Lighting Res. Technol. 2013; **0**: 1–17

Applied scotobiology in luminaire design

R Dick MEng
Canadian Scotobiology Group, Rideau Ferry, Ontario, Canada

Received 25 June 2013; Revised 23 August 2013; Accepted 27 August 2013

Studies of our illuminated environment demonstrate the importance of light to humans, who by evolution are essentially daytime creatures. However, the study of behaviour and the biology that occurs during the night has clearly shown the importance of darkness for both humans and the ecological integrity of the countryside. Since humans are expanding their activity throughout the night and into rural areas, is there a compromise between the human desire for light and the need for darkness? All animals and plants have light thresholds to which they have evolved. We have applied the findings of scotobiology to determine outdoor lighting that minimizes the disruption of artificial light at night on the natural environment and on human health. It is not surprising that the key characteristics to be limited are the brightness, duration and extent of the emitted light, the amount of glare and the spectrum of the emitted light. To test the practicality of these limits, we present the patented design of a luminaire that bridges the desire for 24×7 human lifestyles and the protection of the nocturnal environment.

1. Introduction

It is becoming widely understood that artificial lighting has more than just a local impact. Urban light scattered into the sky is visible as sky glow, which can affect the ecology of an area of over 10 000 km^2 for large population centres. So, although our desire to illuminate the night is mainly confined to urban areas, it has a much wider ecological impact.

During the last half of the 20th century, we have discovered that the most effective way of controlling pollution of the environment is at the source and this applies to outdoor lighting as well. It is not practical to eliminate outdoor lighting but what has been lacking is a quantitative assessment of how much artificial light can be tolerated by the ecosystem. We have taken advantage of the considerable amount of existing knowledge on the impact of light on life forms to develop a compromise that satisfies nature's need for periods of darkness and the human desire for artificial light at night (ALAN). We discuss a few examples of impacts to demonstrate the ecological limits for ALAN.

The levels and periodicity of light affect behaviour and biochemistry in profound ways through circadian and circannual rhythms.[1] All life has evolved and adapted to the natural light levels. So, the ecosystem does not need or want any more light than is provided by natural sources. However, the increase in human activity at night since the industrial revolution and the recent development of 24×7 life styles have increased the human desire for nocturnal lighting. Human vision and activity-based studies have led to rising light levels, as permitted by technology, in order to minimize human risk with the goal of a 'safe' night environment. By including the impact on the environment and human health, we can counter these arguments in what would otherwise be a one-sided debate.

We use scotobiology to assess the biological and behavioural drivers for ALAN.

Address for correspondence: R Dick, Canadian Scotobiology Group, PO Box 79, Rideau Ferry, Ontario K0G 1W0, Canada.
E-mail: rdick@csbg.ca

10.1177/1477153513505758

Scotobiology is the study of the need for periods of darkness and its application provides a rational assessment of ecological limits to outdoor lighting. Current artificial lighting guidelines are based on the capabilities of the lighting technologies in use when the guidelines were written (i.e. based on best practice). Studies of these light levels by researchers documented the resulting improvements in visibility and these were subsequently adopted by professional bodies as guidelines. Governments then adopted these guidelines as 'standards' since there were no competing arguments. This situation is slowly changing. Medical research is now better able to characterize our visual system and studies into our biochemistry and that of wildlife are revealing widespread sensitivities to ALAN. Our recent concern for the environment is placing a greater value on the natural environment and, coincidentally, lighting technologies are advancing to allow lighting that minimizes its adverse effects.

This paper presents the critical characteristics of ALAN and a lighting specification that will significantly reduce the adverse effects while assisting human visibility outdoors at night. In order to test the practicality of these characteristics, we have developed a luminaire that satisfies all these requirements.

Although there is no single lighting condition that represents all niches across a region, we can identify five lighting attributes that are critical to reducing light pollution:

1) The amount of illumination
2) The extent of the illuminated area
3) The degree of glare
4) The spectrum of the emitted light
5) The duration of the illumination

Specifying the characteristics of light is complicated by the range in tolerance that the multitude of life forms have for nocturnal lighting. They have evolved to fill neighbouring, and in many cases overlapping, niches and exercise very different behaviours in response to light. Therefore, a single illuminated or dark condition is not ideally suited for all nocturnal animals. However these studies have revealed a set of basic qualities for ALAN that can be generally applied to minimize its impact.

We approach the determination of the appropriate lighting by first studying the natural brightness of the night. We then assess the threshold levels for a cross-section of creatures for vision, biochemistry and behaviour. The selection of creatures is based on the available literature, which is not extensive. Many species have not been studied for their reaction to low levels of illumination (<20 lux).

2. Amount of light

2.1. Natural light

The natural night is rarely very dark. Twilight and dusk provide a gradual transition between daylight and night-time. Starlight, natural sky glow and zodiacal light provide sufficient illumination for low-level activity as long as there is no artificial lighting to degrade our rod-based night (scotopic) vision. Only under thick cloud cover in a non-light polluted countryside can it be so dark that we cannot see. Natural night-sky light illuminates the countryside to about 0.001 lux and the moon can illuminate the countryside up to 0.27 lux (more typically 0.1 lux) for a period of time each month (Figure 1). All life on Earth has evolved or adapted its behaviour to accommodate this range in night-time illumination.

2.2. Human vision

Historically, human activity at night has been pedestrian with a casual walking speed up to about 1 m/s. For a relatively flat

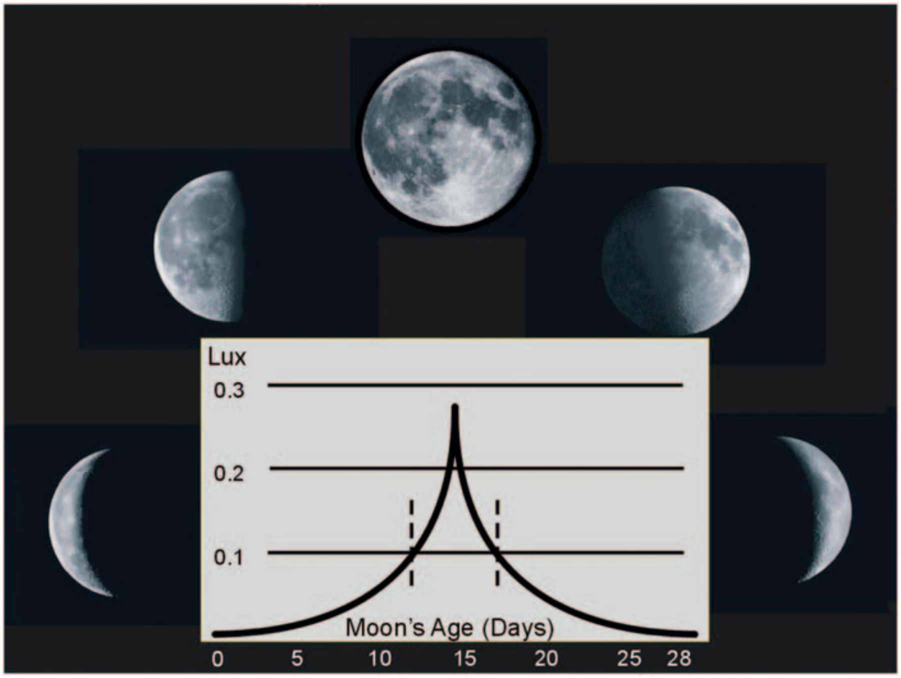


Figure 1 The moon dominates the night sky for about a week centred on its full phase.[2] At other times when its phase is much thinner, it provides relatively little illumination and it sets soon after the sun at night and rises just before the sun in the morning, leaving most of the night dim. The enhanced illuminance centred on the full moon is caused by the optical properties of the lunar regolith at high incident angles.[3] Although the maximum illuminance is about 0.27 lux, this applies to the illumination of the ground with the moon in the zenith under a very clear sky. A more typical illuminance is about 0.1 lux

landscape, starlight is sufficient to provide visibility for a few physical hazards. However, humans are not primarily creatures of the night and the visibility needed for more vigorous activity requires more illumination to provide faster recognition and assessment of hazards.[4] For relatively passive activity, my experience under a range of light levels suggests that very little extra artificial light above a full moon is needed for good visibility. For example, I can read a phone book at 1 lux but not at 0.5 lux.

Modern mechanized human activity is much faster than a walking pace. Hazards are increased with fast vehicles in close proximity to pedestrians. A person walking could take many seconds to react after seeing a hazard, whereas a driver may have only a few seconds to make a decision. The need for reaction times less than about 0.5 s requires light levels greater than the scotopic limits (the full moon). Early studies into light levels and reaction times[4] show that an increase by a factor of 10 in illumination reduces reaction time by only a factor of three – from about 0.5 s to a limit of about 0.17 s. Illumination of about 10 times that provided by the full moon (about 1 lux) reduces reaction times from 0.5 s down to about 0.2 s, which is also the approximate speed of our pupillary reflex.[5]

We are living longer than our ancestors and this exposes us to the degradation of our vision. We are now beginning to realize that light thresholds are not the only limits for vision. Studies into human vision and visibility have tended to use young subjects – especially students of university age. However, the eyes of senior citizens absorb and scatter more light with increasing age and are less responsive to light, especially at short wavelengths.[6,7] Studies of pupil contraction give a threshold of between 1 lux and 3 lux.[8] Higher illuminance cause our pupil to close down – letting in less light (Figure 2). This can be very detrimental to the visual capabilities of senior citizens. As we age, the centre of our lens begins to crystallize (incipient cataracts). However, if our pupil is reduced by relatively bright illumination or glare, light enters our eye primarily through the central crystallized portion of the lens, thereby degrading the retinal image. With less illumination or less glare, more of the light enters the eye through the clear periphery of the lens.

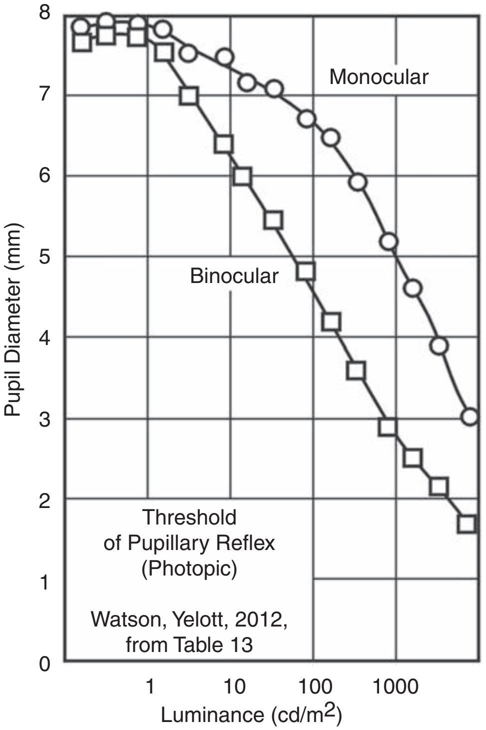


Figure 2 The photopic sensitivity of our pupillary reflex.[9] The pupillary reflex is primarily mediated by the intrinsically photosensitive retinal ganglion cells (ipRGCs). The threshold illumination level is approximately 1–3 lux. This change in pupil diameter is typical of a young adult. The pupil of older subjects has a smaller upper limit less than 6 mm in diameter

2.3. Plants and aquatic life

If ALAN were restricted to only human habitats, then its impact would only be social and cultural. However, plants and animals are strongly affected by the duration of dark periods.[1,10,11] Due to space limitations, we will highlight only two very different life forms – plants and fish, both having significant economic value, to illustrate a few effects of ALAN.

It has been known for almost a century that plants can detect light levels between 0.1 lux and 1 lux[12] and use the length of dark periods to determine the season of the year.[13] They respond to this cue by preparing for the seasonal changes.[14] Extending the length of daylight with ALAN can 'fool' a plant into reacting as though it was still summer; shortening the day can cause some plants to flower out-of-sync with the actual season. For example, it is common practice to artificially extend daylight for chrysanthemums through autumn and then shorten daylight in December to delay them from flowering until Christmas, when they are sold as decoration. We probably do not see many urban plants dying due to seasonal stress caused by ALAN since sensitive plants will have died off earlier in the 20th century and this would be attributed to general 'habitat loss', of which we now know lighting is a component.

The retail food market would like to have the same produce all year. It is known that some fish are daytime feeders, some are nighttime feeders and others are crepuscular (twilight) feeders and this response to light can switch between summer and winter.[15] Although temperature and availability of food influence this pattern, the only long-term predictor of seasonal change is the relative length of daylight/darkness. Fish raised in enclosed aquaculture facilities can be manipulated by changing the length of daylight to shift the period of spawning to later or earlier in the actual year.[16] However, in the wild, late maturation of fish may be out of synchrony with food supplies and supportive temperatures, which can contribute to the reduced survival of fish stocks.

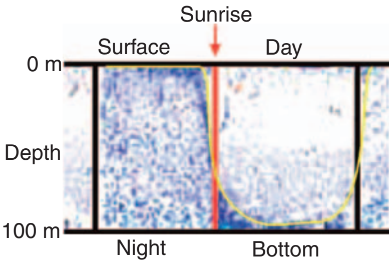


Figure 3 Diel vertical migration of zooplankton recorded in Saanich, British Columbia. It shows the relatively rapid descent of zooplankton during dawn. These records were made during a 3-day old moon (crescent in evening sky) and do not show the effect of the lunar phases[20]

Although moonlight has been a periodic source of nocturnal light since the Earth formed 4.5 billion years ago, it still disrupts the activity of wildlife with its monthly brightening. For example, nocturnal foraging species alter the extent of their travels under the light of the full moon[17] and some zooplanktons restrict their vertical migration in the water column during times of natural lighting.[18,19] Studies on zooplankton, which are near the base of the aquatic food chain, show that they alter their foraging behaviour in response to faint incident illumination. This diel (daily) vertical migration moves organisms through considerable depths (Figure 3) but even the light of the crescent moon (less than 0.02 lux) affects the amplitude of this behaviour (Figure 4).

Studies also support the hypothesis that the behaviour of fish can be compromised by altered lighting patterns[22] as well as temperature. Low temperatures are indicative of

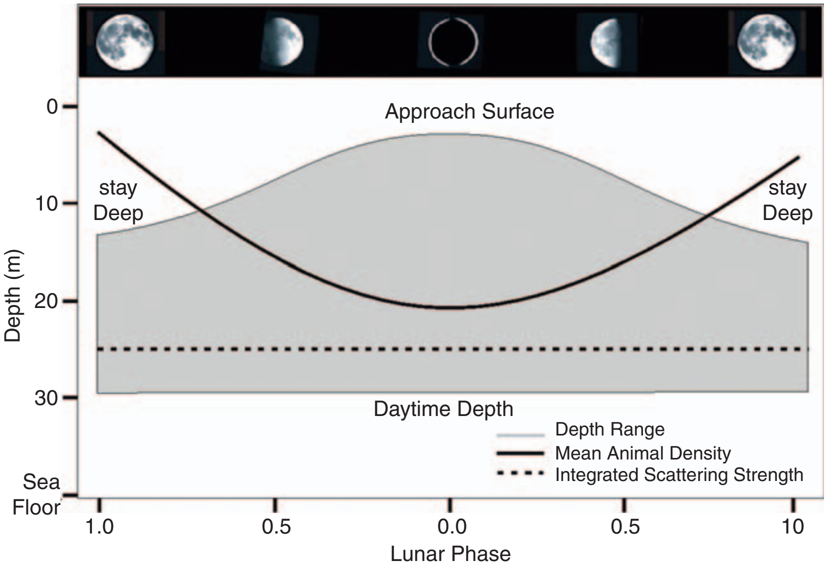


Figure 4 Zooplankton off the island of Oahu, Hawaii, were influenced by the phase of the moon. At surface illuminances of less than 0.1 lux, the surfacing of zooplankton was suppressed. The line for the integrated scattering depth indicates that the column density of animals remained constant during the period. At 25 m scattering depth, the illumination that was sensed by the zooplankton was about 0.02 lux.[21] This is a summary of more detailed data presented in the referenced paper

autumn. However, long periods of ALAN suggest summer, providing conflicting signals that can produce unexpected behaviours. Understanding the illumination thresholds to prevent or minimize these mis-cues is important for the survival of the sports fishing industry on inland waterways and lakes that may be affected by shoreline lighting and artificial sky glow from nearby urban areas.

2.4. Human non-visual aging effects

Many human physiological processes are cyclic, with a period of about a day (circadian rhythms). Evening darkness is associated with the release of the hormone melatonin,[23] which then enables a number of diverse processes to occur while we sleep. The amplitude in the cyclic variation of melatonin is important for our continued good health.

High levels of light during the day are associated with low melatonin concentrations while very low illumination at night is necessary for its release. However, melatonin concentration also decreases with age (Figure 5); thus, even low levels of illumination at night can have a greater effect on limiting melatonin release for senior citizens than for younger subjects.[24]

Our cognitive functions degrade if the amplitude of the cyclic release of melatonin is lowered, so we should maximize the day-time exposure to bright light and minimize our exposure during the night.[27] These findings are particularly important as more senior citizens spend their days indoors. ALAN exacerbates the effects of dementia such as Alzheimer's disease[28] due to this reduced daylight/night contrast. In healthy humans 5–17 lux is already high enough to reduce our night-time levels of melatonin.[29,30] However, new lighting products (LEDs) with prominent blue wavelengths in the spectrum have a much greater impact on our circadian rhythm than suggested by the lux value. The 'blue peak' that characterizes white LEDs targets the non-imaging light sensitive cells in our eyes that influence our biochemistry. What is the night-time threshold in senior citizens below which there is little effect? Animal studies show that illumination as low as 0.2 lux will affect melatonin secretion, leading to increased cancer risk.[31]

3. Lighting specification

The above summary of light thresholds is not exhaustive but it provides a broad sample of ecological impact. It is clear that any ALAN will impact the environment and human health to some extent. However, factoring in human activity with 24 × 7 life styles indicates that illuminances at the eye of 1–3 lux can be used; so this range is a reasonable compromise that should not be exceeded for most applications of ALAN. However, the extent of this illumination should be strictly limited to the area and period it is required in order to minimize its impact on those not partaking

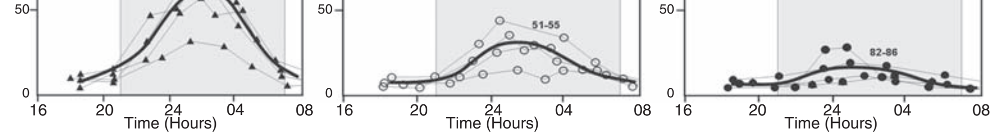


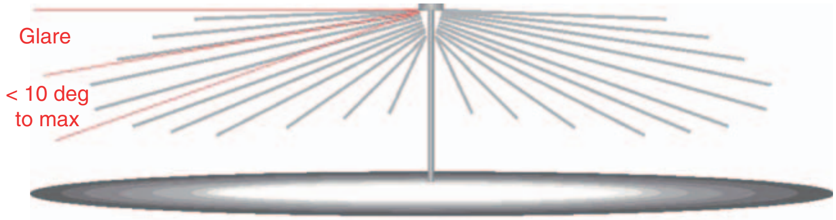
Figure 5 The variation in melatonin concentration over time and with age (left 21–25 years, middle 51–55 years, right 82–86 years) shows the significant decrease in the amplitude that makes senior citizens more susceptible to ALAN[25,26]

in late-night activities and more sensitive species. Higher illuminances may be used on roads with higher speeds and traffic densities, as discussed in supporting documentation for roadway lighting by the IESNA, but well shielded luminaires must be used to limit the illumination to only the roadway and to minimize glare.

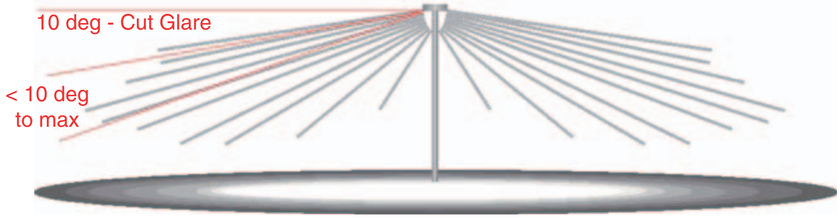
3.1. Extent of the illumination

There are three reasons for limiting the extent of an illuminated area. It reduces light trespass. It limits the impact of ALAN to only the target area and it focuses the light within the target area, so less light is needed for a given purpose. This is usually achieved with 'full cut-off' (FCO) and 'sharp cut-off' (SCO) luminaires that do not directly shine any light above a horizontal plane that passes through the bottom of the fixture (Figure 6). However, the 'FCO' luminaire permits 10% of the light to be emitted below the horizon within 80–90° of nadir (glare zone), which contributes to light trespass and can compromise night vision a 100 m away, as shown in Figure 7, where the light 80° from nadir is clearly visible. Therefore, a more stringent shielding specification is needed to reduce the emitted light in the glare zone. We suggest the more stringent SCO shielding.

It is impossible to completely shield a luminaire. The lamp must be visible from the target if it is to illuminate the target. However, a more restrictive shielding requirement will reduce the apparent brightness of the luminaire when viewed by a person (about 1.8 m tall) in the periphery of the target area. In the 1990s, some manufacturers produced luminaires with 'SCO' shielding that restricted the emission of light within the 10° band below the horizon. These did not become popular because they produced narrower light distributions and hence needed closer spacing than FCO luminaires, thereby increasing the cost of installing the lighting. However, FCO luminaires also create the



Fill Cut-Off (FCO) Luminaire



Sharp Cut-Off (SCO) Luminaire

Figure 6 Comparison between the shielding of full cut-off and sharp cut-off luminaires. FCO luminaires permit up to 10% of their light to be emitted within 10° of the horizon. Sharp cut-off luminaires reduce the amount of light that is emitted within this 10° band to less than 1%. This reduces the amount of emitted light in this 10° 'glare zone'. The maximum light is between 70° and 80° of nadir direct view of the lamp from a considerable distance (about 10 times the mounting height), even though the illuminance on the ground at that distance is insufficient due the glare from the lamp. So, light that shines beyond the target area creates glare, without the benefit of illumination. In order to more tightly contain the illuminated area, the more aggressive SCO shielding is needed.

In rural and semi-rural areas, the ideal would be for the target area to be restricted to less than the foraging range of the local animals. This allows them to detour around the affected area. However, determining the foraging range is complicated by the number of different species that inhabit the area. The foraging range is very roughly a function of the size of the animal[32] and can exceed a hectare. Therefore, it is not possible to prevent all impact in the countryside without setting aside large areas in which no light should be permitted. (This has been done to some degree with Canadian Dark Sky Preserves and more effectively in the new RASC Nocturnal Preserve Program).[33]

3.2. Glare

The definition of glare is complicated by our need to quantify it. In our context, glare will refer to a light source or lit surface that compromises visibility. It can be caused by the direct view of the light-emitting component in the luminaire, which can cause us to squint and will bleach a portion of the retina. Such a bright point or surface also causes our iris to close – letting less light into our eyes. And it will reduce our night vision in less-illuminated areas. These detrimental effects are made worse by imperfect eyes (especially for senior citizens) and the additional scattering of light by airborne particles, weathered windows and scratched eyeglasses. These effects combine to reduce the contrast in the field of view.

Figure 7 Re-lamping a major street. The benefits of FCO luminaires over semi cut-off fixtures are evident. However, roadside commercial signage should be addressed. After-hour signage for closed businesses should be turned off. Minimal traffic does not require 'rush hour' light levels. (Photo by the author)

To reduce glare, the light source must be diffused over a large area. Most road lighting luminaires use refractors to distribute the light. FCO luminaires use internal reflectors to direct the light onto the road. The new LED luminaires have small lenses mounted on each LED and these direct the light onto the target area, so we can see the individual LEDs by looking up from the target area. The luminance of the individual LED is roughly the luminance of a tungsten filament in a clear incandescent bulb. This causes our iris to close down and creates a temporary blind spot in our field of view and the blue spectral components have a potential to reduce visibility or at worst it may cause eye damage.[34] A direct view of the LEDs should not be allowed.

To ensure sufficient illuminance uniformity on a road, more light must be directed to the periphery of the target area than the nadir. However, the light emitted in the zone between 80° and 90° (glare zone) from nadir is particularly distracting unless SCO shielding is used. A uniformity of 3:1 is very good, given the past acceptance of 6:1 uniformity. If the peak illumination is 3 lux, then the minimum can be 1 lux, resulting in sufficient illumination in the periphery for pedestrian traffic if the emission in the glare zone is minimized.

3.3. Light spectrum

The daytime sky is dominated by the sun, which for the most part is white (Figure 8). But as the sun sets, the disk (the sun's photosphere) disappears and the major yellow component of the light is reduced. This large variation in the sun's spectrum does not affect our judgement of the colour due to our mind's ability to correct for these changes. However, this change is noted subconsciously and is used by our biology to determine the time of day. Unfortunately, this important evening colour change can be masked by the broad spectrum (white) ALAN.

Plants take advantage of different parts of the spectrum and insects (mosquitoes) use it to help find their targets (Figure 9). This attraction for mosquitoes results in greater exposure to disease.[40]

Our daytime photopic vision, provided by our cone cells (Figure 10), is about a thousandth the sensitivity of our night-time scotopic vision. However, illumination brighter than a few lux saturates or blinds the rods. The spectral sensitivity of the rod cells is centred on 507 nm. By limiting the emitted spectrum of ALAN to the longer wavelengths where the rod cells are less sensitive, we can preserve our night vision, without significantly affecting our photopic vision.

The transition in colour during twilight from white to blue-plus-red and then to blue (Figure 8) is detected by non-visual intrinsically photosensitive retinal ganglion cells (ipRGCs). Our ability to detect this light is a survival advantage because it keeps us alert for an extended period of safety during twilight while we begin to settle down to sleep, but it also has a biochemical function.

The ipRGC are most sensitive to the spectrum of light centred about the wavelength of 480 nm. The light threshold for individual cells in the literature is around

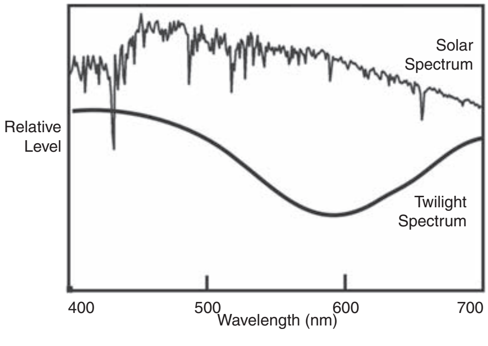


Figure 8 The spectral properties of the sky change from daylight[35] through twilight.[36] Yellow light decreases with twilight as the sun's disk sets below the horizon

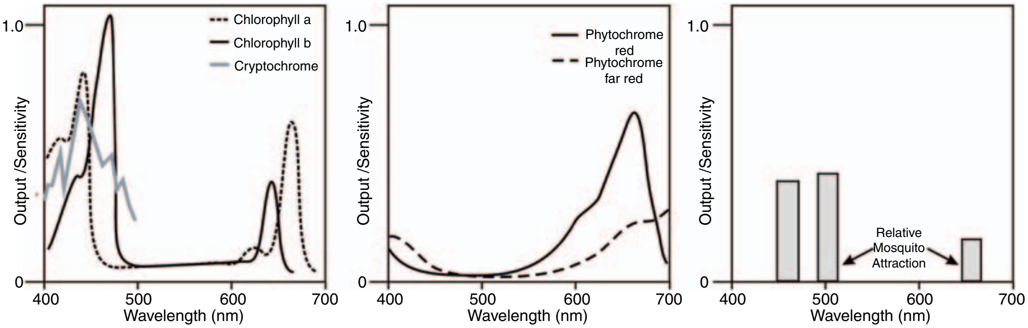


Figure 9 The absorption spectra for three major plant molecules show their preference for blue and red light[37–39] (cryptochrome, chlorophyll and phytochrome). Of these, cryptochome helps mediate the plant's response to light; so plants are primarily sensitive to the blue spectrum of ALAN. Mosquitoes, major disease vectors,[40] are also attracted by blue light and to a lesser extent, red light. The spectral gap between 500 nm and about 650 nm may be used to minimize the impact on these behaviours.

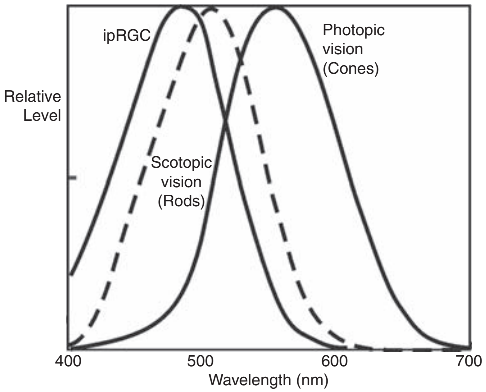


Figure 10 The spectral sensitivity of the two visual detector cells in our retina: rod cells for our night scotopic vision and cone cells for our daytime photopic vision. The intrinsically photosensitive retinal ganglion cells (ipRGCs)[41] are used to 'detect' night-time when the blue light of twilight falls below their detection threshold

1–10 lux[8] and together their network has a threshold sensitivity of very approximately as low as 0.1 lux.[11] However, their biochemistry and neuron logic suggest an even lower sensitivity – at the single photon level –[42] though it seems unlikely that this luminance would affect our circadian rhythm. As the illumination from the sky decreases, these cells are not able to confirm it is still twilight. In response, the hormone melatonin is released[30] to reduce our metabolism and put us to sleep.

This detection of nightfall also enables the release of other hormones that repair damaged tissue and fight infection.[1] These are created in late afternoon in preparation for their release but they begin to break down several hours later and are re-absorbed. Therefore, their production must be well timed with our rest period. If the release of these hormones is delayed, due to the extended period of ALAN, then the benefits of our rest and resulting health are compromised. It is important that ALAN does not contain short wavelength light (less than 500 nm) that will be detected by our ipRGC and alter the timing of biochemical processes during the night.

3.4. Duration

The natural environment is not static; however, nature's tolerance to the length of night, before it has a significant impact on the ecosystem, has not been studied but that does not mean we cannot deduce some guidelines. Two phenomena are twilight and the seasons.

The length of twilight is caused by the gradual setting of the sun and its illumination of the upper atmosphere. In summer, it sets at a low angle, taking about 3.5 minutes for its

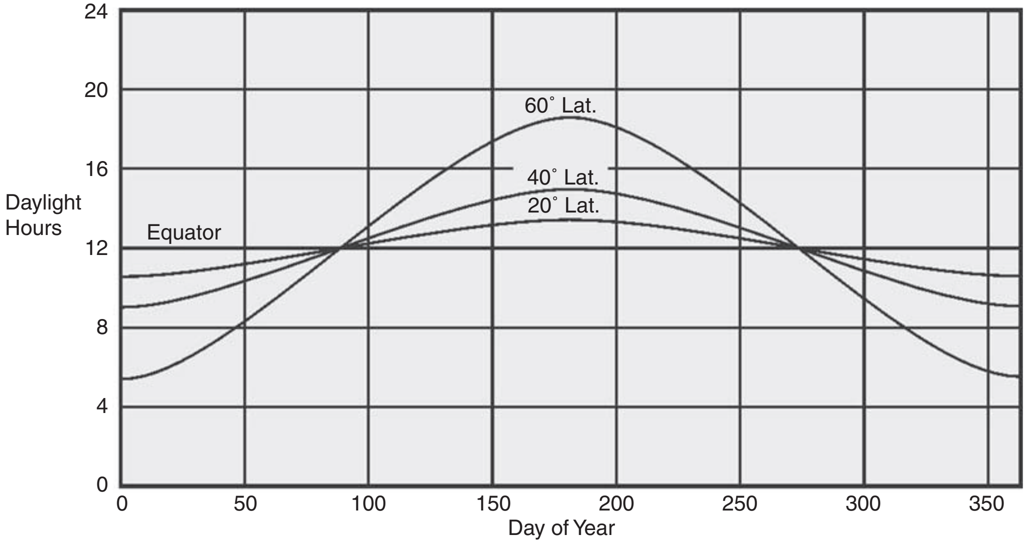


Figure 11 The varying lengths of daylight and darkness are used by plants and animals to estimate the season and prepare for winter[43]

apparent disk to disappear, and another 30–35 minutes for the illumination to fall below 1 lux. Animals take advantage of this time to prepare for night-time. Increasing this time with artificial lighting increases their exposure to predators.

A second effect is the duration of daylight as measured over a year (Figure 11). Only on the equator are the day and night of equal length throughout the year. The annual cycle in the length of day and night increases in amplitude towards the north and south poles. At the mid-latitudes, daylight can range between 8 hours and 16 hours during winter and summer, respectively.

Wildlife and plants use the lengthening period of daylight in the spring and shortening in the autumn as an indication of the time of year.[10,44] Plants generally bloom in spring and drop their leaves in late autumn. Animals prepare for hibernation or migration late in the year. Disrupting the perceived length of the day, or more precisely, the length of the night, can confuse these visual cues and leave some animals and plants ill-prepared for winter.

Although the length of night is used to indicate the season, it is the temperature of the environment and snow cover that causes the real hardship. Temperatures vary considerably from year to year, delaying snowfall for over a month or more. Temperatures at mid-latitudes in North America can result in the first snow in mid-October or December. The change in the length of daylight at these times is about 2 hours (Figure 11) or 1 hour in the morning and again in the evening. By adding the duration of twilight (about 30 minutes), recognizing the weak coupling of season to temperature, and further recognizing the random effects of cloud cover and local shading due to vegetation, we estimate that a permissible duration of ALAN into the night and again in morning of 2 hours will not have a serious impact on local wildlife.

Any ALAN that extends into the night will advance preparations during spring for summer and delay those in autumn for winter. Therefore, determining the duration of ALAN after sunset and before sunrise to permit illumination does not suggest that it is a ‘good idea’. Efforts should be made to reduce the impact from artificial sky glow that is visible beyond the city limits with SCO shielding and reduced illumination levels.

Since ALAN is only used to assist human activity, the light level should match this activity. Although many people have embraced 24 × 7 lifestyles, traffic records for major cities indicate that most people do not. High-speed roadways have the greatest use for high light levels due to the need for short reaction times of motorists. Traffic records (Figure 12) show the clear pattern of high-density traffic during the day and very little traffic at night. During spring, summer and autumn, the periods of greatest traffic volume are during daylight. Only in the winter months does this traffic, bounded by morning and evening rush hours, extend well into night. Reducing the illumination levels, within 2 hours of sunset during summer and most of the spring and autumn (the ecologically sensitive seasons) will not affect most commuters. Leaving the lights fully on throughout the night is therefore a decision based on politics and aesthetics, not necessity.

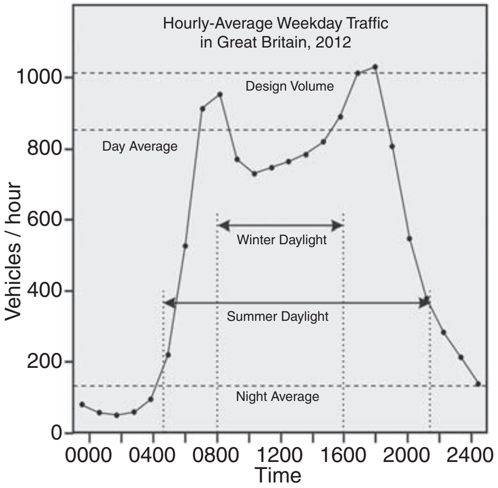


Figure 12 Traffic density along major roadways in Great Britain. Although winter rush hour traffic occurs in relative darkness, summer daylight encompasses rush hour traffic[45]

There are sufficient arguments for reducing ALAN in urban areas based on its impact on human health and the costs of urban infrastructure. The current wildlife within urban areas has survived because of their tolerance to ALAN. Clinical studies into human health issues have shown that ALAN is a contributing factor to a number of ailments.[11] And cities are now subjected to greater economic pressure to reduce electricity consumption. Since about half the municipal electricity is used for outdoor lighting, primarily for streetlights, it is now appropriate to review our use of ALAN.

Decorative lighting is used extensively in urban areas. The historical acceptance of this aesthetic use of light pre-dates our current understanding of its impact on human health. The psychological value for the people that view the displays is limited to only those at the site to view them in the late evening or early night, after which time they should be turned off to conserve electricity and to reduce their impact on the environment. This is not a new suggestion; Vienna turns off many building lights and reduces roadway illumination at 23:00 and 24:00.[46]

4. Luminaire specification and performance

During the development of a lighting protocol for ecologically sensitive areas, it became evident that there were no commercial luminaires that complied with the requirements. To assess the practicality of such a luminaire, we designed a general-purpose luminaire that could be used in environmentally protected areas. Subsequent tests on the prototype showed that it could be used in other rural lighting and urban applications as well. It is currently being upgraded for roadway lighting where the environment and human health are the primary concerns. The targets for the design of the luminaire were:

- The luminaire should be capable of producing illuminances in the range 1–3 lux on the ground over a defined area. These illuminances must be limited in extent due to the sensitivity of other wildlife. The luminaire should produce less than 3 lux at the eye for normal directions of view to avoid affecting scotopic vision.

- The spectrum of the light emitted should be limited to >500 nm to avoid impacting plants, reducing the scattering of light and the attraction of flying insects. It will also reduce the impact of the illumination on our circadian rhythm and our night vision.

- The luminaire should be controlled so that it does not operate for 2 hours before sunrise and 2 hours after sunset. These limits have been derived from traffic patterns and astronomy and atmospherics. However, in cities, these times may be made flexible depending on the season and local traffic flow.

Our luminaire (Figure 13) connects directly to a wide range of AC power. It uses light-emitting diodes that consume less than 25 W at maximum light output and more typically less than 10 W, making it appropriate for off-grid lighting and solar power applications.

4.1. Illumination level and uniformity

The luminaire is designed for a maximum of 1–3 lux, though higher levels are achieved when mounted at lower heights or used with higher currents (up to five times the current used in Figure 13) to allow for various mounting heights and applications.

The optical design can be adjusted for limited backlight to prevent significant light trespass and to reduce vertical-surface glare if it is wall-mounted.

4.2. Degree of glare

All components fit inside the enclosure and luminance is minimal in the glare zone from

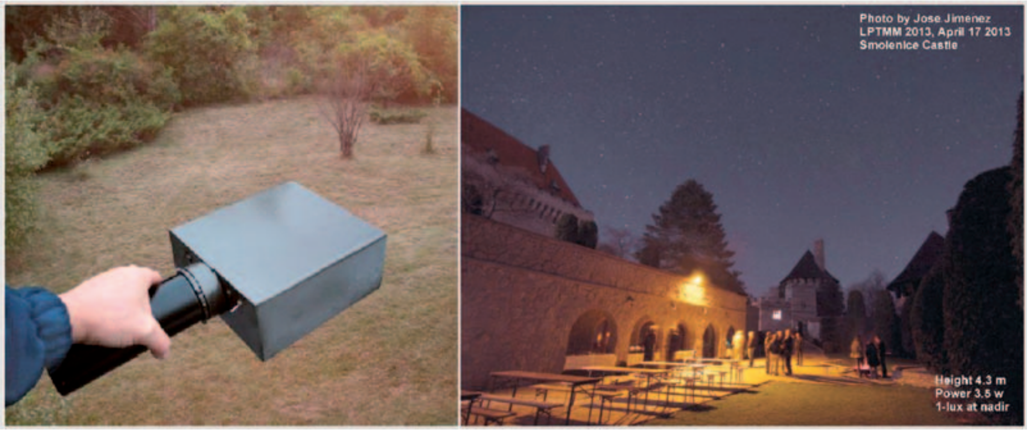


Figure 13 The Canadian Scotobiology Group (CSbG) luminaire has been patented. It is a compact unit with LED light sources powered through an adjustable driver for 110 Vac, 220 Vac or 277 Vac. The thermal design maintains the LED junction temperature to less than 50°C above ambient air temperature at maximum light output, though more typically 20°C for intermediate power settings. The unit was demonstrated at the 2013 Conference on Light Pollution Theory, Modelling and Measurement (photo by Jose Jimenez). The luminaire was mounted at 4.3 m and set for 3.5 W, producing 1 lux at nadir. The main mirror was set for an optional 1.5 m backlight

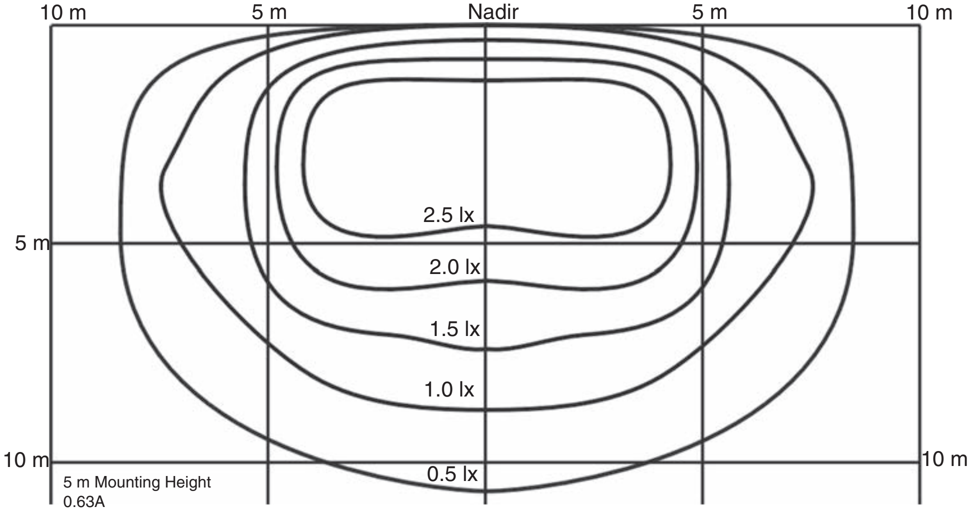


Figure 14 The Canadian Scotobiology Group (CSbG) luminaire provides relatively uniform illumination over an area about 3 × 1.5 times its mounting height with a uniformity of about 3:1. The field-adjustable light output allows for different mounting heights and for lower light levels. The values in the figure are for a mounting height of 5 m using about 25 W. The optics were set for use as a wall-mounted fixture with no backlight. When used along a pathway, the uniformity is 3:1 for a spacing of three mounting heights and 4:1 for a spacing of four mounting heights. Measurements by author

80° to 90° of nadir providing SCO shielding. Reflective baffles prevent a direct view of the LED emitters from outside the luminaire.

A curved main mirror expands the light into a broad uniform pattern. The textured surface increases the effective surface area of the light sources, reducing the apparent luminance of the emitters to about 3% of the original LEDs, and minimizes the light/dark structures in the illumination pattern.

4.3. Light spectrum

The LEDs do not emit wavelengths less than 500 nm and have low emission above 650 nm to minimize the impact on wildlife, human health and plants (Figure 15). Although it has to be tested, the restricted light spectrum seems to be less attractive to mosquitoes, a known vector for infectious diseases[40] than white LEDs, florescent and incandescent light sources.

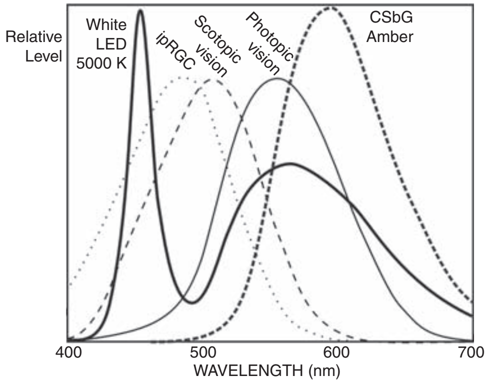


Figure 15 The Canadian Scotobiology Group (CSbG) spectrum differs from typical white LED spectra. The CSbG spectrum is a closer match to our photopic vision than a white light LED spectrum but has low exposure to the ipRGC. It has limited exposure to our scotopic vision so it helps to preserve our night vision. However, the high sensitivity of our scotopic vision at the suggested low illumination levels can still take advantage of this illumination without bleaching our rod cells. Comparing the CSbG amber spectrum to the environmental sensitivities in Figure 9 shows that it also has less impact on wildlife[36,37] and mosquitoes[38] than white LEDs

5. Summary

The study of scotobiology has been used to develop rational limits for ALAN. This is in contrast to our current lighting paradigm that gives the highest priority to human photopic and mesopic vision. To the best of our knowledge, there is no commercially available luminaire that can meet this specification. We have developed and patented a luminaire that is a viable alternative for ecologically sensitive areas and to reduce light pollution for other applications. Although any ALAN will impact the environment, these requirements minimize the adverse effects.

Field tests with the luminaire confirm its performance and the subsequent improvement in visibility as long as there are no unshielded lights in the area. The initial market is for ecologically sensitive areas with human visitors.

Funding

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Acknowledgements

I am grateful to Dr Roseann Runte, President of Carleton University, Ottawa, Canada, for providing access to the University's academic library.

References

1 Koukkari W, Sothern R. *Introducing Biological Rhythms*. Berlin: Springer Science, 2006.

2 Retrieved July 27 2013, from http://home.earthlink.net/~kitathome/LunarLight/moonlight_gallery/technique/moonbright.htm.

3 Heike GH, Vaniman DT, French BM. *Lunar Source Handbook*. Cambridge, NY: Cambridge University Press, 1991Section 9.3.1.

4 Robert AL. Simple time reaction as a function of luminance for various wavelengths. *Perception and Psychophysics* 1971; 10: 397–399.

5 Ellis CJK. The pupillary light reflex in normal subjects. *British Journal of Ophthalmology* 1981; 65: 754–759.

6 Charman W. Age, lens transmittance and the possible effects of light on melatonin suppression. *Ophthalmalogical and Physiological Optics* 2003; 23: 181–187.

7 Illuminating Engineering Society of North America. *IESNA Lighting Handbook*. 9th Edition, New York: IESNA, 2000.

8 West KE, Jablonski MR, Warfield B, Cecil KS, James M, Ayers MA, Maida J, Bowen C, Sliney DH, Rollag MD, Hanifin JP, Brainard GC. Blue light from light-emitting diodes elicits a dose-dependent suppression of melatonin in humans. *Journal of Applied Physiology* 2011; 110: 619–626.

9 Watson AB, Yellott JI. A unified formula for light-adapted pupil size. *Journal of Vision* 2012; 12: 1–16.

10 Rich C, Longcore T. *Ecological Consequences of Artificial Night Lighting*. Washington DC: Island Press, 2006.

11 Pauley S. Lighting for the human circadian clock: Recent research indicates that lighting has become a public health issue. *Medical Hypotheses* 2004; 63: 588–596.

12 Bunning E, Moser I. Interference of moonlight with the photoperiodic measurement of time by plants, and their adaptive reaction. *Botany* 1969; 62: 1018–1022.

13 Warner GW, Allard HA. Effect of relative length of day and night and other factors of the environment on growth and reproduction in plants. *Journal of Agricultural Research* 1920; 88: 553–606.

14 Leopold AC. Photoperiodism in plants. *The Quarterly Review of Biology* 1951; 26: 247–263.

15 Boujard T, Leatherland JF. Circadian rhythms and feeding time in fishes. *Environmental Biology of Fishes* 1992; 35: 109–131.

16 Bromage N, Jones J, Randal C, Thrush M, Davies B, Springate J, Duston J, Barker G. Broodstock management, fecundity, egg quality and the timing of egg production in the

rainbow trout (Oncarhynchus rnykiss). *Aquaculture* 1992; 100: 141–166.

17 Beier P. Effects of artificial night lighting on terrestrial mammals. In: Rich C, Longcore T. (eds)*Ecological Consequences of Artificial Night Lighting*. Washington DC: Island Press, 2006, pp. 19–42.

18 Ringelber J. *Diel Vertical Migration of Zooplankton in Lakes and Oceans*. Dordrecht, The Netherlands: Springer Science BV, 2010.

19 Dodson S. Predicting diel vertical migration of zooplankton. *Limnology and Oceanography* 1990; 35: 1195–1200.

20 Zooplankton: The mighty migrators in Saanich inlet. Retrieved 24 March 2013, from http://venus.uvic.ca/2007/11/zooplankton-the-mighty-migrators-in-saanich-inlet

21 Benoit-Bird KJ, Au WWL, Wisdom DW. Nocturnal light and lunar cycle effects on diel migration of micronekton. *Limnology and Oceanography* 2009; 54: 1789–1800.

22 Bowden TJ, Thompson KD, Morgan AL, Gratacap RML, Nikoskelainen S. Seasonal variation and the immune response: A fish perspective. *Fish and Shell Fish Immunology* 2007; 22: 695–706.

23 Blask D. Melatonin, sleep disturbance and cancer risk. *Sleep Medicine Reviews* 2009; 13: 257–264.

24 Nair NPV, Hariharasubramanian N, Pilapil C, Isaac I, Thavundayil JX. Plasma melatonin – an index of brain aging in humans? *Biological Psychiatry* 1986; 21: 141–150.

25 Meng Y, He Z, Yin J, Zhang Y, Zhang T. Quantitative calculation of human melatonin suppression induced by inappropriate light at night. *Medical and Biological Engineering and Computing* 2011; 49: 1083–1088.

26 Reiter RJ. The pineal gland and melatonin in relation to aging: A summary of the theories and the data. *Experimental Gerontology* 1995; 30: 199–212.

27 Myers B, Badia P. Changes in circadian rhythms and sleep quality with aging: Mechanisms and interventions. *Neuroscience and Biobehavioral Reviews* 1995; 19: 553–571.

28 Campbell SS, Kripke DF, Gillin JC, Hrubovcak JC. Exposure to light in healthy elderly subjects and Alzheimer' s patients. *Physiology and Behavior* 1988; 42: 141–144.

29 Brainard G, Rollag MD, Hanifin JP. Photic regulation of melatonin in humans: Ocular and neural signal transduction. *Journal of Biological Rhythms* 1997; 12: 537–546.

30 Zeitzer J, Dijk D, Kronauer RE, Brown EN, Czeisler CA. Sensitivity of the human circadian pacemaker to nocturnal light: Melatonin phase resetting and suppression. *Journal of Physiology* 2000; 526: 695–702.

31 Dauchy RT. Light contamination during dark phase in photoperiodically controlled animal rooms: effect on tumor growth and metabolism in rats. *Laboratory Animal Science* 1997; 47: 511–518.

32 Swihart R, Slade NA, Bergstrom BJ. Relating body size to the rate of home range use in mammals. *Ecology* 1988; 69: 393–399.

33 Retrieved 9 June 2013, from www.rasc.ca/lpa/guidelines

34 *Effects sanitaires des systèmes d'éclairage utilisant des diodes électroluminescentes (LED)*. Agence Nationale de Sécurité Sanitaire de l'Alimentation, de l'Environnement et du Travail, Saisine n 2008-SA-0408, 19 Octobre 2010.

35 Solar Spectrum, ASTM G173-03. Retrieved 29 May 2013, from http://rredc.nrel.gov/solar/spectra/am1.5/ASTMG173/ASTMG173.html.

36 Lee RL. Atmospheric ozone and colors of the Antarctic twilight sky. *Applied Optics* 2011; 50: F162–F171.

37 Smith H. Chapter 14: Phytochrome action. *The Molecular Biology of Plant Cells*. Berkeley, CA: University of California Press, E-Books Collection, 1982–2004. Retrieved 31 May 2013, from http://publishing.cdlib.org/ucpressebooks/view?docId=ft796nb4n2&chunk.id=d0-e21651&toc.id=& brand=eschol.

38 Folte KJ, Childers KS. Cryptochrome is a blue-light sensor that regulates neuronal firing rate. *Science* 2011; 331: 1409–1413.

39 Bentley M, Kaufman PE, Kline DL, Hogsette JA. Response of adult mosquitoes to light-emitting diodes placed in resting boxes and in the field. *Journal of the American Mosquito Control Association* 2009; 25: 285–291.

40 Barghini A, Medeiros BS. Artificial lighting as a vector attractant and cause of disease

diffusion. *Environmental Health Perspectives* 2010; 118: 1503–1506.

41 Enezi JA. "Melanopic" spectral efficiency function predicts the sensitivity of melanopsin photoreceptors to polychromatic lights. *Journal of Biological Rhythms* 2011; 26: 314–323.

42 Do M, Kang SH, Xue T, Zhong H, Liao HWL, Bergles DE, Yau KW. Photon capture and signalling by melanopsin retinal ganglion cells. *Nature* 2009; 457: 281–288.

43 Adapted from http://www.gandraxa.com/length_of_day.xml. Retrieved 25 August 2013, from http://www.gandraxa.com/length_of_day.xml

44 Hart JW. *Light and Plant Growth*. London, UK: Unwin Hyman, 1988.

45 Retrieved 25 August 2013, from https://www.gov.uk/government/statistical-data-sets/tra03-motor-vehicle-flow

46 Posch T, Puschnig J, Uttenthaler S. Night sky brightness measurements and night sky spectroscopy performed at the Vienna University Observatory: *Proceedings of the Light Pollution: Theory, Modeling, and Measurements Conference*, Bratislava, Slovakia, Apr 17: 2013: 105–112.