Principles and Nomenclature for the Quantification of Light

2

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2.1 Introduction: Why This Chapter Is Necessary

This chapter will not deal with measuring equipment or measuring techniques, but with basic concepts of light quantification. This topic seems confusing, not only to the layman and the student, but also to the expert. Some reasons for this confusion are as follows:

1. The layman and beginning student erroneously regard the "amount" or "intensity" of light as something that can be completely described by a number.
   Such a view disregards the following:
   (a) Light consists of components with different wavelengths. A full description of the light would thus give information about the "amount" of light of each wavelength.
   (b) Light has direction. The simplest case is that all the light we are considering has the same direction, i.e., the light is collimated; the rays are all parallel. Another case is that light is isotropic, i.e., all directions are equally represented. Between these extremes, there is an infinite number of possible distributions of directional components.
   (c) Light may be polarized—either circularly polarized or plane polarized. In the rest of this chapter, we shall disregard this complication, but one should always be aware of the fact that a device such as a photocell may be differentially sensitive to components of different polarization, and polarization may be introduced by part of the experimental setup, such as a monochromator or a reflecting surface.
   (d) Light may be more or less coherent, with light waves "going in step." We will not address this complication in this chapter.
   (e) People often disregard or neglect or confuse the concept of time. We must decide whether we want to express an *instantaneous* or a *time-integrated* quantity, e.g., *fluence rate* or *fluence*, and *power* or *energy*. Power means energy per time unit.
2. Light is of interest for people investigating or working with widely different parts of reality. Experts in different fields have used different concepts and different nomenclature, partially depending on what properties of light have been interesting for them and partly due to the whims of historical development. Only rather recently have there been serious attempts to achieve a uniform nomenclature, and the process is not yet complete.

2.2 The Wavelength Problem

As we cannot always quantify light by giving the complete spectral distribution, we have to quantify it in some simpler way. From the purely physical viewpoint, there are two basic ways. Either we express a quantity related to the number of photons or a quantity related to the energy of light. For a light of single wavelength, the energy of a photon is inversely proportional to the wavelength and the proportionality constant is Planck's constant multiplied by the velocity of light.

There is an ultimate way of calibration only for the energy of light. For this we can use a hollow heat radiator of known temperature, which will radiate in a way predictable by basic physics. Using such a radiator, a photothermal device, such as a thermopile or a bolometer (see Chap. 4), can be calibrated, and then any kind of light can be measured with it and expressed in energy or power units. We can use it for measuring a series of "monochromatic" (i.e., narrow-band) light beams, and they, in turn, can be used for calibrating other measuring devices in either energy or photon units.

Actinometers, i.e., photochemical devices, seem to count photons, but in this case the ability of photons to cause a response (the quantum yield) varies with wavelength.

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We can also use photomultipliers as photon counters, but we should be aware that they do not, strictly speaking, count photons, but impulses caused by photons. Some impulses are not caused by incident photons, but by electrons knocked out from the photocathode by the heat vibration of the atoms in it. We try to minimize this by cooling the photocathode. Furthermore, all photons do not have the same ability to knock out electrons from the photocathode and cause pulses to be counted. This ability is wavelength dependent. Therefore, we cannot use photon counting as an independent calibration method.

The units for expressing light as photons are as follows:

1. Photons (number of photons).
2. Moles of photons (the symbol is mol), which is $6.02217 \cdot 10^{23}$ photons, or a unit derived from this, such as micromole of photons ($6.02217 \cdot 10^{17}$ photons). The symbol for the latter is μmol.

Either of these can be expressed per time and/or per area or (rare in biological contexts) per volume.

The unit for energy is joule (J). Energy per time is power, and joule per second is watt (W). Both can be expressed per area (or, rarely in biological contexts, per volume, i.e., energy density or power density).

You should note that simply giving a value followed by "W/m^2" without further qualification is not defined, since one cannot be sure what kind of area you are expressing with m^2. Is it a flat area or a curved one? If it is flat, what is its direction? This brings us to the topic of the next section.

2.3 The Problem of Direction and Shape

Most light-measuring systems are calibrated using light of (approximately) a single direction, i.e., collimated light. However, light in nature, where most plants live, is not collimated. If the sky is cloudless and unobstructed, the rays coming directly from the sun are rather well collimated, but in addition there is skylight and light reflected from the ground and various objects. A plant physiologist who wants to understand how plants use and react to light has to take this into account.

Traditionally, most measuring devices can be regarded as having a flat sensitive surface, and when we calibrate the instrument, we generally position this surface perpendicularly to a collimated calibration beam. A plant leaf is also flat, so in the first approximation we can measure light in single-leaf experiments with a flat device with the same direction as the leaf. But a whole plant is far from flat (except in very special cases). Different surfaces on the plant have different directions. Ideally we should know the detailed directional (and spectral) distribution of the light impinging on the plant, but this is not possible in practice. Since a plant is a three-dimensional object, it would in most cases be better to determine the light using a device having a spherical shape and equally sensitive to light from any direction. This brings us to the distinction between

1. Irradiance, i.e., radiation power incident on a flat surface of unit area, and
2. Energy fluence rate (or fluence rate for short), i.e., radiation power incident on a sphere of unit cross section. The term fluence rate was introduced by Rupert (1974).

Both these concepts have their correspondences in photon terms. For case 1 the nomenclature is not settled, but it would be logical to use the term photon irradiance. Many people, especially in the photosynthesis field, use the term photon flux density and the abbreviation PFD (PPFD for photosynthetic flux density; see below). For case 2 the term photon fluence rate is well accepted among plant physiologists, but hardly among scientists in general.

Energy fluence is the energy fluence rate integrated over time. By fluence is meant as the same thing as energy fluence.

We shall now compare irradiance and energy fluence for different directional distributions of light (see Fig. 2.1):

1. Collimated light falling perpendicularly to the irradiance reference surface. In this case, the flat surface of unit area and the sphere of unit cross-sectional area will intercept the light equally, and irradiance will be the same as fluence rate.
2. Collimated light falling at an angle α to the normal of the irradiance reference plane. In this case, the light intercepted by the flat surface of unit area will be less than that intercepted by the sphere of unit cross-sectional area. The irradiance will be cos(α) times the fluence rate. Since cos(α) is less than unity, the irradiance in this case will be lower than the fluence rate.
3. Completely diffuse light falling from one side only. The ratio of irradiance to fluence in this case will be an average of cos(α) for all angles α from 0 to $+\pi/2$ weighted by sin(α), i.e., $\int \sin(\alpha)\cdot\cos(\alpha)\cdot dx / \int \sin(\alpha)\cdot dx$ with the integral running from 0 to $+\pi/2$, and this is equal to 1/2. Thus, the irradiance in this case is half the fluence rate. The reason we have to weight cos(α) by sin(α) is that all values of α are not equally "common" and do not have the same probability. The various directions may be thought of as corresponding to points on a big sphere, the center of which is the point of measurement. The sphere can be thought of as divided into a pile of rings, and each ring (corresponding to a value of α) has a radius, and hence a circumference proportional to sin(α).
4. Completely diffuse light from both sides, i.e., isotropic light. The sphere is then hit by light over its whole surface, but for the flat receiver we still count only one surface (irradiance is defined in this way), so irradiance is one quarter of the fluence rate in this case. We can easily remember this if we think that the area of a circle is one quarter of the area of a sphere with the same radius.

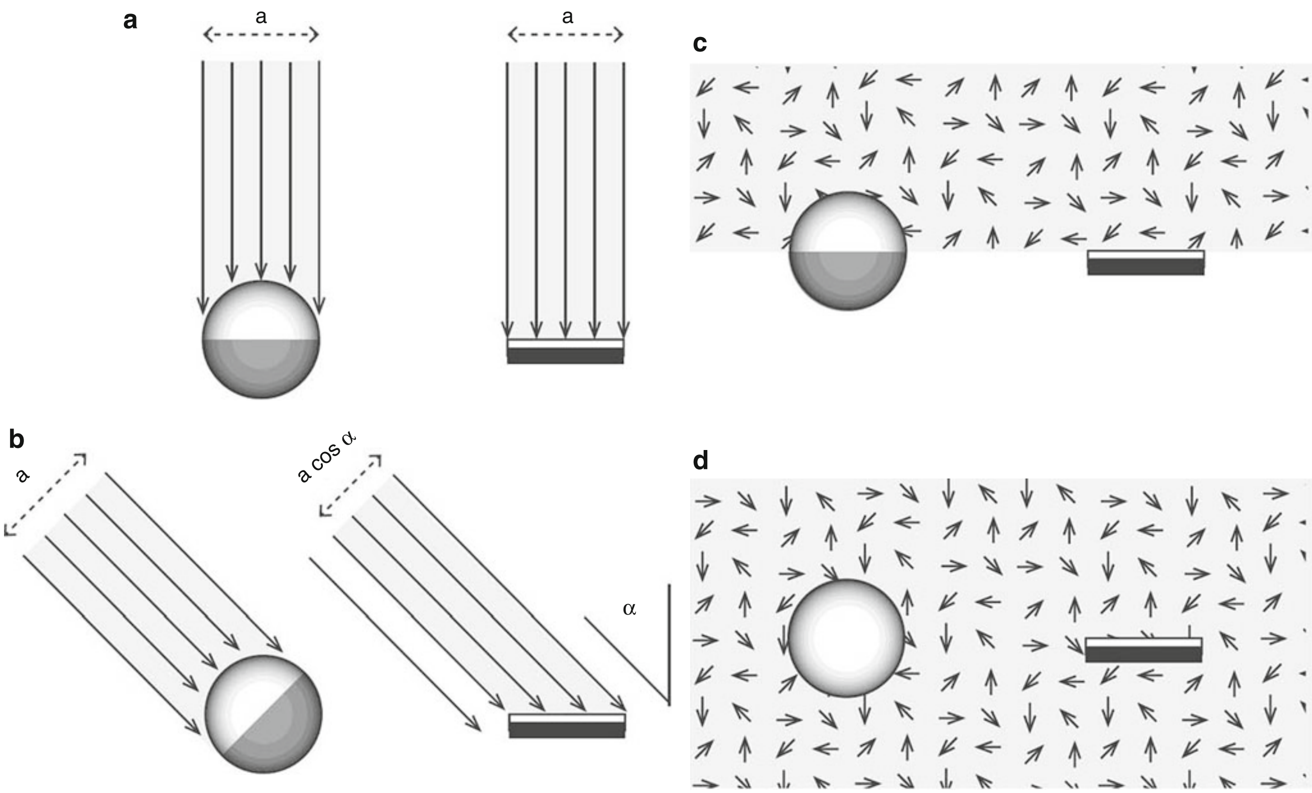

Fig. 2.1 The concepts of irradiance and fluence rate. In (**a**) the incident light is perpendicular to the surface of the flat irradiance sensor. In this case, fluence rate and irradiance are equal. In (**b**) the incidence angle is α. The irradiance sensor then intercepts only the fraction cos α of what the fluence rate sensor does. In (**c**) the light is diffuse, but incident only from above. Then the fluence rate is twice the irradiance. In (**d**) the sensors are immersed in diffuse radiation from all directions, but the irradiance sensor senses radiation only from above. In this case the fluence rate is four times the irradiance (Courtesy Pedro J. Aphalo and Eva Rosenqvist)

We may now make a table of various quantities associated with light measurements (Table 2.1).

In all the above cases, we add the word "spectral" before the various terms if we wish to describe the spectral variation of the quantity. We may thus write, e.g., spectral fluence rate on the vertical axis of a spectrum of light received by a spherical sensor.

What we here have called fluence rate is termed *actinic flux* by atmospheric scientists. Two more terms with the same meaning are *space irradiance* and *scalar irradiance*. The term space irradiance was introduced by Grum and Becherer (1979). The term *spherical irradiance* has been used in similar contexts, but means one quarter of the fluence rate. *Vectorial irradiance* is just the same as irradiance. The reader should use just one system of terms, preferably irradiance and fluence rate, but may encounter all these other terms in the literature.

Few instruments on the market, and very few spectroradiometers, are designed for direct measurement of fluence rate. Most of them are constructed for irradiance measurements and a few for measurement of radiance (see below). But Björn (1995) and Björn and Vogelmann (1996) have shown how irradiance meters can be used for estimation of fluence rate.

Table 2.1 Various quantities associated with light measurements

	Flat receiver	Spherical receiver
Instantaneous values		
Energy system	(Energy) irradiance Unit: W m^{-2}	(Energy) fluence rate Unit: W m^{-2}
Photon system	Photon irradiance (=photon flux density) Unit: mol m^{-2} s^{-1}	Photon fluence rate Unit: mol m^{-2} s^{-1}
Time integrated values		
Energy system	(Energy density) Unit: J m^{-2}	(Energy) fluence Unit: J m^{-2}
Photon system	–	Photon fluence Unit: mol m^{-2}

So far we have been dealing with light falling on a surface, either a flat or a spherical one. But we may need to express other quantities, for instance, the total power (energy per time unit) output of a light source. The unit for this is, of course, W (watt). The power emission per unit area of the source is called the *radiant excitance* and is measured in W/m^2 (just like irradiance and fluence rate, so beware of confusing them). The power emission takes place in different

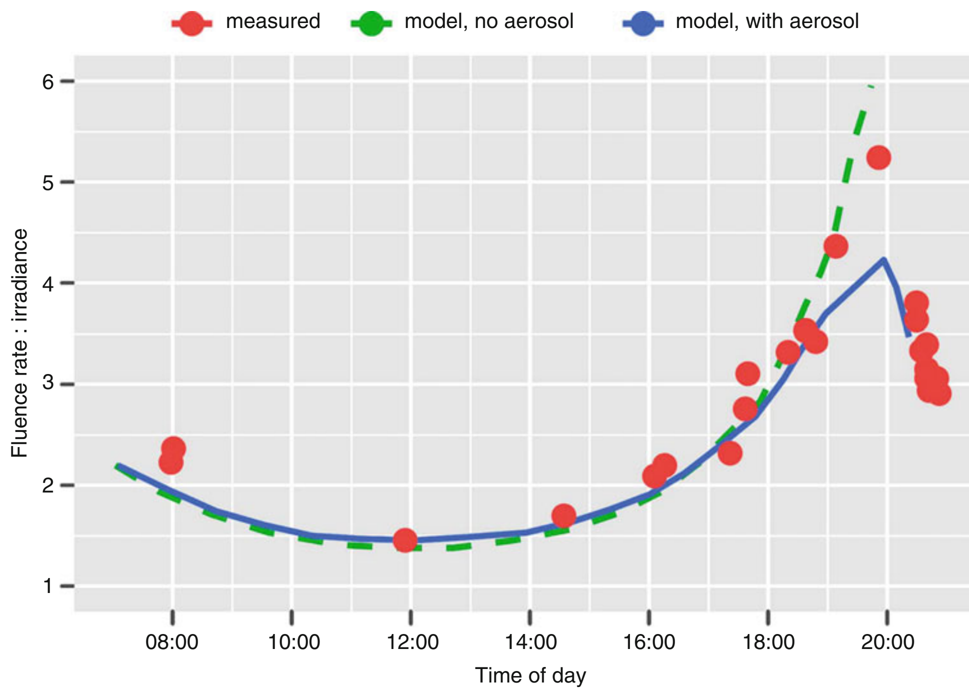

Fig. 2.2 The variation of the ratio of fluence rate to irradiance over a clear summer day in southern Sweden. Presence of small particles in the air (aerosol) dampens the variation. The graph is for cloudless conditions and 400–700 nm ("PAR" spectral band, see Fig. 2.3). For ultraviolet radiation, especially for UV-B radiation, the variation is smaller, because even clean air scatters this radiation to make it to a large extent diffuse. For overcast conditions, the variation is also smaller than for clear skies (Measurements and calculations by the author, plot by Pedro J. Aphalo and Eva Rosenqvist)

directions; in total there is a solid angle of 4π steradians (sr) surrounding a source. Usually the emission is not equally distributed in all directions, so for a certain direction we might like to specify the power emission per steradian. This quantity is called the *radiant intensity* in that direction, and the unit is W/sr. (Note that the term intensity is often (erroneously) used in another and usually not well-defined sense). The radiant intensity per area unit on a plane perpendicular to the light is called *radiance*, and the unit is W/sr/m^2. The official definition of radiance (usually denoted by L) is as follows: radiant power (P), leaving or passing through a small transparent element of surface in a given direction from the source about the solid angle θ, divided by the solid angle and by the orthogonally projected area of the element in a plane normal to the given beam direction, dS cos θ. With mathematical symbols we write: $L = d^2P/(d\Omega\ dS \cos\theta)$ for a divergent beam propagating in an elementary cone of the solid angle Ω containing the direction θ.

If we integrate the radiance over all 4π radians for both Ω and θ, we get back to the fluence rate that we are already familiar with.

Fortunately, the average photobiologist need not keep all these concepts in his or her head at all times. You can look them up when needed. However, you must be clear over the meaning of irradiance and fluence rate and not confuse these two concepts. As a practical illustration of how the ratio of fluence rate to irradiance can vary under natural conditions, see Fig. 2.2.

A comprehensive list of recommended units, concepts, and symbols for photo-science is published by Braslavsky et al. (2007).

2.4 Biological Weighting Functions and Units

Section 2.3 concludes the physical quantification of light. However, there has been a need for additional concepts in connection with organisms and biological problems. Traditionally there has been a special system related to the human perception of light. We can here limit ourselves to *illuminance*, which is expressed in lux. Neglecting the historical development, we can say that lux is the integrated spectral irradiance weighted by a special weighting function. This weighting function is precisely described mathematically, but can be thought of as the average (photopic, i.e., related to strong light vision mediated by cones) eye spectral sensitivity for a large number of people. (Rarely we also see the expression "scotopic lux," which is the corresponding term using the scotopic visibility weighting function.) The photopic visibility function has its maximum at 555 nm, and for this wavelength 1 W/m^2 equals 683 lx. For all other wavelengths, 1 W/m^2 is less than 683 lx. Illuminance integrated over a flat area is called *luminous flux*, and the unit is lumen. Thus lux is lumen per square meter. In older American literature the unit foot-candle (f.c.) is used instead of lux. Foot-candle equals lumen per square foot, and since there are 3.2808399 ft in a meter, there are $3.2808399^2 = 10.763910$ square feet in a square meter, and also 10.763910 lx in a foot-candle. There are also a number of other photometric concepts and units, which we seldom need in photobiology. Many of them are defined in the *Handbook of Chemistry and Physics*.

Similarly we may, for purposes other than vision (reading light, working light), weight the spectral irradiance by other functions. These functions approximate various photobiological action spectra (see Chap 8). One special function is zero below 400 nm and above 700 nm, and unity from 400 to 700 nm. This describes by definition photosynthetically active radiation, or PAR. Usually one uses the spectral photon irradiance to weight by this function, and this is the meaning of the often used term PPFD, photosynthetic photon flux density. To assume photosynthetic zero action outside the range 400–700 nm and the same action for all components within the range is, of course, physiologically speaking an approximation, but an approximation that people have agreed upon, just as the definition of lux involves an approximation that holds well only for photopic (cone) vision.

Other weighting functions are used for "sunburn" meters to yield "sunburn units," but in this field we have to watch out for various "units" used by various people. One kind of sunburn meter used much in the past is the Robinson-Berger meter, but recently a new agreement has been reached for using a weighting spectrum more closely resembling the true sunburn action spectrum (for Caucasian skin). One weighting function to determine safe working conditions shown in Fig. 2.3 is damaging UV. This particular function was agreed upon in 1991 by the International Radiation Protection Association (IRPA) and the International Commission on Nonionizing Radiation Protection (ICNIRP). Another, slightly different function for similar purposes was devised by the American Conference of Governmental Industrial Hygienists (ACGIH).

In reality, of course, different kinds of damage, such as damage to the cornea and to the lens of the eye and to skin of persons with different pigmentation, have different action spectra. Also the standard PAR is an approximation to reality, since different plants, and even the same plant in different states, have different action spectra for photosynthesis.

There are numerous other weighting spectra in use for estimating radiation with other biological actions. We shall address some of them in the chapter on ultraviolet radiation effects.

Some meters, such as lux meters, sunburn meters, and meters for PAR, are constructed with spectral responses approximating the weighting functions and can therefore directly yield the values we want without spectral decomposition of the light. For more precise work, and in the case of, e.g., UV inhibition of plant growth, it is necessary to measure (using a spectroradiometer) each wavelength component separately and weight by the weighting function using arithmetics (usually computers are used).

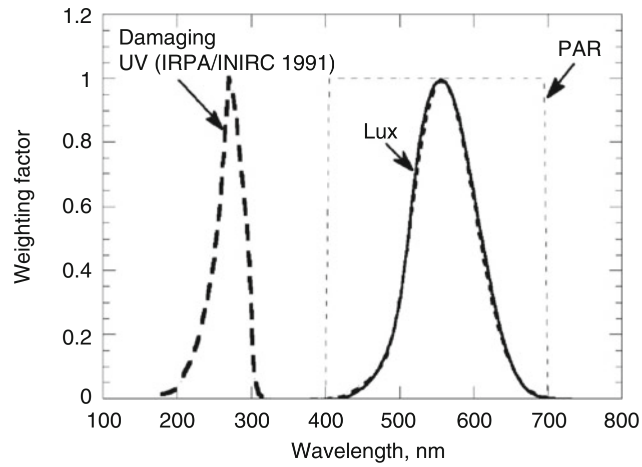

Fig. 2.3 Examples of weighting functions. The damaging UV function is one devised by the International Radiation Protection Association (*IRPA*) and the International Commission on Nonionizing Radiation Protection (*ICNIRP*) and thus having a certain official status. *PAR* stands for photosynthetically active radiation, and this weighting factor is unity from 400 to 700 nm and zero outside this interval. This weighting function is applied more often to photon irradiance or photon fluence rate than to energy irradiance and energy fluence rate. The Lux function is that used for conversion of W/m^2 to lux (or W to lumen). The maximum is here made unity to allow plotting together with the other functions, but in absolute units it corresponds to 683 lx per W at 555 nm. The Lux graph in fact consists of two plots, so close that they hardly can be distinguished in the diagram—both the official values from a table and an analytical approximation consisting of the difference between two Gauss functions: weighting factor = $\exp[-(555-\lambda)/63.25]^2 - \exp[-(495-\lambda)/30]^2/6.8$, where λ stands for wavelength in nm

References

Björn LO (1995) Estimation of fluence rate from irradiance measurements with a cosine corrected sensor. J Photochem Photobiol B Biol 29:179–183

Björn LO, Vogelmann TC (1996) Quantifying light and ultraviolet radiation in plant biology. Photochem Photobiol 64:403–406

Braslavsky SE et al (2007) Glossary of terms used in photochemistry. 3rd ed. (International Union of Pure and Applied Chemistry recommendations 2006). Pure Appl Chem 79:293–465. Available at http://www.iupac.org/reports/III/2002-024-1-300_rec061012.pdf or http://www.iupac.org/reports/1993/homann/index.html

Grum F, Becherer RJ (1979) Optical radiation measurements. Academic Press, New York, pp 14–15

Handbook of chemistry and physics (many editions). CRC Press, Cleveland. http://en.wikipedia.org/wiki/CRC_Handbook_of_Chemistry_and_Physics

Rupert CS (1974) Dosimetric concepts in photobiology. Photochem Photobiol 20:203–212

http://www.springer.com/978-1-4939-1467-8

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