DLC Horticultural Lighting Resources:

Limitations of predicting far-red's effect on photosynthesis

Purpose of this resource

ASABE S640 defines photosynthetic active radiation (PAR) as wavelengths in the 400-700 nm range. Because of this defined range, the DLC does not include non-PAR wavelengths (e.g., far-red wavelengths (701-800 nm) or UV wavelengths (280-400 nm) in its calculations of photosynthetic photon flux (PPF, units: µmol/s) or photosynthetic photon efficacy (PPE, units: µmol/J). LED horticultural luminaires that include non-PAR spectra (including far-red) are not allowed to count these wavelengths toward meeting the DLC's minimum efficacy threshold or its PPF/PPE listing requirements. These luminaires therefore have more difficulty meeting the DLC's minimum requirements or comparing favorably to horticultural luminaires that do not include non-PAR spectra. **This resource explains the limitations of metric development around far-red light and clarifies some assumptions regarding far-red spectra.**

Background

Applicants seeking DLC qualification are directed to use ASABE S640 as the standard document to calculate PPF and PPE. Per S640, PPF is bound between 400-700 nm and intentionally assumes a linear, or additive[1], response. For example, the four SPDs below have the same total PPF because of the assumption of additivity or linearity underlying this metric. This is somewhat different from the calculations of lumens[2] for architectural lighting, although both metrics assume additivity.

Description	SPD 1	SPD 2	SPD 3	SPD 4
Blue PPF (400- 500 nm) µmol/s	50	100	0	25
Green PPF (500- 600 nm) µmol/s	0	0	0	25
Red PPF (600-700 nm) µmol/s	50	0	100	50
Total PPF (400-700 nm) µmol/s	100	100	100	100

PPF is presumably a simplification of yield photon flux (YPF), which is an action spectrum relating narrowband wavelength to photosynthetic rates (as measured by CO_2 uptake) developed by McCree (1972a). Importantly, McCree showed that the assumption of linearity held with YPF when broadband "white light" sources, specifically, mercury, quartz, fluorescent, and metal halide light

[1] Additivity assumes that the value at each underlying wavelength can be summed to give a total value. In other words, 1 photon at 450 nm + 1 photon at 541 nm = 2 photons (and so on for other wavelengths).

[2] Lumens are calculated by using the photopic luminous efficiency function, V(λ), a type of action spectra. In this calculation, the spectral power distribution (SPD) provided in units of watts per nanometer (W/nm) is multiplied by V(λ), wavelength by wavelength, and then the weighted wavelengths are summed together and multiplied by a constant value of 683 lumens per watt (LPW) to determine the lumen value.

sources, were used (1972b). Under these broadband "white light" sources, the measured photosynthetic rate was within 10% of the predicted photosynthetic rate calculated by the YPF action spectrum assuming additivity.

Since the early 1940s, researchers have shown that photosynthesis decreases under longer wavelengths of red light (> 685 nm), known as the "red drop." For example, Emerson et al. (1957) showed that in green and red algae, quantum yields from "far-red" light (from 680 nm to around 720 nm) decreased as a function of increased wavelength, while the quantum yield from wavelengths between 660-685 nm were constant. Increasing the intensity of far-red light alone (with wavelengths between 675-700 nm), and red light alone (with wavelengths between 640-670 nm) resulted in increased photosynthetic rates (until saturation was reached). Additionally and not surprisingly, given the decreased quantum yields under far-red light, the photosynthetic rates were higher, at the same light intensity, under red light than under far-red light.[3]

Notably, however, Emerson et al. (1957) also found that adding auxiliary "white light" at low intensities from a broadband mercury-cadmium light source while providing far-red light greatly increased the photosynthetic rates in a non-linear fashion, far more than when either light source was provided alone. This synergistic, or super-additive effect, is known as the Emerson Enhancement effect.[4] Subsequent research showed that the effect of the auxiliary light alongside far-red light was dependent on three factors: intensity, spectra, and the pigments present in the plant (in this case algae) being studied (Emerson and Rabinowitch, 1960). Importantly, Emerson and Rabinowitch (1960) showed that the action spectrum of the auxiliary light was not only non-linear, but that it also sometimes had a negative effect compared to far-red light alone. In other words, certain combinations of far-red light with shorter wavelengths decreased the quantum yield and this result was specific to the algae pigments.[5]

Other researchers have since confirmed the Emerson Enhancement effect for additional plants (including lettuce, basil, spinach, kale, tomato, cucumber, and others) when far-red is presented with other auxiliary broadband spectra, including white LED sources and blue-red LED combinations (Zhen and van Iersel, 2017; Zhen and Bugbee, 2020). Zhen and van Iersel (2017) showed that adding 110 µmol m^{-2} s^{-1} of far-red light (peak wavelength: 735 nm) to varying PPFDs of "warm-white" or blue-red irradiation increased the net photosynthetic rates with diminishing increases at higher PPFDs. At the lowest PPFD (50 µmol m^{-2} s^{-1}), far-red + blue-red light and far-red + "warm-white" light both increased the net photosynthetic rate to PPFD ratios by 41%. However, the enhancement effect was 33% larger on average under the far-red + blue-red light than under the far-red + "warm-white" light, confirming that the spectrum of the auxiliary light is an important consideration.

Zhen and Bugbee (2020) used an experimental protocol where they measured net photosynthetic rates under far-red light alone (peak wavelengths: 711, 723 and 746 nm; PPFD: 70 µmol m^{-2} s^{-1}), under 40-140 µmol m^{-2} s^{-1} of far-red light in combination with 400 µmol m^{-2} s^{-1} of "cool-white" light, and under 525 µmol m^{-2} s^{-1} of "cool-white" light. Under this protocol, no enhancement was seen across the 14 species of plants studied; instead, the "cool-white" auxiliary light and far-red light showed an additive response if the PAR waveband was extended to 750

[3] ASABE S640 (2017) has since standardized the far-red range as occurring between 700-800 nm.

[4] A synergistic, or super-additive effect results in 1 + 1 > 2.

[5] This negative response is also called a sub-additive response where 1 + 1 < 2.

nm, rather than ending at 700 nm. On the other hand, adding 50 µmol m^{-2} s^{-1} of far-red light (from 711, 723, or 746 nm peak wavelength sources) to 510 µmol m^{-2} s^{-1} of blue-red light did result in an Emerson Enhancement effect, which was largest with the 723 nm far-red source, and smallest with the 746 nm far-red source.

Relationship to current and calculated metrics

Current photosynthetic metrics and measurement detectors assume linearity, or additivity, in their calculations. **The body of research shows that the intensity and spectrum of the far-red light and the intensity and spectrum of the auxiliary (or background) light are important. Thus, simply extending the PAR range to 750 nm will not necessarily result in predictable increases in photosynthesis.** Equally important is that photodetectors have an additive response, so a photodetector with an expanded PAR range would not pick up the Emerson Enhancement effect; it would calculate the same photon flux density from a 720 nm far-red light source, a 450 nm light source, or a broadband "white light" source if the irradiance from these light sources was equal.

To account for the potential Emerson Enhancement effect, we first need a predictive PAR metric that accounts for the intensities and spectra of the far-red and auxiliary sources, which may have an additive, super-additive, or sub-additive response, depending on the combination of the light stimuli (and also perhaps the plant species). This metric must then be validated before it is standardized, so that it can be measured consistently among and between testing organizations. This non-linear metric will have to be measured and calculated with a spectroradiometer, rather than a simple photodetector that assumes an additive response.

Currently, the DLC requirements have a reporting option only for far-red, which sums the wavelength spectral quantum distribution (SQD) between 700-800 nm. Far-red performance thresholds are not currently used for qualification purposes. Only when the potentially revised PAR metric is standardized and able to be measured among accredited testing laboratories, such as Nationally Recognized Testing Laboratories (NRTLs), can the DLC incorporate it into its Technical Requirements.

References

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