From Forest Nursery Notes, Summer 2013

108. © Spectral effects of three types of white light-emitting diodes on plant growth and development: absolute versus relative amounts of blue light. Cope, K. R. and Bugbee, B. HortScience 48(4):504-509. 2013.

HORTSCIENCE 48(4):504–509. 2013.

Spectral Effects of Three Types of White Light-emitting Diodes on Plant Growth and Development: Absolute versus Relative Amounts of Blue Light

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Additional index words. radish, *Raphanus sativus*, soybean, *Glycine max*, wheat, *Triticum aestivum*, light-emitting diodes, photobiology, stem elongation

***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*). We report the photobiological effects of three types of white LEDs (warm, neutral, and cool, with 11%, 19%, and 28% blue light, respectively) on the growth and development of radish, soybean, and wheat. All species were grown at two *PPFs* (200 and 500 μmol·m^{-2}·s^{-1}) under each LED type, which facilitated testing the effect of absolute (μmol photons per m^{-2}·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 × 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, whereas 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 μmol·m^{-2}·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 because 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.**

The application of LEDs for plant growth lighting has been studied for over two decades (Barta et al., 1992; Bula et al., 1991). 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 and Sager, 1990), soybean (Britz and Sager, 1990; Dougher and Bugbee, 2001a; Wheeler et al., 1991), wheat (Barnes and Bugbee, 1992; Dougher and Bugbee, 2001a; Goins et al., 1997), lettuce (Dougher and Bugbee, 2001a; Hoenecke et al., 1992; 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 per m^{-2}·s^{-1} between 400 and 500 nm) rather than the relative amount of blue light (percent of total *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 photoequilbria). 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 μmol·m^{-2}·s^{-1}. Blue light did not affect total DW, 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 and 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 h, respectively, and subsequently transplanted to root modules measuring 15 × 18 × 9 cm (length × weight × height; 2430 cm^3). For the radish and soybean experiments, nine seeds were planted in each root module and for the wheat experiment, 12 seed were planted in each root module. All root modules were filled with soilless media (one peat:one 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·m^{-1} (1.0 and 1.5 mmhos·cm^{-1}). After planting, each root module was randomly placed within one of six growth chambers, which measured 18 × 20 × 26 cm (9360 cm^3) for the 200 μmol·m^{-2}·s^{-1} treatments and 20 × 23 × 30 cm (13,800 cm^3) for the 500 μmol·m^{-2}·s^{-1} treatments (Fig. 1). The inside of all chambers was lined with

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Received for publication 4 Dec. 2012. Accepted for publication 31 Jan. 2013.
This research was supported by the Utah Agricultural Experiment Station, Utah State University. Approved as journal paper no. 8510.
We thank Caleb Knight, Ty Weaver, and Alec Hay for their engineering support and the Space Dynamics Laboratory at Utah State University for helping initiate this project.

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