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**DEVELOPING AN OPTIMIZED LIGHT SPECTRUM FOR
PLANT GROWTH AND DEVELOPMENT**

by

Kevin Richard Cope

**Thesis submitted in partial fulfillment
of the requirements for the degree**

of

DEPARTMENTAL HONORS

in

**Plant Science
in the Department of Plants, Soils, and Climate**

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ABSTRACT

Light-emitting diodes (LEDs) are a rapidly developing technology for plant growth lighting and have become a powerful tool for understanding the spectral effects of light on plants. Several studies have shown that some blue light is necessary for normal growth and development, but the effects of blue light appear to be species dependent and may interact with other wavelengths of light as well as photosynthetic photon flux (PPF). Here we report the photobiological effects of three types of white LEDs (warm, neutral and cool) on the growth and development of radish, soybean, and wheat. All species were grown at two PPFs (200 and 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$) under each LED type, which facilitated testing the effect of *absolute* ($\mu\text{mol photons m}^{-2} \text{s}^{-1}$) and *relative* (percent of total PPF) blue light on plant development. Root and shoot environmental conditions other than light quality were uniformly maintained among six chambers (three lamp types x two PPFs). All LEDs had similar phytochrome photoequilibria and red:far red ratios. Blue light did not affect total dry weight (DW) in any species, but significantly altered plant development. Overall, the low blue light from warm white LEDs increased stem elongation and leaf expansion while the high blue light from cool white LEDs resulted in more compact plants. For radish and soybean, *absolute* blue light was a better predictor of stem elongation than *relative* blue light, but *relative* blue light better predicted leaf area. *Absolute* blue light better predicted the percent leaf DW in radish and soybean and percent tiller DW in wheat. The largest percentage differences among light sources occurred in low light (200 $\mu\text{mol m}^{-2} \text{s}^{-1}$). These results confirm and extend the results of other studies indicating that light quantity and quality interact to determine plant morphology. The optimal amount of blue light likely changes with plant age as plant communities balance the need for rapid leaf expansion, which is necessary to maximize radiation capture, with prevention of excessive stem elongation. A thorough understanding of this interaction is essential to the development of light sources for optimal plant growth and development.

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INTRODUCTION

The application of light-emitting diodes (LEDs) for plant growth lighting has been studied for over two decades (Bula et al., 1991; Barta et al., 1992). Initial studies included only red LEDs because they were the most efficient and emit light that coincides with the maximum absorption of chlorophyll (660 nm). However, it quickly became apparent that some blue light was necessary for normal growth and development of sorghum (Britz et al., 1990), soybean (Britz et al., 1990; Wheeler et al., 1991; Dougher and Bugbee, 2001a), wheat (Barnes and Bugbee, 1992; Goins et al., 1997; Dougher and Bugbee, 2001a), lettuce (Hoenecke et al., 1992; Dougher and Bugbee, 2001a; Yorio et al., 2001), pepper (Brown et al., 1995), spinach and radish (Yorio et al., 2001). At the time these studies were conducted, blue LEDs were only 3 to 4% efficient whereas red LEDs were 15 to 18% efficient (Massa et al., 2006). As such, the goal of these studies was to determine the minimum amount of blue light necessary for normal growth and development (Kim et al., 2005). The efficiency of blue LEDs has since dramatically increased to more than 30%. Because white LEDs are produced by using blue LEDs and phosphors, an increase in the efficiency of blue LEDs has made efficient white LEDs possible (Pimputkar et al., 2009).

Studies on blue light. Wheeler et al. (1991) were the first to propose that the plant developmental response to blue light was dependent on *absolute* blue light levels (μmol of photons $\text{m}^{-2} \text{s}^{-1}$ between 400 and 500 nm) rather than the *relative* amount of blue light (percent of total photosynthetic photon flux, or PPF). This was a departure from other photobiological responses that are determined by ratios of light rather than absolute amounts (e.g. red:far red ratio and phytochrome photoequilibria). These results were reviewed by Yorio et al. (1998).

Later, Dougher and Bugbee (2001a) examined the effects of blue light on growth and development of lettuce, soybean, and wheat using high pressure sodium (HPS) and metal halide (MH) lamps filtered to achieve six blue light levels from 0.1 to 26% at 200 and 500 $\mu\text{mol} \text{m}^{-2} \text{s}^{-1}$. Blue light did not affect total dry weight, and developmental responses were species dependent. Lettuce was the most responsive with dramatic decreases in stem length as blue light levels increased. Soybean stem length decreased and leaf area increased up to 6% blue light. Wheat was not significantly affected by blue light. For lettuce, stem length was better predicted by *absolute* blue light, but for soybean stem length was better predicted by *relative* blue light.

Dougher and Bugbee (2001a), plotted stem length against both *absolute* and *relative* blue light, but because filtered light sources were used, the results may have been complicated by interactions with other wavelengths of light. In our study, we used three types of white LEDs without filters to determine if other plant growth parameters are better predicted by either *absolute* or *relative* blue light.

MATERIALS & METHODS

Plant material and cultural conditions. Radish (*Raphanus sativus*, cv. 'Cherry Belle'), soybean (*Glycine max*, cv. 'Hoyt'), and wheat (*Triticum aestivum*, cv. 'Perigee') seeds were pre-germinated for 24, 36, and 48 hours, respectively, and subsequently transplanted to root modules measuring 15 x 18 x 9 cm (L x W x H; 2,430 cm³). For the radish and soybean experiments, nine seeds were planted in each root module and for the wheat experiment twelve seed were planted in each root module. All root modules were filled with soilless media (1 peat: 1 vermiculite by volume), watered to excess with a complete, dilute fertilizer solution (0.01N-0.001P-0.008K; Scotts® Peat-Lite, 21-5-20), and allowed to passively drain. Five grams of slow-release fertilizer (16N-2.6P-11.2K; Polyon® 1 to 2 month release, 16-6-13) were mixed uniformly into each root module to maintain leachate electrical conductivity measurements between 100 and 150 mS per m (1.0 and 1.5 mmhos per cm). After planting, each root module was randomly placed within one of six growth chambers, which measured 18 x 20 x 26 cm (9360 cm³) for the 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ treatments and 20 x 23 x 30 cm (13800 cm³) for the 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ treatments (Figure 1). The inside of all chambers was lined with high-reflectance Mylar®. Type-E thermocouples connected to a data-logger (model CR10T, Campbell Scientific, Logan UT) were used to continuously monitor temperature. In each growth chamber one thermocouple was used and was adjusted upwards as plants grew, remaining directly above the plant canopy. Temperatures averaged 23.0°C and 24.3°C in the low-light and high-light treatments, respectively. Temperature differences among chambers were less than 0.5°C. To avoid partial shading of the plants, the thermocouples were not shielded; had they been shielded, our measurements indicate that recorded temperatures would have been reduced by about 0.5°C. Radish, wheat and soybean seedlings began to emerge one, two and five days after planting, respectively. All growth chambers were ventilated and exposed to the same room conditions, with an average daytime CO₂ concentration of approximately 450 $\mu\text{mol mol}^{-1}$ (ppm) measured

using a CO₂ probe (model GMP222; Vaisala Inc, Finland) and average relative humidity (RH) of 30% measured using a RH probe (model HMP110; Vaisala Inc, Finland). Dilute fertilizer solution was applied as needed to maintain ample root-zone moisture.

Light treatments. Warm, neutral, and cool white LEDs (Multicomp; Newark, Gaffney, SC) were used. Measurements of photosynthetic photon flux (PPF), yield photon flux (YPF), phytochrome photoequilibrium (PPE), relative (percent of total PPF) amounts of blue (400 to 500 nm), green (500 to 600 nm) and red (600 to 700 nm) light, and the *absolute* ($\mu\text{mol photons m}^{-2} \text{ s}^{-1}$) amount of blue light for all LED treatments in each growth chamber were made using a spectroradiometer (model PS-200; Apogee Instruments, Logan UT; Table 1). The spectral output of each LED type at both PPFs is shown in Figure 2. P_{fr}/P_{total} was measured using a red:far red sensor (SKR110; Skye Instruments, UK), which measures the red light from 630 to 665 nm and far red from 715 to 740 nm (Table 1). During the experiment, PPF was measured using a quantum sensor (LI-188B; LI-COR, Lincoln, NE) calibrated for each treatment against the spectroradiometer. PPF was maintained constant relative to the top of the plant canopy by adjusting the distance between the light source and the canopy. Variability of PPF within each growth chamber was less than 5% and root modules in each chamber were rotated 180° every three days. The photoperiod was 16-h day/8-h night.

Definition of Blue Light. Many previous studies have utilized light sources with UV radiation from either CWF or GF lamps (Yorio et al., 2001; Kim et al., 2004a, 2004b) or MH or HPS lamps (Brown et al., 1995; Schuerger et al., 1997; Dougher and Bugbee, 2001a and 2001b). Because UV-A radiation is often considered to be as effective as blue light for inducing some photomorphogenic responses, blue light has frequently been defined to include UV-A radiation (e.g. 320 to 500 nm). The LEDs in this study contained limited UV-A radiation so we defined blue light as 400 to 500 nm.

Plant Measurements. To minimize the effects of canopy closure in the radish and soybean experiment, four of the original nine plants were thinned at nine and ten days after emergence (DAE), respectively; no plants were thinned in the wheat experiment. For radish and soybean, leaf chlorophyll concentration index (CCI) of the first set of true leaves was measured with a portable chlorophyll meter (CCM-200; Opti-Sciences Inc., Hudson, NH). Experiments were terminated and the plants were harvested at canopy closure 14, 17, and 22 DAE for radish, soybean, and wheat respectively. For radish and soybean, total leaf area was measured following

harvest. The number and length of branches per plant per treatment were measured in soybean and the number of tillers per plant was determined for wheat. For all three species, separated stems and leaves (or tillers in wheat) were dried for 48 hours at 80°C and their dry weight was measured. Root weights were not measured.

Statistical Analysis. There was one replicate study for each species. The number of plants used to calculate the mean are specified in each figure caption. Data were plotted against both the *absolute* and the *relative* amount of blue light. Sigma Plot (version 12.0, SPSS Inc., Chicago, IL) was used to fit regression lines to each data plot. Following the methods used by Dougher and Bugbee (2001a), both graphs were visually compared and the best fit curve was selected as the most likely indicator for the observed photomorphogenic response.

RESULTS & DISCUSSION

Overall, blue light significantly altered development in soybean and radish while wheat was minimally responsive. Each developmental parameter responded differently to the *absolute* and *relative* amount of blue light. This study was conceptually similar to Dougher and Bugbee (2001a), but provided a more detailed and comprehensive analysis of developmental parameters and includes an additional species, radish. It also provides potentially cleaner results because filters were not required to achieve specific blue light levels.

Stem Length. For radish and soybean, *absolute* blue light was a better indicator of stem length than *relative* blue light (Figure 3). Stem length decreased with increasing *absolute* blue light up to 50 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and then remained constant. Interestingly, this response was observed even though phytochrome photoequilibria (PPE) was nearly constant across all three treatments (Table 1 and Figure 4). Wheat was minimally responsive to blue light (Figure 3), confirming the results of Dougher and Bugbee (2001a). Tamulaitis et al. (2005) saw similar results for blue light effects on radish stem length and Wheeler et al. (1991) and Dougher and Bugbee (2001a) saw similar results for soybean. However, Wheeler et al. (1991) reported that the *absolute* amount of blue light was a better indicator of soybean stem length while Dougher and Bugbee (2001a) found that the *relative* amount was a better predictor. The underlying cause for the differences among studies is unclear, but it may be associated with differences in the degree of canopy closure at harvest. Wheeler et al (1991) reported plant number but not growing area while Dougher and Bugbee (2001a) reported both plant number and growing area. Both of these

studies likely provided greater spacing between plants than in this study. The plants in this study formed a closed canopy prior to harvest.

Branching/Tillering and Haun Stage. In soybean, only branches ≥ 1 cm in length were counted. It appeared that branching was dependent on PPF. The number of branches per plant was uniform across all three high light treatments; however, branching was infrequent in the low light treatments (data not shown). In wheat, tillering was also dependent on PPF (tiller number was greater in the high light treatment). As blue light levels increased, the number of tillers produced by each plant increased slightly (data not shown). Tillers were only counted if ≥ 1 cm in length with the average number of tillers per plant calculated for each light treatment at high and low light. Haun stage followed the same trend as tiller number although not as dramatic (data not shown). It was impossible to determine whether these responses were due to the *absolute* or *relative* amount of blue light, but these results are comparable to Barnes and Bugbee (1992) and Dougher and Bugbee (2001a).

Leaf Area. In radish and soybean, *relative* blue light was a better indicator for leaf area (LA) than *absolute* blue light, but the species responded differently (Figure 5). In radish, leaf area decreased up to 15% blue light and then remained constant; in soybean, leaf area appeared to linearly decrease as *relative* blue light increased, and the effect was dependent on PPF. The unusually low point in the high light ($500 \mu\text{mol m}^{-2} \text{s}^{-1}$) treatment in both soybean graphs is attributed to experimental error rather than a blue light effect caused by neutral white LEDs. Unlike the effect of blue light on leaf area, radish cotyledon area was better predicted by *absolute* blue light and decreased as blue light increased up to $50 \mu\text{mol m}^{-2} \text{s}^{-1}$ (the same pattern as seen with stem elongation). LA was not measured in wheat. Although the shape of the curve for soybean in our study differs slightly from Dougher and Bugbee (2001a), these results confirm theirs in that *relative* blue light is a better indicator of leaf area than *absolute* blue light. We were unable to find any previous studies on the effects of blue light on radish development.

Carbon Partitioning to Leaves/Tillers. Percent leaf DW was better predicted by *absolute* blue light in radish and soybean, but the effects were in opposite directions (Figure 6). As *absolute* blue light increased, percent leaf DW decreased in radish and increased in soybean. As *absolute* blue light increased, percent tiller DW (an indication of branching) increased dramatically up to $100 \mu\text{mol m}^{-2} \text{s}^{-1}$. This dramatic increase was due to an increased number of tillers, not necessarily larger tillers. Yorio et al. (2001) saw the same trend in radish although

they were not able to determine whether *relative* or *absolute* blue light was a better indicator for the response. For soybean, Dougher and Bugbee (2001a) found a larger effect of blue light on carbon partitioning to leaves and associated it with *relative* blue light. Differences between studies could be due to spectral differences between the lamps used in their study (HPS and MH) and the white LEDs used in ours. Spectral differences can cause complex interactions that are difficult to explain (Dougher and Bugbee, 2001b). No studies report *absolute* blue light increasing percent tiller DW directly, but they do report increased tillering with increased blue light levels (Barnes and Bugbee, 1992).

Effect of PPF on Dry Weight. Surprisingly, there was no significant effect of blue light on total dry weight gain in any of the three species. Nevertheless, as expected, total dry weight (DW) increased with increasing PPF for all three species. For radish and soybean the relationship was nonlinear; for wheat the relationship was linear (Figure 7). Considering the significant effect of blue light on morphology, we were surprised to find that there was no significant effect of blue light on total DW. Although Dougher and Bugbee (2001a) saw significant effects of blue light on growth at extremely low blue light levels in soybeans and wheat, they also found no effect of blue light between 10 and 26%. These results warrant further investigation since the increase in leaf expansion in low blue light should result in increased radiation capture and thus increased dry weight gain.

Specific Leaf Area. Neither blue light parameter was a better indicator of specific leaf area (SLA). In general, as blue light increased, SLA decreased linearly in both radish and soybean. This response appeared to be dependent on PPF (data not shown). For the ranges of blue light levels used in this study, these results are comparable to Dougher and Bugbee (2001a) for soybean. No comparable literature was found which reported SLA for radish grown under varying amounts of blue light. SLA was not calculated for wheat.

Chlorophyll Concentration. Increased blue light decreased leaf area and slightly increased leaf DW (thus resulting in denser leaves). As a result, the concentration of chlorophyll per *unit leaf area* increased. Interestingly, this did not increase the amount of chlorophyll per *unit leaf mass*. Specific chlorophyll concentration (relative amount of chlorophyll g^{-1}), which was determined by taking the product of chlorophyll concentration index (CCI, relative amount of chlorophyll m^{-2}) and SLA ($\text{m}^2 \text{g}^{-1}$), was not affected by blue light (data not shown). As with SLA, CCI was equally predicted by both *absolute* and *relative* blue light. In general, for both

radish and soybean at high and low light, CCI linearly increased as blue light increased (data not shown). CCI was not measured in wheat because differences were not visually apparent. For soybean, these results differ from Dougher and Bugbee who reported no difference in chlorophyll concentration as blue light increased (2001a). No literature was found on CCI for radish grown under varying amounts of blue light. Since CCI was not measured for wheat, it could not be compared to the literature.

Phytochrome Photoequilibrium. It is unlikely that the variation in the amount of far red radiation (700 to 800 nm) between the three types of white LEDs contributed to photomorphogenic responses by affecting phytochrome. Differences were less than 0.02 (Table 1), indicating that any phytochrome involvement in the spectral responses observed in these studies would likely be negligible.

YPF/PPF Ratio and Photosynthetic Efficiency. The YPF/PPF ratio of our light sources varied by less than 6% (from 0.86 to 0.91; Table 1). For a given light source, YPF has the potential to provide a better indication of net photosynthesis than PPF because YPF weights the quantum yield (moles of carbon fixed per moles of photons absorbed) for each wavelength of light (McCree, 1972). Thus, YPF should provide a better estimate of the photosynthetic efficiency of a given light source than PPF, and DW gain should increase as YPF increases. We estimated photosynthetic efficiency by calculating dry weight gain per unit leaf area. Surprisingly, we found that photosynthetic efficiency slightly decreased as YPF increased, especially in high light (Figure 8). This indicates that neither YPF nor PPF was a good indicator of the photosynthetic efficiency of the light sources in this study. Our results suggest two things: one, that YPF may undervalue the efficiency of blue and green light in whole plants and plant communities, and two, that leaf expansion and radiation capture have a larger effect on growth than YPF.

CONCLUSIONS

Absolute versus Relative Amounts of Blue Light. Most, but not all, of our results are similar to Dougher and Bugbee (2001a). Both studies sought to determine the effect of blue light on plant development, but the primary objective of our study was to determine which developmental parameters are best predicted by *relative* blue light and which by *absolute* blue light. We found that some developmental responses were a combination of both, but others were

better predicted by one or the other. An increase in *absolute* blue light, up to $50 \mu\text{mol m}^{-2} \text{s}^{-1}$, better predicted a decrease in stem elongation in radish and soybean and also predicted a decrease in cotyledon area in radish. Furthermore, as *absolute* blue light increased, percent leaf DW decreased in radish and increased in soybean. In wheat, as *absolute* blue light increased, percent tiller DW increased dramatically up to $100 \mu\text{mol m}^{-2} \text{s}^{-1}$. However, an increase in *relative* blue light predicted a decrease in leaf area in radish and soybean. As blue light increased, chlorophyll concentration *per unit leaf area* (measured as CCI) increased, but chlorophyll concentration *per unit leaf mass* remained constant. Although an increase in blue light increased branching in soybean and tillering in wheat, and decreased SLA in radish and soybean, neither the *absolute* or *relative* amount of blue light better predicted any of these responses. As expected, growth increased with increasing PPF, but surprisingly, increasing blue light had no effect on total dry weight. Overall, PPF better predicted the photosynthetic efficiency of each light source than YPF. Because many developmental responses are determined by *absolute* blue light, our results also indicate that high PPF can partially substitute for low *relative* blue light in a given light source.

Manipulating Plant Growth and Development. It is clear that light quantity and quality interact to determine plant morphology. The optimal light spectrum for plant growth and development likely changes with plant age as plant communities balance rapid leaf expansion necessary to maximize radiation capture with prevention of excessive stem elongation. A thorough understanding of this balance is essential to the development of LED light sources for plant growth and development. Overall, the low blue light from warm white LEDs increased stem elongation and leaf expansion while the high blue light from cool white LEDs resulted in more compact plants. Initial growth under cool white LEDs should promote the growth of short, sturdy hypocotyls. Subsequent transition to warm white LEDs, should promote leaf expansion. Finally, after canopy closure, cool white LEDs should be used again to prevent excessive stem elongation. These effects could also be obtained by modulating the electrical current to red and blue monochromatic LEDs, thereby achieving different blue ratios without the requirement for two sets of LEDs.

White LEDs. Cool white LEDs may be the light source of choice because their high percentage of blue light (25%) means that they can meet the blue light requirements for normal development, even at low PPF. Furthermore, our measurements indicate that cool white LEDs

are more electrically efficient than the neutral and warm white LEDs (data not shown). The efficiency of LEDs is rapidly increasing and is approaching the efficiency of high pressure sodium lamps (Pimputkar et al., 2009). As the cost per photon decreases, we expect rapid incorporation into commercial applications.

LITERATURE CITED

- Barnes, C. and B. Bugbee. 1992. Morphological responses of wheat to blue light. *J. Plant Physiol.* 139:339-342.
- Barnes, C.; T.W. Tibbitts; J.C. Sager; G. Deitzer; D. Bubenheim; G. Koerner; B. Bugbee. 1993. Accuracy of quantum sensors measuring yield photon flux and photosynthetic photon flux. *HortScience.* 28(12):1197-1200.
- Barta, D. J.; T.W. Tibbitts; R.J. Bula; R.C. Morrow. 1992. Evaluation of light-emitting diode characteristics for a space-based plant irradiation source. *Adv. Spac. Res.* 12(5):141-149.
- Britz, S.J. and J.C. Sager. 1990. Photomorphogenesis and photoassimilation in soybean and sorghum grown under broad spectrum or blue-deficient light sources. *Plant Physiol.* 94(2):448-454.
- Brown, C. S.; A. Schuerger; J.C. Sager. 1995. Growth and photomorphogenesis of pepper plants under red LEDs with supplemental blue or far-red lighting. *J. Amer. Soc. Hort. Sci.* 120(5):808-813.
- Bula, R.J.; R.C. Morrow; T.W. Tibbitts; D.J. Barta; R.W.; R.W. Ignatius; T.S. Martin. 1991. Light-emitting diodes as a radiation source for plants. *HortScience.* 26(2):203-205.
- Dougher, T.A.O. and B. Bugbee. 2001a. Differences in the response of wheat, soybean, and lettuce to reduced blue radiation. *Photochem. and Photobiol.* 73(2):199-207.
- Dougher, T.A.O. and B. Bugbee. 2001b. Evidence for yellow light suppression of lettuce growth. *Photochem. & Photobiol.* 73(2):208-212.
- Goins, G. D.; N. C. Yorio; M. M. Sanwo; C. S. Brown. 1997. Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. *J. Expt. Bot.* 5:143-149.
- Hoenecke, M. E.; R.J. Bula; T.W. Tibbitts. 1992. Importance of 'blue' photon levels for lettuce seedlings grown under red-light-emitting diodes. *HortScience.* 27(5):427-430.
- Kim, H.H.; G. Goins; R. Wheeler; J.C. Sager; N. Yorio. 2004a. Green-light supplementation for enhanced lettuce growth under red and blue LEDs. *HortScience.* 39(7):1617-1622.
- Kim, H.H.; G. Goins; R. Wheeler; J.C. Sager. 2004b. Stomatal conductance of lettuce grown under or exposed to different light qualities. *Annals of Botany.* 94:691-697.

- Kim, H.H.; R. Wheeler; J.C. Sager; N. Yorio; G. Goins. 2005. Light-emitting diodes as an illumination source for plants: A review of research at Kennedy Space Center. *Habitation*.10:71-78.
- Massa, G.D.; J.C. Emmerich; R.C. Morrow; C.M. Bourget; C.A. Mitchell. 2006. Plant-growth lighting for space life support: A review. *Grav. and Spac. Biol.* 19(2):19-29.
- McCree, K. J. 1972. The action spectrum absorptance and quantum yield of photosynthesis in crop plants. *Agric. Meteorol.* 9:191-216.
- Pimputkar, S., J. S. Speck, S. P. DenBaars, and S. Nakamura. 2009. Prospects for LED lighting. *Nature photonics*. 3(4):180-182.
- Sager, J. C.; W.O. Smith; J.L. Edwards; K.L. Cyr. 1988. Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data. *Transactions of the ASAE*. 31(6):1882-1889.
- Schuerger, A.C.; C.S. Brown; E.C. Stryjewski. 1997. Anatomical features of pepper plants (*Capsicum annuum* L.) grown under red light-emitting diodes supplemented with blue or far-red light. *Annals of Botany*. 79:273-282.
- Tamulaitis, G.; P. Duchovskis; Z. Bliznikas; K. Breive; R. Ulinskaite; A. Brazaityte; A. Novickovas; A. Zukauskas. 2005. High-power light-emitting diode based facility for plant cultivation. *J. Phys. D: Appl. Phys.* 38:3182-3187.
- Yorio, N.C.; R. Wheeler; G. Goins; M. Sanwo-Lewandowski; C. Mackowiak; C. Brown; J.C. Sager; G. Stutte. 1998. Blue light requirements for crop plants used in bioregenerative life support systems. *Life Sup. and Biosph. Sci.* 5:119-128.
- Yorio, N.C.; G. Goins; H. Kagie; R. Wheeler; J.C. Sager. 2001. Improving spinach, radish, and lettuce growth under red LEDs with blue light supplementation. *HortScience*. 36(2):380-383.
- Wheeler, R.M.; C.L. Mackowiak; J.C. Sager. 1991. Soybean stem growth under high-pressure sodium with supplemental blue lighting. *Agron. J.* 83:903-906.

TABLES & FIGURES

Table 1. Spectral characteristics of warm, neutral, and cool white LEDs at two photosynthetic photon fluxes (200 and 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$). For a discussion on the difference between photosynthetic photon flux (PPF) and yield photon flux (YPF), see Barnes et al. (1993). Yield photon flux (YPF) and phytochrome photoequilibrium (PPE) were determined according to Sager et al. (1988).

LED Type	PARAMETER								
	PPF	YPF	YPF/PPF	PPE	R:FR	Amount Blue	% of Total PPF		
	$\mu\text{mol m}^{-2} \text{s}^{-1}$		Ratio	P_{fr}/P_{total}	Ratio	$\mu\text{mol m}^{-2} \text{s}^{-1}$	Blue	Green	Red
Warm	200	180	0.90	0.84	5.10	22.6	11.3	42.8	45.9
Neutral	200	176	0.88	0.84	5.60	38.2	19.1	47.9	33.0
Cool	200	172	0.86	0.83	6.10	55.6	27.8	49.0	23.2
Warm	500	455	0.91	0.84	4.71	49.0	9.80	41.3	48.9
Neutral	500	440	0.88	0.84	5.11	89.5	17.9	46.6	35.5
Cool	500	430	0.86	0.83	5.73	125.0	25.0	49.6	25.4



Figure 1. *Experimental set-up showing growth chambers, LED arrays, root modules, and thermocouples. The crop shown is radish on the day of harvest. Note the differences in plant form across treatments, which are arranged (left to right) warm, neutral, and cool white LEDs.*

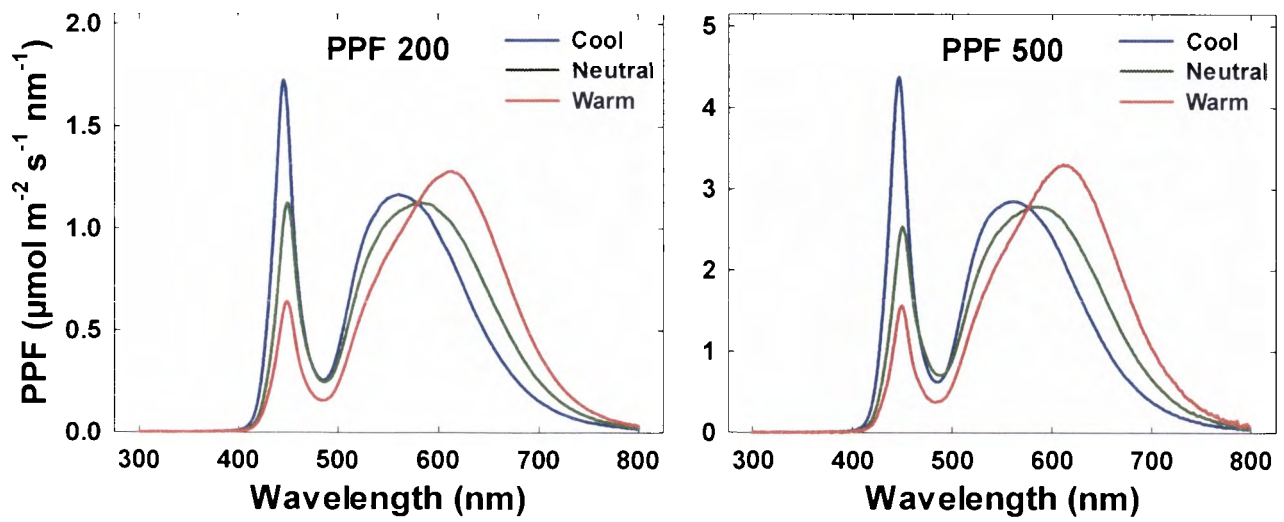


Figure 2. Spectral distribution of warm, neutral, and cool white LEDs at 200 and 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Both spectra are shown because over-driving the LEDs to achieve 500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ caused a slight spectral shift in all three LED types.

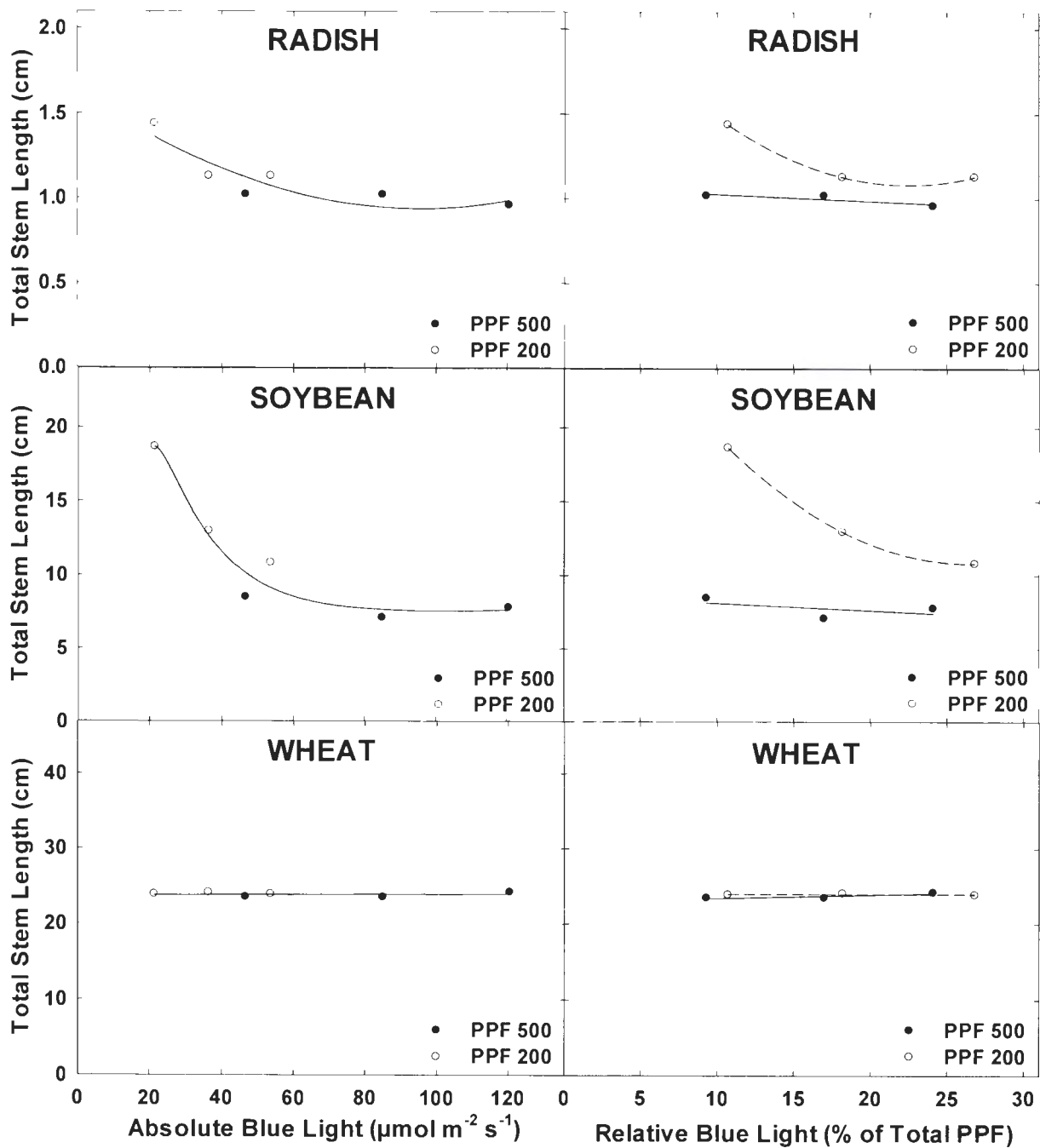


Figure 3. The effect of absolute and relative blue light on stem length in radish, soybean, and wheat. For radish and soybean, each data point represents the average of five plants with measurements taken 14 and 17 DAE, respectively; for wheat, each data point represents the average of 12 plants grown for 22 DAE. Stem length was better predicted by absolute blue light than relative blue light. Wheat was unaffected by blue light.

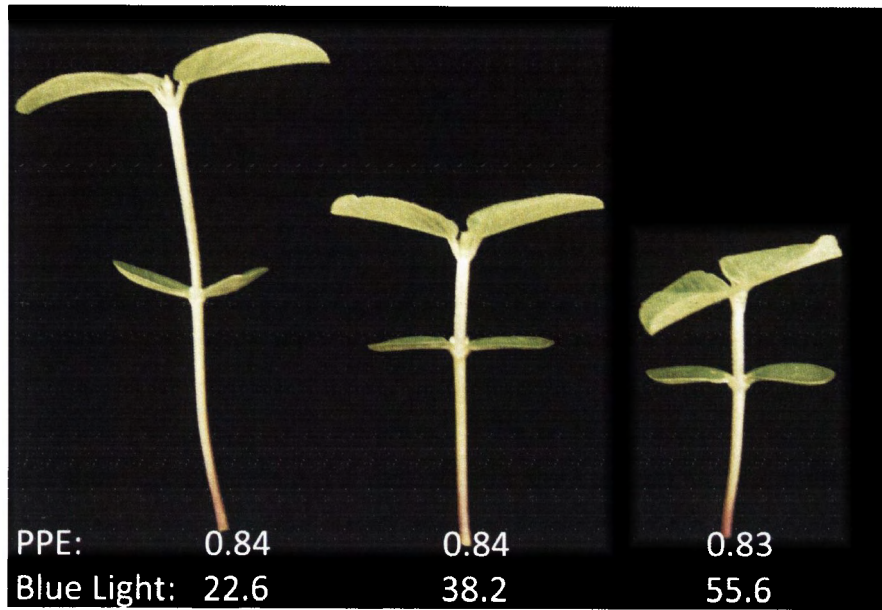


Figure 4. *The effect of absolute blue light ($\mu\text{mol m}^{-2} \text{s}^{-1}$ of blue photons) on soybean stem length at 9 DAE in the low light treatment ($200 \mu\text{mol m}^{-2} \text{s}^{-1}$). Stem elongation decreased with increasing blue light even though phytochrome photoequilibria (PPE) was nearly constant across treatments.*

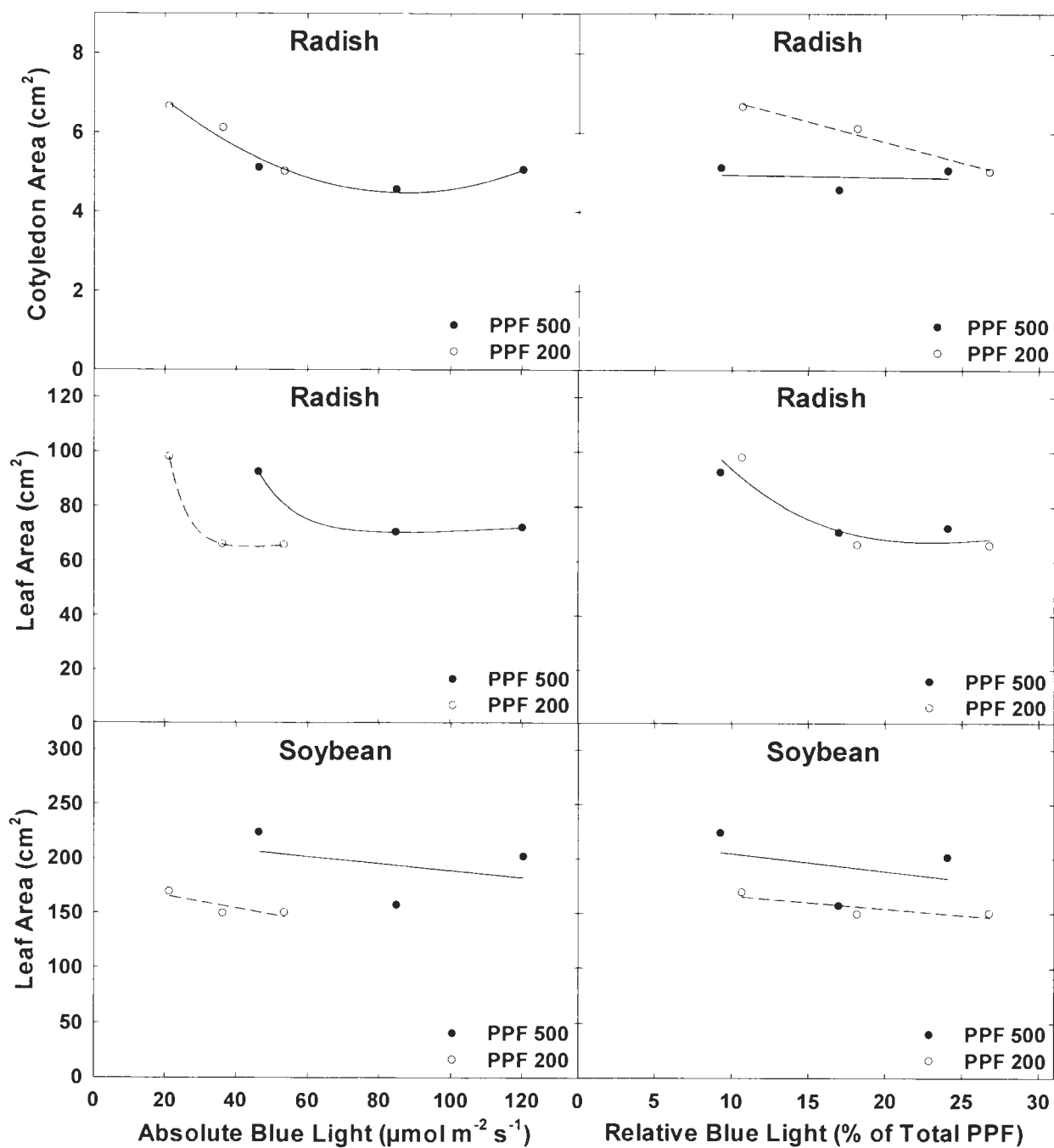


Figure 5. Effect of absolute and relative blue light on cotyledon and leaf expansion. For radish and soybean each data point represents the average of five plants with all measurements taken 14 and 17 DAE, respectively. Leaf area was not measured for wheat. The unusually low point in the high light ($500 \mu\text{mol m}^{-2} \text{s}^{-1}$) treatment in both soybean graphs is attributed to experimental error rather than a blue light effect caused by neutral white LEDs.

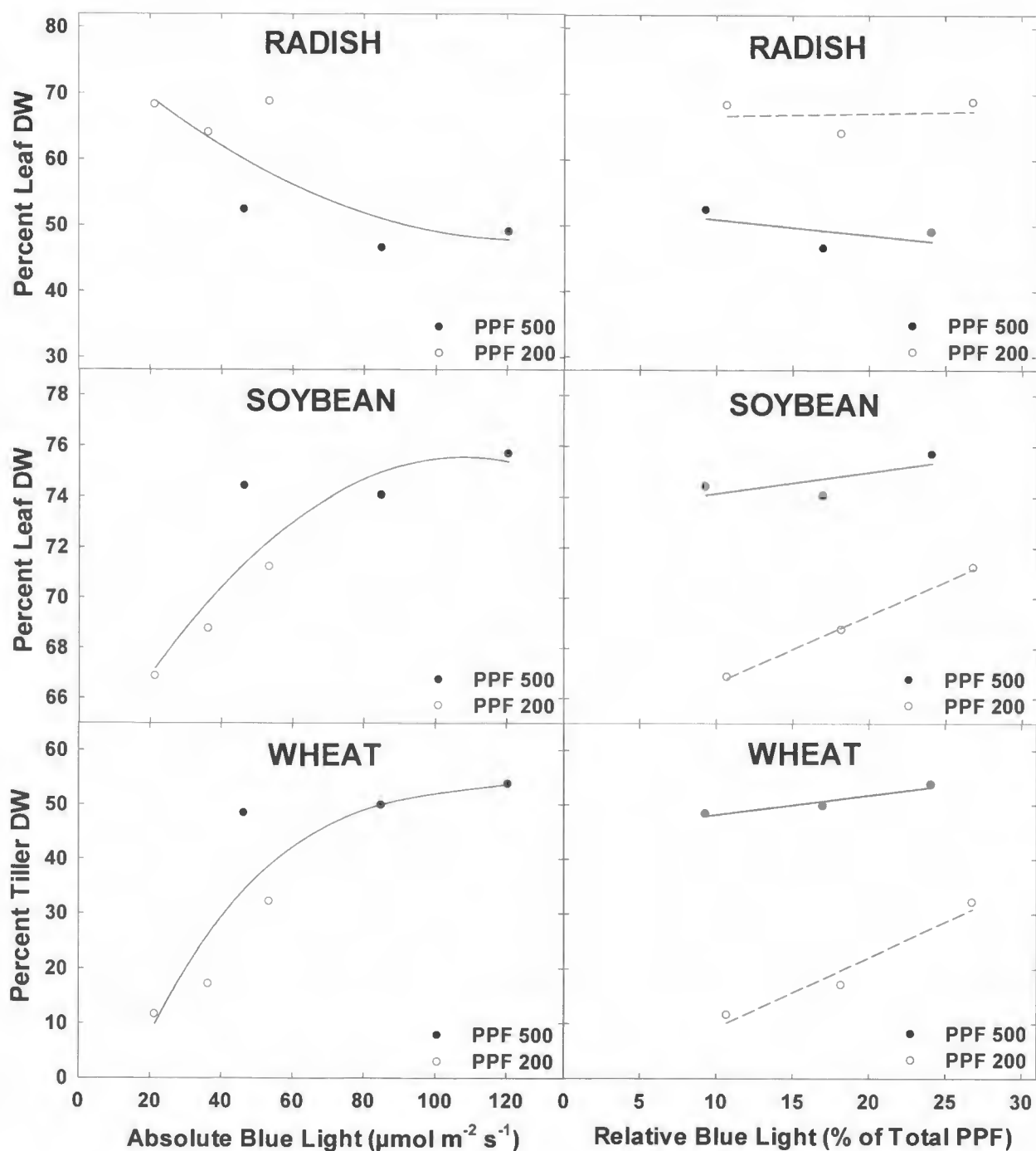


Figure 6. Effect of absolute and relative blue light on percent leaf dry weight in radish and soybean and percent tiller dry weight in wheat. For soybean and radish, each data point represents the average of five plants with measurements taken 14 and 17 DAE, respectively; for wheat, each data point represents the average of 12 plants with measurements taken 22 DAE.

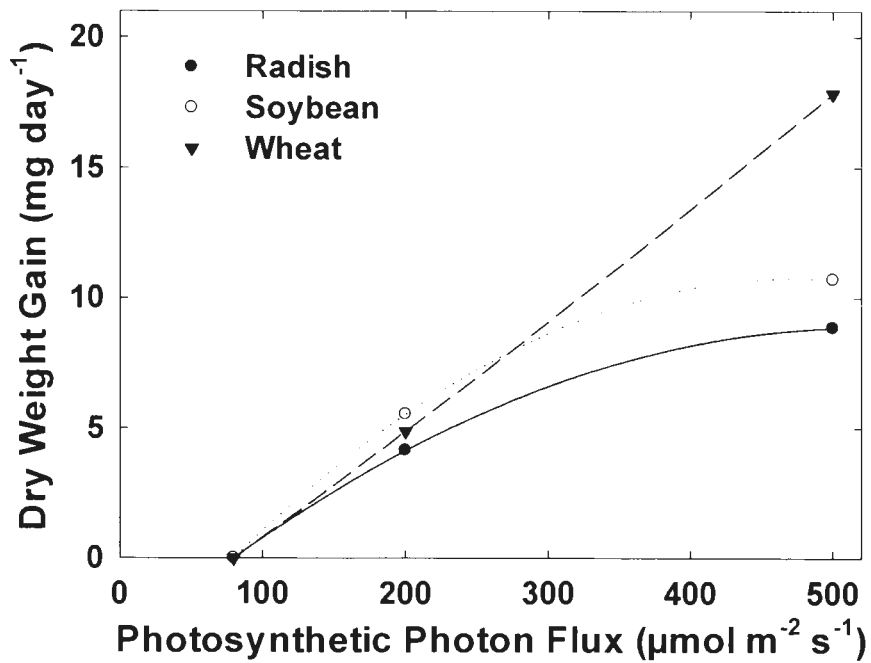


Figure 7. *The effect of photosynthetic photon flux (PPF) on dry weight gain. For soybean and radish, each data point represents the average of five plants with measurements taken 14 and 17 DAE, respectively; for wheat, each data point represents the average of 12 plants with measurements taken 22 DAE. The whole plant light compensation point was estimated at 80 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for all three species.*

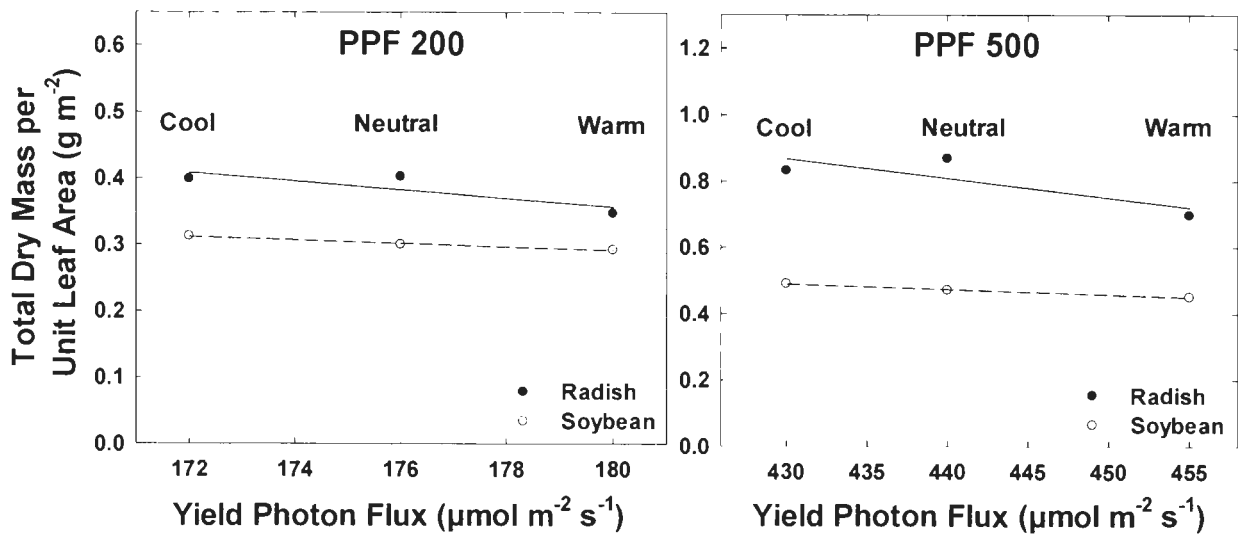


Figure 8. *The effect of yield photon flux (YPF) on total dry mass per unit leaf area. If YPF is an effective predictor of photosynthetic efficiency, the lines should increase with increasing YPF. The downward slope of these lines indicates that other photobiological factors have a larger effect on photosynthesis than YPF. YPF may undervalue the efficiency of blue and green light in whole plants and plant communities.*

AUTHOR'S BIOGRAPHY

Kevin Cope was raised in Salem, UT, which is where he developed a strong interest in plants and biology in general. He was highly successful in his academic studies and maintained a 4.0 GPA through graduation with high honors from Spanish Fork High School in May 2007. While in high school, Kevin simultaneously completed an Associate of Science Degree in General Studies with high honors from Utah Valley University. His academic achievements earned him the New Century scholarship and after applying to Utah State University he was also awarded the Presidential Scholarship and an Undergraduate Research Fellowship.

As an active member of the USU Honors program, Kevin earned a dual-major in Plant Science (emphasis: Research) and Biology. He also earned two minors in Chemistry and Crop Biotechnology. As an undergraduate, at the national level, Kevin was associated with the American Society of Horticultural Science (ASHS), the American Society of Plant Biologists (ASPB), and the International Plant Propagator's Society-Western Region (IPPS-WR). He was selected as one of two students nationwide to receive the ASHS Scholars Award in 2012. That same year, he was also awarded the Bruce Brigg's Memorial Scholarship from the IPPS-WR. Within the College of Agriculture, Kevin excelled in undergraduate research and was selected as the 2012-2013 Undergraduate Researcher of the Year.

Kevin will graduate in May 2013 with a 3.90 GPA, Magna Cum Laude distinction, and Honors in University Studies and Departmental Honors. By the time he begins his Ph.D. at the University of Wisconsin-Madison in August 2013, he will have published four papers in peer-reviewed journals, two extension publications, and an article in the 2012 IPPS Conference Proceedings. He plans to earn his Ph. D. in Cellular and Molecular Biology and will work on a project entitled: "Poplar (*Populus* sp.) as a model to dissect ectomycorrhizal symbiotic signaling in woody perennials." Kevin looks forward to a career in academia and is excited to spend his time researching and teaching in the field of plant science.