LI-COR inc.

TECHNICAL NOTE

Comparison of Quantum Sensors with Different Spectral Sensitivities

Technical Note #126

Introduction

Almost all the energy on the earth's surface comes directly or indirectly from the sun. Plants convert this energy into usable forms through photosynthesis. Historically, measuring photosynthetically active radiation (PAR) was somewhat subjective because scientists disagreed about what constitutes PAR and how it should be quantified, but a consensus has emerged regarding the definition of PAR. Building upon the research of Federer and Tanner (1966) and Biggs et al. (1971), which advanced the standardization of PAR measurement instruments, numerous commercial manufacturers produce sensors intended to measure PAR. Due to differences in sensitivities of these instruments, some can introduce significant errors when measuring light from artificial sources or in conditions other than direct sunlight. In this application note, we describe 1) the history and theory behind PAR measurement, 2) a method for assessing measurement errors in PAR sensors, and 3) how different types of PAR sensors may introduce errors into measurements.

McCree (1972a) argued the need for a standardized definition of light for photosynthesis measurements. The basis of his argument was that photosynthesis is driven by and quantitatively proportional to the number of photons absorbed by a leaf and that photosynthesis is only driven by light in a specific range of wave lengths. He expressed concern that the spectral distribution of the light used in photosynthesis research varied substantially across studies and stated that in order to compare magnitudes of photosynthetic rates it is essential that everyone use the same criteria to carefully define the light.

Only light the leaf absorbs can be used for photosynthesis. Transmitted or reflected light will not be used. The spectrum of light absorbed by the leaf (Figure 1a) is typically measured using a spectroradiometer and an integrating sphere. The internal surfaces of an integrating sphere are coated with a highly reflective, diffusive material, resulting in uniform illumination of the sphere walls. This system allows measurement of almost all of the transmitted and reflected light of a subject material over the wavelength range of interest. If we know the spectral transmittance (T) and reflectance (R) of a leaf we can calculate the absorptance (A) as A = 1-T-R where A, T, and R are expressed as fractions of total incident light. The absorption spectra for leaves may vary between species, because of differences in leaf morphology and individual leaf history (e.g. stress, light, and nutrition).

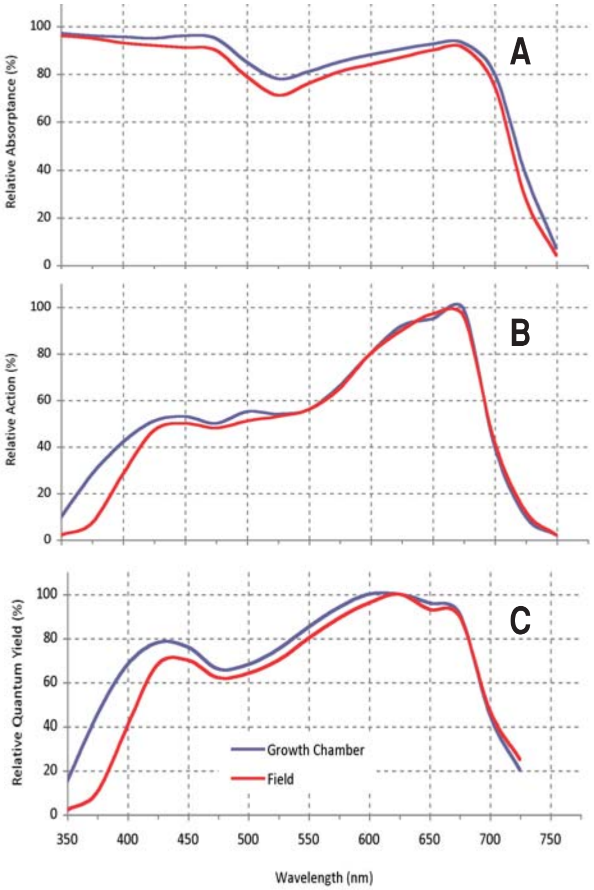

Figure 1. For leaves grown in the field and in a growth chamber, normalized (a) leaf absorptance spectra, (b) leaf photosynthetic action relative to incident energy, and (c) leaf yield relative to quantum of energy absorbed (from McCree 1972a).

In order to evaluate how efficiently light is used to drive photosynthesis over a given wavelength range, photosynthetic rates can be normalized by the energy incident on the leaf (relative action spectrum; Figure 1b) or by the quanta of light absorbed by the leaf (relative quantum yield; Figure 1c) at each wavelength. As might be expected, the wavelength range of the spectrum for relative quantum yield coincides with the wavelength range for the relative action spectrum; however, the relative quantum yield is much less variable across the entire spectral range of response. McCree (1972b), compared variations in the relationships between photosynthesis and different measures of light and found that variation was reduced by a factor of two when photosynthesis was normalized to quantum flux (μmol m^{-2} s^{-1}) rather than irradiance (energy units, W m^{-2}). This means photons of any wavelength between 400 and 700 nm can drive photosynthesis with similar efficiency. Quantitatively, we know the photosynthetic reactions require about 8 to 10 photons for each molecule of CO_2 fixed (Nobel 1991).

Experimental data show there can be significant variation in the spectral response of photosynthesis due to species variation as well as growth history. Therefore we cannot define a single sensor with a perfect spectral response for all plants and conditions (unless it is a spectroradiometer) and must be satisfied with a physically well-defined measuring stick that the scientific community accepts. Although the photosynthetic efficiency of an absorbed quantum of blue light is somewhat less than an absorbed quantum of red light, scientists have agreed that the ideal sensor will be equally responsive to all photons across the 400 to 700 nm wavelength range so the response will be flat across the spectrum. Since almost all photosynthetic activity is driven by photons in the 400 to 700 nm wavelength range, it has become universally accepted that the ideal sensor should have clear cutoffs to light below 400 nm and above 700 nm (Figure 2). This convention allows us to define and measure PAR as the incident quantum flux in the 400 to 700 nm range without involving any experimental plant responses (McCree 1972b). In the literature the terms PAR, PPF (photosynthetic photon flux) and PPFD (photosynthetic photon flux density) have been used interchangeably, and all with the same definition.

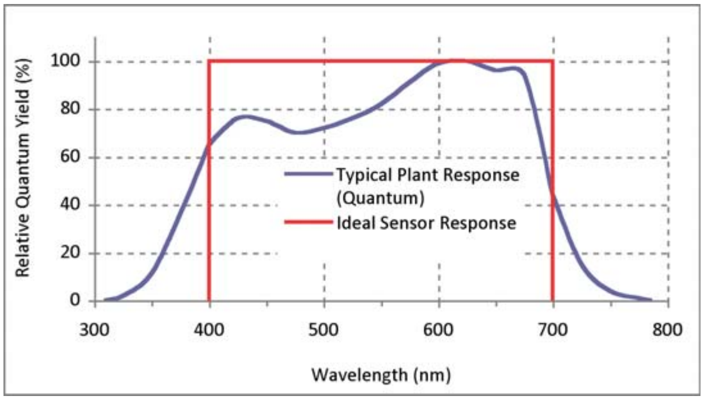

Figure 2. Ideal sensor response and response of a typical plant.

Comparison of Quantum Sensors

Actinity errors for 3 popular sensor types were calculated using equation (11), derived in the Appendix. A Cary 17D spectrophotometer, modified to measure the spectral response of light sensors, was used to measure sensor output relative to a known reference in 1 nm steps from 360 to 760 nm. An LI-1800 spectroradiometer was used to collect source light spectra under various lighting conditions. Relative spectral responses of three commercial quantum sensors that approximate perfect sensors are given in Figure 3, and the relative spectra for common light sources are given in Figure 4. Actinity errors are shown in Table 1.

Table 1. Summary of quantum sensor errors under a range of lighting conditions and light sources. [1]ASTM Standards volume 12.02 from ASTM-E892. [2]Tungsten Halogen reference lamp operated at 3150°K color temperature.

Light Source	Sensor Errors (%)		
	GaAsP	LI-COR	K&Z
Open Sky[1]	6.5	1.7	-4.3
Tungsten Halogen Reference Lamp[2]	0.0	0.0	0.0
Daylight Under Soybean Canopy	12.2	3.6	60.7
Red LED 680nm Peak	-84.2	-3.4	-13.7
Fluorescent - Cool White	23.7	1.8	-9.5
HID - HP Sodium	28.1	1.9	-9.1
HID - Metal Halide	19.0	1.9	-8.6

A Gallium Arsenide Phosphide based sensor (GaAsP with diffuser) (Figure 3a), underestimates photon flux from 400 to 500 nm (blue light) substantially and has little sensitivity above 650 nm (red light). This insensitivity leads to underestimations of available quanta in artificial light conditions where a significant portion of the light is beyond 650 nm. For example, the PAR measurement of a red LED with a 680

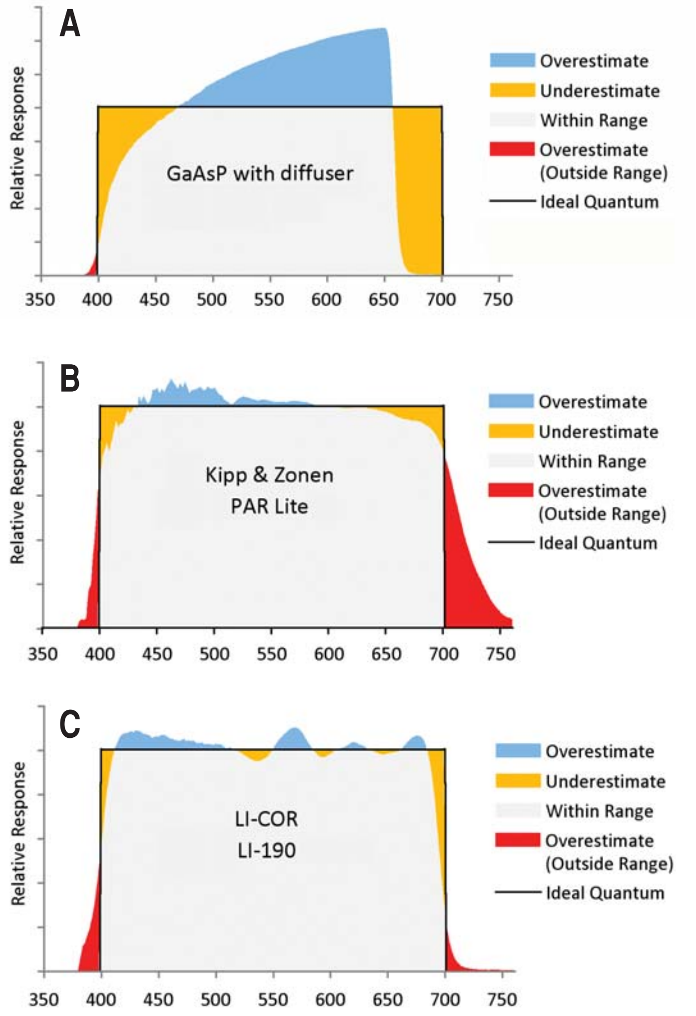

Figure 3. Comparison of the spectral responses of 3 different sensors to the ideal response. Sensitivity of each sensor is normalized so that the total overestimate equals the total underestimate between 400 and 700 nm.

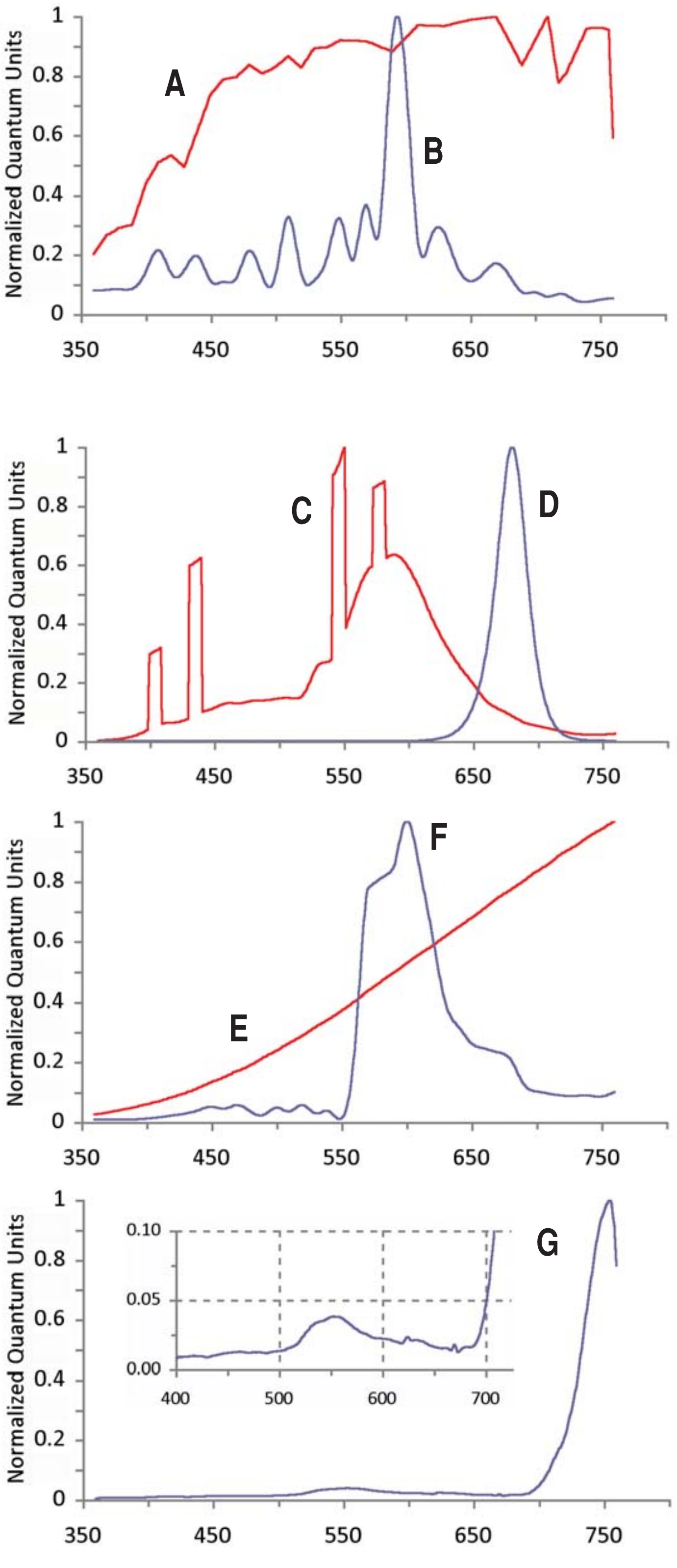

Figure 4. Spectra of light sources used in calculating sensor errors, photon units (μmol m^{-2} s^{-1} nm^{-1}) normalized to the maximum. (a) Open sky[1]; (b) Metal Halide; (c) Cool white fluorescent; (d) Red LED, 680 nm peak; (e) Tungsten halogen[2]; (f) High pressure sodium; (g) Daylight under soybean canopy.

nm peak was underestimated 84% (Table 1). The Kipp and Zonen PAR Lite sensor has a reasonably flat response with a small bias toward the blue end but a relatively poor cutoff at 700 nm (Figure 3b). This poor cutoff results in overestimation of available quanta in situations where a significant portion of available light is beyond 700 nm, such as in a forest understory or the understory of a soybean canopy (Table 1). The sensitivity of the LI-COR LI-190 oscillates around the ideal quantum response and has sharp cutoffs below 400 nm and above 700 nm (Figure 3c). Output of the LI-190 is not biased significantly at either the blue or red ends of the spectrum. The actual area under each deviation from ideal is small and errors tend to cancel. Errors for the LI-190 were less than 5% for all light sources (Table 1).

In an acknowledgement of the problems described above, some manufacturers provide an additional calibration coefficient for measuring PAR from electric light sources. However, an electric light calibration coefficient will often increase measurement errors if the spectral output of the artificial light source differs from that of the light source used to generate the calibration coefficient.

Summary

All three of these popular sensor types are reasonably accurate when measuring broad spectrum PAR typical of open sky conditions. However, if the objective is to measure light modified by a plant canopy or light from an artificial or monochromatic source, a sensor with a relatively flat response across the 400 to 700 nm wavelength range and sharp cutoffs outside that range is required to give accurate results. Of the sensors tested, only the LI-COR LI-190 meets these requirements. These results are essentially consistent with the detailed comparison by Ross and Sulev (2000), who found systematic errors for the LI-190 were less the 1%, whereas for the Kipp and Zonen PAR Lite sensor, errors were from 1 to 8% under the same radiation conditions. All of the sensors tested can be calibrated to give accurate results for open sky, but only the LI-190 will give accurate estimates of PAR regardless of the light source.

References

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[1] ASTM Standards volume 12.02 from ASTM-E892.

[2] Tungsten halogen reference lamp operated at 3150 °K color temperature.

Appendix

Federer and Tanner (1966) and Ross and Sulev (2000) give methods to perform comparisons of light sensors with different spectral sensitivities. We wish to find a means to determine how closely results from real quantum sensors measuring PAR of real light sources compare to results from an ideal quantum sensor measuring the same sources. For simplicity, we limit the discussion to quantum sensors measuring PAR in quantum units, but the discussion can be generalized to include other sensors as well (Ross and Sulev, 2000).

Following Federer and Tanner (1966), we define relative sensor response as $r(\lambda) = R(\lambda)/R_m$, where $R(\lambda)$ is the sensor output (mV or μamp) per photon at wavelength λ (nm), and R_m is a normalizing factor equal to the maximum output over the wavelength range of interest. R_m has units of μamp (or mV) (μmol m^{-2} s^{-1})$^{-1}$ and will turn out to serve as a calibration coefficient. We also define relative photon flux of the light source per unit wavelength as $i(\lambda) = I(\lambda)/I_m$, where $I(\lambda)$ is photon flux per unit wavelength (μmol m^{-2} s^{-1} nm^{-1}), and I_m is a normalizing factor equal to photon flux at the wavelength where $I(\lambda)$ is maximum. With these relations,

$$R(\lambda) = R_m r(\lambda) \tag{1}$$

and

$$I(\lambda) = I_m i(\lambda). \tag{2}$$

Total light intensity is

$$I = \int I(\lambda)d\lambda = I_m \int i(\lambda)d\lambda \tag{3}$$

and sensor output P is

$$P = \int R(\lambda)I(\lambda)d\lambda = I_m R_m \int r(\lambda)i(\lambda)d\lambda. \tag{4}$$

For a perfect PAR sensor, $r(\lambda) = 1$ for all wavelengths between 400 and 700 nm, and zero everywhere else, so

$$P_p = R_{mp} I_m \int_{400}^{700} i(\lambda)d\lambda \tag{5}$$

where the subscript p specifies a hypthetical perfect quantum sensor. The quantity $I = I_m \int_{400}^{700} i_c(\lambda)d\lambda$ gives photon flux summed over 400 to 700 nm, which is PAR, the quantity we seek.

If we have a calibration light source with known maximum intensity I_{mc} and relative spectral distribution $\int_{400}^{700} i(\lambda)d\lambda$, then we can calibrate a perfect sensor by computing the coefficient R_{mp} in equation (5).

$$P_{pc} = R_{mp} I_{mc} \int_{400}^{700} i_c(\lambda)d\lambda \tag{6}$$

Using equation (3),

$$R_{mp} = P_p / I_c \tag{7}$$

where the subscript c references a calibrating light source over 400 to 700 nm. Now we can use the coefficient R_{mp}, which serves as a calibration coefficient, and sensor output P_p to measure PAR for any light source with arbitrary intensity and spectrum.

$$I = P_p / R_{mp} \tag{8}$$

Real quantum sensors like the LI-190 are calibrated and used in exactly this way. The problem is that real sensors are not perfect. The output of a real sensor is determined by both the light source and the spectral response of the sensor according to equation (4), not just the light source, as in equation (5) for a perfect sensor. This means there will be errors when measuring light sources having spectra that are different from the calibration light source. The magnitude of those errors is a measure of how well a real quantum sensor approximates a perfect quantum sensor; we call them *actinity errors*.

Ideally, when a quantum sensor measures light with different spectra, the sensor output depends only on the properties of the light sources and not on those of the sensor. We can see if this is true for a perfect sensor by computing the ratio P_p/P_{pc}. Combining equations (7), (8), and (3),

$$\frac{P_p}{P_{pc}} = \frac{I}{I_c} = \frac{I_m \int_{400}^{700} i(\lambda)d\lambda}{I_{mc} \int_{400}^{700} i_c(\lambda)d\lambda} \tag{9}$$

This ratio depends only on the properties of the light sources, so if our knowledge of the calibrating light source is correct, the measured value of an unknown light source will also be correct. But this is not true for a real sensor because its output depends on spectral response of the sensor as well. This can be seen by computing the ratio P/P_c for a real sensor using equation (4) for the measured and calibration light sources.

$$\frac{P}{P_c} = \frac{I_m \int r(\lambda)i(\lambda)d\lambda}{I_{mc} \int r(\lambda)i_c(\lambda)d\lambda} \tag{10}$$

The ratio of equation (10) to equation (9) gives the extent to which a real sensor deviates from an ideal sensor when the sensor is used to measure a light source with a spectrum different from that of the calibration source.

$$\frac{P/P_c}{P_p/P_{pc}} = \frac{\int r(\lambda)i(\lambda)d\lambda \int_{400}^{700} i_c(\lambda)d\lambda}{\int r(\lambda)i_c(\lambda)d\lambda \int_{400}^{700} i(\lambda)d\lambda} \tag{11}$$

Equation (11) gives the mathematical definition of actinity errors for PAR sensors calibrated in photon units. Federer and Tanner (1966) pointed out that it does not depend on the absolute output of the sensor, or absolute intensity of the sources, but only on their relative spectral properties. This allows us to compare the accuracy of real sensors to perfect sensors for a variety of light sources knowing only the relative spectral response of the sensors and relative spectra of the light sources.

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