What is light pollution

Definition

Light pollution **is the alteration of light levels in the outdoor environment (from those present naturally) due to man-made sources of light.**

(A peer-reviewed 2000 article where it was published with slightly different wording is [1]. Previous to that, confusing concepts of light pollution have been common, limiting it just to "adverse effects", "skyglow" etc. This practice continues even now, unfortunately. Some consequences of such pollution (*by* light and *of* natural light) are welcome by some and disliked by others, some consequences are considered adverse by everybody. Many consequences are not known yet: the relevant discipline scotobiology [2] is just emerging. The most general consequence is a disruption of a day-night cycle as it had existed on Earth for billions of years.)

How it can be quantified

– absolutely

As for all pollutants, light added artificially to the environment can be measured by

concentration of the pollutant in some volume of the environment (of air or water). For light, a convenient unit for this purpose is lumen per square metre (it can be further divided by speed of light to get a true volume concentration). It can be computed from a pair of fish-eye images (integrating the luminance over the full space angle). Seldom used for light.

emissions – amount of pollutant released to the environment within a time interval by some source. For light expressed most easily as lumen seconds. On packaging of lamps (incandescent, fluorescent and other discharge ones), their nominal luminous flux (rate of emissions) in lumens is usually given.

For light as a pollutant, two additional properties are relevant: its **direction** and **spectrum**. Complete characterisation of rate of emissions (from any surface) or of pollutant influx (to any irradiated volume element) is given by a quantity called spectral radiance. It is a function of both direction and wavelength (or, alternatively, wavenumber, frequency or photon energy). Watt per steradian per square metre per nanometre ($W.sr^{-1}m^{-2}.nm^{-1}$) belongs to its common units. From this quantity, the parameter "how bright is this spot" called luminance can be computed, integrating spectral radiance × spectral sensitivity of human daylight perception (photopic vision); its unit is candela per square metre.

In general, any radiometric or photometric quantity can be employed as a measure of light pollution in some situation. For example, any **source of pollution** (e.g., a single luminaire) can be characterised integrally (as a whole) by specifying how large luminous intensity it emits in each direction. This is an adequate parameter for very distant sources appearing as points. However, if a visible source is so close that it does not appear as a point, larger kinds (like long fluorescent tubes instead of small high-intensity discharge burners) with the same luminous intensity may be less polluting, as their luminance is lower (the same luminous intensity is produced by a larger surface).

Amount of pollutant hitting some surface is a useful integral measure in case of light. Per second and square metre, it it is measured directly by a luxmetre; the quantity is then illuminance, its unit is lux. The orientation of the surface element makes illuminance differ from direction-less pollutant concentration (luminance is integrated just over the proper half of the full space angle and multiplied by cosine of angle of incidence to the surface element –

then light tangential to the surface makes no contribution to its illuminance). Per whole area and time interval, it can be expressed in lumen seconds.

– relatively

Light is always present naturally. Thanks to that, there is a convenient way of expressing light pollution by giving the ratio:

$$\frac{\textit{man-made part of any photometric or radiometric quantity}}{\textit{natural part of the same quantity}}$$

In most cases, it's preferable to express pollution this way: as a dimensionless number rather than by photometric units. An amount of light which is a serious pollution at night may be negligible at noon. Even when there is a sharp boundary between the polluted and unpolluted part of a visual scene, people do not notice the pollution if the artificial contribution to the luminance of the polluted spot is below one per cent of its natural luminance (assuming it holds even for "blue luminance"). In many cases, even ten per cent increase of luminance over the natural value may not be noticed (if there is no sharp boundary between areas of differing luminance) – because of that, pollution which is less than 10 % of natural light level is often considered as insignificant.

For example, people are concerned with man-made increase of light amounts from clear night skies (a typical reported quantity is sky luminance in zenith, or the man-made increase of that luminance divided by natural luminance), because of the loss of visibility of stars. Relative pollution may be however much higher under overcast sky, implying a huge disruption of the natural environment.

Let's compute it. Under overcast moonless night sky, the natural amounts of light are about ten times less than under clear sky. If the absolute amount of artificially added light would be the same in both cases, in relative terms it would therefore cause ten times more pollution under overcast sky, locally. However, far from emission sources, even the intruding absolute light amounts can rise, as the light cannot escape to the space and is reflected back to the ground by clouds. This can be further amplified by snow. Then the same emissions, which cause *increase* of incident light amounts say by 100 % under clear sky (it means the man-made and natural parts are about the same, pollution is 1 in relative terms, very *significant and conspicuous*), cause relative pollution of at least 100, hundred times more than under clear sky! (In the remote areas of the largest Czech national park the relative concentration of the pollutant (light) under overcast sky was three hundred times larger than under clear sky, as measured in winter 2005.)

The *radiometric or photometric quantity can be itself a ratio*, a number with no unit, like contrast. Then the pollution by man-made light can be expressed even as a *decrease* of a quantity from its natural value. It is adequate to say that *stars get dimmer due to light pollution*: it means their contrast to the surrounding sky becomes lower, when the luminance of that sky is increased due to man-made light. To compute it exactly, each star can be ascribed an element of a space angle, which is perceived as a point by our vision (depending on acuity, sky luminance and brightness of the star, it can be a circle with a diameter of $1'$ to $5'$ for young people with good eyesight). So we can speak about luminance of a star, like about luminance of any target which should be seen. Then the (Weber's) contrast of target is

$$\frac{\textit{luminance of the target} - \textit{luminance of the background}}{\textit{luminance of the background}}$$

– doubly relatively

Ratio of contrasts in polluted and unpolluted situation is the best measure of pollution, as regards visibility of faint lights. They include stars and another celestial phenomena, fireflies and glowworms, or plentiful faint sparkles of light (bioluminiscent plankton) which are so wonderful in sea, but mostly unknown to population in areas where strong artificial lighting is ubiquitous.

It is not just a matter of their visibility for people. In case of luminous insects, in polluted environments they don't recognise each other over long distances, don't find mates, cease to reproduce and their populations collapse eventually (this is common in towns and cities, unfortunately). For marine life, the ecosystem consequences of loss of visibility of bioluminiscent signals on moonless or overcast nights are not understood yet, but can hardly be negligible.

Reduction of contrast can wipe out whole terrestrial panoramas, even the very outlines of giant mountains ([3]).

– with special regard to physiology of vision

Vision does poorly register absolute levels; due to adaptation, it adjusts itself to the prevailing light levels. E.g., stars are perceived as dimmer if some other, additional light comes to our eyes. This added light may come from spots of high luminance, as from luminaires, windows of lit rooms, vehicle lights and outdoor surfaces illuminated on purpose. Stars become invisible in urbanised environments not just because of increased sky luminance, but also because of glare (including veiling luminance produced by dispersion of light inside eyes) and mostly because of changed adaptation of vision due to increased light levels. In fact, the sky may be perceived as black or very dark from such heavily polluted sites, unlike in nature where vision adapts to its luminance during twilight and night: natural clear night sky is never dark between the stars, being the main source of illumination of terrestrial landscape.

So, light pollution not only diminishes contrasts, but due to animal and human vision getting adapted to artificially increased light levels, light pollution *reduces the number of photons registered at retina* from the natural sources. Physiologically, such sources *become fainter* not just in relative, but even in absolute terms. This further reduces their visibility, as more contrast is needed if are to be noticed (contrast sensitivity is worse at the bottom end of the span of perceived luminances than in its middle).

Where the direction or a spectrum plays a role

With closed eyelids, we almost don't perceive direction of the incoming light, but it is still important: if it comes from one side only, we can turn to the other side (reducing illuminance of our face this way). Similarly, trees affected by acid deposits brought by a wind coming from west are less affected at their east side. With open eyes however, we notice even tiny spots with increased luminance. Any artificially lit terrain on a distant slope spoils the natural appearance of the scene, any directly visible light becomes a conspicuous detail of it (a very prominent pollution), even if it would contribute just a tiny fraction of total light input to our eyes. Directly visible lights are also the most harmful for wildlife, security (by an effect called glare) and aesthetics, or even the very visibility of the true landscape including the sky.

Not just the mere (photopic) amount of light, but also its spectral composition (perceived often as a colour by us and many other organisms) is to be considered. E.g., pure blue light (with no green or red component) contributes little to the usual photopic quantities, as lumens or candelas, but can be still conspicuous (altering, i.e. polluting the natural scenery). Moreover, namely such light of shortest wavelengths is the signal which says to us and other animals if it's day or night, it controls the animal metabolism. An established way of taking somehow into account the spectral composition of light is expressing it in "scotopic lumens" as well (these are relevant for deep-night vision, when photopic luminances don't go over 1 $\mathrm{mcd/m^{-2}}$), computed using a spectral sensitivity function which culminates at 500 nm instead of at 555 nm as for photopic vision. In analogy, red, green and blue lumens or candelas might be introduced, e.g. by considering them to be all equal for summer daylight (they can be measured easily by using

RGB digital imaging; B lumens are a good measure of metabolism-relevant light [5]).

If we need to light something at night to see its details, we can suppress the blue component (or ideally the whole shortwave half of the light spectrum) to save our health and reduce the harmful impact of artificial lighting to wildlife (avoiding ultraviolet is important too, to protect wildlife). Low-pressure sodium lighting is an old outdoors example, yellow light indoors (blue being mostly filtered out by a yellow foil or a glass baking paint) is very comfortable (author's family has such a separate lighting system for evening and night for two years already). For occasional blue-demanding tasks as proofs of colour magazines, a small non-filtered spot light may be used for a limited time (just for a central part of the field of view). Some caution is needed with very blue-deficient lighting when people with certain types of colour blindness should use it.

Imposing obligatory geometric and spectral limits on artificial lighting can reduce some relevant measures of pollution (and its harmful consequences) by orders of magnitude, even if the total emissions (measured in photopic lumens) will remain similar as before. This makes light easier to handle than most another pollutants. Of course, even the growth of total emissions is to be stopped and reversed to a steady decline, to get the pollution levels back to values which may be tolerable, all adverse effects of lighting considered (for light, those of the end of 19th century might be almost surely regarded as sustainable, an interim goal might be a decline to levels of 1970).

References and further links

1. *"alteration of natural light levels in the outdoor environment owing to artificial light sources"* – that's the first published scientific definition, as appeared in: Cinzano et al. 2000, *Monthly Notices of Royal Astron. Soc.*, 318, 64
   (online: The artificial night sky brightness mapped from DMSP Operational Linescan System measurements, 1MB pdf).

2. definition of Scotobiology at 2003 Ecology Of The Night conference pages.

3. Brychtová J, Hollan J, Krause J: *Evaluation of the influence of artificial illumination of selected ski resorts to nature and landscape of Giant Mts. Nat. Park.* July 2005, in Czech. Available at http://amper.ped.muni.cz/noc/krnap (some English excerpts are within a 2006 report for IDA).

4. Stockman A, Sharpe LT, 2000: Spectral sensitivities of the middle- and long-wavelength sensitive cones derived from measurements in observers of known genotype. *Vision Research*, **40**, 1711–1737. The photopic sensitivity data, together with the standard CIE scotopic data, can be downloaded at http://cvision.ucsd.edu.

5. Hollan J: *Metabolism-influencing light: measurement by digital cameras.* Poster at Cancer and Rhythm conference, Graz 2004. Online as a 1MB pdf.

6. Save the Night in Europe, a comprehensive new source aimed not just at clear sky luminance.

7. www.urbanwildlands.org, a site of the Ecological Consequences of Artificial Night Lighting project (contains links to an excellent article Ecological Light Pollution and to conference proceedings).

8. Clark B.A.J: *A Rationale for the Mandatory Limitation of Outdoor Lighting.* 4 May 2006, online as a 0.3MB pdf.

9. Digital imaging photometry with common cameras – results, methods and perspectives (8MB pdf, lecture slides by J. Hollan for a meeting of IAU commission 50, Prague, August 2006).

Jan Hollan, December 2006 / January 2007

Changes:

1. Term *immissions* has been used in the December first version of the text. This is however not common in English, unlike in many other European languages (even if EPA lists it), perhaps due to a problem that it could not be distinguished from *emissions* in English pronunciation, as the beginning *e* is read as *i* there. This is fortunately not the case for a similar pair of terms emigrate - immigrate.
2. *Alteration* instead of Increase used in the definition, to be fully consistent with general definition of any pollution. Of course, in case of added light (and most other pollutants) the alteration of *absolute* levels is mostly *increase*. Generally, decreases from natural absolute levels of occurrence can result from reactions of primary pollutants with the environment (e.g., daylight can be diminished by emissions of sulphur oxides, due to induced decreased transparency of the air, but this is no light pollution, but say a sulphate and aerosol one). However, light pollution leads even to absolute decrease of signal registered from faint lights by eyes at night (due to visual adaptation). Very conspicuously, it can cause a *decrease* of the important quantity (as visibility is concerned): of contrast.
3. *Non-visual photometry* and adverse effects footnotes added, double relative (ratio of contrasts) pollution measure included, examples of a decrease of quantities (contrast and number of registered photons) from their natural levels due to light pollution added.

Footnotes

On light added indoors

There is no doubt that it may be unwanted, and that it is even toxic in some cases (causing sleep and metabolism disturbances). However, a simple rule that anything over the natural levels is to be considered pollution could be applied perhaps just for bedrooms at night. Otherwise, some desirable levels might be taken as a base, but these are very individual (and the indoor space may be shared by several people). Still, night light levels so large that they reduce production of melatonin (below the production which would take place naturally with no artificial lighting), should be considered polluting. In this sense, common light levels produced by nowadays artificial (electric) lighting have to be considered a significant pollution of the indoor *night* air, similarly as tobacco smoke *any time*. Keeping B illuminance of eyes below 1 lx during the time when we don't sleep at night is to be recommended, keeping it below 0.25 lx can be considered *safe environmental limit* for people (this is the natural maximum outdoors at night, which should be tolerated by most organisms due to eons of evolution; some rodents are still hundred times more sensitive, probably due to the fact they inhabit dark niches). Having spots of artificially increased luminance in the field of view, however, could hardly be considered as pollution, unlike outdoors.

On adverse effects

Light is so popular throughout the human history and prehistory, that it is still felt as a heresy, even by leading proponents of light pollution abatement, to regard all man-made light outdoors as pollution. There is no other way, however. We make like some cases of pollution (like a decent lighting of a yard where we have a party), we may well tolerate other (the neighbour's one...), but pollution has its definition which does not depend on what people like or dislike at the moment, and what is the polluting agent. When it's light, then it's light.

Was DDT, broadly applied outdoors in the fifties and sixties, a pollution? Sure it was, even if considered entirely beneficial in those times. Is a single LED in the middle of the Sahara a pollution? Sure it is, as a litter at least: just stones and sand should be there and some hardly visible wildlife, in a non-polluted state. A metal cover of a beer bottle would be a pollution too, a bottle itself, broken or not, as well. At night, a shining (ordinary, no 70lm) LED would be visible not just from an immediate vicinity, like in daylight. Even from 1 km it could be as bright as Vega... surely tolerable, if it would serve as a vital pilot light, but still a pollution. The mere existence of pollution does not depend on if anybody is watching or objecting.

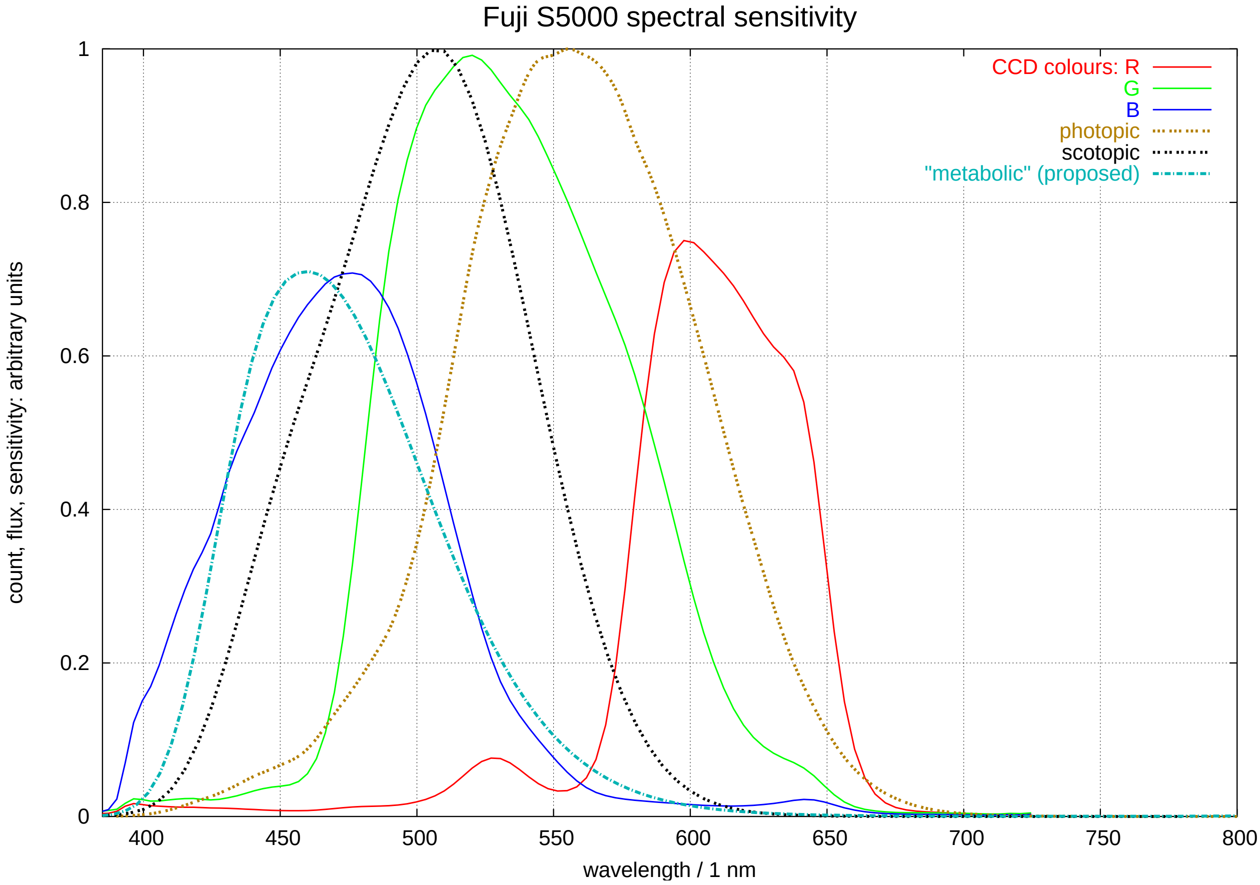
We can live with some pollution, as we can live with beer, wine and brandy. We should enjoy their positives, but not forget their toxic aspects. We should get the adverse effects under our control. And as with brandy and children, or beer and bears, we should be aware there are organisms which are much more vulnerable to damage by some of those agents we love so much. E.g., there are night frogs who never cross a continuously lit road: once lit, it becomes a barrier dividing the previously continuous habitat.

On blue luminance

Traditional photometry deals with human daylight (photopic) vision, with human deep-night (scotopic) vision, and attempts to quantify visual performance at intermediate light levels (mesopic vision). In SI, these photometric quantities are fixed to radiometric ones just at a single wavelength of 555 nm. The SI definition is

> The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

For light in real world, which contains electromagnetic radiation of various wavelengths, there are but approximations of correspondence of amounts perceived by human vision (true photometry) and of those measured by instruments. This was enabled by investigations resulting in various luminosity functions of the two visual systems in humans [4]. The author of present text has proposed a different approach, enabling to introduce many analogues of these luminosity functions. One of them is the action spectrum of the non-imaging visual system (a third one in humans) affecting melatonin production [5].



If the particular action spectrum has at 555 nm a value whose relative uncertainty is considerably larger than that at the maximum of the spectral curve, setting its fixed point just at 555 nm would lead to large uncertainty of the so-defined lumens etc. In some cases, the whole spectrum may be poorly known. Still, responses of a sensing system (animal or instrumental) based on it may be calibrated by setting them to be the same as photopic quantities, for some light spectrum taken as a reference. The author proposes [5] natural sunlight for that; on example of a digital camera with R, G and B pixels: *"By setting their B luminance to photopic one (measured by a luxmeter, or computed astronomically), the camera is simply calibrated."* To confine the choice of a reference light composition still more, AM1.5 global sunlight might be taken as a standard. Repeatability at the level of one per cent could be achieved this way.

A similar system exists in astronomical photometry. It stems from true visual photometry, then it was extended to photography as a light-sensing tool, and finally to electric devices. All filter-based measurements (even the detector itself behaves as a filter, responding differently to different wavelengths) are calibrated on stars of a spectral class A0: the reported values for any such star (Vega is used as the primary standard) should be always the same, regardless if the detector records a portion of UV, visual or infrared domain. A0 stars are good standards for stellar photometry, but sunlight is easier to use for terrestrial multicolour photometry. Astronomical photometry results are mostly expressed as dimensionless logarithmic quantities (with a unit called magnitude, difference of 2.5 mag corresponds to 10 decibels in acoustic analogy, i.e. to ratio of luminous flux densities of 10, star having just 0 mag gives a luminous flux density of 2.56 μlm/m^2), terrestrial photometry should use photometric units like lux and its colour analogues to make the reported values easy to understand. All photometry concerning wavelengths usual in nature (daylight, airglow, moonlight) could and should become an analogue of photometry based on human photopic vision.