Characterization of Anthropogenic Light Pollution via Stratospheric Remote Sensing

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1. Abstract

The alteration of the natural nighttime environment due to artificial light at night (ALAN) can disrupt ecological systems and affect human health. Inefficiencies in lighting use have downstream consequences for climate, economies and health. High resolution, regional-scale data of the nighttime environment is not readily available yet is necessary to address this issue. Mapping light emissions from a stratospheric balloon platform provides data of sufficient quality to further our understanding of the impacts and possible solutions to this health and environmental stressor.

For this work, we designed and flew instrumentation on latex high altitude balloons for remote sensing of nighttime lights. We collected tens of thousands of images across an urban to rural footprint centered on the city of Indianapolis, Indiana (Fig. 1). Our results indicate land zoned for commercial use contributes 20.5% of all light emissions while only comprising 7% of land area. These results also corroborate an earlier study that road lighting contributes only an estimated 14% of total emissions, where our study shows a contribution of 24.3%, including other light sources on the roads.

Comparing on-orbit observations from the VIIRS instrument to those collected with our method (Fig. 2), we can estimate the quantity of light unaccounted for due to the short (blue) wavelength insensitivity of the VIIRS sensor. This method can identify sources of light pollution on a regional scale. Our results indicate policy addressing commercial lighting may be the most efficient mitigation strategy in developed areas. By quantifying the color of the light observed, we can better estimate the total nighttime light emission missed by broadband satellite observations. These observations can aid in the study of nocturnal species with either light aversion or affinity by characterizing artificial light in their environment. This method can help effectively guide planning and policy to maintain benefits of lighting while reducing energy consumption, minimizing the health and ecological impacts of light pollution and protecting the nighttime environment.

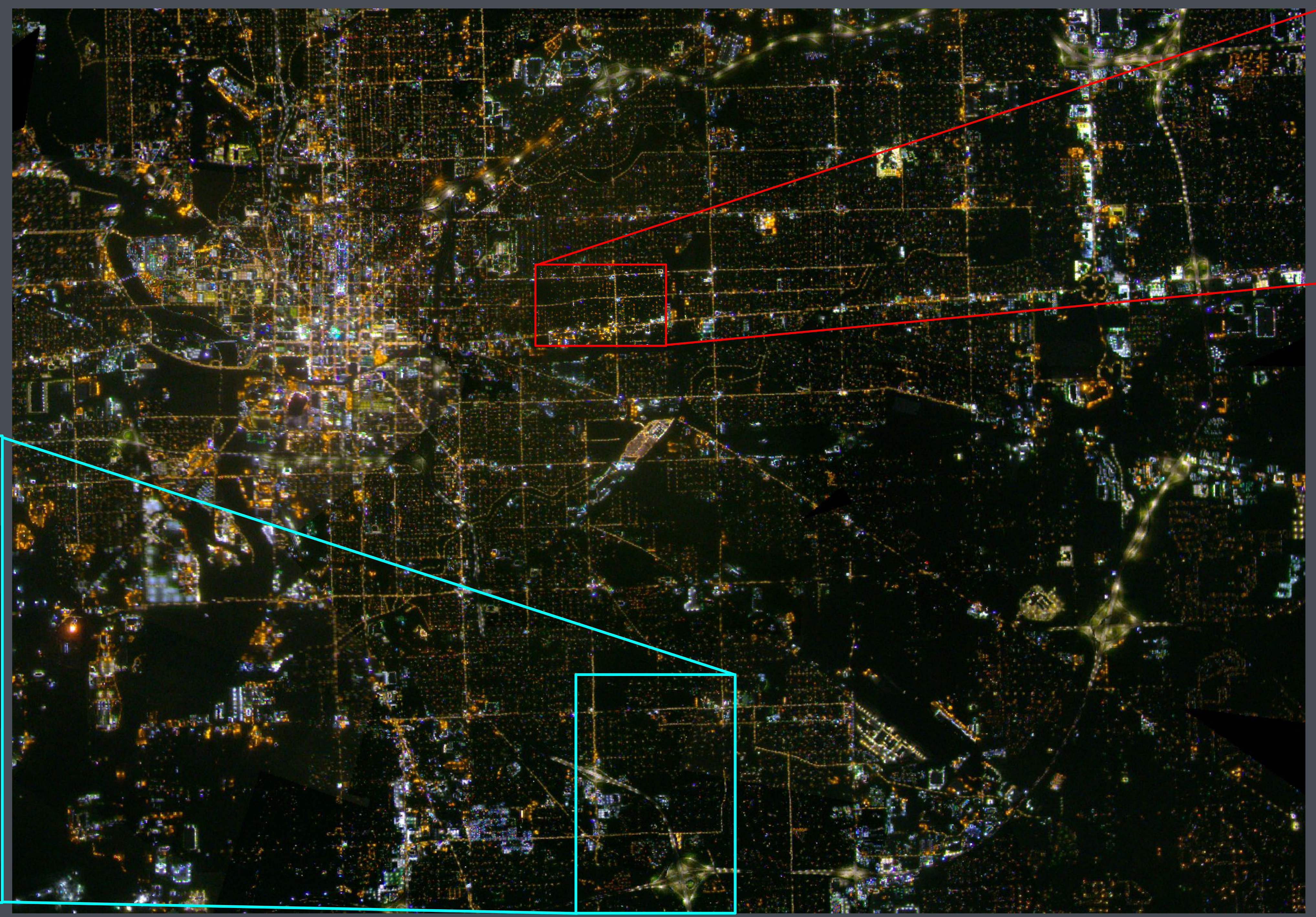

Fig. 1: Mosaic of NITELite images from May 13, 2022 of the light emission from Indianapolis, Indiana.

Fig. 2: Comparison of VIIRS DNB to NITELite data.

2. Context

ALAN is the contamination of the natural nighttime environment by light of anthropogenic origin. It is an under-examined environmental stressor affecting ecosystems, human health, economies and the environment:

- 69% of all mammal species are nocturnal requiring the dark of night for survival [1].
- ALAN has been correlated to negative health outcomes in humans such as obesity, stress, sleep deprivation, and potentially certain cancers [2–5].
- The U.S. Dept. of Energy estimates global light emissions measured from orbit - i.e., with no utility - cost $50B annually and in the US alone 380 TWh of energy is expended on outdoor lighting. This equates to an estimated 164 million metric tons of CO_2 emissions annually [6].

3. Methodology

Nighttime Imaging of Terrestrial Environments (NITELite) is an imaging system flown to the stratosphere on latex high-altitude balloons for the remote sensing of nighttime light emissions. The hardware consists of three down-pointing cameras - a nadir and two off-axis industrial CMOS cameras - that produce a 1920x1200 pixel, Bayer RGB, 12-bit image. The system is programmed to autonomously collect rapid sequences consisting of five raw images with 50ms exposures followed by a 100ms uncompressed tiff from each camera about every 8s. The altitude during imaging was from 15.0 km (±800 m) providing an average GSD of 3.4 m/px.

Images were collected on the night of Friday, May 13, 2022, centered on the city of Indianapolis, Indiana (Fig. 1). The flight reached an initial stable altitude at 22:00 local time and imaged until 23:50. Over that time, the system traveled a total path length of approximately 70 km.

Images were selected for land coverage with an aim to generate a full map of georeferenced images from the neutral buoyant period. Only nadir images that contained no discernible cloud cover or motion blurring were used in our analysis. The images were georeferenced in QGIS using visually identifiable light sources in a Google Satellite layer as ground control points (GCPs). Multiple iterations of this process were performed for each georeferenced image to improve the accuracy of the positioning. Only nadir images with no overlap were used. The 11 selected images covered a range of population densities, so a variety of scenarios was sampled (Fig. 4).

We then used GIS parcel data available through the state of Indiana, which includes property codes used for tax purposes. We binned all property codes into seven broad zones: Agricultural, Industrial, Commercial, Residential, Governmental, Tax Exempt, and Infrastructure. For each image, we clipped parcel boundaries so that only individual land parcels falling entirely within the image borders were included in the analysis. R, G and B channel values were summed for each parcel and within the total area covered by roads using the zonal statistics tool in QGIS. The channels were summed to find the total pixel brightness. A value of 150/px, derived from a best fit with VIIRS DNB lunar corrected data, was subtracted to correct for lunar illumination.

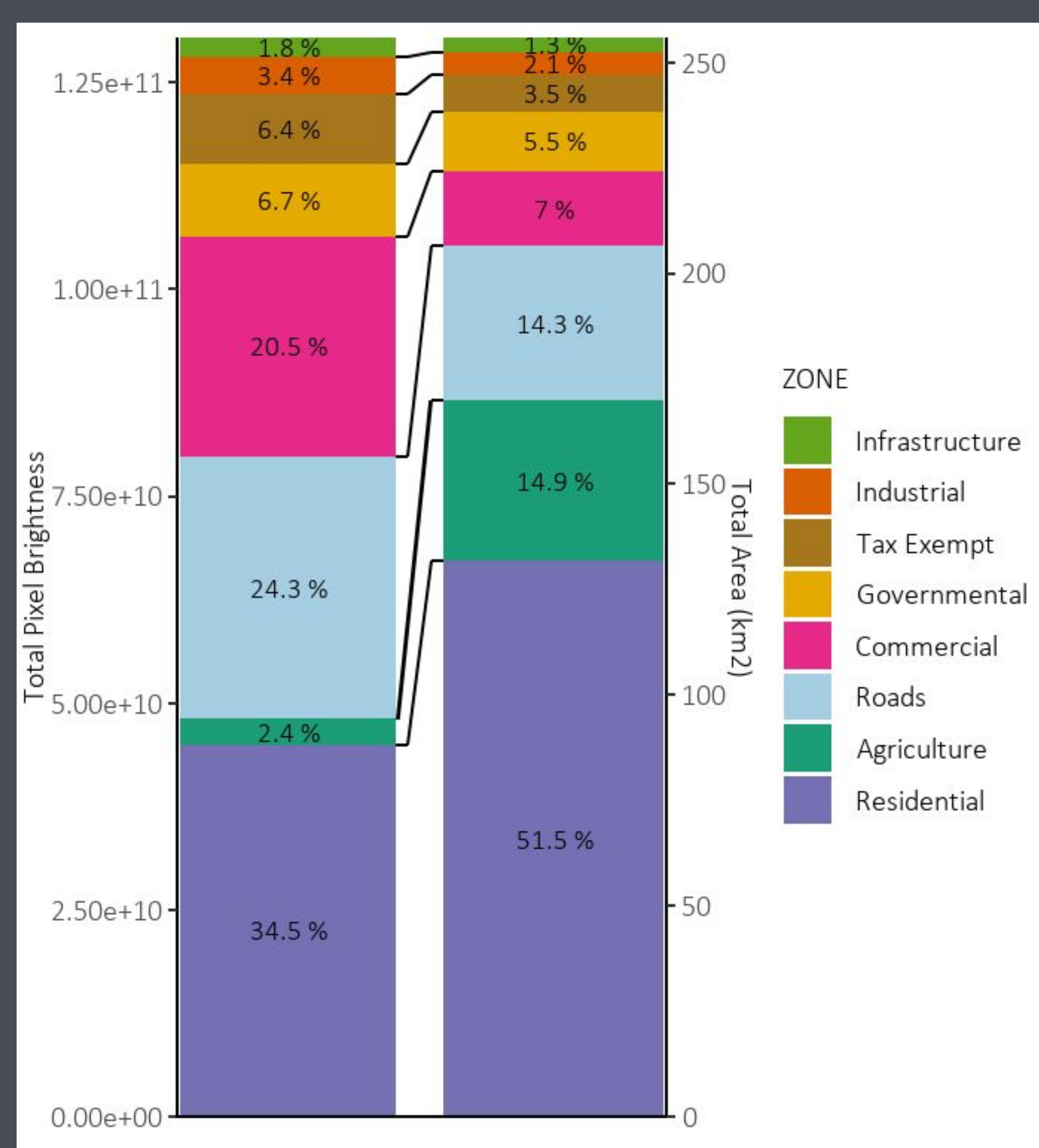

Fig. 5: Total Pixel Brightness (left) and Total Area (right) of all images combined. Colors indicate contributions from different zones.

4. Results

- Commercial land emitted nearly 3 times the light in proportion to its area, emitting 20.5% of total light while covering only 7% of the total area.
- Residential land emitted 34.5% of all light while covering 51.5% of all land. Although, it was the single greatest emitter by zone.
- By parcel, Commercial areas emitted significantly more than any other zone. Nearly 50% more than the median value of the next closest emitter by parcel (Fig. 6).
- Observed Road emissions are on the high end of percentage of contribution versus previous studies [7].
- Correlating to VIIRS DNB (linear fit, R^2=0.8934), significant outliers in blue and/or total emission were able to be identified.

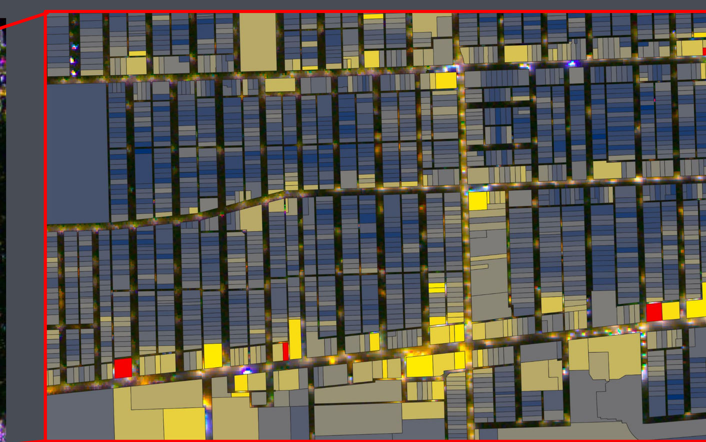

Fig. 3: Parcels by brightness showing increased residential exposure with proximity to commercial areas.

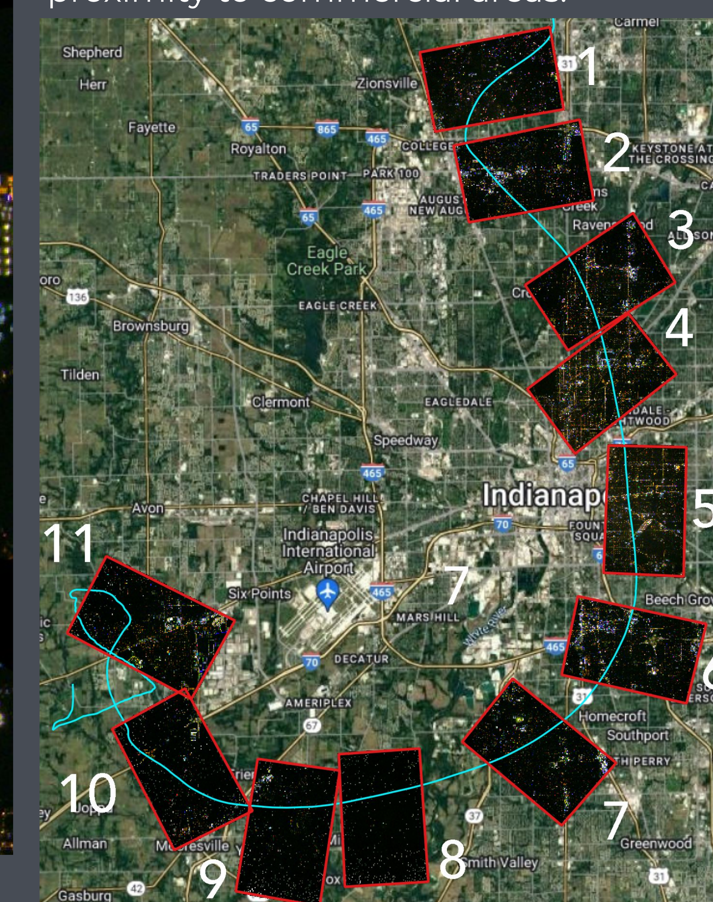

Fig. 4: Flight path (cyan) and location of the 11 images used for this analysis

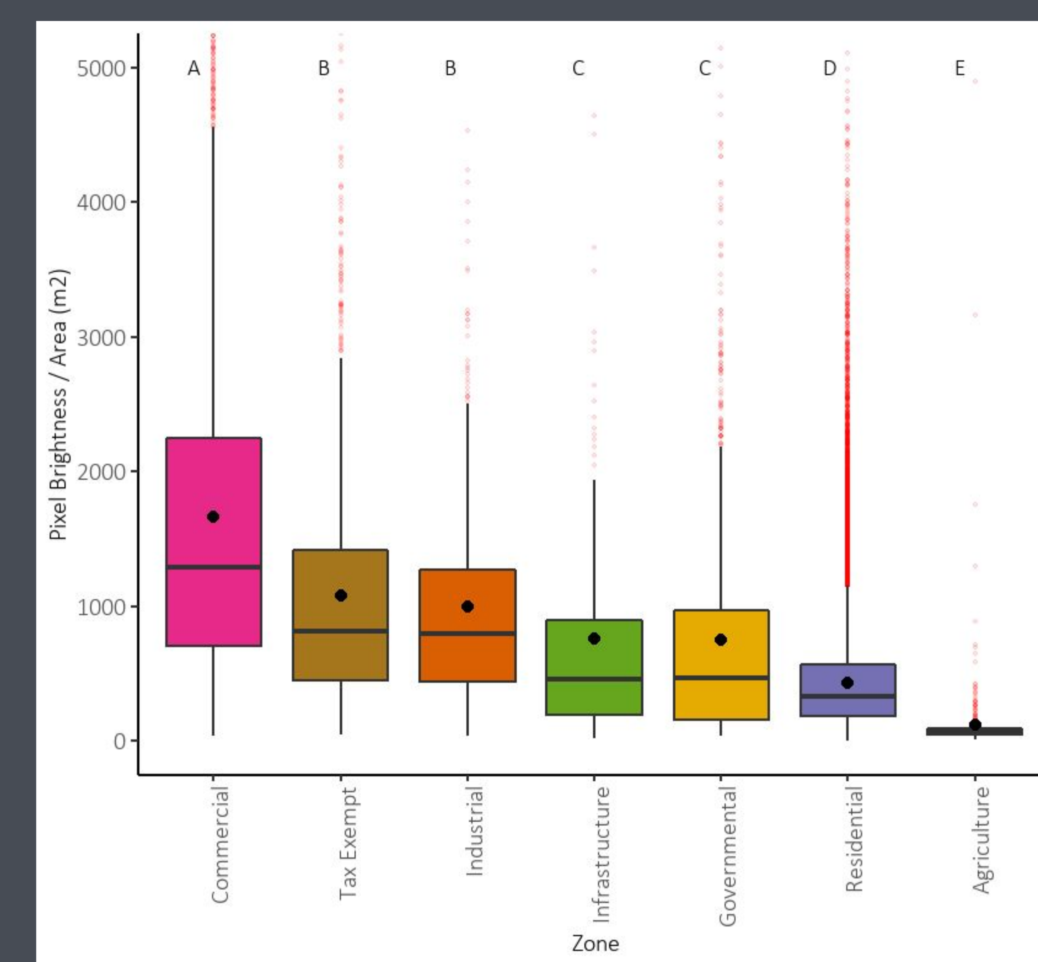

Fig. 6: Total Pixel Brightness per area across parcels within land use zones (KW χ2=8966.7 p<0.0001), (Commercial n=4255, Tax Exempt n=1389, Industrial n=588, Infrastructure n=217, Governmental n=1351, Residential n=94,313, Agriculture n=436). Black dot indicates mean, black bar indicates median, box indicate 1st and 3rd quartiles. Letters correspond to significance groupings according to Dunn's Test.

5. Discussion

While residential land emitted proportionately less light than the area it covered, it is still the largest overall emitter, contributing 34.5% of light. Visually observing residential subdivisions within our study images revealed that light sources include exterior lighting on houses and overspill from streetlights (Fig. 3). This can help inform public policy, legislation and community actions around reducing light pollution through targeted regulation, infrastructure updates (e.g. retrofitting outdoor lighting) and educational outreach (e.g. informing homeowners).

Commercial land emitted 20.5% of the total light while covering only 7% of the study area and were the highest emitting parcels per area on average. The source of the greatest median emissions in commercial zones is from hotels and the greatest mean emission is from shopping centers while commercial offices were statistically similar. When accounting for area, fast food properties have the highest mean and median emission followed by auto services (this subclass includes gas stations, service stations, car washes and car dealerships). Considering the time of these observations, (22-00h local) this level of emission from these businesses indicates lighting is being used beyond the normal hours of their operation. Possible solutions to mitigating light from these kinds of properties could include lighting schedules restricted to operating hours. If these facilities are in use, it will be important to support shielded lighting options that mitigate the escape of light into areas outside of their intended use.

6. Areas of Future Study

The work discussed here has been entirely focused on summed pixel values over regions and parcels. Given the data we have collected, there are several potential lines of research that can be explored:

- Can we quantify the amount of blue light emission missed in VIIRS DNB data?
- How light corridors and barriers affect wildlife movement and behavior?
- Are there demographic correlations (socio-economic, racial/ethnic, etc.) in ALAN emission?
- Can the RGB data be used to inventory sources by spectral type?

7. Acknowledgements

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8. References

[1] Bennie, J. J., Duffy, J. P., Inger, R., & Gaston, K. J. (2014). Biogeography of time partitioning in mammals. Proceedings of the National Academy of Sciences, 111(38), 13727–13732. https://doi.org/10.1073/pnas.1216063110

[2] Touitou, Y., Reinberg, A., & Touitou, D. (2017). Association between light at night, melatonin secretion, sleep deprivation, and the internal clock: Health impacts and mechanisms of circadian disruption. Life Sciences, 173, 94–106. https://doi.org/10.1016/j.lfs.2017.02.008

[3] Xiao, Q., Gee, G., Jones, R. R., Jia, P., James, P., & Hale, L. (2019). Cross-sectional association between outdoor artificial light at night and sleep duration in middle-to-older aged adults: The NIH-AARP Diet and Health Study. Environmental Research, 180, 108823. https://doi.org/10.1016/j.envres.2019.108823

[4] Park, Y.-M. M., White, A. J., Jackson, C. L., Weinberg, C. R., & Sandler, D. P. (2019). Association of Exposure to Artificial Light at Night While Sleeping With Risk of Obesity in Women. JAMA Internal Medicine, 179(8), 1061–1071. https://doi.org/10.1001/jamainternmed.2019.0571

[5] Walker, W. H., Bumgarner, J. R., Walton, J. C., Liu, J. A., Meléndez-Fernández, O. H., Nelson, R. J., & DeVries, A. C. (2020). Light Pollution and Cancer. International Journal of Molecular Sciences, 21(24), 9360. https://doi.org/10.3390/ijms21249360

[6] 2022 Solid-State Lighting R&D Opportunities. (2022). US Department of Energy.

[7] Kyba, C., Ruby, A., Kuechly, H., Kinzey, B., Miller, N., Sanders, J., Barentine, J., Kleinodt, R., & Espey, B. (2020). Direct measurement of the contribution of street lighting to satellite observations of nighttime light emissions from urban areas. Lighting Research & Technology, https://doi.org/10.1177/1477153520958463