# What is light pollution, and how do we quantify it?

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## Contents



## Introduction to Pollution

Generally, pollution is an impairment of the purity of the environment [10]. As a pure, reference state of the environment, its natural state is to be considered, if applicable and adequate – as in the case of the air, and natural water bodies outside buildings. Then, for example, even an anthropogenic change of its temperature is considered to be pollution: a thermal one.

For indoor air, the reference state may be the same, especially if the interior is generously connected to the exterior by windows – surely in the case of chemical or particulate air pollution.

In many cases indoors, other reference values may represent purity, i.e. absence of pollution. We adapt buildings' interiors deliberately to make them non-natural. Even particles naturally present outdoors, like pollen, may be filtered by a ventilation system to achieve purer air indoors. Evidently, the pollen-laden indoor air in spring or summer might be considered as polluted by allergic persons; the reference value when he or she considers the air as pure might be far lower than that occurring outdoors naturally. The same might apply to a sound-reducing barrier represented by walls and windows against natural outdoor sounds – people sleeping after night-work might rightly consider loudly singing birds as noise pollution of their artificial bedroom environment, meant to remain silent even in the morning. Another example

is indoor air being warmer in winter than the outdoor air but not being considered as thermally polluted. Rather than a pure state, the desirable state of the artificial indoor environment is the reference. Of course, the definition of the desirable state is a subjective one. An opposite example from the thermal domain might be a pleasant cold morning air, entering the windows of an office which have just been opened at the beginning of a sunny summer's day – if the office has not been massively ventilated during the night and remained hot from the afternoon, the outdoor air entering the room becomes thermally polluted soon, losing the refreshing effect...

So, for indoor environments adapted by people on purpose, the reference values representing an unpolluted state might be not the ones which would be present in surrounding nature, but another ones preferred by people within the interior – whenever they are not compromising their health. Odour, sound, and light which diminishes human health, even if welcomed (by others, possibly), are surely to be considered as pollutants.

Pollution as an impairment of purity (natural purity outdoors or desired purity indoors) is a qualitative category. Quantitatively, it might be unmeasurable, imperceptible, just noticeable, negligible, insignificant, tolerable, very apparent, serious, dangerous, even life-threatening... This classification is very observer-dependent. How the amount of pollution should be classified and whether it should be tolerated further, is a matter of culture, research, agreement and development of knowledge. We pollute our environment and cannot eliminate most kinds of pollution. However, we should mitigate them.

Pollution can be further categorised according to the environment being polluted (air, water, soil, landscape) and by the type of pollutant (biological, chemical, physical). The usual physical pollutants causing air pollution are: solid or liquid particles; energy in form of sound; electromagnetic waves/quanta or heat; and radionuclides.

If the natural state is the reference frame, pollution is exclusively anthropogenic, assuming situations where people are not just a minor, barely noticeable part of the larger environment nature (as in very ancient times). However, as the reference frame, a *usual* natural state can be taken instead, or even a usual state of human-influenced environment. Then an alteration of that usual state by natural forces, for example volcanic eruptions, storms, or floods might be called pollution too. See the French wikipedia item pollution for more info.

In the case of light, the polluting agents are photons of corresponding energy, or electromagnetic waves of corresponding frequency, artificially added to the environment. The reference state (as some light is always present) varies with the natural day/night cycle. The non-polluted state outdoors is an environment with only natural sources of light. Does it sound too restrictive? Then remember an example of another kind of pollution, that of inland waters. Any river should ideally be without serious biological, chemical and physical pollution: in a state where its water would be drinkable – as was the case in most of Europe even 200 years ago.

The very term *pollution* was used predominantly in a religious context before modern times. It began to acquire its current scientific meaning from the 19th to the 20th century, increasingly after 1950, e.g. in case of eutrophication of waters. This was accompanied by an emerging and rising awareness that emitting wastes into the environment degrades it, and restricts its use, and is dangerous to human health. Pesticides became considered to be a real source of pollution only after Rachel Carson's Silent Spring book had been published in 1962, and in the case of artificial fertilisers, even later.

The term 'pollution' remains rather emotive. How it could be that somebody is polluting, when he/she behaves properly, and in what is perhaps the only possible or known way? It could be argued that native people living in the wilderness, or even poor, uneducated people living in overpopulated areas do not pollute, as they are just a part of nature, struggling for survival and happiness. It could be further argued that the notion of pollution becomes appropriate only after people develop or gain an awareness that some of their activities have negative consequences and that better alternatives exist, with less damaging consequences for wildlife, their own health and the well-being of future generations. In this sense it would

be inappropriate to speak about $CO_2$ from fossil fuels as about a pollutant, if it is emitted by people knowing nothing about increasing the greenhouse effect. This was the case with all humanity (with the exception of Svante Arrhenius and a couple of others) a century ago. However, rising carbon pollution of the atmosphere is a sad reality, even if many people still do not know that they are seriously polluting when burning fossil fuels. This shows that it is hardly tenable to limit the term pollution just to activities whose originators know 'there is a problem'.

Light and noise may be the most recent examples of this difficulty. If somebody believes it necessary to cut grass as often as possible with a very loud motor-driven strimmer, or that there should be dusk-to-dawn lights on his house at night, blinding everyone who approaches (and attracting insects from large distances), it might be difficult to explain to him that he produces unacceptable pollution which should and can be easily mitigated. Those who light roads, he might agree that it is not really necessary to light the surrounding treetops or mountains as well as the road, but would insist that the road lighting itself cannot be regarded a pollution, as 'it is needed and does not harm anybody'... Evidently, it is difficult to use *pollution* as a neutral term, assuming no 'sin' when unconsciously created, and no 'horror' if not very large or damaging (see footnote 3).

## Definition

**– outdoors**

**(Outdoor) 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 article (2000) where the definition was published with slightly different wording is [1]. Before that, contradictory concepts of light pollution had 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 welcomed by some and disliked by others; some consequences are considered adverse by all. Many consequences are not yet known: the relevant discipline (scotobiology) [2] is just emerging. The most general consequence is a disruption of the day-night cycle as it has existed on Earth for billions of years.

**– indoors**

Natural indoor lighting conditions due to windows and outdoor environment with its natural light sources offer an analogous baseline. This is adequate for times when people indoors don't wish to alter their environment by artificial lighting, as during sleeping time or when enjoying looking out through windows. Then a slightly adapted version of the above definition is adequate:

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

However, a significant part of our indoor life includes use of artificial lighting. Then another definition is to be applied:

**Indoor light pollution is such alteration of light levels in the indoor environment due to sources of light, which compromises human health**

For *health*, the official World Health Organisation definition is to be used: *'Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity.'* (see the Wikipedia's item Health quoting WHO).

Lights found obtrusive by somebody should be definitely considered as polluting. But even if nobody finds the indoor light conditions obtrusive or unpleasant (e.g. because of perceiving them as necessary, common or even desirable), the environment might be still regarded as light-polluted whenever some metabolic parameters of the organism are shifted, due to artificial light, outside the range which is considered as being proper for a healthy function of the organism – a typical parameter is the concentration of the hormone melatonin, which should follow its natural course driven by the natural daily light and darkness cycle. In our epoch of electric lighting it does not follow that course. Outside the season of naturally short nights, the production of melatonin in humans does not last the whole 'civil night', up to 15 hours in central Europe in December. Lack of melatonin has been hypothesised to have profound health consequences, and further and further studies support this hypothesis. See footnote 2.

Under closer inspection it appears that the last definition and the middle one have considerable overlap: intrusion of light from outdoor man-made sources into a room at night may compromise the health of people if they find it disagreeable (i.e. being not in a state of complete mental well-being anymore), not to mention cases when their sleep is disturbed.

## How it can be quantified

The text in this section deals with the case that the reference unpolluted situation is an environment with light of natural origin only. For indoor spaces with artificial lighting, the reference unpolluted state would be that one when the light is not compromising health; these levels may be difficult to find with any certainty. Some guideline values are proposed within footnote 2.

### – 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 the lumen per square metre (it can be further divided by the 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). Watts per steradian per square metre per nanometre ($\mathrm{W.sr^{-1}m^{-2}.nm^{-1}}$) 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 the 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 luxmeter; the quantity is then illuminance, its unit is lux. The orientation of the surface element causes illuminance to differ from directionless pollutant concentration (luminance is integrated just over the proper half of the full space angle and multiplied by the cosine of the 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. Because of this, a convenient way of expressing light pollution by giving the ratio is:

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

In most cases, it is preferable to express pollution this way: as a dimensionless number rather than by photometric units. An amount of light which causes 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 true even for 'blue luminance'). In many cases, even a 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 this, pollution which is less than 10 % of natural light level is often considered as insignificant.

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

Let us compute this. Under an overcast moonless night sky, natural amounts of light are about ten times less than under a clear sky. If the absolute amount of artificially added light is the same in both cases, in relative terms it would therefore cause ten times more pollution under an overcast sky, locally. However, far from emission sources, even the intruding absolute light amounts can rise, as the light cannot escape to 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 a clear sky (meaning that the man-made and natural parts are about the same, pollution is 1 in relative terms, very *significant and conspicuous*), cause relative pollution at least a hundred times greater than under a clear sky! (In the remote areas of the largest Czech national park the relative concentration of the pollutant (light) under an 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 sufficient 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 the luminance of a star, like the luminance of any target which we aim to see. 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 the visibility of faint lights. They include stars and another celestial phenomena, fireflies and glow-worms, or plentiful faint sparkles of light (bioluminescent plankton) which are so wonderful in the sea, but mostly unknown to populations in areas where strong artificial lighting is ubiquitous.

It is not just a matter of their visibility for people. In the case of luminous insects, they fail to recognise each other over long distances in polluted environments, do not find mates, cease to reproduce and their populations eventually collapse (unfortunately, a common occurrence in towns and cities). For marine life, the ecosystem consequences of loss of visibility of bioluminescent signals on moonless or overcast nights are not yet understood, 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 the physiology of vision**

Vision poorly registers absolute levels; due to adaptation, it adjusts itself to the prevailing light levels. For example, stars are perceived as dimmer if some other, additional light comes to our eyes. This added light may come from spots of high luminance, e.g. from luminaires, windows of lit rooms, vehicle lights and outdoor surfaces purposely illuminated. Stars become invisible in urbanised environments not just because of increased sky luminance, but also because of glare (including veiling luminance produced by the dispersion of light inside the eye) 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 the terrestrial landscape.

So, light pollution not only diminishes contrasts, but due to animal and human vision adapting to artificially increased light levels, light pollution *reduces the number of photons registered on the retina* from 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 they are to be noticed (contrast sensitivity is worse at the bottom end of the span of perceived luminances than at its middle).

## Where the direction or a spectrum plays a role

With closed eyelids, we barely perceive the direction of the incoming light, but it is still important: if it comes from one side only, we can turn towards the other side (thereby reducing the illuminance of the face). Similarly, trees affected by acid deposits brought by a wind coming from the west are less affected on their east-facing sides. 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 (and very prominent pollution), even if it contributes just a tiny fraction of total light input to our eyes. Directly visible lights are also the most harmful for wildlife, security (through an effect called glare) and aesthetics, or even the very visibility of the true landscape including the sky.

We should take into account not just the mere (photopic) amount of light, but also its spectral composition (perceived often as a colour by us and many other organisms). For

example, pure blue light (with no green or red component) contributes little to the usual photopic quantities, as expressed in lumens or candelas, but can still be conspicuous (altering, i.e. polluting the natural scenery). Moreover, such shortest-wavelength light is the signal to us, and to other animals, that it is day or night, and it controls the animal's metabolism. An established way of somehow taking into account the spectral composition of light is by also reporting its 'scotopic luminous flux' (it is relevant for deep-night vision, when photopic luminances do not exceed 1 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, 'renormalised red, green and luminous flux' or luminous intensities might be introduced. Renormalisation might consist in considering them to be all equal for summer daylight (they can be measured easily by using RGB digital imaging; 'B luminous flux' is 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 short-wave half of the light spectrum) to safeguard 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 (outdoor) example; yellow light indoors (blue being mostly filtered out by a yellow filter gel or transparent glass paint) is very comfortable (the author's family has had such a separate lighting system for evenings and nights for four years now). For occasional blue-demanding tasks such 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 if people with certain types of colour blindness 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 as photopic luminous flux) remain similar to before. This makes light easier to handle than most other pollutants. Of course, even the growth of total emissions should be halted and reversed towards a steady decline, to get pollution levels back to values which may be tolerable, taking into consideration all adverse effects of lighting (for light, those of the late 19th century might be almost surely regarded as sustainable, while an interim goal might be a decline to the levels of 1970).

## References and further links


1. *'alteration of natural light levels in the outdoor environment owing to artificial light sources'* – the first published scientific definition, as it 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 see at 2003 *Ecology Of The Night* conference pages:
   http://muskokaheritage.org/ecology-night

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 http://amper/noc/english/canc_rhythm/g_camer.pdf.

6. Save the Night in Europe, a comprehensive source aimed not just at clear sky luminance. http://savethenight.eu

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.* Document Version 2.4, 29 February 2008. Online as http://amper.ped.muni.cz/bajc/lp181.pdf.

9. Hollan J: *Digital imaging photometry with common cameras – results, methods and perspectives.* Lecture slides for a meeting of IAU commission 50, Prague, August 2006. Online as http://amper.ped.muni.cz/light/lectures/06IAU50t_small.pdf (8 MB).

10. Cinzano P: *What is light pollution.* Online as http://www.savethenight.eu/What%20is.html. Retrieved on July 10, 2008.

## Changes:

1. The term *immissions* has been used in the 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 the 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 the 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 to an absolute decrease of signal registered by the eyes from faint lights at night, due to visual adaptation. Very conspicuously, it can cause a *decrease* of the quantity important for visibility: 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 in January 2007

4. *Indoor light pollution* definitions included in July 2008, an introduction on pollution in general and a footnote on man-made sources of light. The footnote of indoor light has been shortened.

5. *Pollutants* footnote added in August 2008.

6. *Acknowledgements:* Major language correction made by Bob Mizon on September 15, 2008. Michael Tabb and Christopher Baddiley read the text as well. I am very thankful to these CfDS personalities. My thanks are also due to Barry Clark, Steve Willner and Pierantonio Cinzano for advice concerning the early 2006 and 2007 drafts of the text. Matěj Hollan helped me with clarifying various meanings of 'pollution' in August 2008. None of them is responsible for the contents of the present paper of course.

7. *Photometry:* The bad jargon of having various lumens etc. has been replaced by having various quantities (depending on spectral luminous efficiency functions and on the normalisation) but just one standard set of units (October 2008).

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## Footnotes

### 1 On man-made sources of light

Predominantly, they are electricity-related sources, i.e. various kinds of lamps in developed countries. Flame sources may prevail in non-electrified regions. However, in principle, even strong, conspicuous secondary sources of sunlight might be included, as sun reflections in car windscreens or in tilted windows of buildings. If perceived as glaring lights, considering them as causes of light pollution might be more valid than including them just in the broad category of visual pollution (containing three-dimensional artifacts altering the desired natural or cultural landscape).

### 2 On light added indoors

There is no doubt that indoor light is toxic in some cases, causing sleep and metabolism disturbances. In this sense, common light levels produced by today's artificial (electric) lighting have to be considered a significant pollution of indoor *night* air, similar to tobacco smoke at *any time*. Keeping B illuminance of eyes below 1 lx during the time when we do not sleep at night is to be recommended; keeping it below 0.25 lx can be considered a *safe environmental limit* for humans (this is the natural night-time outdoor maximum which can be tolerated by most organisms due to eons of evolution; some rodents are still a hundred times more sensitive, probably due to the fact they inhabit dark niches).

A special kind of indoor light pollution might arise in a situation when even the natural outdoor sources of light compromise the health of people indoors, altering the desired indoor light levels. People needing to sleep in the daytime are an example, and glare coming from windows is an even more usual one, especially for people working at computer screens. This is the reason why the 'man-made' attribute was omitted in the latter definition.

### 3 On adverse effects

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

Was the application of DDT, broadly used outdoors in the fifties and sixties, a pollution? Surely it was, even though it was considered entirely beneficial in those times. Is a single LED in the middle of the Sahara a pollution? Surely it is, at least as environmental 'litter': only stones and sand should be there, and some (hardly visible) wildlife, in a non-polluted state. A metal beer-bottle cap would qualify as pollution too, as well as the bottle itself, broken or not. At night, a shining (ordinary, not 70lm) LED would be visible not just from an immediate vicinity, as in daylight. Even from 1 km away, it could be as bright as the star Vega... surely tolerable, if it is meant to be a vital reference light, but still a pollution. The mere existence of pollution does not depend on whether anybody is watching or objecting.

We can live with some pollution, just as we can live with beer, wine and brandy. We can enjoy their positives, without forgetting their toxic aspects. We should bring their adverse

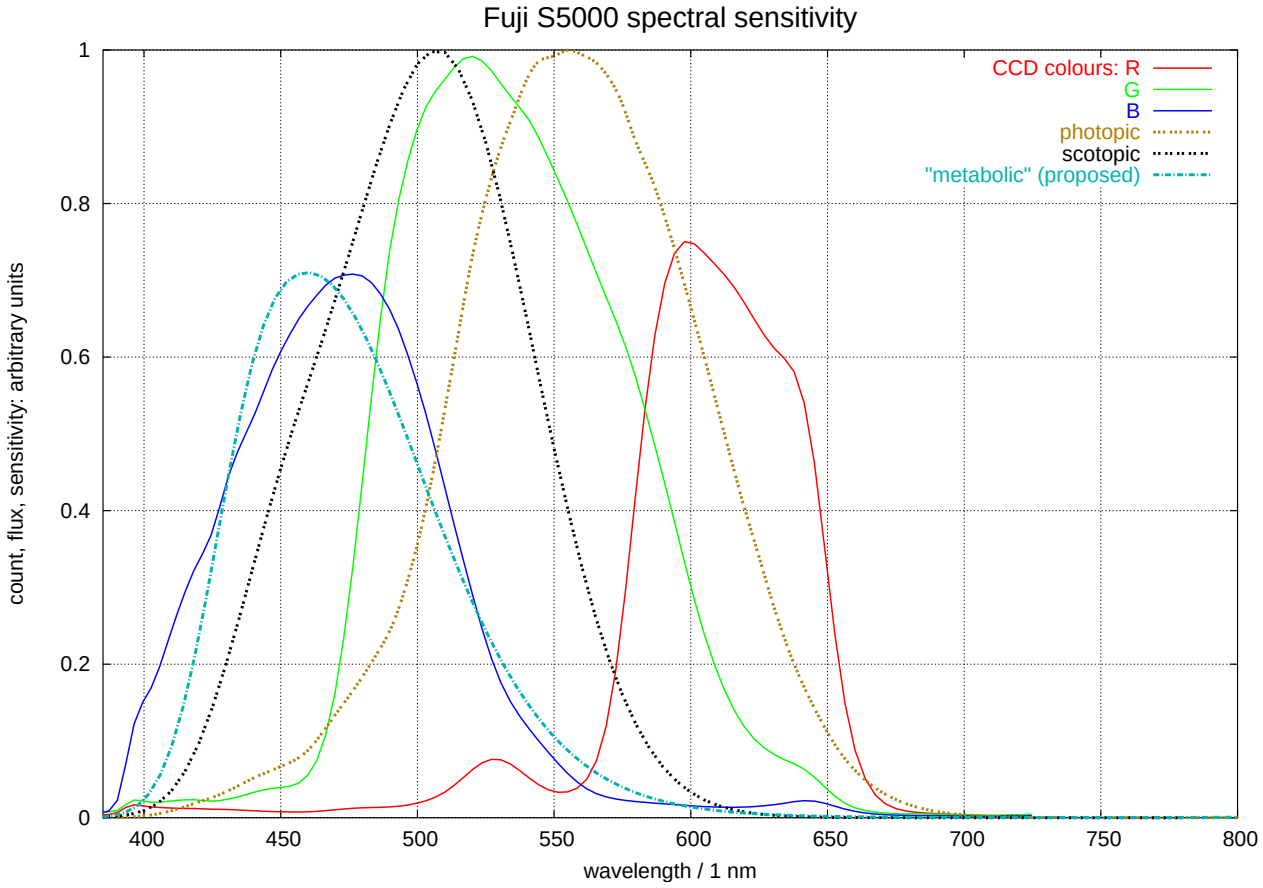
effects under our control. And as with brandy and children, or beer and bears, we should be aware there are organisms which are much more vulnerable to damage by some of those agents we love so much. For example, there are nocturnal frogs which never cross a continuously lit road: once lit, it becomes a barrier dividing the previously contiguous habitat.

## 4 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 $540\times10^{12}$ hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

For light in the real world, which contains electromagnetic radiation of various wavelengths, there are but approximations of correspondence between amounts perceived by human vision (true photometry) and those measured by instruments. This was established by investigations resulting in various spectral luminous efficiency functions of the two visual systems in humans [4]. The author of the present text has proposed a different approach, enabling us 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 luminous flux etc. In some cases, the whole spectrum may be poorly known. Still, responses of a sensing system (animal or instrumental) having such a poorly known spectral sensitivity may be recalibrated by setting them to be the same as (easy to measure) photopic quantities for some well known 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 the B luminance to a 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, having been extended to photographic light-sensing tools, 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 A0V: the reported values for any such star (Vega is used as the primary standard) should always be the same, regardless of whether 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, a difference of 2.5 mag corresponds to 10 decibels in acoustic analogy, i.e. to a ratio of luminous flux densities of 10; a star having just 0 mag gives a luminous flux density of 2.56 $\mu$lm/m$^2$), terrestrial photometry should use photometric units like lux to make the reported values easy to understand. All photometry concerning light-containing wavelengths usual in nature (daylight, airglow, moonlight) could and should become an analogue of photometry based on human photopic vision. Instead of the proper SI radiometric normalisation at $540\times10^{12}$ Hz, which would result at vary different values for various spectral luminous efficiency functions applied to common light sources, photometric quantities renormalised to AM1.5 clear sky global light might be recommended for most purposes. For scotopic ones, the renormalisation would result in dividing the SI values by 2.5. For another spectral luminous efficiency functions, such a coefficient may be still less well known. In spite of that, properly renormalised photometric values can be taken seriously.

## 5 On pollutants

In a typical technical sense, pollution is due to a pollutant, some microscopic agent dispersed in the environment. The German word Schmutz (meaning dirt) indicates this view well, as well as the term Verschmutzung for pollution, not being charged with religious overtones. However, macroscopic objects may represent pollution too. A common case is litter. Sometimes it may just spoil the beauty of the environment. Sometimes it can even be fatal to animals, as in the case of plastic bags in the sea. Even objects regarded as necessary or welcome by some may be regarded as spoiling or polluting the environment, or more precisely, our way of experiencing it – power lines, roads, billboards, cars, etc. See http://en.wikipedia.org/wiki/Visual_pollution. Visible non-natural lights and lit objects at night belong to this category too, changing the landscape profoundly.

This brings us back towards the religious context: the world is damaged by a presence of unwanted man-made phenomena. Night-time darkness can be easily considered sacred, together with its celestial lights. An extreme notion of pollution, which has to be respected too, is purely religious: something (permanently) polluted due to the mere past presence of an intruding factor, for example a man stepping on top of a sacred mountain. The purity can eventually be restored by a proper ritual...

I know of no such attitude to light. Pollution by light can be cleaned up without any such ceremony, simply by switching the light sources off. Still, the consequences of past light pollution may persist for decades: like absent darkness-dependent animals, or people with a childhood experience of starry heavens – and therefore an interest in this phenomenon. Subjecting whole populations to growing and living without the night, without the heavens, is the largest social experiment ever. Light at night may be a far more serious pollutant than many others...