The Biological Basis for the Canadian Guideline for Outdoor Lighting 3 – Impact of the Extent of Lighting

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Abstract

A light shines as far as the eye can see—even to the edge of the observable Universe, but its brightness dims with distance. Although this dimming renders distant light innocuous, its impact close to the source can alter the ecology and reduce visibility. This paper will discuss and quantify the impact of area lighting on the health and well-being of animals and the ecology of the affected region.

Introduction

There are two questions that should be addressed when considering to what extent we should illuminate the landscape. How large an area do we need to illuminate, and how much glare from the lamp luminance can we tolerate? The first affects the ecological impact and the second affects the vision of animals and in particular humans—since only humans want, and use the light.

As naturalists of the night, amateur astronomers witness the extent of artificial (anthropogenic) light at night (ALAN). It may be a neighbour's patio light, or a streetlight that shines between buildings into their backyard. ALAN is not limited to urban areas. It is also produced by car headlights and even beacons on tall communication towers.

Figure 1 — The Entrance to a National Park. Unshielded wall packs shine into the eyes of motorists as they approach the kiosk. The luminance of the lamps overwhelms visibility in the area, and even the Stop sign. The glare masks any obstacles and hazards beyond the kiosk. The wall packs shine into bush and forest—disrupting the habitats and attracting predators and insects.

Our current society makes lights unavoidable because of our predilection for ALAN. Light fixtures are expensive to install and maintain, so there should be a reluctance to install them. However, they can offer enhancements to safety and security, and they can provide an urban aesthetic.

In the second article of this series, we differentiated between the need for luminance and illuminance (Dick 2020b). The role of luminance is to provide light to illuminate an area, or as a point source to attract attention, whereas illuminance is the light that falls on a surface that provides situation awareness, reveals hazards, or assists in navigation across the space. Although there is a need for luminance to shine far from the lamp, there does not seem to be a need for illumination that shines beyond the area of human activity, which we call the target area, and yet this is a consequence of most outdoor lighting.

Satellite imagery provides a regional perspective to the impact of ALAN. Light accompanies people as they migrate out of cities and take up residence in the less-congested countryside. This light delineates the system of rural roads and hamlets across the region. Most homes have outdoor lighting. Without shielding, these lights shine out across the roads and are visible from the neighbouring properties along the highways. These residential lights are augmented by widely spaced streetlights that mark intersections and bends in the roads.

Due to the low tax base of most rural municipalities, these roadway luminaires tend to be old, unshielded, and poorly maintained. Many were installed in the era when the mantra was "more light is better than less" and shields were either unavailable, or roadway officials did not believe they were necessary. Even today, the amount of light along a rural road

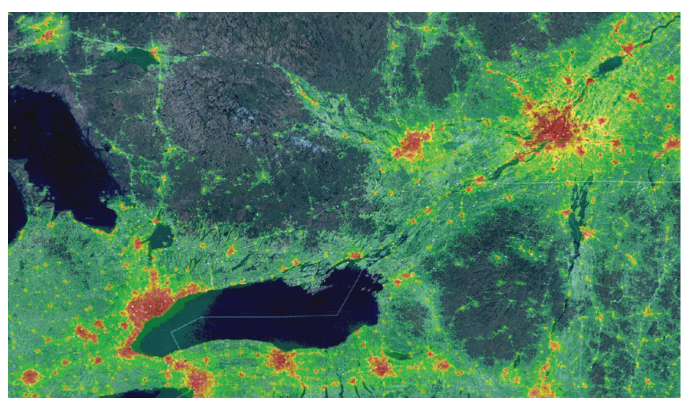

Figure 2 — Light delineates the system of rural roads across eastern Ontario. People migrating from urban to rural areas bring urban lighting standards with them. In doing so they change the landscape away from the rural environment they wish to experience. Rural activity (pedestrian and vehicular) is significantly less than what is experienced in a city, yet illumination levels may exceed urban standards. (Source: www.lightpollutionmap.info, 2019 Data Release)

is selected based on marking the right of way regardless of the glare it creates, or the amount of vehicle traffic at night.

The regional perspective in Figure 2 reveals continuous illumination along rural roadways, and accentuated by the dark forested areas between the roads. These "lines of light" sever and fragment animal habitats. Most areas coloured "dull green" will have artificial skyglow on the local horizon—illuminating the countryside and undermining the natural aesthetic and ambience of the night, and the star-filled sky. The combined effect of this illumination is to raise the ambient lighting significantly above the natural background.

It may seem obvious to prevent the spreading of "green" across the map, but to do so requires a change in our priorities and our approach to lighting.

Figure 3 — View down a rural road with an approaching car. Although modern bright headlights provide illuminance to increase visibility for the driver who cannot see the luminance of their lights, the glare is debilitating for the opposing traffic.

Ecological Extent Of Light

Nocturnal wildlife is affected by both the luminance and illuminance of light (Dick 2020b). Therefore, if ALAN is deemed necessary for human activity in an area (i.e. it is a priority), is there a rational extent we can impose on the light to minimize its impact on the ecosystem while still enabling human activity?

There are several approaches to lighting that depend on whether it is for illumination or luminance. We begin with illuminance.

If predators can see their prey, then the prey is vulnerable. Many animals take advantage of anonymity for safety and hide in the darkness, but nocturnal foraging animals must be mobile, which forces them to move out from the shadows under the trees and bushes.

The extent of their foraging range is a function of how far they are able to travel during the night. This is reflected by their body mass (Swihart 1988). Smaller animals (low mass) tend to have short legs and travel shorter distances in a given period of

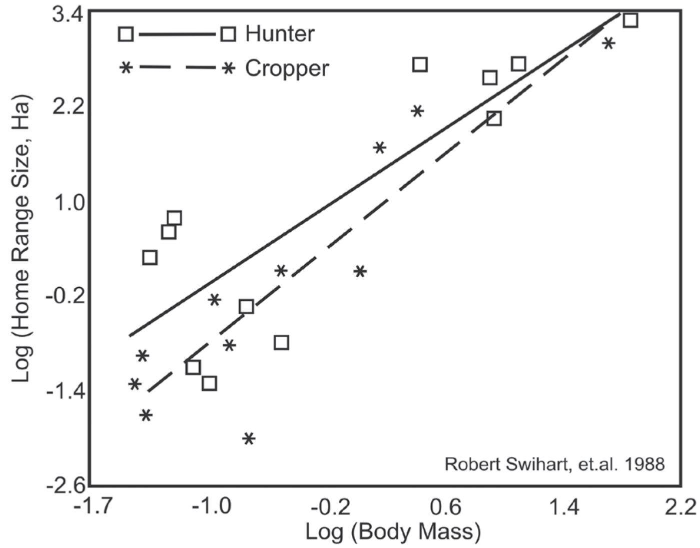

Figure 4 — Foraging range versus body mass. Foraging animals need a range sufficiently large enough to provide enough food for their survival. Larger animals require more food, but larger body size, and hence longer limbs, enables them to exploit a more expansive area. Smaller animals may not be fast enough to circumnavigate an illuminated area within a single night. If the illuminated area is too large, then its normal foraging area will become fragmented and more restrictive. This forces animals to abandon the area for a larger uncontaminated range.

time. The visible extent of the illuminated landscape presents visible barriers across their foraging range requiring costly detours that affect their use of energy and their survival from predation.

Animals learn when an area is not safe, and they relocate. However, most habitats are already in ecological balance. Changing the number of animals and the mix of species within a habitat will cause that ecosystem to re-balance—resulting in a new set of winners and losers. But regardless, change is inevitable.

The new balance may take many seasons to be established—beginning at the low end of the animal food chain that most people are not aware of. It is only after the change has affected the larger animals that people begin to take notice. The media place the blame on "habitat disruption" due to the expansion of urban areas and in the growth in the rural population, and perhaps water and noise pollution. Rarely has ALAN been raised as a contributor to this disruption so, until recently, ALAN continued unreported and uncorrected.

The luminance of an unshielded light fixture will also impact wildlife. Most mammals have similar eyesight to humans. So, glare that reduces human vision will affect animals as well. Unshielded lights undermine their dark adaptation and reduce their ability to see into the shadows.

Figure 5 — Unshielded light from Commercial Facility. Although the purpose of outdoor lighting is to improve safety, many industrial sites reduce lighting costs by using inexpensive unshielded luminaires. In this case, roughly 25% of the light energy shines off the property. Not only does the lack of shielding produce glare across the site, it impacts the surrounding landscape and visibility along adjacent roads. With proper shields, this wasted light could be "harvested" to improve site visibility and safety. (Credit Roland Dechesne)

Even relatively dim lights can undermine animal survival. Birds use the stars to navigate through the night (Emlen 1975). So, their vision is sensitive enough to use at least the brighter celestial objects. They recognize the patterns of stars and their orientation to compensate for the passage of time, and their direction of flight. Unshielded light can confuse the recognition of the celestial patterns. Patterns of "point sources" quickly change as birds fly over isolated urban lighting. And, artificial sky glow will confuse extended features like the Milky Way and the polarization of the skylight. These can lead to navigation errors that waste energy during long migrations or will delay the animal's arrival at their destination.

The bane of Canadian summers is the mosquito. Their olfactory sense allows them to follow smells upwind, but light will attract them from greater distances. The luminance of an unshielded lamp is greater than the low albedo of most clothing, so the main attractor is the lamp, not the people. Once close to their "blood meal" they may home in by smell.

Figure 6 — Spider web under an outdoor light along a pedestrian way in the Muskoka District north of Toronto. Each luminaire in the string of lights had a web.

The attraction of unshielded lights will concentrate insects that will increase the success of predators. Examples are spider webs built near outdoor lighting. So, it is important to shield light fixtures to minimize the visibility of the lamp at a distance.

Light fixtures along the shorelines of waterways will affect both aquatic life (Dick 2020b), and the safety of late-night boaters. Not only does the luminance of the lamp create glare but the light reflecting off a wavy water surface will obscure floating hazards.

Shoreline lighting also affects the aquatic ecology (Watersheds Canada 2019). The low-angle emission across the water is well below the critical angle for the reflection off a smooth water surface (45°), but wave action causes greater angles that let light penetrate the water column. This extends twilight illumination into the night, and raises illumination levels at greater depths than normal.

Figure 7 — Shoreline Glare along Waterway. Most outdoor lighting is left on through the night—yet serves no practical purpose because the people are indoors or asleep. Glare from these lights reflects off the water and prevents boaters' visibility of hazards, and can confuse navigation by masking shoreline features and navigation buoys. Although this low emission angle is below the critical angle for the reflection off the water's surface, wave action causes light to penetrate the water column to affect aquatic life.

Optics of Shielding

There are three reasons for shielding luminaires: to reduce debilitating glare, to limit the extent of the illumination and to preserve the aesthetics of the natural landscape.

An argument that is used to not shield light fixtures is, "Shielding will limit the extent of the illumination, thereby requiring more lights." However, the illumination far from

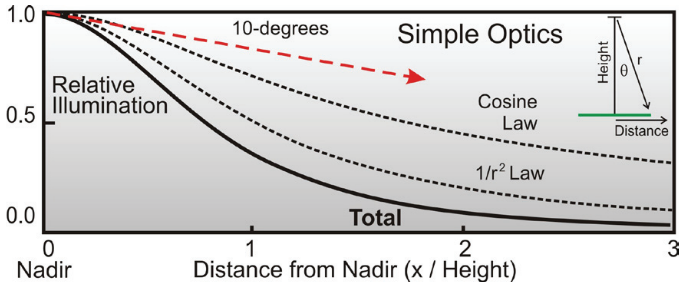

Figure 8 — Falloff of illumination with distance. Two geometric effects cause a decrease in illumination with distance from the luminaire. The surface of the expanding bubble of illumination increases with the radius^2—thereby diluting the luminance over a larger area. And the angle at which the light hits the ground becomes more shallow with distance. This is referred to as the cosine law and the distribution is called Lambertian. Combining these causes a rapid falloff in illumination with distance from the luminaire. These effects can be reduced with optics that project more light into the periphery.

the light source is not helpful in the face of the glare from the unshielded light. Figure 9 shows that a fixture with simple or no optics has a limited range of use, and the light that shines beyond this range contributes only glare, which can actually reduce visibility.

Emitted light shines into an expanding shell whose surface increases with the square of the radius. Therefore, ground illuminance (lux or lumens/m^2) produced by the light fixture decreases with the square of the distance, so that doubling the distance from the light reduces the illuminance by a factor of four.

Also, the angle at which the light hits the ground will become shallower with distance, so the incident light becomes diluted over the larger area in the periphery—further reducing the illuminance on the ground. Combining these effects shows that illumination beyond about 1.5-mounting heights is less than 1/10 that at the nadir, making it look relatively dim. Industry guidelines for roads and pathways recommend limits to this non-uniformity from 3:1 to 6:1 (average/minimum), which depend on the speed and traffic that the road or pedestrian path are expected to carry (IESNA, 2000). The equivalent "maximum/minimum" uniformity can be over 10:1, so the periphery will appear too dim with respect to the brightest areas.

If the illumination level is the only metric in the lighting designer's toolbox, then increasing the lamp luminance might satisfy the low peripheral illumination. However, this increases the glare, which further reduces the effectiveness of the illumination. Reducing the glare from the lamp with shielding is the only effective solution.

Carefully designed optics can expand the illuminated area by projecting more light into the periphery. However, this can also increase the amount of light that is projected close to the horizon—in the glare zone—within 10° below the horizontal. This low-angle light becomes very sensitive to the mounting

Figure 9 — Aesthetic Lighting at Rural Home. This image was taken at 3 a.m., when the homeowners were absent. The 750 W lamps over-illuminate the entrance and obscure hazards and wildlife along the road. The light attracts vandals and thieves by putting the property's outdoor furniture and equipment on display. The better it looks to the owners, the better it looks to "ne'er-do-wells," and they won't need flashlights to do their nasty deeds.

and alignment of the fixture. Consider the headlights of an approaching car. Modern headlights have optical systems that focus the light below the horizon to limit the glare for on-coming vehicles, but if not aligned properly, or if the grade of the road is not flat, these systems produce debilitating glare for other drivers.

Some luminaires should not be shielded. If the light serves to mark the place of an intersection or hazard, then it should

Figure 10 — Comparison of the luminance of the Moon to an LED streetlight. The Moon illuminates the countryside to a maximum of about 0.1 lux (scotopic vision) with a luminance of only 4,000 cd/m^2 (4,000 nits). The small emitters in a LED fixture must illuminate a very large surface to levels suitable for our photopic vision (>3-lux) requiring a luminance of 100,000 to over a million nits.

be visible from a distance (i.e. aircraft avoidance beacons). However, for most marker lights, the brightness need only be greater than surrounding lights. When other fixtures are shielded, marker lights require far less luminance. In ecologically protected areas, very low luminance marker lights can be used because management has control over the shielding of the other installed lighting.

However, there is currently no control over the luminance of residential and commercial lighting in urban areas. Marker luminance in built areas will be situation dependent. Only a few rural municipalities "request" that light fixtures not shine onto roadways specifically because of its hazardous glare (United Counties of Leeds and Grenville, Ontario).

Natural light sources near the horizon can be debilitating. For example, Venus (1 cd/m^2) is a brilliant spectacle above the tree line against the fading twilight. The brightest nocturnal object is the full Moon at 4,500 cd/m^2. However, Venus and the Moon tend to be obscured by trees as they approach the horizon where they might be within a pedestrian's field of view.

The relatively low altitude of a marker light will appear in front of dark trees or bushes and close to the observer's field of view—exasperating visibility for pedestrians. Therefore, a luminaire with the luminance of Venus, and especially the Moon, will appear very bright and distracting.

This leads to the conclusion that even some natural light levels can be disruptive. However, natural lighting is transient, whereas ALAN is permanent. Later in this series of papers we will be addressing ways to reduce this impact as well.

Existing Shield Solutions

The luminance of ALAN undermines visibility and the ecology. Metrics have been developed to quantify the problem, but metrics alone are not a "solution." Optics and shields should be required to contain the glare to within the target area and prevent light trespasses beyond its borders.

Fixtures are classified by, among other things, the amount of shielding. There are three ranges of shielding: no shielding, partial shielding, and fully shielded. Globe lights and most dusk-to-dawn fixtures have no shielding. They emit light over almost 4π-steradians. Older fixtures have partial shielding called Cut-Off (CO) and Semi-Cut-Off (SCO). Fully shielded luminaires include Full Cut-Off (FCO) and Sharp Cut-Off (ShCO) fixtures. Only the FCO and the ShCO fixtures do not shine light directly into the sky.

The difference between the FCO and ShCO fixtures is the amount of light allowed to shine within the "glare zone" 10° below the horizon. Light shining close to the horizon is visible almost "as far as the eye can see," which is particularly important for motorists and pedestrians because it produces glare close to the centre of their field of view. FCO fixtures limit this light to 10% of the total light output and ShCO to 1%.

Figure 11 — Luminaires with different glare characteristics. The cut-off limits apply to the light that shines above the horizon and contributes directly to artificial sky glow. (a) The typical dust-to-dawn luminaire has very limited shielding. They are designed to scatter light at angles except directly upward. Less than 25% of the light illuminates the nadir. (b) Full Cut-Off fixtures can be identified by their "flat and horizontal window." The recessed lamp prevents up-light and limits the emission within 10 degrees below the horizon to 10% of the total light output. (c) The "drop glass" cobra fixture is called a "Semi Cut-Off" —allowing up to 5% up light. A shallower lens, called a "Cut-Off", allows 2.5% up light.

BUG Rating

The optics of light fixtures can be designed to tailor the emission of light into specific directions and vertical zones. This provides another tool in the designer's toolbox. Simple shields are not perfect due to diffraction in the optics and light scatter from external shields, so a practical specification for shielding must tolerate these effects. The BUG Rating classifies the degree of shielding. BUG stands for Back-light, Up-light and Glare. This helps users to select luminaires that, minimize the amount of glare for a given application.

The BUG Rating refines the light distribution and consolidates this information into a relatively simple format

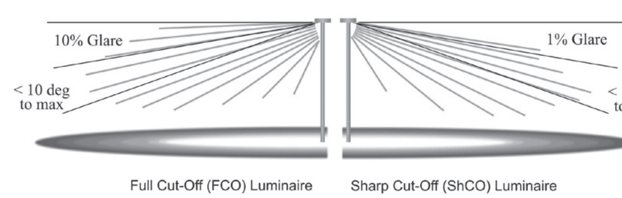

Figure 12 — Comparison of Full Cut-Off and Sharp Cut-Off fixtures. The difference between these classifications is the amount of light that shines within the Glare Zone because it creates glare well beyond the practical illuminated area. FCO has been the "standard" for over two decades. Low-impact fixtures use ShCO that limit this glare to only the illuminated area. Therefore, ShCO fixtures create virtually no glare beyond the target area.

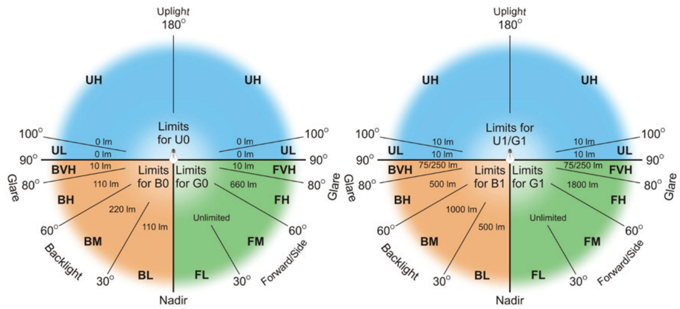

Figure 13 — Diagram defining lighting zones in "BUG" photometric system. Most Full Cut-Off luminaires (except when parts of the luminaire extend below the aperture of the luminaire) have no "up-light," so UH and UL are usually zero. The left image shows the lumen limits for B0, U0, and G0. The right image is for B1, U1, and G1. Notice that G1 has some up light and much more light at higher angles. (Ref: IES TM-15-07)

(IES 2011). The luminance pattern of the fixture is characterized by the azimuth and elevation angle of the emitted light (see Figure 13).

To limit the extent of the illuminated area, and the apparent luminance of the lamp, the light should only shine into the lower sectors (BL and FM). However, it is sometimes desirable to illuminate into the periphery. Therefore, the amount of light in the high-elevation sectors becomes important (BH and FH). Note that back light produces light trespass and glare into buildings behind the luminaire. If the luminaire is mounted on a wall, this back-light will make the wall appear very bright—contributing to glare visible beyond the target area.

The amount of light in each sector is used to classify the overall BUG rating of a luminaire. The limits for each sector are shown in Figure 13 for B=U=G=0 and B=U=G=1. In determining the BUG rating, the lumens emitted in each zone must be less than the limiting values—irrespective of the total lumen output of the luminaire.

Depending on the luminance of the light fixture and the amount of light emitted in the glare zone (within 10° below the horizon), the Glare component can range from G0 to G4. For example, a FCO 1000 lumen luminaire is G1 (1,000 lumens x 10% = 100 lumens) but a 1000 lumen Sharp Cut-Off luminaire is G=0 (1,000 lumens x 1% = 10 lumens). For more general applications, the BUG rating might be: B0-1, U0, G0-1. A limited amount of light in the glare zone is permitted for G0 because it is virtually impossible to produce a practical light that has zero light within 10° of the horizon—due to light scatter in the optics and their protective window.

Summary

Since luminance is required to illuminate an area for human activity, it will be impossible to eliminate the contamination of this area. The best that can be done is to minimize the extent of the contamination beyond the target area.

Luminaires with CO and SCO shielding, with their up light and horizontal emission, will illuminate the sky and create bright "false stars" above the horizon, which can confuse the navigation of animals and affect their night vision. Such luminaires also emit significant light that illuminates a wide area—affecting the foraging range of many animals. However, it must be recognized that even the popular FCO, and even ShCO luminaires will cause some degree of distant contamination. Therefore, in addition to limiting the extent of the ground illuminance, reducing the lamp luminance will also reduce the glare and should be minimized below a "practical" ecological threshold (Dick 2020b).

How does the luminance of Venus compare to that of urban and roadway lighting? The industry guideline for the apparent luminance of an illuminated road surface is about 0.5–1.0 cd/m^2 (IES 2000). However, traffic lights are over 1 million times brighter in order to outshine streetlights and automobile headlights. This undermines any practical ecological threshold for an urban lighting guideline. Indeed, the lack of control over urban traffic and automobile lights impacts visibility limits along roadways. The high-luminance lighting along roadways has no parallel in nature. Therefore, a lighting guideline that limits luminance to preserve the ecological integrity of a space may not be applicable to some urban areas. However, it may provide an alternative perspective for urban (residential) lighting that can be more environmentally sound and "sustainable."

We have reviewed the impact of brightness (Dick 2020b). Shielding is a second "tool" to limit the impact of ALAN. However, these limits may not be sufficient, so we must bring to bear controls on other light attributes. The next paper considers the colour, or more specifically, the spectrum of the emitted light. ✶

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