Light Spectrum Affects Maximum Rate of Carboxylation & Electron Transport

Many greenhouse operations use supplemental lighting to extend the growing season and increase crop yield. Electricity for lighting, however, can be expensive. It has been estimated that electricity associated with supplemental lighting can account for as much as 30% of operating costs (van Iersel and Gianino, 2017). With rapidly advancing technology, growers now have the option of light-emitting diode (LED) lighting to reduce the high electricity cost associated with supplemental lighting. LED lights generally have good efficacy, longevity, and controllability, and can provide narrow wavebands of light. This offers unique opportunities for growers to manipulate crop physiology by changing light spectrum and intensity. This requires a better understanding of the effects of light spectrum and intensity on crop photosynthesis, growth, and development.

Many commercially available growing lights use red and blue LEDs because of their high efficacy. Red and blue also represent peaks in the photosynthetic action spectrum, or McCree spectrum, and have the highest quantum yield of CO_2 fixation across the whole light spectrum (McCree, 1971). Between these two lights, red lights have a higher quantum yield than blue light, meaning that crops can utilize red photons more efficiently (McCree, 1971). However, McCree collected his data at low *PPFD* and with one waveband at a time, ignoring potential interactions among photons with different wavelengths. There is compelling evidence that at higher *PPFD*, the efficacy of green light can be higher than that of red light (Terashima et al., 2009), while far-red light increases photosynthesis synergistically when combined with shorter wavelengths of light (Zhen and van Iersel, 2017). The effects of different spectra on crop growth and development are not limited to photosynthetic physiology, but can also affect crop morphology and secondary metabolism in a crop-specific manner (Ouzounis et al., 2015). The physiological reasons for spectral and crop-specific effects are not well understood.

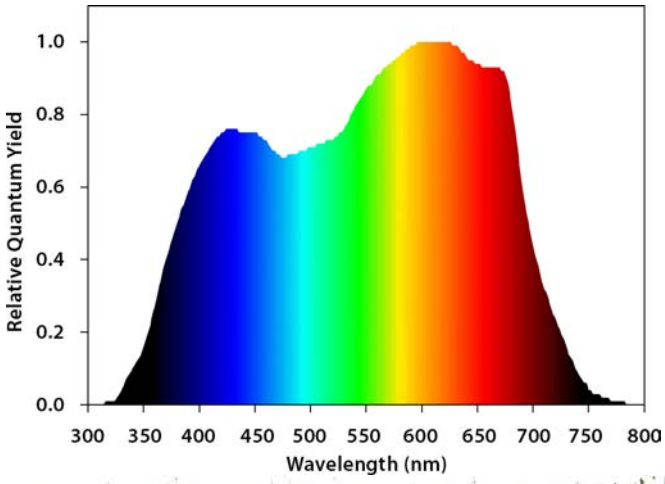
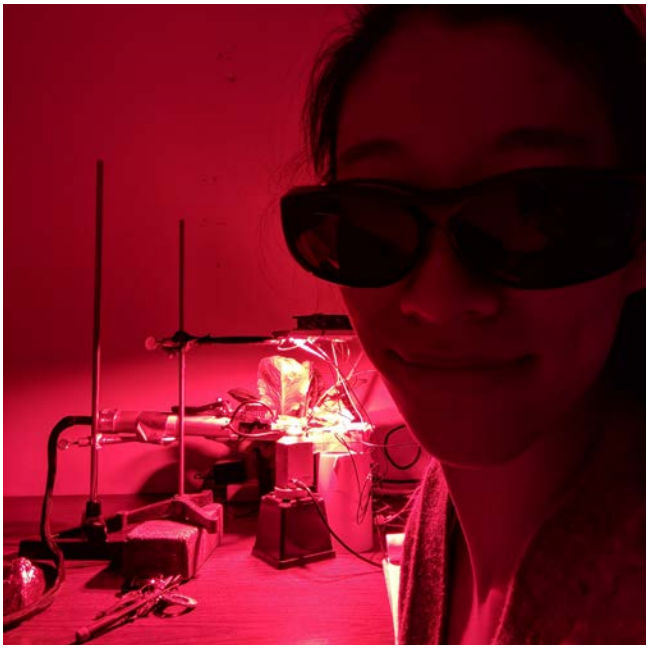


Figure 1.
Relative quantum efficiency curve.
(Adapted by Marc van Iersel from McCree (1971))



Jun Liu, Ph.D. student under Dr. Marc van Iersel, working with far red LED light.

To explore the underlying physiological mechanisms of responses to red and blue light, we constructed photosynthetic assimilation CO_2 response (A/C_i) curves to quantify the photosynthetic characteristics of lettuce plants under both red and blue LED light. A/C_i curves quantify net photosynthetic rate (noted as A, assimilation) as a function of internal leaf CO_2 concentration (noted as C_i).

The traditional method to construct A/C_i curves involves steady-state gas exchange measurement that exposes a plant to a certain light intensity and CO_2 concentration until that plant reaches a steady physiological state, then moves on to the next CO_2 concentration.

There are a few drawbacks to this method: 1) it takes a long time to collect a single A/C_i response curve, typically 30 minutes; 2) within that time frame, other biological responses may arise and complicate the interpretation (Stinziano et al., 2017). A recent technique, rapid A/C_i response (RACiR), addresses those limitations by taking non-steady-state measurements of gas exchange, which greatly accelerates the process (Stinziano et al., 2017). The RACiR technique requires rapid control of the CO_2 concentration in the leaf cuvette and high temporal resolution but can complete an A/C_i response curve within minutes. Newer leaf gas exchange systems, like the CIRAS-3, have rapid response times, facilitating this new approach.

We constructed A/C_i curves on 3 lettuce plants under red and blue light at saturating *PPFD* (1,000 µmol/m²/s) provided by the LED light source in the leaf cuvette of the CIRAS-3 Portable Photosynthesis System. Although leaf absorptance of red and blue light can differ, using saturating PPFDs assure that such absorptance differences do not skew the results. Each A/C_i response recorded 150 photosynthetic measurements at CO_2 ranging from 3 to 950 µmol/mol inside the leaf cuvette and was completed in 6 minutes. Examples of A/C_i curves of lettuce are shown to the right.

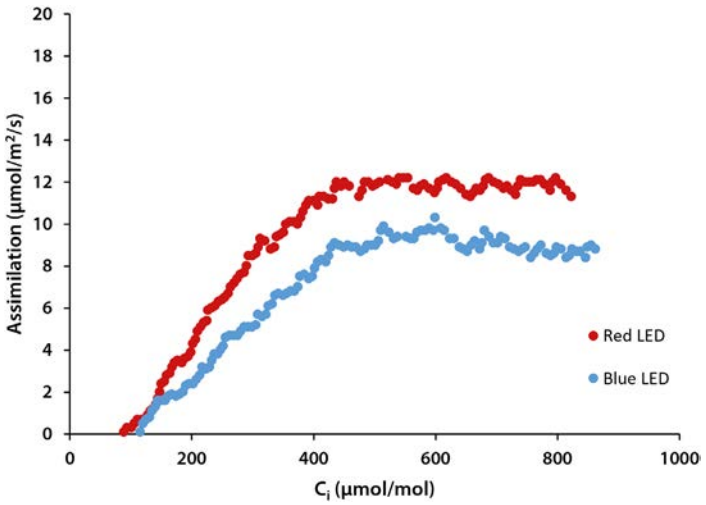


Figure 2. Examples of A/C_i curve measured lettuce leaf under light of 1000 µmol/m²/s

Curve fitting for A/C_i curves followed the protocol developed by Sharkey et al. (2007). The maximum rate of Rubisco carboxylation ($V_{c,max}$), the maximum rate of electron transport (J_{max}) and the maximum rate of triose phosphate utilization rate (TPU) were determined for both colors of light. Please also refer to our Application Note: *High-Speed CO_2 Ramping Technique, Rapid A/C_i Curves in Minutes* available on our web site (https://ppsystems.com/wp-content/uploads/AN_CIRAS-3_Rapid-A-Ci-Curves.pdf).

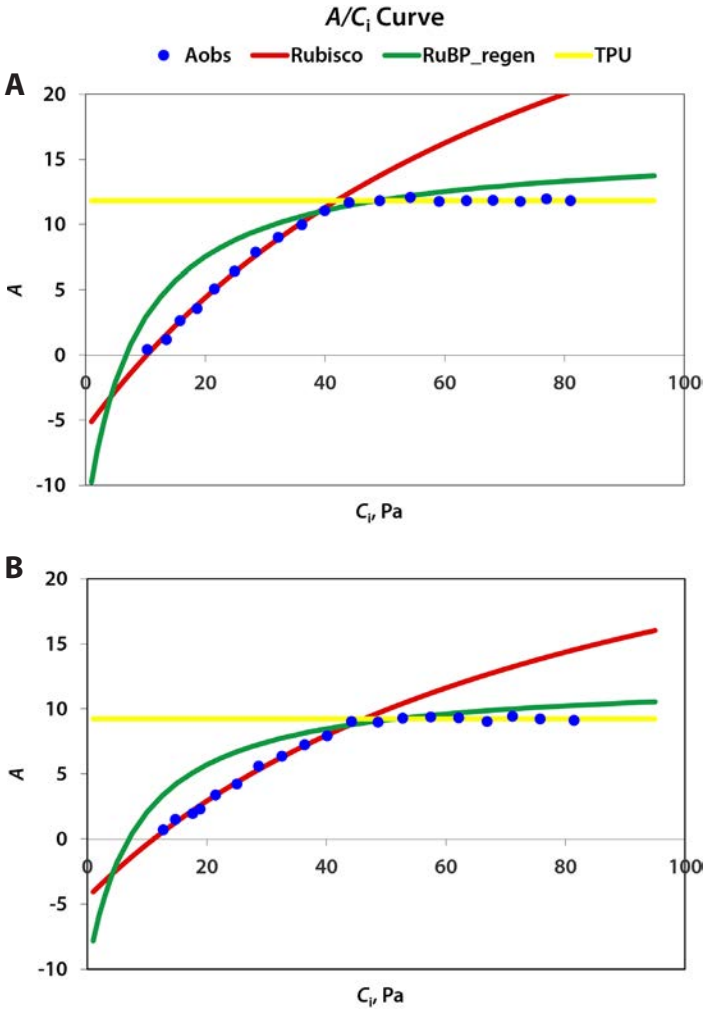


Figure 3. Curve fitting for A/C_i curves under red and blue LEDs using the method developed by Sharkey et al. (2007). Blue dots represent averaged assimilation (µmol/m²/s) measured by CIRAS-3. Red lines represent the limitation imposed by Rubisco carboxylation activity when CO_2 supply was low. Green lines represent the limitation imposed by electron transport rates as CO_2 concentration increased. Yellow lines represent limitation imposed by rate of triose phosphate utilization, i.e. the formation rate of end-product of Calvin cycle. Figure 3A and B show the fitted A/C_i curves for lettuce plants under red and blue LED light, respectively.

Under red LED light, $V_{c,max}$ of lettuce averaged 37.4 µmol/m^2/s. $V_{c,max}$ under blue LED light, 27.4 µmol/m^2/s, was lower than that under red light. This implies that red light outperformed blue light at upregulating carboxylation activity of Rubisco. The maximum rate of electron transport (J_{max}) under blue light (47.3 µmol/m^2/s) also was lower than under red light (58.4 µmol/m^2/s), as was triose phosphate utilization (4.16 and 3.30 µmol/m^2/s under red and blue light, respectively).

According to the McCree action spectrum, red light has a higher quantum yield of CO_2 fixation than blue light. This difference in quantum yield appears to be correlated with the carboxylation capacity of RubisCO, J_{max}, and triose phosphate utilization. Counterintuitively, a possible explanation for this difference is that chlorophyll absorbs blue light more effectively than red light. This allows red light to penetrate into leaves more deeply. This can enhance electron transport in deeper cell layers, thus allowing more cells to contribute to leaf CO_2 fixation. In addition, some of the blue light is absorbed by carotenoids and flavonoids that transfer harvested energy less efficiently to reaction centers than chlorophyll a and b do (Akimoto et al., 2005). This can further reduce J_{max} under blue light. Also, several Calvin cycle enzymes require light for their activation and deeper light penetration into leaves may thus facilitate activation of Calvin cycle enzymes in more cells. Enhancing electron transport and Calvin cycle activity in deeper cell layers can enhance the overall photosynthetic capacity of leaves. This is consistent with the results from our rapid A/C_i curves.

Jun Liu, Ph.D. student under Dr. Marc van Iersel, taking photosynthetic measurement with the CIRAS-3 Portable Photosynthesis System.

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To learn more about Dr. van Iersel's work, visit the UGA Horticulture Physiology Lab website: http://hortphys.uga.edu/ and HortLAMP.

If you would like to learn more about this application or speak with one of our experienced technical staff, please feel free to get in direct contact with us via any of the contact information listed below:

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