A Sensor to Measure Extended PAR (ePAR): the Sum of Photons from 400 to 750 nm

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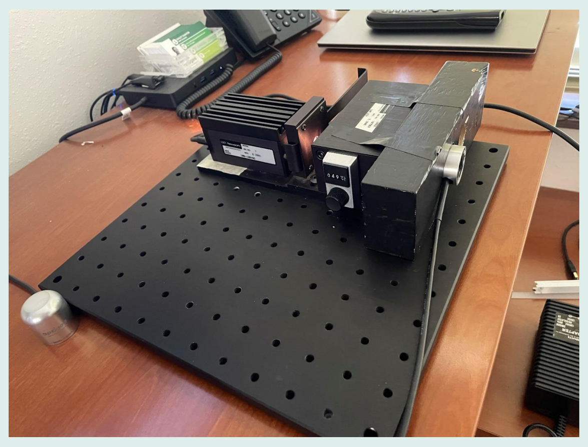
Methods and Materials



A monochromator was used to measure the spectral response of the SQ-610 ePAR sensor. Using the measured spectral response, the method of Federer and Tanner (1966) was used to calculate spectral error for radiation sources typically used to grow plants.

A collimated radiation source (cool white LED in custom-built box) was used to measure the directional response of the SQ-610. This directional response was compared to the directional response measured outdoors under sunlight.

A temperature-controlled chamber was used to measure the temperature response of the SQ-610. Temperature error was calculated as the difference from a spectroradiometer.

Background

Photosynthetically active radiation (PAR) has historically been defined as equal weighting of photons within the 400-700 nm range and no weighting of photons outside of this range. This definition is based on data collected on plant leaves illuminated with narrowband radiation sources (Inada, 1976; McCree, 1972a; McCree, 1972b).

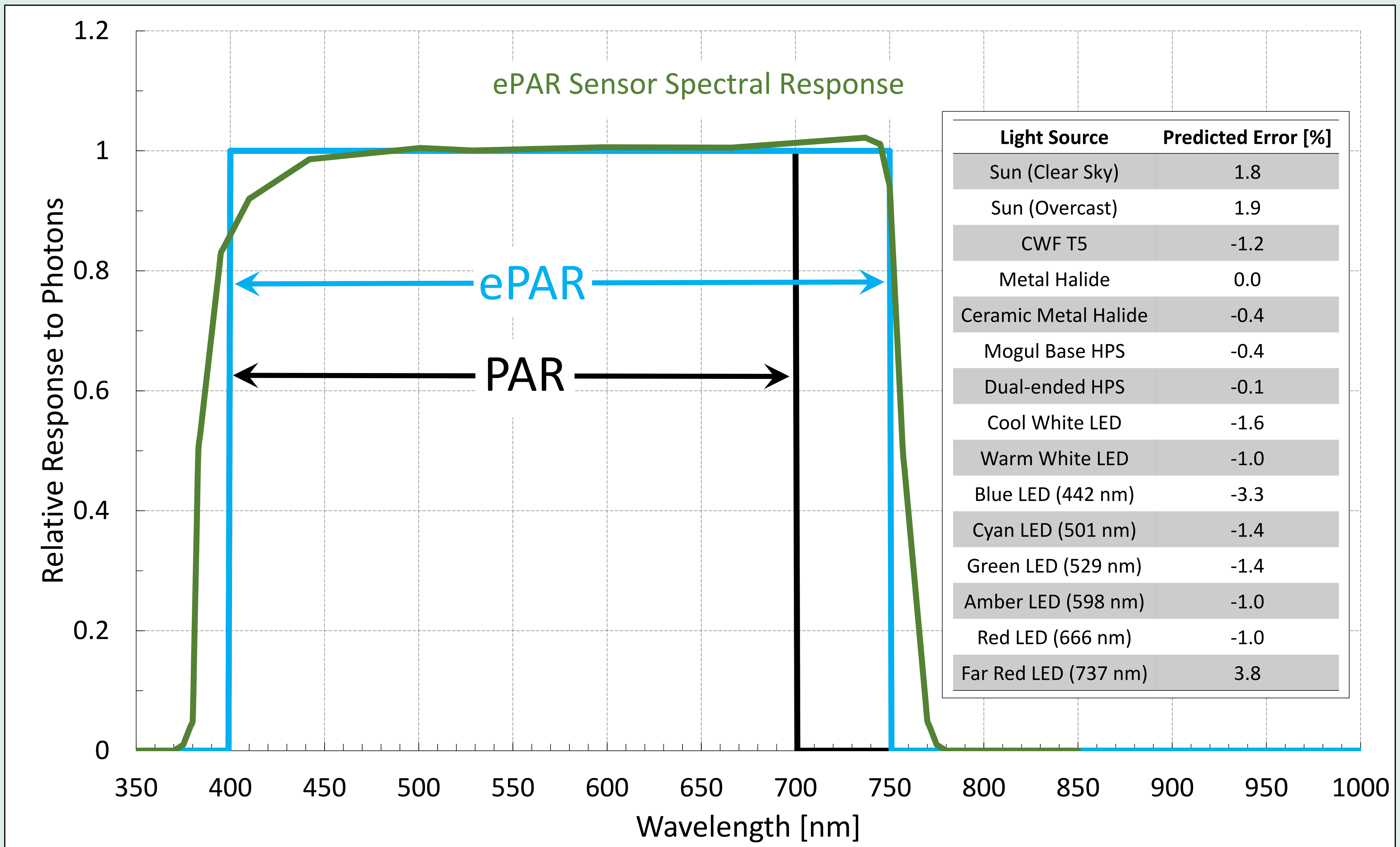
Data from recent studies indicate that far-red photons synergistically interact with photons in the historically defined PAR range of 400-700 nm to increase photochemical efficiency in leaves (Hogewoning et al., 2012; Murakami et al., 2018; Zhen and van Iersel, 2017; Zhen et al., 2019). Measurements from whole plants and plant canopies indicate adding far-red photons (using far-red LEDs with peaks near 735 nm and outputting photons across a range of about 700-750 nm) to radiation sources outputting photons in the 400-700 nm range increases canopy photosynthesis equal to the addition of the same number of photons in the 400-700 nm range for multiple species, and C3 and C4 photosynthetic pathways, but far-red photons alone are photosynthetically inefficient and result in minimal photosynthesis (Zhen and Bugbee, 2020a; Zhen and Bugbee, 2020b).

This research suggests that far-red photons drive canopy photosynthesis with similar efficiency as photons in the traditional PAR range when they are acting synergistically with photons in the 400-700 nm range, meaning when far-red photons are added to radiation sources outputting 400-700 nm photons. Thus, far-red photons need to be included in the definition of PAR (Zhen et al., 2021).

Rather than redefine the historic definition of PAR, a new set of weighting factors for photosynthetic efficiency that extends PAR (ePAR) have been proposed that include far-red photons between 700 nm and 750 nm (see Figure 1). The weighting factors for ePAR define a new metric for quantification of radiation driving photosynthesis, extended photosynthetic photon flux density (ePPFD), the sum of photons within the 400-750 nm range (photons weighted by the ePAR factors).

A sensor designed to measure ePPFD (Apogee Instruments Model SQ-610) compared favorably to traditional quantum sensors designed to equally weight photons in the 400-700 nm range for radiation sources outputting photons in the 400-700 nm range (see Table 1 and Figure 1).

Results



Light Source	Predicted Error [%]
Sun (Clear Sky)	1.8
Sun (Overcast)	1.9
CWF T5	-1.2
Metal Halide	0.0
Ceramic Metal Halide	-0.4
Mogul Base HPS	-0.4
Dual-ended HPS	-0.1
Cool White LED	-1.6
Warm White LED	-1.0
Blue LED (442 nm)	-3.3
Cyan LED (501 nm)	-1.4
Green LED (529 nm)	-1.4
Amber LED (598 nm)	-1.0
Red LED (666 nm)	-1.0
Far Red LED (737 nm)	3.8

Figure 1. The spectral response of the SQ-610 ePAR sensor and definitions of PAR and ePAR. Predicted spectral errors under common light sources were calculated from the sensor spectral response using the method of Federer and Tanner (1966) and are shown on the on the table as a percentage.

Table 1. Theoretical and measured ratios of ePAR to PAR. The SQ-610 is an ePAR sensor; the SQ-500 is a traditional PAR sensor. In a previous study, the SQ-500 and the LI-COR 190R quantum sensors matched each other within 3 % under most light sources used to grow plants (Blonquist and Johns, 2018).

Light Source	Theoretical Ratio	SQ-610:SQ-500
Sun	1.17	1.21
Overcast	1.18	1.22
CWF T5	1.03	1.03
Metal Halide	1.03	1.05
Ceramic Metal Halide	1.07	--------
Mogul Base HPS	1.03	1.02
Dual-Ended HPS	1.06	--------
Cool White LED	1.01	1.01
Warm White LED	1.03	1.02
Blue LED (442 nm)	1.00	0.99
Cyan LED (501 nm)	1.00	1.01
Green LED (529 nm)	1.00	0.98
Amber LED (598 nm)	1.00	1.02
Red LED (666 nm)	1.01	0.99
Far Red LED (737 nm)	16.90	19.26

Conclusions

The theoretical ratios of ePAR to PAR are between 1.00 and 1.07 for radiation sources typically used to grow plants. The exceptions to this are sunlight, with a ratio of about 1.17, and far red LEDs, with a ratio of about 17. The measured ratios closely match the theoretical ratios, indicating that the Apogee ePAR sensor (model SQ-610) accurately measures ePAR.

- Spectral error is less than 4 % for radiation sources typically used to grow plants.
- Directional error is less than 4 % for zenith angles less than 75° when measured in the field and in the lab.
- Temperature error is less than 4 % from 0 to 40 C.
- Long-term stability is less than 1 % change per year.

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