Earth and Space Science: Making Connections in Education and Public Outreach
ASP Conference Series, Vol. 443
Joseph B. Jensen, James G. Manning, and Michael G. Gibbs, eds.

Astronomy Meets the Environmental Sciences: Using GLOBE at Night Data

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Abstract. The GLOBE at Night database now contains over 52,000 observations from the five annual two-week campaigns. It can be used as a resource to explore various issues related to light pollution and our environment. Students can compare data over time to look for changes and trends. For example, they can compare the data to population density or with nighttime photography and spectroscopy of lights. The data can be used in a lighting survey, to search for dark sky oases or to monitor ordinance compliance. Students can study effects of light pollution on animals, plants, human health, safety, security, energy consumption, and cost. As an example, we used data from the GLOBE at Night project and telemetry tracking data of lesser long-nosed bats obtained by the Arizona Game and Fish Department to study the effects of light pollution on the flight paths of the bats between their day roosts and night foraging areas around the city of Tucson, AZ. With the visual limiting magnitude data from GLOBE at Night, we ran a compositional analysis with respect to the bats' flight paths to determine whether the bats were selecting for or against flight through regions of particular night sky brightness levels. We found that the bats selected for the regions in which the limiting sky magnitudes fell between the ranges of 2.8–3.0 to 3.6–3.8 and 4.4–4.6 to 5.0–5.2, suggesting that the lesser long-nosed bat can tolerate a fair degree of urbanization. We also compared this result to contour maps created with digital *Sky Quality Meter* (http://www.unihedron.com) data.

1. Introduction

Light pollution is a serious and growing problem worldwide. It wastes valuable energy, creates health and safety risks for humans, and can affect the habits and habitats of animals. Light pollution also ruins the night sky for everyone's enjoyment and can disrupt professional astronomy research.

For the last five years the National Optical Astronomy Observatory (NOAO) has played a leadership role in the GLOBE at Night worldwide star "hunting" program. GLOBE at Night is an international citizen science program that allows everyone to assess the brightness of their night sky by visually noting the faintest stars in Orion or by taking highly repeatable measurements with a low-cost digital meter and posting their results to the Internet.

The database now contains over 52,000 observations from the five annual two-week campaigns. It can be used as a resource to explore various issues related to light pollution and our environment. Students can compare data over time to look for changes and trends. For example, they can compare the data to population density or with nighttime photography and spectroscopy of lights. The data can be used in a lighting survey, to search for dark sky oases or to monitor ordinance compliance. Students can study effects of light pollution on animals, plants, human health, safety, security, energy consumption, and cost.

The ASP workshop brought together educators, mostly community college professors, who had an interest in using these types of data sets in their classrooms or to make changes in their community. Together we discussed the types of comparisons and analyses that can be made. We shared our tips and their concerns in making such a program feasible. Participants received a CD Rom containing all GLOBE at Night data from the last five years in six different formats.

We present here the example of comparing the GLOBE at Night data with data from telemetry of the threatened and endangered (T and E) Lesser Long-Nosed Bat in Arizona to examine whether or not the bats are preferentially staying in darker areas while traveling between roosts and foraging areas. The bat telemetry was provided by the Arizona Game and Fish Department. The comparative study was done in 2010 by a "Research Experience for Undergraduates" student [DB] and his advisor [CEW]. The results of the study are expected to invoke similar projects for other T and E species of animals around the United States.

2. Lesser Long-Nosed Bats

Until fairly recently, light pollution was essentially unheard of as a legitimate form of human interference with Earth's ecosystem. While light pollution had been discussed with reference to degrading sky conditions causing poor observing conditions for observatories, the first reference to the ecological impacts of artificial lighting is F. J. Verheijen from 1985, in which he coined the term photopollution (Verheijen 1984). Excess lighting has since been shown to have well-studied negative impacts on both humans, particularly at wavelengths corresponding to blue light (Moore and Wainscoat 2010), and wildlife, such as hatching sea turtles (Witherington and Martin 1996).

The lesser long-nosed bat (Leptonycteris curasoae yerbabuenae) is a federally endangered species of nectivorous bat native to the central California, southern Arizona, and New Mexico in the United States, as well as Mexico, Honduras, Guatemala, and El Salvador (International Union). The lesser long-nosed bat feeds primarily on nectar and pollen from agave flowers and nectar, pollen and fruit from saguaro and organ pipe cacti (Cole and Wilson 2006). When these flowering plants are not in bloom, the bats in the Tucson area feed from hummingbird feeders. In their 2005 Comprehensive Wildlife Conservation Strategy, the Arizona Game and Fish Department made recommendations for conservation methods to mitigate the impacts of human activities on the lesser long-nosed bat (Arizona Game and Fish Department 2006). Though light pollution is not explicitly stated as an ecological stressor by the CWCS, "enforcement activities along border" is listed as such. This stressor includes the illumination placed along the border with the goal of spotting potential illegal immigrants more easily. The illumination creates another source of light pollution.

The effects of light pollution on bat species throughout the world are neither particularly well known nor well documented, though the effects are receiving greater academic attention of late. These effects can come from general light pollution along flight corridors between day roosts and feeding areas (Lowery et al. 2009, Stone 2009) or direct illumination of day roosts (Boldogh et al. 2007). Bats have previously been shown to select against areas of high artificial lighting when flying between day roosts and nighttime feeding areas. One study demonstrated avoidance when local lighting codes are used as a proxy for the intensity of the light pollution over a particular area (Lowery et al. 2009). A second study has shown that bats will change their flight paths when new artificial lighting sources are placed in areas along the bats' normal route between roosts and feeding areas (Stone et al. 2009). A study of the direct illumination of particular day roosts in Hungary has shown that it affects particular species of bat more strongly than others, but that it correlates with decreased forearm length and body mass in juvenile bats compared to juveniles in non-illuminated roosts (Boldogh et al. 2007).

Light pollution can also affect the predator-prey relationships between bats and other species. Artificial lighting attracts swarms of insects at night, which, in turn, attracts bats who will take this opportunity to catch an easy meal (Bat Conservation Trust 2008). Unfortunately, the illumination of the bats' potential feeding area is thought to put the bats at greater risk of predation by normally diurnal kestrels (Bat Conservation Trust 2008). The lesser long-nosed bat is nectivorous, and therefore not affected by insects' habits around artificial lights. However, they are known to forage at hummingbird feeders, which are found in areas inhabited by people. This infers these areas will be more well-lit, thereby putting lesser long-nosed bats at higher risk of predation.

3. Method

Our light pollution data comes from the GLOBE at Night project,[1] which, since its inception in 2006, has allowed citizen scientists from more than 100 countries around the world to contribute over 50,000 data points detailing the night sky brightness in their respective areas of the world. The GLOBE at Night project runs for two weeks during the month of March when the moon will not be up and the easily recognizable constellation of Orion will be easily visible to almost all parts of the world. The project provides maps of the stars visible in the night sky at a range of different magnitudes of sky brightness, ranging the integer magnitudes 1 (only 1st magnitude or brighter objects are visible) through 7 (7th magnitude objects are visible to the unaided eye). GLOBE at Night asks participants to match up what they see in the sky to one of the provided images, and submit that information along with the location, date, and time at which the observation was made. Volunteers can also submit the readings gathered with a *Sky Quality Meter* (Unihedron), which gives a measure of the night sky brightness in units of magnitudes per square arcsecond. This data is all freely available to the public[2] and downloadable in different file formats.

We first obtained telemetry tracking data of local lesser long-nosed bats used in a previous study (Lowery et al. 2009) by the Arizona Game and Fish Department. This

[1] `http://www.globeatnight.org`

[2] `http://www.globeatnight.org/analyze.html`

data showed approximate flight paths between the bats' day roosts and their night foraging areas, which were primarily hummingbird feeders in people's backyards. The flight paths and foraging areas can be easily distinguished from one another. Foraging areas are identified by clusters of points being relatively close to one another. This data is shown in the left panel of Figure 1. The lines shown do not represent the actual flight paths that the bats took, but rather are straight-line interpolations between time-consecutive telemetry data points intended only to demonstrate continuity between points.

We then used the data gathered from the GLOBE at Night project in the Tucson area between the years 2006 and 2010, shown in the right panel of Figure 1. For the purposes of this project, we defined this as the area bounded by 32° 45' N to 31° 30' N and 111° 45' W to 110° 15' W based on the density of the available data. We also removed any data points where the volunteers stated that the sky was more than 50% clouded at the time they made their respective observations, as such data were not representative of the actual conditions of the sky on a clear, moonless night. We then used this data to construct a contour plot of the night sky brightness in ArcGIS as in the left panel of Figure 2.

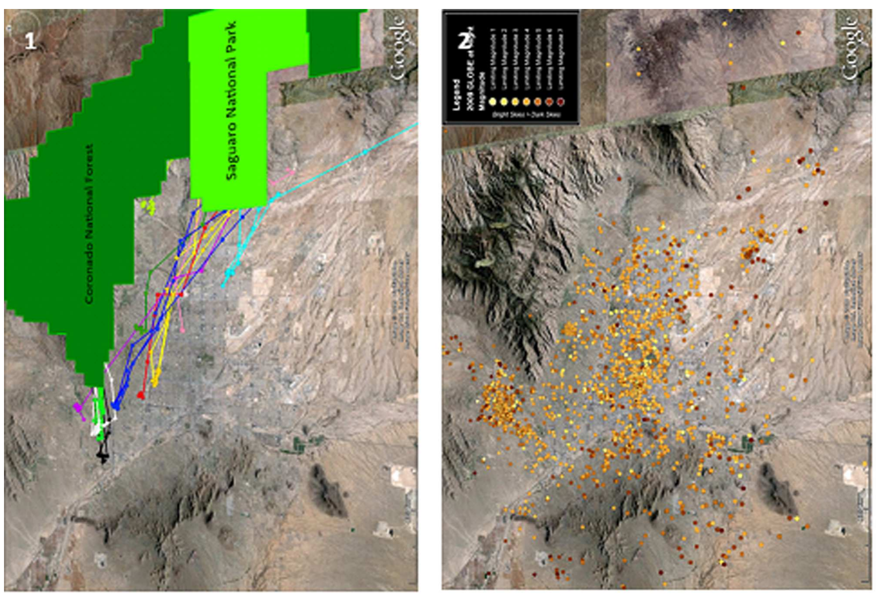

Figure 1. *(Left)* The approximate flight paths taken by the lesser long-nosed bats between their roosts and foraging areas. *(Right)* The GLOBE at Night visual observation data used in the study.

In order to determine whether or not the bats selected for or against areas that had greater amounts of light pollution, we intersected the telemetry data corresponding to the bats' flight paths with the contour plot in ArcGIS (thus assigning each telemetry point a night sky brightness value based on that derived from the contour plot). We only used the telemetry points corresponding to the bats' flight paths because including the foraging points would bias the statistics in favor of whatever the sky brightness levels of their foraging areas are. Further, the foraging points tell us nothing about how the bats migrate between their day roosts and foraging areas. The flight path telemetry points would be compared to a set of 120 random data points within the study area through compositional analysis. Using random points to determine the relative abundances of the different regions of night sky brightness somewhat resembles the Monte Carlo method of integration. The study area was chosen as the least convex polygon containing all of the bats' flight path telemetry points, and is shown with the random points in the right panel of Figure 2.

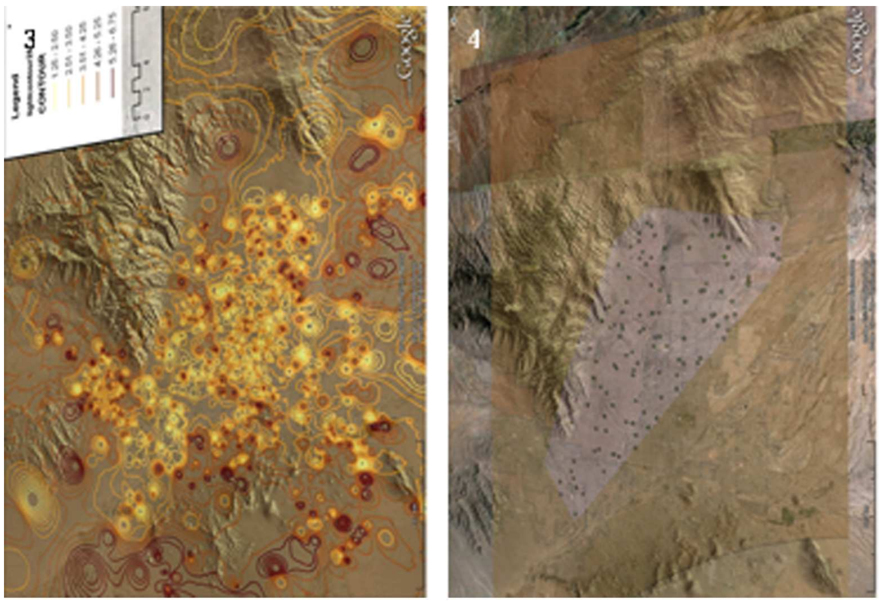

Figure 2. *(Left)* The contour map of Tucson's night sky brightness as constructed in ArcMAP. *(Right)* The least convex polygon representing our study area and the random points used to determine the distribution of night sky brightness levels.

In preparation for the analysis, we separated the night sky brightness values, which ranged between 2 and 6 within our study area, into 20 groups that differed by increments of 0.2 magnitudes (that is to say, one group compiled all of the points between 2.0 and 2.2, the next between 2.2 and 2.4, and so on). We then determined what percentage of the random points fell into each category in order to determine the abundance of each level of night sky brightness within our study area. We performed the same procedure for the individual bats, determining what percentage of the telemetry points recorded for each bat fell into which category.

We then performed compositional analysis using the statistics generated from our data described above. Compositional analysis compares the resources (in this case, night sky brightness) available in a particular study area (represented by the distribution of values attached to the random points) to the resources used in that area (represented by how frequently a bat's telemetry points were found in an area of a particular night sky brightness).

4. Results

The output results from the compositional analysis are displayed in Table 1. The 'Limiting Magnitude' column indicates the range of night sky brightness levels incorporated by that range. The values listed under the columns 'Upper' and 'Lower' are percentage values that represent the bats' proportionate use of each region (that is, the percentage of telemetry waypoints found in regions of particular night sky brightness levels as compared to all waypoints). The 'Available' column gives the percentage of random points that fell into the corresponding night sky brightness range. When the 'Available' value falls between the 'Upper' and 'Lower' values, the selection is neutral. When 'Available' is greater than 'Upper,' the bats are selecting against that region and when 'Available' is less than 'Lower,' the bats are selecting for that region of night sky brightness.

Table 1. The results from the compositional analysis.

Limiting Magnitude	Lower	Upper	Available	Selection
2.0–2.2	0	0	0.0083	Avoid
2.2–2.4	0	0	0	
2.4–2.6	0	0	0	
2.6–2.8	0	0	0	
2.8–3.0	0.0106	0.0368	0.0083	Prefer
3.0–3.2	0.0505	0.0962	0.0083	Prefer
3.2–3.4	0.056	0.1035	0.025	Prefer
3.4–3.6	0.046	0.0902	0.15	Avoid
3.6–3.8	0.1347	0.2004	01083	Prefer
3.8–4.0	0.1248	0.1887	0.15	
4.0–4.2	0.0522	0.0985	0.1917	Avoid
4.2–4.4	0.0632	0.1129	0.125	Avoid
4.4–4.6	0.1136	0.1755	0.0667	Prefer
4.6–4.8	0.0812	0.1359	0.075	Prefer
4.8–5.0	0	0.005	0.025	Avoid
5.0–5.2	0.0111	0.0377	0.0083	Prefer
5.2–5.4	0	0.012	0.0083	
5.4–5.6	0	0	0.0083	Avoid
5.6–5.8	0	0.015	0.25	Avoid
5.8–6.0	0	0	0.0085	Avoid

5. Analysis and Discussion

Our first results, derived solely from the night sky brightness measurements obtained from the GLOBE at Night datasets, show that the bats statistically select for two different ranges of night sky brightness, from limiting magnitude ranges 2.8–3.0 to 3.6–3.8 and 4.4–4.6 to 5.0–5.2.

While the bats' preference for the darker regions of the study area (limiting magnitudes 4.4–4.6 to 5.0–5.2) comes as no surprise based on prior research, the consequences of their selection for the 2.8–3.0 to 3.6–3.8 range could be quite interesting. This suggests that lesser long-nosed bats are willing to tolerate a fair degree of urbanization. Research by Carlos Martinez del Rio and Hector Arita published in 1990 found that lesser long-nosed bats have more keen visual senses than most bats. This suggests that lesser long-nosed bats rely more on visual cues for flight and navigation, in which case increased lighting levels would not necessarily have a negative impact on them.

The main source of systematic uncertainty comes from the locations of the bat telemetry points relative to the locations from which data was taken. The bats' flight paths are along the border of the area in which data is gathered, so the area to the north of the bats' flight paths is under-sampled relative to the area to the south. This forces the contour plotting software to extrapolate night sky brightness levels into these regions, creating potentially unrealistic night sky brightness levels in such areas.

A second source of error comes from the nature of the data gathering technique, alone. Because the data we are using to construct the contour map of night sky brightness comes from visual estimates of integer limiting magnitudes from a large variety of individuals, there's bound to be a relatively large uncertainty in each individually measured limiting magnitude. While the uncertainty cannot necessarily be characterized easily, we can probably estimate the uncertainty to be about 0.5 magnitudes in either direction based on the need for participants to round whatever they observe down to the nearest integer value. The best solution to this source of error, and even the first source of error, would be to use the objective Sky Quality Meter (SQM) measurements gathered through the GLOBE at Night project to construct our contour map of Tucson's night sky brightness.

A third source of uncertainty is introduced by the use of radio telemetry to track the bats in flight. The bats were first captured, marked with lightweight radio transmitters, and released. A single telemetry tracking device can detect a signal from a narrow range in front of it, but this only gives a direction and cannot be used to determine the source's distance from the detector. Using multiple detectors in unison, however, can determine the two-dimensional area from which the signal must be originating. The exact locations of the radio sources, as a result, cannot be directly determined. Rather, a maximum likelihood estimator is used to find the most likely point within the area identified by the telemetry data where the source was actually located. Each telemetry point associated with the bats' flight paths has an estimated uncertainty of one square kilometer. The only direct way to correct this would be to use GPS tracking devices mounted on the bats rather than radio emitters. However, currently, no GPS unit is small or lightweight enough that it would be allowed for use in this manner. The other potential solution would be to take the mean of the distribution of night sky brightness levels within the estimated uncertainty area and use that as the night sky brightness value for that corresponding waypoint.

6. Conclusion

When we first started this project, we created a contour map of Tucson's night sky brightness using the visual magnitude data, as seen in the left panel of Figure 3. This map was created from the 2,500 data points shown in Figure 1. We then overlaid the bats' flight paths as shown in the right panel of Figure 3, and visually noted that the bats appeared to have a preference for flight through the dark corridor along the border between Tucson and the mountains to the north of the city. The limiting sky magnitude in this area was 4 or darker. Our initial hypothesis, however, was challenged when we used the statistical method of compositional analysis to determine the bats' preferences and found a split preference between dark and light regions.

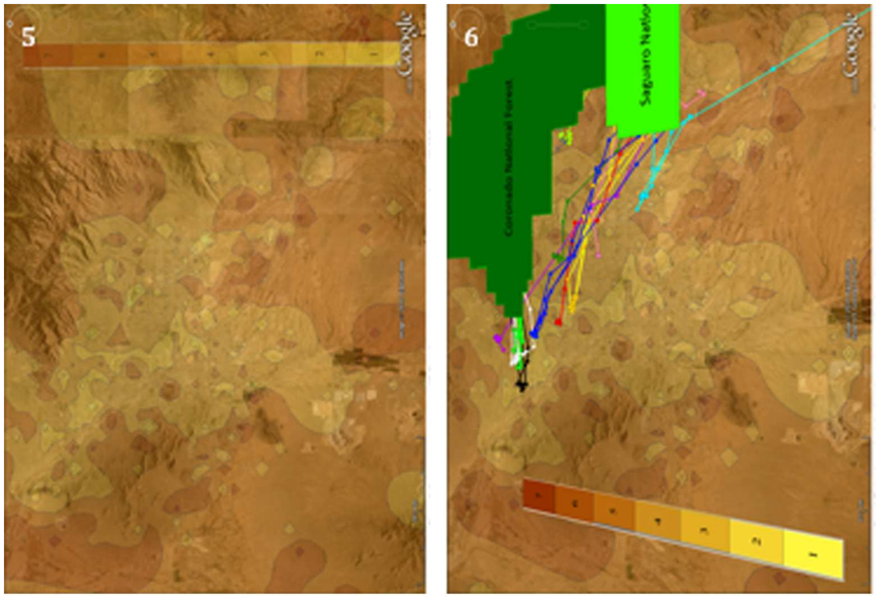

Figure 3. *(Left)* Contour map constructed in 3D Field from the GLOBE at Night limiting magnitude data. *(Right)* Bat telemetry displayed on the left panel.

More recently, we used the nearly 500 SQM measurements submitted to GLOBE at Night from the years 2007-2010, whose locations are shown in the upper left panel of Figure 4. We initially did not use this data because we believed that we would get a better result from the more abundant visual data. However, a comparison between the contour plot made with the SQM data (upper right panel of Figure 4) and the image of Tucson taken as part the Defense Meteorological Satellite Program (DMSP) (Lower left panel of Figure 4) show remarkably similar patterns of light and dark areas in and around Tucson. The DMSP takes annual measurements of the light intensity that escapes Earth's atmosphere.[3] The DMSP data is available as Google Earth overlay files online.[4] The correlation between these two methods of measuring light intensity shows us that using SQM data to measure light pollution levels is a more reliable method than using visual limiting magnitude observations. This relationship between DMSP and SQM data has been analytically substantiated by Luke Kaim (2010).

Finally, we overlaid the bats' flight paths onto the contour map created with SQM data, as shown in the bottom right panel of Figure 4. Through visual analysis, we see that most of the bats' flight waypoints fall in regions with sky brightness of 18 magnitudes per square arcsecond or darker. This result is particularly interesting because 18 magnitudes per square arcsecond, when converted into a limiting sky magnitude, gives a limiting magnitude of 4 ± 0.5, which corroborates our initial hypothesis. The

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[3]NASA website for the Defense Meteorological Satellite Program: http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/dmsp.html

[4]http://www.ngdc.noaa.gov/dmsp/kml/DMSP_Global_Composites_v4.kmz

conversion from magnitudes per square arcsecond to sky limiting magnitudes is given in (Schaefer 1990).

Using light pollution data acquired through the GLOBE at Night citizen science project, we were able to statistically identify the reaction of lesser long-nosed bats to the availability of different levels of night sky brightness in the Tucson area. We hope that this study is a starting point for future studies of the effects on light pollution on wildlife by combining GLOBE at Night Data with data like that obtained by the Arizona Game and Fish Department. For future studies, we plan to continue looking for different methods with which to analyze our data, and rely more on using SQM data for our measurements.

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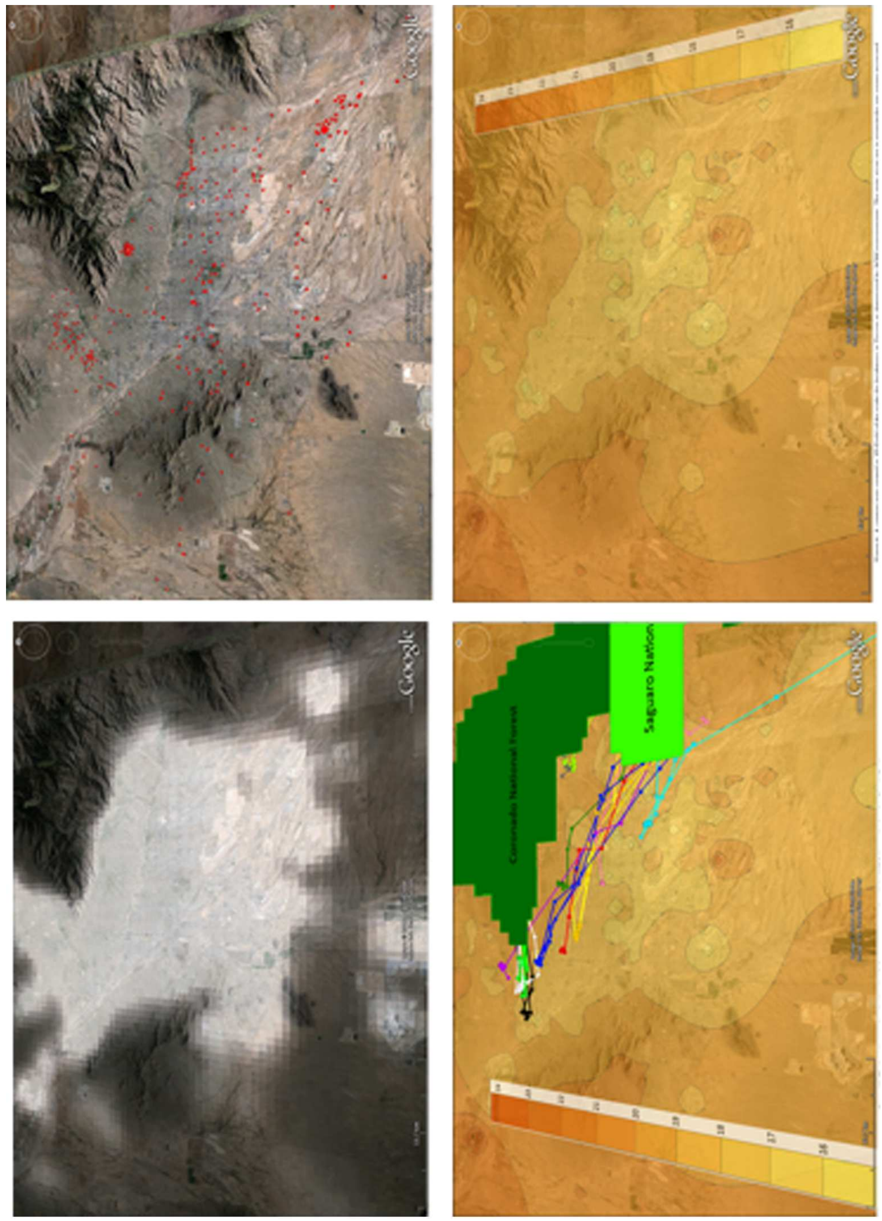

Figure 4. *(Upper Left)* The locations of the SQM data points (shown in red) in the Tucson area. *(Upper Right)* A contour map of the night sky brightness as determined from SQM measurements (in units of magnitudes per square arcsecond). *(Bottom Left)* 2009 DMSP image of Tucson at night under cloudless conditions. Whiter areas indicate brighter skies. *(Bottom Right)* Bat telemetry from upper right.