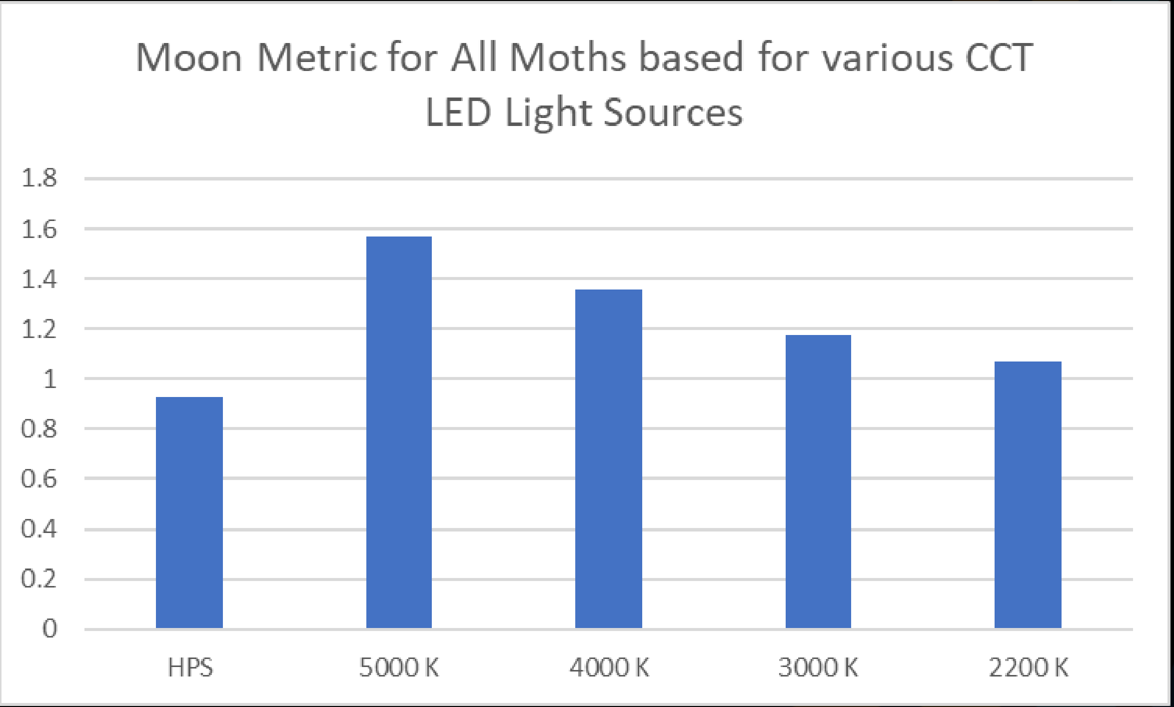




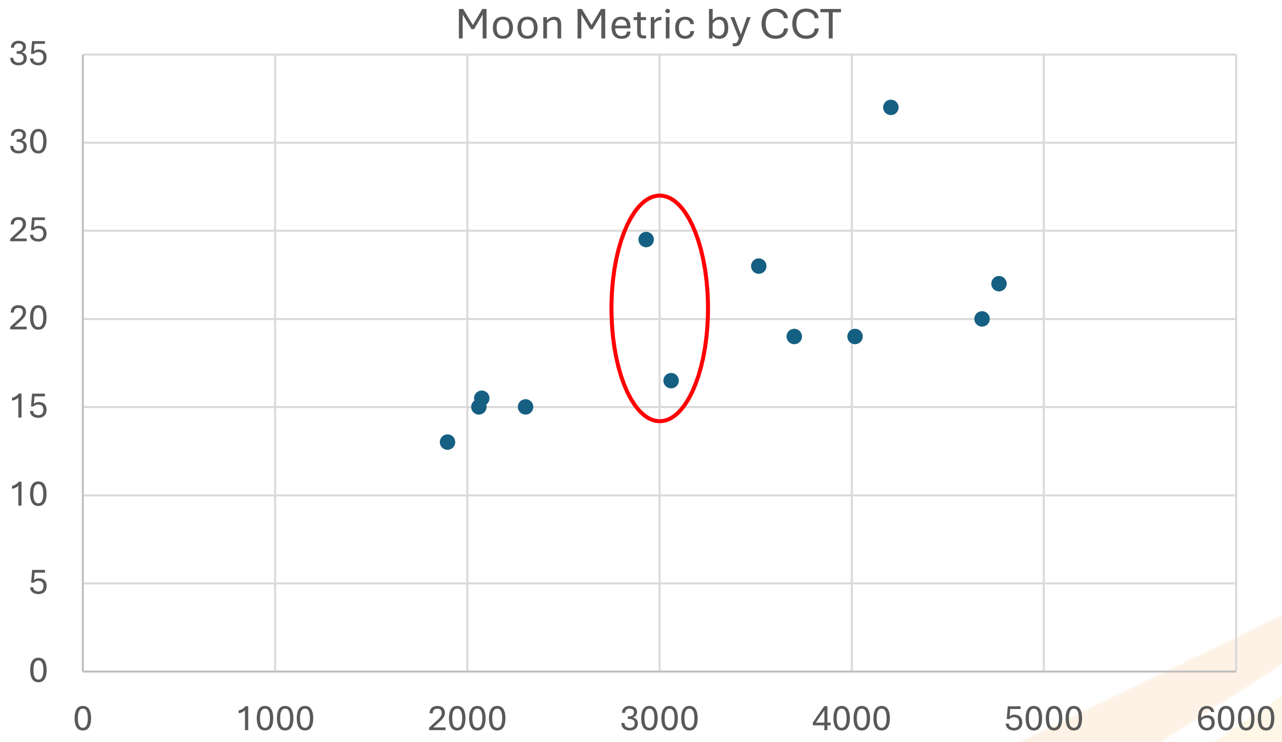
By Light Source





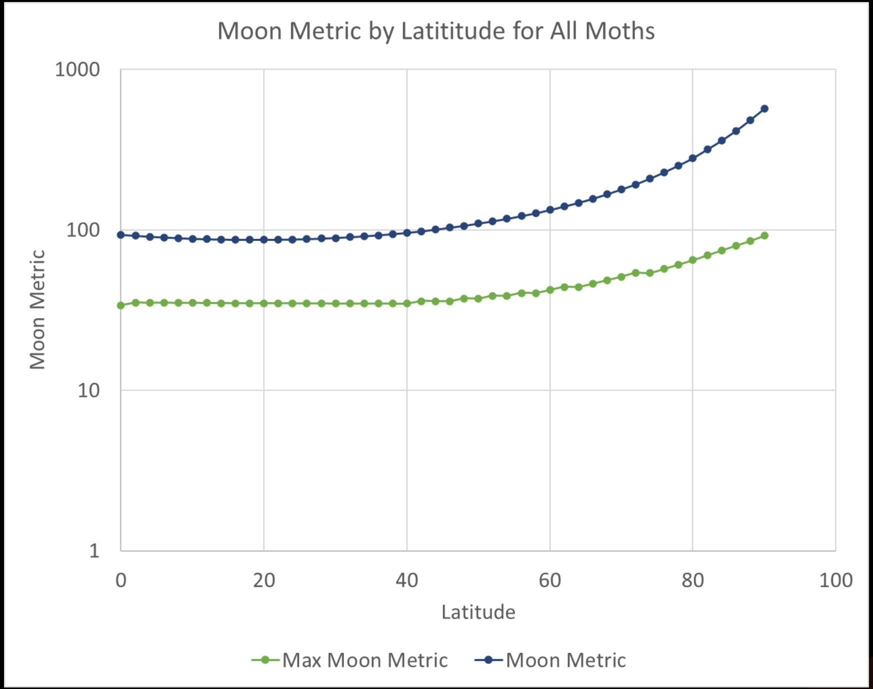


By CCT



Moon Metric by CCT
35
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000

By Latitude



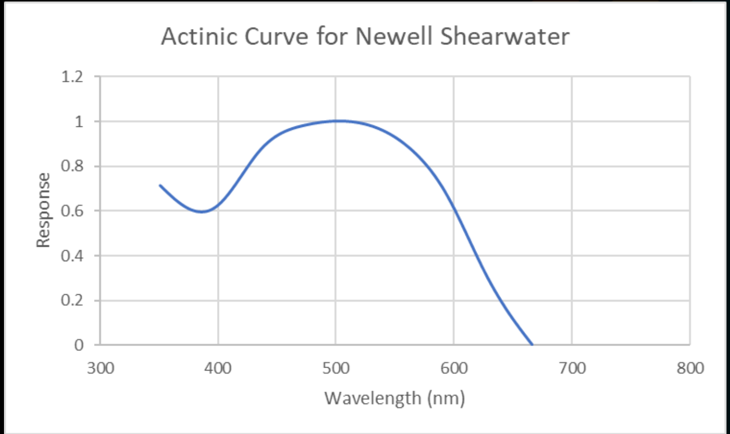
Moon Metric by Latititude for All Moths
1000
100
10
1
Moon Metric
0
20
40
60
80
100
Latitude
Max Moon Metric
Moon Metric

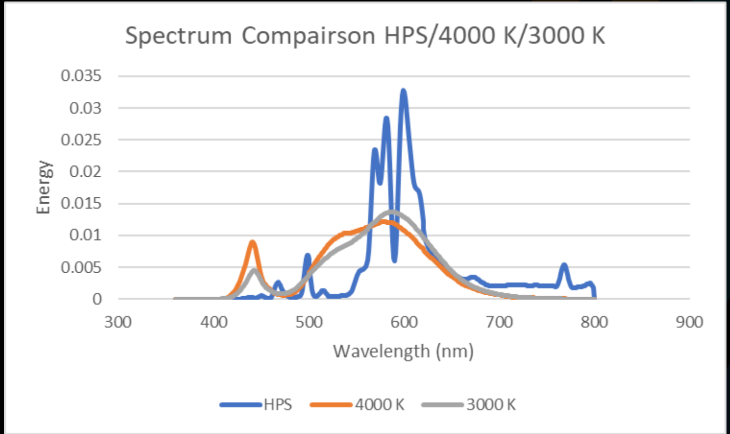
Design Metric Example

- Newell Shearwater in Hawaii

- Conversion from HPS to LED

- Hawaii Highway A – 4000K
- Hawaii Highway B - 3000K





Results

	Highway A		Highway B	
	HPS	4,000 K	HPS	3,000 K
Illuminance (lux)	16.6	13.3	15.9	14.6
Moon Metric from Maximum Illuminance	43.28	42.07	41.46	43.40

Discussion

- The developed moon model and impact factor can be used with any spectrum of light source and any actinic curve.
- The impact of the lighting design on a species is generally much higher than the impact of the moon.
- Very difficult to use as a threshold metric
  - Many combinations of time, spectrum, animals, and locations
- We instead recommend that the metric be used as a comparison tool when considering a specific location and alternative lighting designs.
- It is highly unlikely that any lighting design will be able to meet a 1 moon criteria.
  - Research into an appropriate moon metric level for a lighting system is required to be able to establish lighting criteria and warrant levels.

Developing a Design Metric

- Using the Metric as an Impact Factor to Scale lighting design recommendations

	HPS	4,000 K	3,000 K
Design Level	12		
Impact Factor	0.633	0.768	0.722
Percent Reduction		0.824	0.877
Modified Design Level		9.9	10.5

Conclusions

- The lighting levels from installed lighting systems are typically much higher than the illuminance from the moon
  - This requires investigation of a design criteria to establish a lighting design recommendation based on the moon metric.
- The moon metric generally follows the CCT in terms of magnitude.
  - The spectrum must be used for the metric and not simply the CCT.
- The metric is an effective comparison tool, but additional research is needed to clarify an acceptable magnitude of impact.

Recommendations / Future Efforts

- Identify the magnitude of a change in the metric which would have an impact on a species.
- Identify a potential design metric threshold to establish a design recommendation.

Q & A