Photons, Flux, and Some Light on Philology

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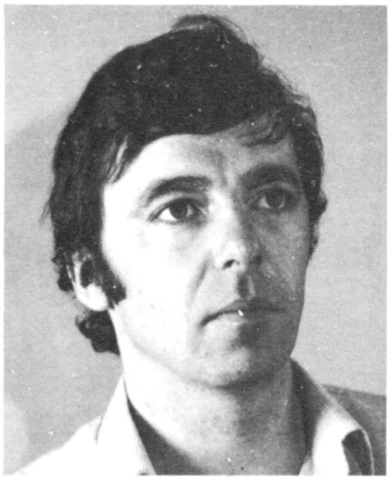
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Many articles have appeared in recent years recommending or defining terminology and units for measuring radiation energy in experiments with plants. A large group of these publications (1, 7, 8, 9, 10, 11, 12, 19, 22, 23) present the units and nomenclature which have been agreed upon, and promoted by, the American Society of Agronomists (ASA), the American Society of Agricultural Engineers (ASAE), the American Society for Horticultural Science (ASHS), and the USDA North Central Regional Growth Chamber Use Committee (NCR-101). The most recent addition to this series has just been published in *HortScience* (10). The authors advocate adoption of their guidelines by researchers, reviewers, and editors on a worldwide basis. However, there is still both international and interdisciplinary disagreement on the terminology, and to a lesser extent, the units used for radiation measurements in the plant sciences. In many instances, these disagreements have been reduced to para-semantic arguments. On the other hand, there are many discrepancies in the literature which are due to inaccurate etymology, thereby leading to the potential danger that the grammatical roots of the nomenclature will be altered artificially. The purpose of this communication is to indicate these discrepancies before incorrect terminology becomes widely accepted.

In the most recent recommendations of the ASHS and the NCR-101 committee (10), the authors propose that energy flow per unit area (Wm^{-2}) in the 400–700 nm waveband be described as the (photosynthetic) **irradiance**. In the same article, however, the recommendation is made that the spectral composition of energy flow per unit area be described either in the same way, i.e., *spectral irradiance*, or that the term **spectral energy flux density** may be used. The ASAE (1), although cited by Krizek and McFarlane (10) as being one of the groups involved in these guideline decisions, proposes that both **irradiance** and **energy flux density** are acceptable terms for measurements of photosynthetically active radiation. Clearly, complete agreement among groups on a consistent terminology is required before worldwide agreement can be achieved (4, 5).

The proposal (10) that the term *lux* should continue to be permitted seems retrogressive to us. The usage of photometric units in the plant sciences has declined rapidly in recent years, and this decline must be welcomed because photometric units, such as **lux**, describe light only in terms of the radiation perceived by the human eye. Krizek and McFarlane do emphasize that, if **lux** is used, it must be reported only if a parallel reading of PAR (photosynthetically active radiation) is made and the presentation of **lux** is for historical reasons only. [It should be noted that this was not clear in the original article (10) as the footnotes to Table 2 were omitted, but are found in *HortScience* 19(1):17.] Nevertheless, we feel that measurements in older literature in terms of **lux** or other photometric units (e.g., **candela**, **footcandle**, **lumen**) should be interpreted by the individual reader in terms of their approximate energy or photon content.

A more serious criticism is the misuse of the term **flux density** to describe **flux**. This error is very common in the photobiological literature (e.g., 6, 17, 20, 21). The only publication cited in the 1st paragraph which provides definitions (1), defines **flux** as the *rate of flow* of energy or photons, and **flux density** as the radiant or photon flux *per unit plane area*. This usage is etymologically incorrect according to standard reference sources and is not consistent with usage in physics (except nuclear physics) and engineering.

In 2 reference works, **flux** refers to "the rate of transfer of fluid, particles or energy (as radiant energy) *across a given surface*" (14), and "the volume or mass of fluid or particles transferred *across a given area* perpendicular to the direction of flow in a given time" (24). These 2 definitions of *flux* use the terms "given surface" or "given area" in a dimensionless context (albeit implying area) thereby requiring addition of a term for the dimensional unit, i.e., density, as has been promoted in the guidelines cited above.

The following 3 definitions of **flux** differ in that they include the area unit within the definition (italics added):

> "The rate of flow of mass, volume, or energy *per unit cross-section* normal to the direction of flow" (2).
>
> "The amount of some quantity flowing *across a given area* (often a unit area perpendicular to the flow) per unit time; the quantity may be, for example, mass or volume of fluid, electromagnetic energy, or number of particles" (13).
>
> "The rate of flow of any fluid *across a given area*; the amount which crosses *an area* in a given time; it is thus a vector *referred to unit area*" (3).

Another argument for using **flux** and not **flux density** is that the term density usually is used in physics to describe volume, not area. This use is seen within the S.I., where the term density is used to define area in the

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cases of heat flux density (Wm^{-2}) and current density ($A\ m^{-2}$) but is used to define volume in the cases of mass density ($kg\ m^{-3}$), electric charge density ($C\ m^{-3}$) and, of particular relevance here, energy density ($J\ m^{-3}$). Clearly, usage of the term density should be avoided, not only because flux already defines area, but also because density is used inconsistently in S.I. units. It is proposed here that the units referred to as "flux density" ($W \cdot m^{-2}$, $W \cdot m^{-2} \cdot nm^{-1}$, $mol \cdot s^{-1} \cdot m^{-2}$, $mol \cdot s^{-1} \cdot m^{-2} \cdot nm^{-1}$ in reference 9) should be denoted simply **flux**. For the same reason, the units W, $W\ nm^{-1}$ and $mol\ s^{-1}$ which are referred to as various forms of "flux" by Krizek and McFarlane (10) are misnomers. A preferable term is **flow rate**, which, based on the reference works cited previous, and others, is the rate of transfer of a quantity and does not account for area.

It will be noted by many that the terms **fluence** and **fluence rate** are not included in the article by Krizek and McFarlane (10) even though these terms are presented and defined by one of the cooperating groups (1). Although detailed discussion is beyond the scope of this commentary,it should be emphasized that these terms are still recommended for use by several journals in the plant sciences and in general photobiology. The basic differences between the term **flux** and the original definition of **fluence rate** are of fundamental importance. **Flux** describes radiation arriving at a flat surface. The **flux** arriving at a flat surface decreases as a function of the angle of incidence, so a proportionality factor must be applied to radiation arriving at other than normal incidence. This factor is $1/\cos \theta$, where θ is the angle between the plane of incidence of the radiation and the normal (line perpendicular to the surface). With a perfect receiver, the response at 45° off-axis incidence would be the cosine of 45°, i.e., 0.707 of that at normal incidence, and at 60°, 0.500 of the response at normal incidence. Thus, if 100 light particles from source A arrive at normal incidence to a plane surface and 100 arrive from source B at 60° from normal incidence, the cosine-weighted **flux** is 100 plus 50 or 150 particles per unit area per unit time.

The term **fluence** was introduced (17) to describe the radiation treatment at a specific point in space and is defined as the total radiant energy which has entered a small sphere surrounding that point, divided by the sphere's cross-sectional area. The important points which should be borne in mind are that we consider here radiation entering an imaginary 3-dimensional object — i.e., a transparent sphere, and that the measurement is a function of the sphere's cross-sectional area. An ideal collector (which is a spherical diffusing object) responds equally to radiation at any point on its surface. Therefore, if we place the collector for measurement of **fluence rate** in the same position as that hypothetically used in the previous paragraph to measure **flux**, the detector will measure 100 particles from source A plus 100 particles from source B, i.e., 200 particles per unit area per unit time.

Table 1. Terminology and units for describing the radiation arriving at a *flat surface*. The acceptance angle of the radiation detector is 180° or less and a cosine correction is applied to radiation arriving at angles which are not normal to the receiver surface.

Term or quantity	Unit
Energy content	
Radiant energy	joule (J)
Energy flow rate[z]	$J\ s^{-1}$ *or* watt (W)
Energy applied[y]	$J\ m^{-2}$
Energy flux	$W\ m^{-2}$
Photon content	
No. of photons[x]	dimensionless
Avogadro's no. of photons	mol
Photon flow rate[z]	s^{-1} *or* $mol\ s^{-1}$
Photons applied[y]	m^{-2} *or* $mol\ m^{-2}$
Photon flux	$m^{-2}\ s^{-1}$ *or* $mol\ m^{-2}\ s^{-1}$

[z]The term **flow rate** is preferable to **flow** because flow does not in itself imply rate (e.g., 3, 13).
[y]The energy applied, or number of photons applied, refers to the radiation measured. It is usually necessary in analytical photobiology to determine the quantity of radiation absorbed by the photoreceptor; the appropriate terms in this situation are the **energy absorbed** and the (number of) **photons absorbed**, respectively.
[x]The term photon is preferable to quantum because the photon is specifically a quantum of electromagnetic radiation. Other types of quanta exist; for example, the phonon is the quantum of a lattice vibration. Quantum is acceptable if it is clear that electromagnetic radiation is being referred to.

Table 2. Terminology and units for describing radiation arriving at a *point*. The radiation detector has a spherical acceptance angle of 360° and the measurement is the integral of radiation from all directions arriving at that point.

Term or quantity	Unit
Energy content	
Radiant energy	joule (J)
Energy flow rate	$J\ s^{-1}$ *or* watt (W)
Energy fluence[z]	$J\ m^{-2}$
Energy fluence rate	$W\ m^{-2}$
Photon content	
No.	dimensionless
Avogadro's no. of photons	mol
Photon flow rate	s^{-1} *or* $mol\ s^{-1}$
Photon fluence[z]	m^{-2} *or* $mol\ m^{-2}$
Photon fluence rate	$m^{-2}\ s^{-1}$ *or* $mol\ m^{-2}\ s^{-1}$

[z]**Energy fluence** and **photon fluence** refer to the amount of energy or number of photons applied to an object. In analytical photobiology, account will be taken of screening factors to determine the **absorbed energy fluence** or **absorbed photon fluence**, respectively.

The **energy flux** is exactly the same as the **energy fluence rate** for a single parallel beam of radiation (such as that provided by most projector-based sources in photobiology) traversing a surface perpendicular to the beam. If the angle of incidence is not perpendicular to the surface, the terms are no longer synonymous. However, within the limits of a solid angle of about 25° — and this situation exists where point sources are used and in some growth chambers — there is only a small (less than 10%) difference between the 2 definitions. Difficulties arise when the radiation arrives at larger solid angles than about 25°. For measurement of radiation under a uniformly overcast sky, for example, the **fluence rate** would be double the **flux** on a horizontal surface, and the difference between definitions is, of course, important. Applied strictly (17, 18), therefore, interchangeable usage of **fluence rate** and **flux** is only permissible under limited conditions.

An etymologically correct terminology is presented in Table 1 to describe the energy content and the photon content of radiation arriving at a flat surface. It is noteworthy that when misuse of the term *flux* is avoided and the term *density* is omitted, terminology is simplified. For comparative purposes, we present in Table 2 the terminology and units for describing the radiation arriving at any angle at a specific point within a small, imaginary sphere.

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