countryman and instrument maker William Würdermann in 1870, to help build and maintain instruments for the ongoing United States Coast Survey ordered in 1807 by Thomas Jefferson. Würdermann established a profitable business in Washington, DC, producing ever-better instruments including portable transit, surveyor, and zenith telescopes. Eventually Fauth and brothers-in-law George N. Saegmuller and Henry Lockwood established their own business in 1874, under the name of Fauth & Co. They manufactured various surveying and measuring instruments (Figure 10), as well as equatorial mounts for astronomical telescopes. In the process, they won awards at the Cincinnati Industrial Exhibitions of 1876 and 1882. After Fauth retired back to Germany in 1887, Saegmuller continued trading under the name Fauth & Co, until 1892. The largest known telescope made by Fauth & Co is an 8-inch refractor at Santa Clara University in California (Fried, 1994). ✶

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The Biological Basis for the Canadian Guideline for Outdoor Lighting 1. General Scotobiology

by Robert Dick, M.Eng., P.Eng., FRASC

Abstract

The subject of limiting outdoor lighting seems straightforward—it saves electricity and reduces glare, but society has a predilection for activity at night that requires more than natural light. This extends beyond urban areas. "Cottage country" is well lit along the shoreline, and even campgrounds filled with amateur astronomers have lots of unshielded lights. Although these tend to be red, they still undermine our night vision (Dick, 2016) and change the nocturnal ambience.

The main problem of whether outdoor lighting is good or bad depends on who is judge. Is there a less equivocal way to assess or define acceptable outdoor lighting, especially in rural areas? Must rural lighting follow "Best Practices" for cities?

This is the first in a series of papers that will discuss the science behind the ecological impacts of artificial (anthropogenic) light at night. It will propose rational solutions to reduce these impacts and will define the characteristics of artificial light that minimize these disruptions that we call lighting with "low-ecological impact."

Although taking an ecological approach to outdoor lighting is unusual, we have observed that if the nocturnal environment is preserved for wildlife, it is usually sufficient for astronomy. Although it is understood that observatories may require a curfew during the three weeks centred on the new Moon. This first paper will set the stage for this somewhat unorthodox exploration into light.

Scotobiology

Scotobiology is the study of the biological need for periods of darkness. Unlike photobiology, it concentrates on the benefits of darkness, not the benefits of light— subtle but significant. This study began following the 2003 Ecology of the Night Conference hosted by Parks Canada in the Muskoka District north of Toronto. Although light pollution was generally believed to be a problem for astronomers, it became evident from the diversity of research topics; it is an ecological and human health issue.

Scotobiology transcends the usual fragmented fields of animal biology and behaviour, and human heath and vision, which

Figure 1 — The Milky Way in early winter over Rideau Lake, Ontario. "Cottage country" is becoming increasingly contaminated with urban light as cottagers install urban-type lighting on buildings and along shorelines. (R. Dick, 2019)

may be the reason for the lack of awareness in the scientific literature. Outdoor lighting was a niche subject in each field. However, by focusing on the similar patterns and sensitivities of nocturnal biology and behaviours, the impact of light in these diverse disciplines could be integrated.

When exploring the impact of artificial light at night (ALAN) on our health, and the ecosystem in general, we must be careful about what the science indicates and what it is silent on. To wit: the absence of proof is not the same as proof of absence. So, although there may be no "proof" on a topic, we should discount anecdotal reports. Indeed, we should not let our ignorance prevent us from making rational judgements.

Scotobiology is a new approach to studying the environment, so it is understandable there are many gaps in the knowledge. We have to extrapolate what is known with one species to judge its impact on another. There are three basic assumptions when applying scotobiology to ALAN.

1) The ecosystem is in balance if it has existed for a protracted period of time.

2) A change in the environment will impact the ecological balance.

3) Changing the ecological balance will impact all species in that environment.

Therefore, a change to the environment that has been found to affect one species will have an affect on others because the balance will be affected. Even though a specific environmental change has not been studied for a particular species, it does not follow that the species is not affected. And to understand how some species are affected we can apply those known effects (guardedly) to those that have not been studied.

Introduction: In the Beginning

Life on Earth began with single-cell prokaryotes soon after the crust solidified. Two billion years later, some of these branched off to form more complex eukaryotes, which co-existed with the prokaryotes (*Scientific American* 1999). Only 600 million years ago multi-cellular organisms appeared. Life then increased in complexity and evolved into what we see today. So, life as we see it now is relatively recent (less than 1/8 the Earth's age).

Throughout all this time, the environment was subject to a diurnal and annual progression of day, night, lunar month, and the seasons. Tidal braking by the Moon slowed the rotation of the Earth, so the days became longer, and complex weather patterns ensured the year-to-year seasons were not constant. Since the occurrence of multi-cellular life, the day has lengthened from less than 21 hours (Kahnle 1987) to the current 24 hours. Excluding catastrophic events, changes were very slow.

Any life on the land experienced significant changes in climate as plate tectonics shifted the mobile crust from the equator to higher latitudes, and vice versa, but genetic evolution and adaptive behaviour were able to keep pace with these slow changes, allowing many creatures to evolve with the evolving environment. Genetic evolution can be revealed in just a few decades of environmental changes (Bonnet, 2019), but those that didn't adapt (behaviour) or evolve (genetic) went extinct.

Stephen Gould once wrote about the tree of life that peaked in diversity about 500 million years ago, "We must recognize that this tree may have contained a maximal number of branches near the beginning of multi-cellular life and that subsequent history is for the most part a process of elimination and lucky survivorship of a few." (*Scientific American* 1994) Or to maintain the metaphor: since that time, the tree of life has been losing its less adaptable branches.

Figure 2 — A gathering of amateur astronomers in Southern Ontario. Visitors illuminate campgrounds in national, provincial, and private parks. Although most astronomers use red light, it disrupts the ambiance of the night. (R. Dick, 2012, Starfest)

Slow change of the environment promotes evolution, but abrupt change leads to extinction.

The Need for Night

The environmental difference between day and night is obvious and profound. The cycle of day and night has helped drive evolution that created an ecological balance between diurnal and nocturnal life. Light is the obvious difference between day and night, with temperature and humidity also being important. To survive day and night, animals must develop means to forage, mate, navigate, migrate, and avoid predators, and the predators must develop ways to see at night to hunt.

These two environments double the number of niches for life and make the ecosystem robust and tolerant to other changes in the environment, including weather and climate.

The current state of mammal vision dates back to the era of dinosaurs (phys.org, 2016) and is the result of several detours along the way. It has been proposed the human deficiency of blue-sensitive daylight cones may have originated from blue-sensitive cones evolving into the more sensitive rod cells for night vision. Then when human precursors returned to a diurnal species, we were left with a deficit of blue cones.

This demonstrates the relationship all species have to their photo environment, and given time, are subject to evolutionary change but these changes may take thousands or millions of years. Current mammals are, for the most part, locked into their diurnal and nocturnal preferences, but share aspects of similar eye geometry, architecture, and visual chemistry. Therefore, changing the day or the night will affect most species.

Artificial (anthropogenic) light at night fundamentally changes the environment into one for which no life has evolved. The impacts and the challenges are at all levels: behaviour, biochemistry, cognition, and genetics. As we shall discuss, ALAN undermines the ecological integrity of the ecosystem and puts the survival of all its members at risk. It should not be a surprise that since humans are animals, we are subject to the same impacts on our physical and mental health. To better understand these effects, we need to compare or contrast the differences between natural light at night and ALAN as it relates to vision, biology, and ultimately health and survival.

Global emissions of ALAN into the night sky have been monitored since the late 1950s, and more precisely for the last two decades (Cinzano et al., 2000; Falchi et al., 2016). These programs have shown the direct correlation between ALAN and urban areas, and our industrial and recreational activities. However, the rate of increase exceeds the growth of populations and economies, which suggests there are other social and technical reasons for the increase of ALAN (Kyba et al., 2020).

The impact of ALAN on life has been studied for over a century but only in the last few decades has this impact been shown to undermine human health as well (Davis et al., 2001), and the degree that it disrupts the ecological integrity of the environment (Rich and Longcore, 2006).

Human Vision

Genetically, humans are hunter-gatherers, optimized for a lifestyle not that much different from the animals we hunted and study today, and we share the same natural photo environment.

Humans are the only species that want ALAN and need it for activity after dark. So, we need to explore the lighting requirements for human vision.

The primary use for ALAN is to make people aware of the environment around them. The more widely used term is "situation awareness" (Wikipedia) and it gives us a wide spatial perspective.

Situation awareness refers to more than just illuminating a patch of ground, which could be considered "task lighting." It refers to awareness of the region and how it changes as we walk through it. The Moon illuminates the landscape "as far as the eye can see," so a pedestrian's knowledge of the area develops as they walk toward and pass by features and hazards. In contrast, a single light fixture illuminates a much more limited area. The bright light prevents anyone from seeing "beyond" the illuminated patch, and thus reduces perspective and safety.

Much less light is needed for situation awareness as the illuminated area is expanded. This can be experienced in a city where a typical short residential street and adjacent properties may be illuminated with 2kW of electric lighting.[1] It reveals the neighbourhood. Whereas "spot lighting" does not provide a context—resulting in psychologically uncomfortable and potentially dangerous situations.

Our vision is a function of the structure of our eye and the action spectrum of its components. Critical to our view of the

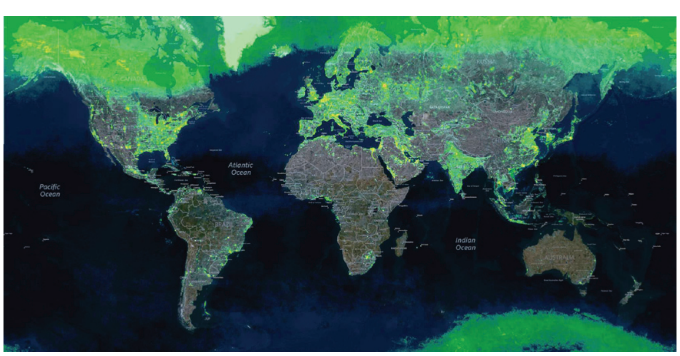

Figure 3 — Distribution of ALAN over the Earth. The most densely populated areas emit the most light into the sky. However, even rural areas contribute by raising the background emissions. The wide green bands in the north and south are due to solar illumination "over the pole" (midnight Sun) in that hemisphere's summer. (www.lightpollutionmap.info, 2019 data)

Figure 4 — Vulnerable pedestrian "on display."

world is also our brain, which applies "neural algorithms" to create coloured images that are pieced together and give us vision.

Natural light in the environment has a dynamic range of illumination of more than 1 billion:1. We have two sets of cells to cover this range and the spectral responses (action spectra) of these cells have differentiated between the bright day and dark night. Both have characteristics tailored, or optimized, for those two environments.

Which visual cells are used in our vision depends on the amount of ambient light. Cone-shaped cells provide our photopic vision during the day and are the only cells that give us the sensation of colour. The night is too dim for these cells, so our night vision defaults to our more sensitive scotopic vision that uses rod-shaped cells.

The cone cells have a peak spectral sensitivity at 555 nm (yellow). During the day there is a mechanical and a photochemical feedback mechanism to help protect our eyes from extreme brightness. First, our iris closes down reducing the amount of light that enters our eyes. Second, there are synaptic interactions in the retina (neural adaptation) that rapidly adjust (200 msec) for light variations of 100×–1000× (Boyce, 2014a). And third, the light-absorbing chemical (rhodopsin) in the cells becomes depleted at high light levels and reduces our cone sensitivity (Rushton & Henry, 1968; Geisler, 1978). The latter effect produces a dim "blind spot" in our field of view after looking at a bright light. Eventually these cells recover (a minute or so). This would not have been a problem for our ancestors due to the natural slow change in brightness from daylight to dark but can be a nuisance when walking from a bright room into the night, or when exposed to headlight glare from cars.

There are three sets of cone cells with "pigments" that absorb spectral bands centred on 420 nm (blue), 530 nm (yellow), and 580 nm (red) (Webvision). These are concentrated in the centre of our field of view— primarily within a 20-degree circle. Of particular interest is the number of each type of cell. The blue sensitive cells make up only 6 percent of the cones, with the yellow and red cells making up the remainder. The lack of blue cones means our visual acuity in blue light is very poor, which aligns with the relatively poor blue colour correction and focal distance of our eye's lenses.

At low light levels, the far more sensitive rod cells provide our night vision. During the day they are bleached by the bright sunlight but recover during the fading twilight to progressively replace the loss of our cone-vision. The rod cells are crowded out of the centre of our field of view by the cones but dominate the periphery. This is why astronomers use averted vision—so the faint light of celestial objects will fall on the more sensitive night vision cells. Our rod cells are most sensitive to 505 nm (green light), which is the peak wavelength of the reflected light from the Moon. So, they are spectrally well suited to our survival at night. The price of their sensitivity is the lack of colour vision.

During twilight we use a combination of our photopic and scotopic vision called mesopic vision. We can recognize this state because colours are visible but become de-saturated as the light dims—halving in brightness every five minutes or so. The mesopic vision is critical for safety, yet it is a particularly difficult time for our vision. If light levels fall too quickly (in a few seconds or so as experienced with urban lighting), our rod cells cannot recover fast enough from being bleached by the high photopic levels. This leaves a period where neither the cones nor rods can function—we are temporarily blind. So, there is little benefit from our mesopic vision with urban settings.

Our iris constriction is controlled, in part, by the detection of light by non-visual cells called the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs). A luminance level of about 1 cd/m^2 will begin to constrict our iris (Watson & Yellott, 2012) (approximately the luminance of Venus in our sky). At about 2.5 cd/m^2, our pupil area is halved, letting in 50 percent of the incident light. So even relatively dim light sources, emitting spectra to which the ipRGCs are sensitive, will contract our pupil.

These ipRGCs are extremely sensitive, responding to single photons (Pickard & Sollars, 2011), but react slowly to faint light. They also provide information to regulate our circadian rhythm and related biochemical processes. They contain the photochemical called melanopsin, which is different from the rod and cone cells. It has a peak spectral sensitivity at about

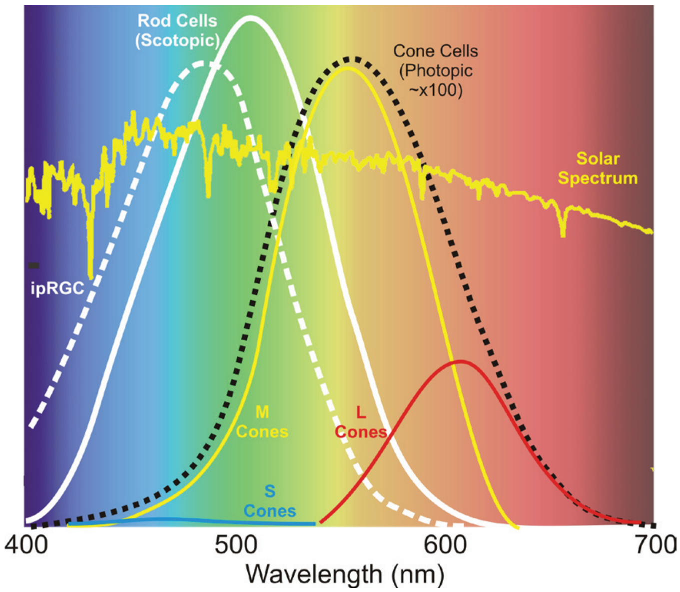

Figure 5 — Action Spectra for three sets of light detectors in our retina. The three types of cone cells detect colour with a peak sensitivity at 555 nm photopic vision,1931 CIE). The rod cells have a peak sensitivity at 505 nm (CIE 1951). The ipRGCs (twilight detectors) have a peak sensitivity at about 480 nm.

480 nm that corresponds to the blue sky of twilight. This is more than coincidence—it provides a survival advantage during twilight, so we refer to these cells with the less-prosaic name of "twilight detectors."

Our eyesight degrades as we age—with about 40 years being the time when our visual acuity, light sensitivity, and colour recognition requires us to wear eyeglasses, use a lower illumination level, and more illumination, respectively (Boyce 2014b). The eye's components become less transparent and scatter short wavelengths greater than younger eyes do. As hunter-gatherers, humans did not live much beyond 40 years, but today we live long enough to experience the degradation of our vision.

Summary

Although ALAN is for humans, it also affects the biology and behaviour of wildlife. The degree of impact will depend on the species and their photo environment (day, crepuscular, or night), behaviour (foraging, predator, or prey) and how these are affected by weather and seasonal change.

The tolerance of animals to ALAN will set the ecological limit for outdoor lighting and is the reason for the ecological focus of a lighting guideline, and not just the human predilection for light at night or for stargazing. At night the animals are the majority. They share the night with us. It would be rude to ignore their needs when we are their uninvited guests.

The next paper in this series will address the ecological impact of the brightness of ALAN. Later in this series will be papers reporting on the impact of the extent of the light, its spectra, and timing. ✶

Endnotes

1 Based on illuminating a 600-metre-long road from house-front to house-front (20,000 m2) with 100 lm/W luminaires to about 10 lux. Uniformity (maximum/average) of residential streets is roughly 10:1.

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